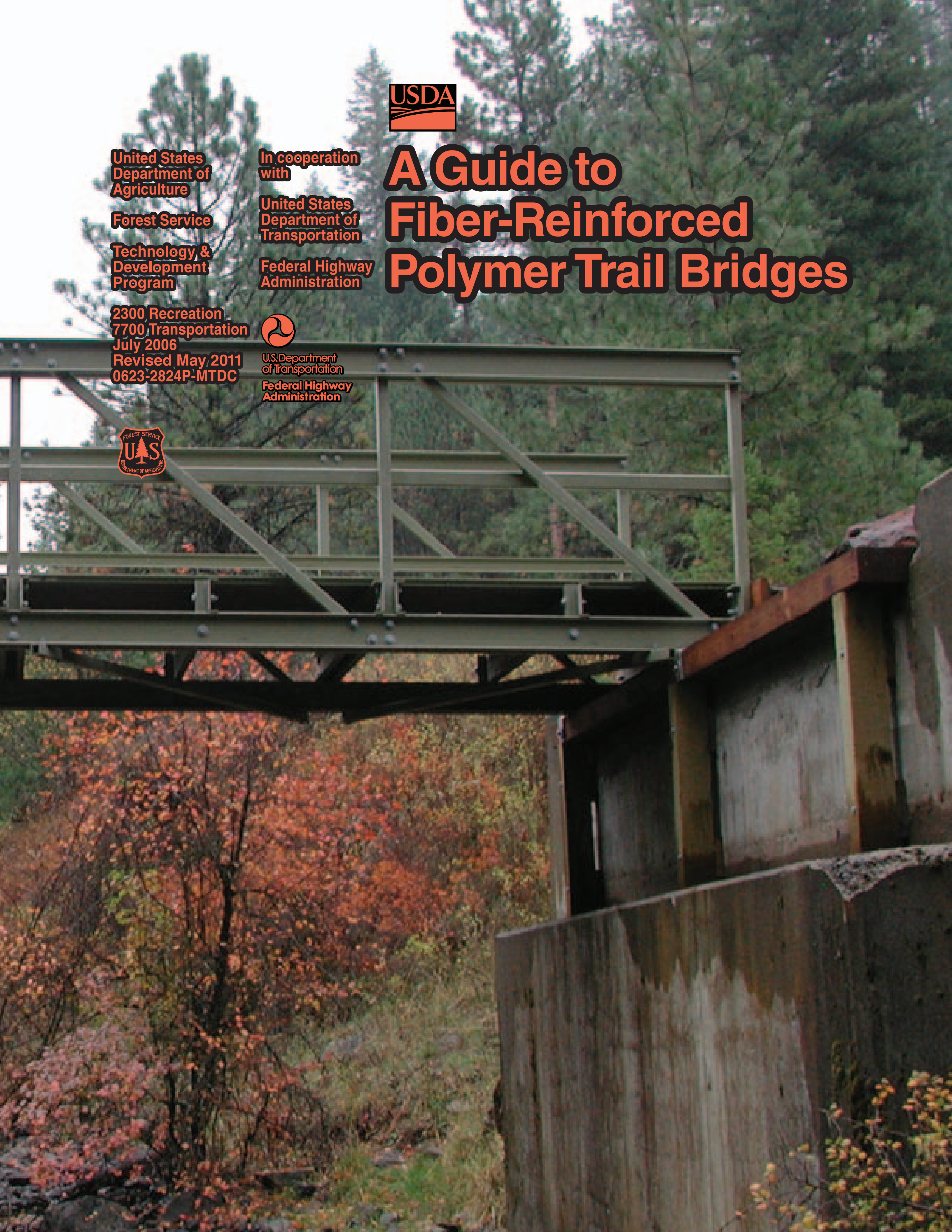

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A Guide to Fiber-Reinforced Polymer Trail Bridges

This document was produced in cooperation with the Recreational Trails Program of the Federal Highway Administration, U.S. Department of Transportation.

Notice

U.S. Department
of Transportation
**Federal Highway
Administration**

A Guide to Fiber-Reinforced Polymer Trail Bridges

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Contents

Introduction

Figure 1—A fiber-reinforced polymer trail bridge in the Santa Fe National Forest.

Trail bridges (figure 1) not only provide convenient access to the national forests for hikers or packstock, but also can protect fragile riparian ecosystems. Trail bridges can be difficult—in some cases, dangerous—to build. The bridges may be miles from a trailhead. Hauling the bridge materials on packstock through steep, rugged country and relying only on human power for assembly and installation makes the work challenging. Helicopters can't be used in wilderness areas without permission of the forest supervisor, and they may be too expensive for some projects even where they can be used.

Historically, trail bridges were built from native logs cut on the site. Most areas do not have logs that are strong enough to span longer crossings. In addition, trail bridges made from native logs may have a life expectancy of no more than 5 to 15 years. At some sites, repeated replacement of bridges made from

Highlights...

- Fiber-reinforced polymer trail bridges are lighter and easier to assemble than traditional bridges built from wood or steel.
- At some remote sites, the advantages of light weight and ease of assembly may make fiber-reinforced polymer trail bridges a better alternative than wood or steel bridges.
- Wood for bridges made from native materials may be in short supply at some remote sites.
- Fiber-reinforced polymer materials are easy to damage when they are being transported to the bridge site and when they are being assembled.
- This report includes the results of controlled tests and case studies of field installations of fiber-reinforced polymer bridges.

native logs has left small clear cuts around the bridge site. Increasing recreational use and tightened budgets also contribute to the need for lightweight, low-maintenance bridges that are easy to construct.

Fiber-reinforced polymer (FRP) bridges, commonly called *fiberglass bridges,* offer a potential solution. FRP trail bridge members are fabricated from reinforcing resins (commonly referred to as polymers or plastics) and strands of materials (usually fiberglass) with tensile and bending strengths comparable to those of steel or concrete.

FRP materials are lightweight and durable. Common shapes match those of the rolled steel materials used for trail bridge components, such as tubes, channels, *W* shapes, and angles. The lightweight FRP structural members are easier to transport to remote locations than common bridge materials, such as steel or timber. In addition, their light weight makes them simpler and safer to assemble.

During the 1990s, several national forests and national parks installed FRP trail bridges, but very little was known about their design or long-term durability. An evaluation was needed to verify that FRP trail bridges were acceptable, safe, and economical.

In 1997, the Fiber-Reinforced Polymer Trail Bridge Project at the Missoula Technology and Development Center (MTDC) began evaluating the feasibility of FRP materials for trail bridges used by the U.S. Department of Agriculture (USDA), Forest Service and the U.S. Department of the Interior, National Park Service. One of the project's first accomplishments was to arrange a partnership with the U.S. Department of Transportation's Federal Highway Administration (FHWA), Eastern Federal Lands Highway Division, Bridge Design Group to jointly design, fund, test, and install prototype trail bridges.

A 44-foot bridge was funded and designed by the FHWA. A 22-foot bridge was purchased by the Forest Service as an "off-the-shelf" bridge designed by E.T. Techtonics, Inc., a major supplier of FRP trail bridges.

A second partnership with FHWA's Recreational Trails Program helped to fund this project and disseminate the results.

The plan for these prototype bridges was to:

1—Have an experienced bridge-design group review the available design information and develop a design and drawings.

2—Install the bridges at a test facility and monitor bridge behavior under design loading and severe environmental conditions.

3—Install the bridges at field locations to determine installation strategies and techniques.

4—Monitor the field installations to determine unique maintenance requirements.

5—Publish a guide explaining FRP technology and presenting design methodologies, performance-based specifications for purchasing materials, and recommendations for installation and maintenance.

Background on FRP Trail Bridges

The first FRP pedestrian bridge was constructed in Israel in 1975. Since then, FRP pedestrian bridges have been constructed in Asia, Europe, and North America. A list of FRP pedestrian bridges constructed in the United States is included in appendix E. Composites may form all or part of a bridge, such as the deck or tower columns of a bridge that uses other standard materials, such as timber or steel. FRP technology is being used in both trail and road bridges. FRP bridge superstructures typically are made with vinyl ester or polyester resin reinforced with E-glass fiber. They are engineered and prefabricated before being assembled and installed at a bridge site.

Composites at a Glance

The most common and readily available FRP material is referred to simply as fiberglass. Fiberglass is a composite with a polymer resin matrix that surrounds, coats, and is reinforced by glass fibers (figure 2).

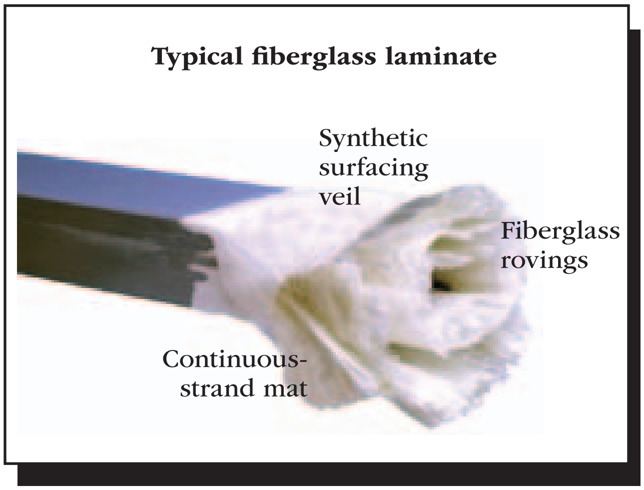


Figure 2—The composition of FRP materials.—*Courtesy of Strongwell*

Although resin alone would be strong enough for some applications, bridges require reinforcing fibers. While many fibers could reinforce resins, the low cost of glass fiber makes it the primary reinforcement used in FRP bridge components. The E-glass fibers are good electrical insulators and have low susceptibility to moisture damage and high mechanical strength. The amount of fiber in composites used for structural applications ranges from 45 to 75 percent. The type of resin determines corrosion resistance, resistance to flame, and maximum operating temperature, while contributing significantly to other characteristics, including resistance to impacts and fatigue.

The strength of FRP materials, including fiberglass, is determined by the type, orientation, quantity, and location of the reinforcing fibers. Reinforcing fibers are primarily longitudinal, creating members having very high tensile strength. The resin binds the reinforcing fibers in a matrix and provides some rigidity. Fiberglass weighs between one-fourth and one-fifth as much as steel, but has similar strength. The modulus of elasticity of fiberglass is similar to concrete and about one-eighth that of steel.

Fiberglass members have a surface layer of polyester fabric and resin (a surface veil) to protect against corrosion, water intrusion, and degradation by ultraviolet (UV) light. The glass fibers carry the loads imposed on the composite (impact strength, stiffness, and tension), while the resin matrix serves as a binder to distribute the load across all the fibers in the structure.

Many FRP bridges are composed of closed-section shapes (tubes). These shapes provide better buckling and torsional characteristics than do open shapes such as *W* shapes or channels (figure 3). Sometimes, open sections are used for bridges, but closed sections should be used whenever possible.

The two main manufacturing processes for composites are pultrusion and extrusion. FRP composite products usually are produced by pultrusion, while some other composite products, such as wood-plastic decking and siding, typically are produced by

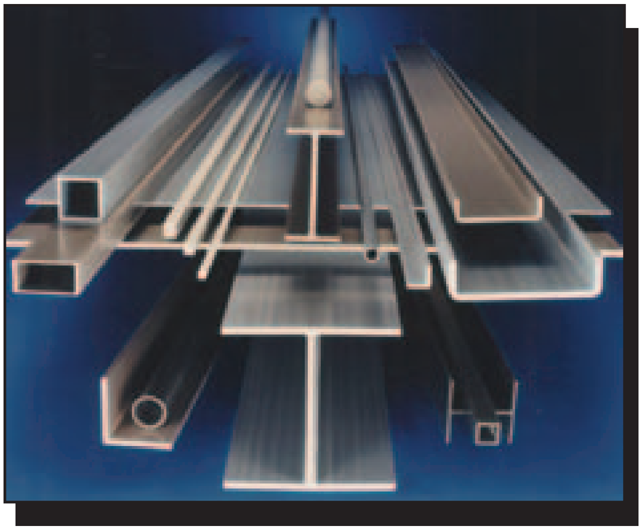


Figure 3—Some different shapes (open and closed) for FRP members. —*Courtesy of Strongwell*

extrusion. Pultrusion is a manufacturing process (figure 4) for producing continuous lengths of FRP structural shapes with constant cross sections, such as rods, beams, channels, and plates.

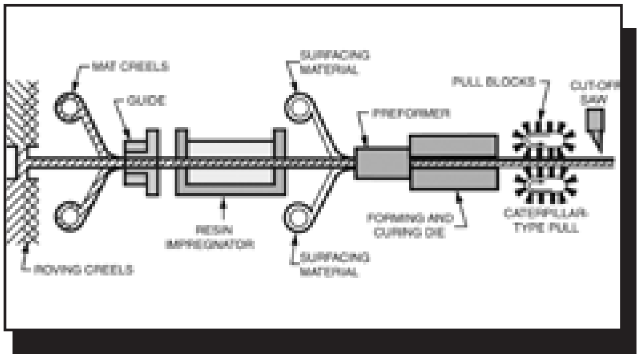


Figure 4—The pultrusion process for manufacturing FRP.—*Courtesy of Strongwell*

Pultrusion

The raw materials used to manufacture FRP members are a liquid resin mixture (containing resin, fillers, and special additives) and flexible textile reinforcing fibers. Pultrusion involves using a continuous pulling device to pull these raw materials through a heated steel-forming die. The reinforcing fibers are in continuous forms, such as rolls of fiberglass mats, called *doffs*. The reinforcing fibers are pulled through a resin bath that saturates (wets out) the fibers with a solution containing the resin, fillers, pigment, catalyst, and any other additives.

A preformer squeezes away excess resin and gently shapes the materials before they enter the die. In the die, the reaction that sets the resin is activated by heat and the composite is cured (hardened). The cured shape (profile) is pulled through a saw that cuts it to length. The hot material needs to be cooled before it is gripped by the pull block (made of durable urethane foam) to prevent the pull blocks from cracking or deforming the FRP materials. For more indepth information on composites, see the *Introduction to Composites* by the Composites Institute of the Society of the Plastics Industry, Inc. (1998).

Advantages of FRP Materials

The advantages of composites in trail bridge applications include their light weight (figure 5), high strength, resistance to corrosion, and fast, easy installation. These properties make them competitive with standard bridge materials in situations where access and construction present difficulties. Composite materials can be designed to provide a wide range of tensile, flexural, impact, and compressive strengths. They can be formed into any shape and colorants can be added to allow the structures to blend with most landscapes. The use of composites prevents large trees from being overharvested near bridge sites and eliminates any potential environmental impacts of treated wood or galvanized steel used in riparian environments. Composites cost less than stainless or high-carbon alloy steel components that might be used in highly corrosive environments.

Figure 5—FRP members are lightweight and can be lifted by hand.

Disadvantages of FRP Materials

One disadvantage of FRP materials is their relatively high cost compared to wood or unpainted low-carbon steel. Other disadvantages include:

- The need for different saw blades and drill bits than those used with wood or steel.

- Bridge designs controlled by the amount of deflection rather than the strength needed to keep the bridge from failing (because of the flexibility of FRP materials).

- Proprietary bridge designs (rather than designs based on standard specifications).

- Limitations on enviromechanical performance.
  - —At high temperatures the material's strength decreases and deflection increases.
  - —These materials continue deflecting under heavy, sustained loads (creep).
  - —Impact loading during collisions can damage these materials.

- Limited experience with FRP materials in the construction design industry.

- Lack of design standards and codes.

- Lack of performance history.

Cost

FRP trail bridges cost about as much as equivalent steel bridges and almost twice as much as timber bridges. Costs for remote trail bridges are very difficult to compare because installation costs can be as high as 50 to 70 percent of the bridge's total cost. Maintenance costs for FRP composite bridges can be less than the maintenance costs for wood or timber bridges. In addition, fiberglass components are easy to transport and install, which can represent potential cost savings compared to transporting and installing timber or steel components.

The materials for a 30-foot-long by 3-foot-wide fiberglass side truss bridge (with a design loading of 125 pounds per square foot) might cost $117 per square foot. The materials for a comparable glue-laminated beam type of bridge could cost just $65 per square foot. The heaviest piece of fiberglass would weigh 80 pounds, while the glue-laminated beams for a comparable timber bridge would weigh 1,200 pounds.

Planning, Ordering, and Installing FRP Trail Bridges

In the Forest Service, the recreation program has the responsibility for planning and conducting environmental analyses for trail bridges. The forest engineer is responsible for ensuring that a site survey and hydraulic and geotechnical investigations are completed for each bridge site.

FRP trail bridges in national forests require specific approvals. The Forest Service Manual 7722 requires regional director of engineering approval of all "major and complex" trail bridges and forest engineer approval of all "minor" trail bridges. Because of their uniqueness, FRP bridges are considered a complex trail bridge (from the trail bridge matrix). The authority for designing and inspecting trail bridges falls under Forest Service Manual 7722 for design and Forest Service Manual 7736 for inspection.

All Forest Service FRP trail bridges should be added to the trails INFRA database, and inspected within the required inspection interval by qualified, certified bridge inspectors.

Planning

Proper planning for trail bridges should be a joint effort between specialists in recreation, engineering, and other resources. To ensure proper siting, include trail managers, hydrologists, soil scientists, archeologists, and wildlife biologists during planning.

Proper sizing and location of the bridge are an important part of its design. Consider adequate clearances for flooding and for ice and debris flow in the bridge's design and layout. The forest engineer is responsible for selecting the foundation and its design, along with the hydraulic design. A full hydraulic analysis for 100-year floods and debris is needed.

Types of Composite Bridges

FRP structural profiles are designed using traditional framing systems (such as trusses) to produce FRP pedestrian bridges. The selection and design of the truss system depends on the needs of the owner, the bridge's loading, and the site conditions.

The two basic types of FRP pedestrian bridges are the deck-truss and side-truss (pony-truss) bridges. Deck-beam FRP bridges have been used for boardwalks, but are rarely used for trail bridges (figure 6).

Figure 6—This boardwalk on Staten Island was constructed using an FRP deck-beam system.—*Courtesy of E.T. Techtonics, Inc.*

Deck-truss bridges have fiberglass trusses and cross bracing under the deck with handrails attached to the decking (figure 7). Side-truss bridges have the superstructure trusses on the sides of the bridge. Pedestrians walk between the trusses (figure 8). Refer to the *Trail Bridge Catalog* (*http://www. fs.fed.us/eng/bridges/*) for more detailed descriptions of these bridges.

Bridge configurations are a major concern for longer spans. For spans of 30 feet or more, side-truss FRP bridges should have outriggers at all panel points (see figure 8) to provide lateral restraint for the compression flanges. FRP bridges longer than 60 feet that

Figure 7—A deck-truss FRP bridge in Olympic National Park. This bridge uses FRP materials for the trusses and wood for the rails, maintaining a natural appearance for a high-tech structure.

Figure 8—A side-truss FRP bridge in the Gifford Pinchot National Forest.

are used by pack trains should have a deck-truss design. That design places the trusses under the deck, increasing restraint on the compression flanges (see figure 7) and increasing the frequency characteristics of the bridge, an important consideration for the live loads generated by pack trains.

FRP bridges are not recommended for bridges longer than 50 feet in areas where snow loads are more than 150 pounds per square foot. The walkway wearing surface or decking can be designed using wood or FRP composite panels or open grating, depending on the bridge requirements.

Delivery Methods

Fully assembled bridges come as a complete unit and are delivered to the nearest point accessible by truck. A small crane or helicopter (figures 9 and 10) can place the bridge on its foundation. Decking may be shipped separately to minimize lifting weight. Depending on the location, shipping the bridge and decking separately may increase the shipping cost. Fully assembled bridges should be built by a contractor who has the heavy equipment required for this task.

Figure 9—A helicopter carrying a trail bridge.

Figure 10—A track hoe placing a trail FRP bridge on its abutments.

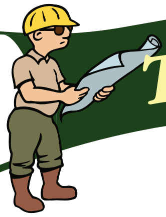
Partially assembled bridges typically are delivered as individual assembled trusses. All other connecting components, such as crosspieces, bracing, and decking, are shipped separately. Sometimes carts, all-terrain vehicles (ATVs), or trailers can haul the trusses to the jobsite. This method is not suitable for moving trusses long distances or over rough terrain, but may allow a volunteer construction crew to transport the structure short distances and install it.

The most common approach is to have individual components shipped separately. They can be unloaded from the trucks by as few as two workers, usually at the trailhead or a nearby staging area. No special equipment will be needed to unload the components, and delivery of the bridge's components does not need to be coordinated with the bridge's assembly. Volunteers or force-account crews can carry the components to the bridge site. This method of construction works best for remote sites with limited access. Once everything is at the site, the bridge can be assembled easily using standard handtools. Spans up to 40 feet long usually can be built in less than a day by as few as three workers.

Ordering an FRP Trail Bridge

Some of the most important considerations before deciding what type of materials to use for your bridge are ease of construction, the weight of the materials, the risk of impact damage, and cost. Because an FRP deck or superstructure may cost more than wood and as much as steel, part of the scoping process involves evaluating all costs associated with a project, including the costs of all available types of material for the trail bridge.

An FRP trail bridge should be ordered using standard contract specifications. An example of a CSI specification from E.T. Techtonics, Inc., is included in appendix C. Other suppliers are listed in appendix G.



Things to Consider...

1—Does an FRP bridge meet the visual, aesthetic, or Built Environment Image Guide (BEIG) considerations for this site?
2—How long does the bridge need to be?
3—What type of live loads will the bridge be subjected to?
  —Will the bridge be used only by pedestrians?
  —Will horses, pack trains, ATVs, snowmobiles, motorcycles, bicycles, or other vehicles use the bridge?
4—What are the snow loads for the area? Has a facilities engineer or local building official been contacted to learn the required snow loads for the area? Required snow loads can be checked on MTDC's *National Snow Load Information* Web site at: *http://www.fs.fed.us/eng/snow_load/*
5—What type of FRP bridge should be used (deck truss or side truss)?
6—How wide will the deck need to be and what type of deck material should be used? Should the deck include a wearing surface for horses, ATVs, or snowmobiles?
7—What type of railing system is required?
8—Are wood curbs required to protect FRP trusses from ATVs?
9—Will it be more practical to order the bridge fully assembled, partially assembled, or unassembled?

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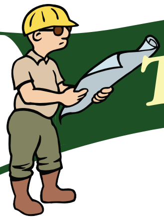

Things to Consider...

10—Have the plans been stamped by a professional engineer who has experience with FRP and pedestrian bridge design? In the case of Forest Service bridges, has the design been reviewed by the required authorities?

11—What is the climate at the bridge site? What are the highest temperatures? How long do those temperatures last? How much exposure to the sun will the bridge receive?

12—Is an FRP bridge the best type of bridge for this site?

13—Is an FRP bridge the most cost-effective bridge for this site?

Tips

- Do **NOT** drag trusses across the ground.
- Make a skid or dolly to haul trusses to the bridge site.
- Strap pieces together before hauling them to the bridge site to prevent them from bending out of the intended plane.
- Do **NOT** scratch members. Repair all scratches with the sealant recommended by the bridge manufacturer.
- Pick paths for hauling components to the bridge site that will not require bending or twisting the components.
- Store all components flat, and support them with many blocks to prevent them from bending and to keep them off the ground so they will not be damaged by water and dirt.

Transportation, Handling, and Storage

Transportation, handling, or storage problems can damage or destroy FRP components. Examples are shown in the section on *Case Studies and Failures*. Here are some tips for transporting, handling, and storing FRP materials based on the case studies and on the experience of the Trails Unlimited Forest Service Enterprise Team.

Construction and Installation

Bridges can be delivered fully assembled, partially assembled, or in pieces. Typically, bridges for remote sites are delivered to the trailhead or to the district shop (figure 11).

In most cases, short spans can be installed quickly by volunteers or work crews who assemble the two trusses near the crossing. Two workers can assemble the trusses of a simple 40-foot bridge. A larger crew will be needed for a short time to carry or pull the trusses to the bridge foundation, to carry some mate-

Figure 11—FRP bridge materials being delivered to a staging area.

rials to the far bank, and to stand the trusses up on the foundations (figure 12).

Cross pieces and bracing are bolted underneath, connecting the two trusses. Bolting the cross pieces and bracing can take several hours if all work must be done from the deck level, but may not take as long if some portions of the bridge can be reached from below. Finally, the decking and safety rails are installed.

Figure 12—A skyline system can be used to haul bridge materials to an abutment across a stream.

When the stream is not far below bridges with long spans, the easiest method of installation is to use construction lumber for several temporary supports (figure 13) in the streambed. Bottom chords, posts, diagonals, and the top chords are added in sequence until the bridge is fully constructed on the foundations. A small hydraulic jack or pry bar may have to be applied at the panel points to align the bolt holes. Supports are removed and decking is added.

Figure 13—Sometimes, temporary supports must be used when constructing longer bridges.

The manufacturer should provide step-by-step assembly instructions. Assembly instructions for the Falls Creek Bridge are included in appendix I.

This type of assembly is appropriate for volunteer groups with experience using handtools. A small crew can install a 50-foot side truss trail bridge easily in 2 to 3 days using this method. Volunteers must be properly trained to prevent damage to the FRP components.

When the stream is far below bridges with long spans, installation usually is left to experienced contractors. Typically, trusses are assembled near the site and pulled across individually using “skylines” attached to trees near the streambank (see figure 12). This type of construction requires rigging experience. On some sites, a helicopter may be needed to lift the trusses into place (see figure 9).

The following tips were suggested by Forest Service personnel who work for the Trails Unlimited Enterprise Team.

TIPS

1—Study the drawings and the installation plan ahead of time. Consider laying the components out in the approximate order in which they will be installed. This will help workers become familiar with the components and their order of installation. Try to have an experienced installer at the site.

2—Ensure that you have the correct components and that they are oriented correctly.

3—Follow the manufacturer's instructions and the installation sequences.

4—Measure and stake the bridge abutment work sites (figure 14).

5—Clear and level the abutment work sites (figure 15).

6—Verify the bridge's measurements and layout before constructing the bridge abutments (figure 16). Improper abutment construction has contributed to many bridge failures. Abutments need to be designed by engineers and constructed as designed to prevent failure.

7—In tight working conditions, be especially careful to carry the correct end of long members in first.

8—Assemble bridge trusses at an assembly site or near the bridge abutments (figure 17).

Continued


Figure 14—Staking out a bridge site with a cloth tape.


Figure 15—Clearing an abutment with a small trackhoe.


Figure 16—Constructing an abutment for an FRP bridge.

Tips

When assembling trusses, use a tapered bar and a straight bar to line up the bolt holes (figure 18). Tap bolts lightly. Start a bolt at each side and use the mounting bolt to force the alignment bolt or straight bar out. Build as much of the top and bottom chords as can be handled before setting the trusses into place. The added stiffness will make construction easier. Bolt heads should always be on the inside of the top chord and on the outside of the bottom chord. If you have to use force to drive the bolts, something is out of alignment. No bolts should have to be driven except for the deck bolts that pass through the wooden decking and into the top flange. Bolts should not be more than finger tight.

9—Set trusses upright (figure 19) and haul them into place. Based on our experience, trusses carried upright will not flex as much as if they were carried flat and are less likely to be damaged. (Manufacturers say that trusses won't be damaged by flexing and can be carried more easily and safely when they are carried flat. Several people should carry each truss so it's not just supported at the ends.)

10—Install the bridge clips on the abutments and position the completed trusses on the abutments. Square up the trusses and make sure they are parallel to each other (figure 20). Take measurements and verify them. Make sure that all members are in alignment and that all outriggers are installed at the proper

Figure 17—Assembling a truss on level ground near the bridge site.

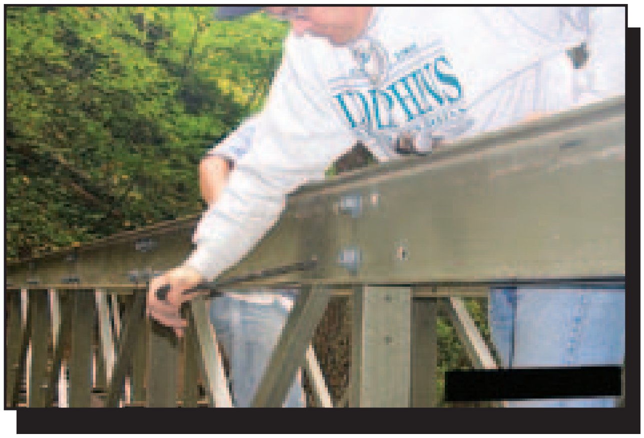

Figure 18— A tapered bar can be used to align bolt holes.

Figure 19—Trusses are set upright before being moved into place.

Continued

TIPS

ocations. Install the bridge clips to keep the trusses upright and finger tighten the bolts.

11—Put the three deck boards that have carriage bolts in place: one near each end of the bridge and one in the middle. Leave the bolts loose enough to allow the decking to be adjusted. Install the cross and diagonal bracing between the bottom chords and finger tighten the bolts (figure 21).

12—Place planks on the bridge (figure 22) except for the two end pieces, which should be left off until the bridge clips have been tightened.

13—Set the bridge's camber using a cross member and a hydraulic jack. Make sure not to lift the truss off the abutment (bolts are only finger tight at this point). Tighten the bolts until the lock washers are compressed (flattened) or until fiberglass begins to deflect. **Do NOT overtighten** because fiberglass **will crack** (figure 23).

14—Tighten truss bolts from the center out and from the top to the bottom. Tighten the center bolts first, bolts at the first panel point on the right, bolts at the first panel point on the left, bolts at the second panel point on right, bolts at the second panel point on the left, and so forth. Tightening bolts in this order is essential for load transfer and proper functioning of an FRP trail

Continued

Figure 20—Squaring up bridge trusses.

Figure 21—Installing and fastening cross bracing.

Figure 22—Fastening deck planks.

TIPS

bridge. Follow all of the manufacturer's instructions and guidelines.

15—Check the bridge's camber and adjust the bridge as necessary (figure 24) to get the camber as close as possible to specifications. Longer bridges require more precise camber.

16—Fasten planks to the bottom chords and stringers.

17—Tighten the bridge clips to the sills.

18—Place treated timber backwalls at the ends of the bridge and fasten them in place, compacting the soil around the backwall. Use two to four stainless-steel screws to secure the backwall. Backwalls may move over time, particularly if the bridge is used for horses, mountain bikes, and off-highway vehicles.

19—Place the end planks on the bridge and fasten them down.

20—Use touchup paint for damaged areas. In extreme cases, it may be wise to spray sealant over the entire structure, encapsulating the bridge. Damaged members must be repaired or replaced before removing any temporary supports.

21—Fasten the wood rails to the side trusses.

Continued

Figure 23—Overtightening bolts cracked two tubes.

Figure 24—A tape measure can be used to check a bridge's camber and deflection.

TIPS

22—Tighten until lock washers are compressed, or until the fiberglass begins to deflect. Retighten the bolts every 5 years. Bolted connections will loosen over time because of vibration. Repeated bolt tightening helps maintain the bridge's strength. (Overtightening bolts cause various kinds of damage to FRP materials. **Do NOT overtighten**.)

23—Do not remove any members of the completed bridge (figure 25) after the temporary supports have been removed—doing so can lead to deflections and forces for which the bridge was not designed, possibly causing the bridge to fail.

Figure 25—The finished FRP bridge.

The Forest Service requires that a qualified contracting officer's representative or inspector certified in trail bridges be involved in the construction of all FRP trail bridges.

Safety and Tools

In the Forest Service, a Job Hazard Analysis (JHA) must be completed for every project. Follow the JHA recommendations for personal safety equipment, as well as direction in the *Health and Safety Code Handbook*, and the manufacturer's assembly instructions (example installation instructions are in appendix I). Wear hardhats, steel-toed boots, gloves, and safety glasses during construction. Tools required for installation and inspections are typically simple carpentry tools, such as hammers, tape measures, levels, socket wrenches, tapered drift pins, and screwdrivers (figure 26). Carbide drill bits and saw blades are best for drilling or cutting FRP materials.

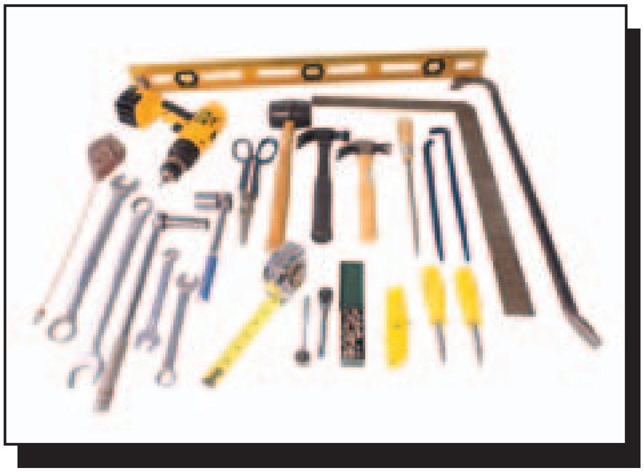

Figure 26—Typical handtools used to construct FRP bridges.

Design of FRP Bridges

Forest Service Manual 7720.04a requires approval by the regional engineer for designs of all "major and complex" trail bridges. All FRP bridges are considered to be complex. Each forest is responsible for its decision to use FRP materials. The bridge must be designed by a qualified engineer experienced in the design of trail bridges and the use of FRP materials. Other jurisdictions may have different requirements—know the requirements you need to meet.

Design Specifications for FRP Pedestrian Bridges

By early 2006, no design specifications for FRP pedestrian bridges had been approved in the United States. E.T. Techtonics, Inc., has submitted *Guide Specifications for Design of FRP Pedestrian Bridges* to the American Association of State Highway Transportation Officials (AASHTO) for approval. These guide specifications are in appendix B. Other professional organizations are addressing the recommended use and specifications of FRP materials and products using them, including the American Society of Civil Engineers (ASCE), the American Society of Testing and Materials (ASTM), and the FHWA.

Design and material specifications are now available only through manufacturers of FRP materials. In the absence of standard material and design specifications, manufacturers' specifications should be followed. There is no way to validate the information manufacturers supply other than by performance history or testing. Errors may exist. Different manufacturers use different resin-to-reinforcement formulas when constructing FRP members, so material properties will differ. The designer should be certain to use the manufacturer's design manual and specifications.

Design Concerns

With any new technology, methods must be developed to predict long-term material properties and to predict structural behavior based on those properties. This information is incorporated in specifications for design parameters, material composition and variance, size tolerances, and connections. Methods for inspection and repair also are derived from long-term testing and observation.

Although specification development and further testing is in progress, standard FHWA specifications and ASCE Load Resistance Factor Design (LRFD) procedures won't be available for the next 5 to 6 years, as reported by Dan Witcher of Strongwell and chairman of the Pultrusion Industry Council's Committee on LRFD Design Standards. Two leading manufacturers of FRP structural products, Strongwell and Creative Pultrusions, Inc., have specifications and design safety factors listed on their design manual CDs. Appendix G has contact information for these manufacturers.

The designer should be aware that shear stresses add more deflection to loaded beams than the classic flexural deflection. Temperatures above 80 degrees Fahrenheit reduce allowable stresses and FRP materials may sag or elongate under sustained loading (time-dependent effects, called *creep*). A temperature of 125 degrees Fahrenheit decreases FRP strength by 30 percent and stiffness by 10 percent (Creative Pultrusions, Inc. 2004; Strongwell 2002). The design needs to consider the service temperature range. FRP members must be designed for lower allowable stresses (no more than 40 percent of the ultimate allowable stress) to minimize creep.

Lateral stability needs to be addressed for different types of bridge configurations. For spans of 30 feet or more, side-truss FRP bridges should have outriggers at all panel points (see figure 8) to provide lateral restraint for the compression flanges. FRP bridges longer than 60 feet that are used by pack trains should have a deck-truss design. That design places the trusses under the deck, increasing restraint on the compression flanges (see figure 7) and increasing the frequency characteristics of the bridge, an important consideration for the live loads generated by pack trains.

Attention to details can help reduce performance problems with FRP bridges:

- Avoid hollow tubes with walls less than ¼ inch thick.

- Fill at least 12 inches of each end of hollow tubes with solid material.

- Provide a drain hole at the bottom of the tube so trapped water can drain.

Bridges made with FRP materials perform differently than bridges made with steel, concrete, or wood. Take these differences into account when designing bridges with FRP materials.

Other Concerns

FRP bridges have many different design considerations. Pack trains may produce vibrations that match the fundamental frequency of the bridge, which may cause the bridge to fail. The natural frequency of the bridge and live loads should be taken into account when ordering the structure. Because of FRP's typically low modulus of elasticity, most designs will be controlled by deflection limitations and not strength requirements. Although the criterion for deflection is somewhat arbitrary, AASHTO guidelines for pedestrian bridges recommend that the deflection of members (in inches) be less than the length of the supporting span divided by 500 (L/500). FRP manufacturers and designers recommend L/400, which would allow more deflection.

Inspecting and Maintaining FRP Bridges

Many types of inspections can be used when rating the condition of FRP pedestrian bridges. This section describes nondestructive testing (NDT) methods, required equipment, and general procedures for conducting the inspections. The NDT methods are listed in order of increasing complexity. The last six require specialized experience or equipment and should be performed by consultants under contract. This information was gathered as part of a study by the Construction Technology Laboratories for inspection of FRP bridge decks (National Cooperative Highway Research Program, Project 10-64, *Field Inspection of In-Service FRP Bridge Decks*). Inspections are required at least every 5 years for Forest Service trail bridges.

Most routine FRP bridge inspections use the two primary methods of visual and tap testing. More complex methods should be adopted only if the primary methods are not adequate to observe or assess unusual conditions. The cost to inspect a bridge using some of the more complex methods may be more than the cost of replacing the bridge.

Visual Testing

Visual testing (VT) is the primary NDT inspection method adopted by bridge inspectors, and is well suited for assessing the condition of FRP pedestrian bridges. The basic tools required are a flashlight, measuring tape, straightedge, markers, binoculars, magnifying glass, inspection mirrors, feeler gauges, and a geologist's pick. Visual inspection generally detects only surface defects, such as cracking, scratches, discoloration, wrinkling, fiber exposure, voids, and blistering.

To help detect defects or cracking that might go unnoticed with VT, a static or dynamic live load test can be done. Loading the bridge with an all-terrain-vehicle or any live load can help reveal hidden cracks and undesirable movement.

Tap Testing

Tap testing is the second most common type of NDT performed on an FRP bridge. Tap testing is a fast, inexpensive, and effective method for inspecting composites for delamination or debonding. The mechanics of the test are analogous to "chain drag" delamination surveys used to inspect reinforced concrete bridge decks, or for inspections of wood timbers by sounding with a hammer.

The inspector taps the surface with a hammer or coin and listens for a distinctive change in frequency, indicating a void or delamination. A clear, sharp ringing indicates a well-bonded structure, whereas a dull sound indicates a delamination or void. Geometric changes within the structure also can produce a change in frequency that may be interpreted erroneously as a defect. The inspector must be familiar with the features of the structure. Tap testing does not require NDT certification. A bridge engineer or inspector can perform this NDT method with very little training.

Thermal Testing

Thermography is effective for identifying discontinuities close to the surface, such as delamination, debonding, impact damage, moisture, and voids. Thermography uses an ambient or artificial heat source and a heat-sensing device, such as an infrared (IR) camera, to measure the temperature variation within the sample. Heat can be applied to the surface by natural sunlight or by a pulsed light source. An IR camera measures the temperature variation of the object. Subsurface variations such as discontinuities or voids in the material will cause slight changes in the wavelength of IR energy that radiates from the object's surface. These discontinuities in the material or emissivity differences can be detected by IR cameras.

Acoustic Testing

Acoustic testing relies on changes in sound waves to reveal defects under loading. A structure under certain load levels produces acoustic sound (known as an acoustic emission), usually between 20 kilohertz and 1 megahertz. The emission is from the stress waves generated because of deformation, crack initiation and growth, crack opening and closure, fiber breakage, or delamination. The waves come through the solid material to the surface, where they can be recorded by one or more sensors or transducers. Acoustic tests involve listening for emissions from active defects and are very sensitive when a structure is loaded.

Ultrasonic Testing

Ultrasonic testing uses high-frequency sound in the range of 20 kilohertz to 25 megahertz to evaluate the internal condition of the material. This method involves applying a couplant (typically water, oil, or gel) to the area to be inspected and scanning the area with a transducer (or probe) attached to the ultrasonic testing machine. The couplant serves as a uniform medium between the surface of the area being scanned and the transducer to ensure the transmission of sound waves. Discontinuities that can be detected include delamination, debonding, resin variations, broken fibers, impact damage, moisture, cracks, voids, and subsurface defects. Unlike visual inspection, tap testing, or thermography, ultrasonic testing requires a high level of expertise to conduct the test properly and to interpret the data.

Radiography

Radiography uses a penetrating radiation source, such as X-rays or gamma rays, and radiographic film to capture images of defects. Differential absorption of the penetrating radiation by the object will produce clearly discernible differences on radiographic film. Radiography requires access to both sides of the structure, with the radiation source placed on one side and the film on the other. Typical discontinuities that can be detected include some delaminations and some debonds (depending on their orientation), voids, resin variations, broken fibers, impact damage, and cracks. Radiography equipment can be hazardous if not handled or stored properly. This method requires a high level of skill to conduct the test and to evaluate the images.

Modal Analysis

Modal analysis evaluates a structure's condition based on changes in the structure's dynamic response. The structure is instrumented with an array of accelerometers and dynamic load tests are performed to extract modal parameters with selected frequencies and mode shapes. This method requires capital investment for sensors and data acquisition equipment, staff training, and a relatively high skill level to set up the equipment and to reduce and interpret the data. This method should be used only if other techniques are unable to address concerns about hidden damage and the overall structural performance of an FRP bridge.

Load Testing

During load testing, a bridge is instrumented with sensors such as strain gauges, accelerometers, and displacement sensors before being subjected to a known live load with a specific loading pattern. The instruments can measure the response of the structure during load tests and help determine the bridge's long-term structural health. Load testing requires investing in sensors and data acquisition equipment, and the development of the skills needed to set up the equipment and to reduce and interpret the data. This method is used only if other methods are unable to address concerns about hidden damage and the overall structural performance of an FRP bridge.

Comparison of Inspection Methods

Visual testing is the simplest and most commonly used method. It allows the inspector to rapidly detect gross imperfections or defects such as cracks, delamination, or damage from impacts. Visual testing often can help detect imperfections, such as lack of adhesive, edge voids, discoloration, and deformation. To a trained inspector, visual testing immediately identifies areas needing more detailed examination. This technique requires interpretation, so inspectors should be trained to know what they are looking for and what any variation might mean to the strength and reliability of the bridge component. Visual testing cannot:

- Quantify the extent of damage
- Inspect components that are not visible

Tap testing or *sounding* is another excellent and easy-to-use method for inspecting FRP materials for delamination. The inspector listens for any change in sounds while tapping FRP surfaces. Although tap testing can be used on pultruded sections, it is less effective in detecting delaminations or debonds. Most common problems on FRP bridges can be identified using a combination of tap testing and visual testing.

Neither tap testing nor visual testing requires specialized equipment. With some training, both methods are easy to incorporate into an inspection program. Other testing methods such as thermal testing, acoustic testing, ultrasonic testing, radiography, modal analysis, and load testing are much more complex, expensive, and time-consuming.

Qualifications for Inspectors

The Forest Service inspector and team leader qualifications in the Forest Service Manual, section 7736.3, *Qualification of Personnel for Road Bridges*, should be used. FRP pedestrian bridges are considered complex trail bridges. Inspectors also should have additional qualifications and experience so they can identify the need for advanced inspection methods, such as acoustic, ultrasonic, or radiographic testing, and interpret the test results. Specialized NDT engineers, employed by consultants, may need to perform these inspections.

Visual Signs of Damage and Defects

Inspectors need to look at the structure as a whole as well as at specific spots. Particular problems to look for are discussed below.

Side Trusses

All trusses should be vertical and should not have any buckling (figure 27) or out-of-plane bowing (figure 28). Either condition would be an indication of a buckling failure. The nature of FRP materials will

Figure 27—This FRP bridge in Redwood National Park began to fail when a loaded mule train was halfway across. No one was injured.

Figure 28—The top chord bowed on the left side truss of the Staircase Rapids Trail Bridge in the Olympic National Forest.

cause such problems to become worse over time. Buckling is a particular concern if the structure will be subjected to long-term loads such as snow loads.

Deflection

Trusses are typically designed with a slight arch that should be visible. If the arch is not present, the plans should be reviewed and compared to the structure to see if the deflection is within design specifications. Excessive deflection could be an indication of loose bolts or connection failure. The deflection should be noted and monitored closely.

Connections

All connections should be inspected carefully for cracking (figure 29). This is especially significant for connections secured with a single bolt. A two-bolt connection allows the second bolt to take up some of the load of a ruptured connection. All bolts are load bearing, so any loose connections must be tightened. Overtightening bolts may crack the FRP member, affecting its strength and structural stability.

Figure 29—This joint at the top of a vertical post was damaged when bolts were overtightened. The material was thinner than the 1/4 inch minimum now recommended.

Blistering

Blistering appears as surface bubbles on exposed laminated or gel-coated surfaces. In the marine industry, blisters generally are attributed to osmosis of moisture into the laminate that causes the layers to delaminate, forming bubbles. FRP bridge members are not as thin as boat hulls. Osmosis to a degree that would cause blistering is rare. Trapped moisture subjected to freeze-thaw cycles might cause blistering, but the blistering probably would affect just the outside layer of the material without affecting the material's structural performance.

Voids and Delaminations

Voids are gaps within the member. They can't be seen if the composite laminate resin is pigmented or if the surface has been painted or gel coated. If the void is large enough and continues to grow, it may appear as a crack on the surface. Often, voids are hidden and can lead to delamination over time. End sections of FRP materials can delaminate during construction if connections are overtightened, causing the laminations to separate (see figure 29).

Discoloration

- Discoloration of the FRP material (figure 30) can be caused by a number of factors, including:

Figure 30—The lower section of this member of an FRP bridge is discolored because the coating that protected it from ultraviolet light wore off.

- Chemical reactions, surface deterioration because of prolonged exposure to ultraviolet light or exposure to intense heat or fire.
- Crazing and whitening from excessive strain, visible mainly on clear resins.
- Subsurface voids that can be seen in clear resins because the material was not completely saturated with resin during manufacture.
- Moisture that penetrates uncoated exposed resin, causing freeze-thaw damage called *fiber bloom*.
- Changes in pigmentation by the manufacturer, although this is not a structural problem.

Wrinkling

Fabric usually wrinkles because of excessive stretching or shearing during wet out. Wrinkling is not a structural problem unless it interferes with the proper surface contact at the connection or prevents the surface veil from bonding to the internal material.

Fiber Exposure

Fiber may be exposed because of damage during transportation or construction (figure 31). Left unattended, the fibers would be susceptible to moisture and contamination, leading to fiber bloom.

Figure 31—This truss was damaged by dragging or improper handling.

Cracks

The face of an FRP member may be cracked because connections were overtightened (see figure 29) or the members were damaged by overloading (figure 32) or impact. Cracks caused by impact from vehicles, debris, or stones typically damage at least one complete layer of the laminated material.

Figure 32—The bottom chord was damaged by dynamic loads from ATV traffic, by bolts that were overtightened, or by overloading.

Scratches

Surface veils can be abraded from improper handling during transportation, storage, or construction. Scratches are shallow grooves on the FRP surfaces. These are usually just unsightly surface blemishes, but, if severe, they can develop into full-depth cracks. Scratches (see figure 31) are judged severe when they penetrate to the reinforcing fibers, where they can cause structural damage.

Repair and Maintenance

Damage found during inspections should be repaired. Evaluate the damage and contact the FRP manufacturer to discuss proper repair options. Some of the FRP manufacturers have developed repair manuals. Strongwell has published a *Fabrication and Repair Manual* that covers minor nonstructural repairs. The manual covers maintenance cleaning, sealing cuts and scratches with resin, splicing cracks, filling chipped flanges with resin, filling holes, and repairing cracks with glass material impregnated with resin.

FRP bridges need to be maintained annually to ensure that they remain in service. Cleaning decks, superstructures, and substructures helps to ensure a long life. Resealing the surface veil with resin improves resistance to ultraviolet radiation and helps prevent moisture from penetrating and causing fiber bloom. Polyurethane or epoxy paint can be applied to parts that will be exposed over the long term. If cracks, scratches, and other abrasions are not repaired, the FRP member will be susceptible to fiber bloom and deterioration.

Bridges Tested at the Forest Products Laboratory

In the fall of 1997, the FRP Trail Bridge Project Team selected two sites for fiberglass trail bridges. The first site was in the Gifford Pinchot National Forest northeast of Portland, OR, 1½ miles from the Lower Falls Creek Trailhead. A 44-foot-long by 3-foot-wide trail bridge (overall length is 45'6") was needed. This area has extreme snow loads (250 pounds per square foot). This bridge was funded by the FHWA and designed by their Eastern Federal Lands Bridge Design Group in consultation with E.T. Techtonics, Inc.

The second site was in the Wallowa-Whitman National Forest near Enterprise, OR, at the Peavine Creek Trail-head. A 22-foot-long by 6-foot-wide pack bridge was needed to fit abandoned road bridge abutments. The snow load at this site, 125 pounds per square foot, is more typical of Forest Service locations. This bridge was funded by the Forest Service and designed by E.T. Techtonics, Inc. The fiberglass channel and tube shapes for both bridges were manufactured by Strongwell and supplied by E.T. Techtonics, Inc.

Design Overview

The Falls Creek Trail Bridge was designed in accordance with AASHTO's *Standard Specifications for Highway Bridges* and the *Guide Specifications for Design of Pedestrian Bridges*.

Neither specification deals with FRP bridges, because specifications have not yet been approved—a major impediment for trail bridge designers. Additional guidance and design techniques were developed from sources in the FRP composite industry.

The *Design Manual for EXTREN Fiberglass Structural Shapes* (2002), developed by Strongwell, is a good source of information on the individual structural components. Because the FRP composite sections were patterned after shapes used in the steel industry, some guidance and design techniques were developed based on the *Manual of Steel Construction* (1989) from the American Institute of Steel Construction. In addition, E.T. Techtonics, Inc., helped interpret and modify existing information, provided test data on the strength of joints and connections, suggested improvements (such as filling the ends of hollow members), and reviewed the final design.

Each structural member of the bridge was designed with respect to standard strength parameters, including allowable tension, compression, bending, and shear stresses, as well as combined stresses due to axial forces and moments acting together. Primary loads included dead, snow, and wind loads. The design forces and moments were the maximum values generated by analysis.

Allowable design stresses were determined by dividing the ultimate strength of the FRP material (the strength at which it would break based on the manufacturer's data) by the following safety factors:

Design stress	Safety factor
Tension and bending	2.5
Compression	3.0
Bearing	4.0

To ensure that the bridge could support the anticipated snow loads, the stresses during the test at the Forest Products Laboratory were limited to no more than 30 percent of the ultimate bending and tensile strength. A full description of the design process, member stresses, and equations is in appendix H.

Materials

The structural sections making up the trusses for the two trail bridges were manufactured by Strongwell, a major manufacturer of fiberglass structural shapes, and came from the company's EXTREN line. EXTREN products contain glass fibers embedded in an isophthalic polyester resin (see glossary in appendix A). Each member also included a surface veil layer of polyester nonwoven fabric and resin for protection from ultraviolet exposure and corrosion. The decking also was a Strongwell product. It included a 6-millimeter ($^1\!/_4$-inch) EXTREN sheet with a gritted surface on top of DURAGRID I-7000 25-millimeter (1-inch) grating. The composition of the grating is similar to that of the structural shapes except that the grating contains a vinyl ester resin binder. All of the FRP composite sections were manufactured using the pultrusion process.

Only two other materials were used in the superstructure of these bridges. The sections were connected with ASTM A307 galvanized bolts. The superstructures were attached to the foundations by ASTM A36 galvanized-steel anchor bolt clip angles.

Simulated Design Live Load Testing

Fiber-reinforced composite materials have different structural properties than conventional construction materials, such as steel, concrete, and timber. To verify the design of the 44-foot bridge, and to investigate the behavior of both the 22- and 44-foot bridges under actual use conditions, we tested both bridges under harsh environmental conditions while they were subjected to their full design loadings.

After the FHWA completed the design of the 44-foot bridge in the spring of 1998, materials for both bridges (figure 33) were shipped to the Forest Products Laboratory in Madison, WI, for full-scale testing. Weather conditions in Madison are severe, ranging from –30 to 100 degrees Fahrenheit. Humidity is relatively high, averaging about 65 percent.

Figure 33—Two FRP bridges—one 22 feet long (left) and the other 44 feet long (right)—were tested at the Forest Products Laboratory in Madison, WI.

The materials (figure 34) for the 22-foot bridge weighed about 1,700 pounds. The materials for the 44-foot bridge weighed about 4,400 pounds. A five-person crew (two representatives from E.T. Techtonics, Inc., two engineers from the FHWA, and one engineer from the Forest Service) began constructing the 22-foot bridge on an FPL parking lot at about 2 in the afternoon. Three hours later, the bridge was completed. Construction of the 44-foot bridge began at about 8 the next morning and the construction was completed by early afternoon. A small forklift set both bridges onto 10-foot-long concrete traffic barriers, which served as bearing supports.

Figure 34—The materials for an FRP bridge after delivery to the Forest Products Laboratory.

The bridges were installed in a back parking lot and loaded to their full design loading (250 pounds per square foot for the 44-foot bridge and 125 pounds per square foot for the 22-foot bridge). Plywood boxes constructed on each bridge deck and filled with landscaping rock provided the load. Rock was 30 inches deep on the deck of the 44-foot bridge and 15 inches deep on the deck of the 22-foot bridge.

Deflection gauges (figure 35) were placed at the second panel point (4/9ths of the span) and at the middle of the span of both trusses on the 44-foot bridge. Refer to appendix D for a drawing showing the location of the deflection and strain gauges. Because the bridge has nine 5-foot panels, the midspan deflection gauge is in the middle of the center panel. The 22-foot bridge has four 5-foot, 6-inch panels so the deflection gauges were placed at the center panel point of both trusses.

Figure 35—The typical setup of a deflection gauge used to test bridges.

Deflection measurements were taken immediately after loading and at several intervals during the first day. Readings were taken daily at first, then weekly and monthly after movement stabilized. Deflection measurement continued for 7 days after the test loads were removed. Neither of the bridges completely returned to the original, unloaded deflection. Bridge deflections were monitored from October 1998 until August 1999. Refer to appendix D for data and graphs. The bridges performed well under load. Actual deflections closely matched the design deflections. When the bridges were disassembled, they had only minor problems.

One hole in a two-bolt connection between hollow members elongated and cracked on the 22-foot bridge (figure 36). The elongation was caused by slightly mismatched holes in the connecting members. Bolt holes need to be very closely aligned when members are fabricated. During testing, only one bolt was engaged initially. That hole elongated and began to fail. When the hole had elongated enough so that the second bolt became engaged, the connection held, preventing complete failure. The member was replaced with an end-filled (solid) member with precisely drilled holes before the bridge was placed at its final location.

Figure 36—This tube cracked when bolts were overtightened on one of the bridges being tested at the Forest Products Laboratory.

Analysis of Test Data

The deflection of the 44-foot bridge increased gradually at a decreasing rate for the first 30 days of loading, before stabilizing at a deflection of about 1.25 inches at midspan and 0.90 inch at the second panel point. This deflection was close to the calculated deflection of 1.30 inches at midspan. The deflection remained stable until about day 216 (May 3, 1999). At that point deflections began increasing at a slow, constant rate until day 280 (July 6, 1999) when the deflection increase accelerated. By day 289 (July 15, 1999), the deflection had again stabilized at about 1.49 inches.

The deflection of the 22-foot bridge followed much the same pattern. The wire used to measure deflection on side 2 was bumped while the bridge was being loaded, resulting in a slight difference in the deflections measured on each side of the bridge. The deflection graphs, although slightly displaced from one another, are nearly identical for both trusses.

Fiberglass has a low modulus of elasticity (or stiffness) compared to other materials. When fiberglass is embedded in a polymer, the behavior of fiberglass is somewhat plastic—accounting for the gradual movement to the anticipated deflection over the first 30 days of the test.

As temperatures rise, fiberglass loses strength and stiffness. The increases in deflection correspond closely to increases in daytime temperatures in Madison. Information provided by Strongwell indicates that the ultimate stress can be reduced by as much as 30 percent when temperatures reach 125 degrees Fahrenheit and the modulus of elasticity can be reduced by 10 percent. Although reduced strength during hot weather concerned us during several weeks of the test period, real-life concerns would be minimal. Our design loading is snow load. The July and August pedestrian and stock loadings are brief and can be assumed to be no more than 85 pounds per square foot.

The bridges did not totally return to the unloaded condition because:

- The material is plastic and gradually reformed to the deflected shape.
- Some slippage occurred in the bolt holes at the bolted connections.

Refer to appendix D for data and graphs.

Disassembly and Installation at Field Sites

On August 8 and 9, 1999, the bridges were disassembled (figure 37) and all the components were visually inspected for damage and wear. The bridges were shipped to their respective sites for permanent installation in September of 1999. The 44-foot bridge was installed in the Gifford Pinchot National Forest during October of 1999. The 22-foot bridge was installed in the Wallowa-Whitman National Forest during the summer of 2000.

Figure 37—Disassembling an FRP bridge after testing at the Forest Products Laboratory.

Falls Creek Trail Bridge

A county detainee crew hand-carried the 4,400 pounds of materials for the 44-foot Falls Creek Trail Bridge in late September (figure 38). Components for a comparable steel-truss bridge would have weighed about 10,000 pounds. That material would have been extremely difficult to pack to the bridge site, because the individual steel members would have weighed

Figure 38—Installing one of the tested FRP bridges at Falls Creek in the Gifford Pinchot National Forest.

up to 500 pounds. The heaviest fiberglass members weighed 180 pounds. Even though these members were 45 feet long, they were flexible enough that they could be bent around tight corners of the trail.

The concrete abutments were cast during the first week of October 1999. An eight-person crew began installing the bridge the following week. Installation was completed shortly after noon of the second day. The bridge spans a very steep, sharply incised, intermittent channel about ¼ mile from a very popular scenic falls (figure 39). The Forest Service estimates peak use of this trail to be as high as 300 persons per day.

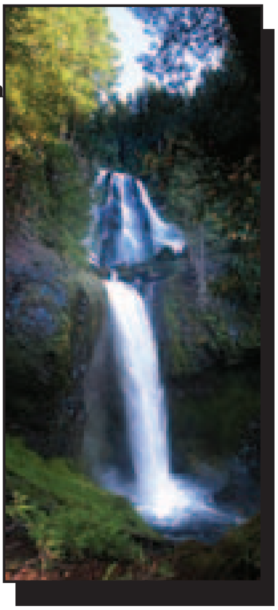

Figure 39—The Falls Creek Trail Bridge provides access to this waterfall.

Peavine Creek Trail Bridge

The 22-foot-long bridge was installed on the former site of a road bridge. The bridge was designed to be placed directly on the existing abutments. The site was accessible by a truck that delivered the materials and a small backhoe.

The bridge was built on the approach roadway and lifted in one piece onto the abutments. The bridge was constructed by the Wallowa-Whitman National Forest road crew and set in place in 1 day. Because the road crew was not familiar with FRP materials, they overtorqued the bolts, cracking several of the hollow tubes. These cracks, which have been monitored since installation, have closed slightly because of bearing compression of the FRP materials.

Reinspection

The bridges were reinspected during the fall of 2004. The cracks at the connections had not changed significantly and the members had a chalky appearance because the surface veil had developed fiber bloom. The Falls Creek Bridge had developed cracks at top post and at floor beam tie-down connections. Additional information is in the *Case Studies and Failures* section.

Case Studies and Failures

Case studies can show the problems and concerns that arise when FRP bridges are used in the national forests. The author and engineering staff from local forests inspected five FRP bridges that have been installed since as early as 1991. The bridges were in the Gifford Pinchot, Medicine Bow-Routt, Mt. Hood, Tahoe, and Wallowa-Whitman National Forests. The problems found on each structure fell into three categories:

- Transportation and storage
- Construction
- Environmental

Transportation and Storage Problems

FRP members can be scratched when they are dragged to the site. Scratches damage the protective coating of the fiberglass. Flexural damage may occur when members are bent or stressed during transportation or while they are stored. Care needs to be taken when materials are unloaded from trucks and trailers.

Members of the queen-post bridge (figure 40) on the Mt. Hood National Forest were scratched when they were dragged to the site (figure 41). These scratches can be fixed by sealing them to prevent moisture from wicking into the member.

Figure 40—This deck-truss FRP bridge in the Mt. Hood National Forest has an inverted queen-post configuration.

Figure 41—This truss was damaged when it was dragged or handled improperly.

Construction Problems

Construction problems can occur when members are overstressed or bent excessively during installation. Dropping or impacts can crack FRP. Overtightening bolts may cause members to crack and may affect their strength and structural stability.

The Falls Creek Trail Bridge (figure 42) is a good example of construction problems. Some bolts were overtightened with a pneumatic power wrench, cracking some members at the connections when the bridge was assembled at the Forest Products Laboratory. Figure 43 shows a rectangular tube with an $\frac{1}{8}$-inch sidewall, only half the thickness recommended for trail bridges.

Figure 42—A side-truss FRP bridge in the Gifford Pinchot National Forest.

Figure 43—This floor beam tie was damaged when bolts were overtightened.

Cracked connections may have been prevented by just tightening bolts until the lock washers began to flatten out and by being careful not to overtorque the nuts. Sometimes, connections with minor hairline cracks can be sealed with protective coating and monitored. If minor cracks are not sealed, the exposed fibers will wick water into the material. As the water freezes and thaws, the member will deteriorate. If members have major cracks, they should be replaced. Otherwise, the entire structure could fail.

Construction problems also occurred on the Medicine Bow-Routt and Wallowa-Whitman National Forests. The Medicine Bow-Routt bridge is a 20-foot-long by 5-foot-wide side-truss structure (figures 44 and 45), built in 1995. The Wallowa-Whitman National Forest bridge is a 22-foot-long by 6-foot-wide structure (figures 46 and 47), built in 1998. Both bridges had minor

Figure 44—A side-truss FRP bridge in the Medicine Bow-Routt National Forests.

Figure 45—This joint at the top of a vertical post was damaged when bolts were overtightened.

Figure 46—A side-truss FRP bridge in the Wallowa-Whitman National Forest.

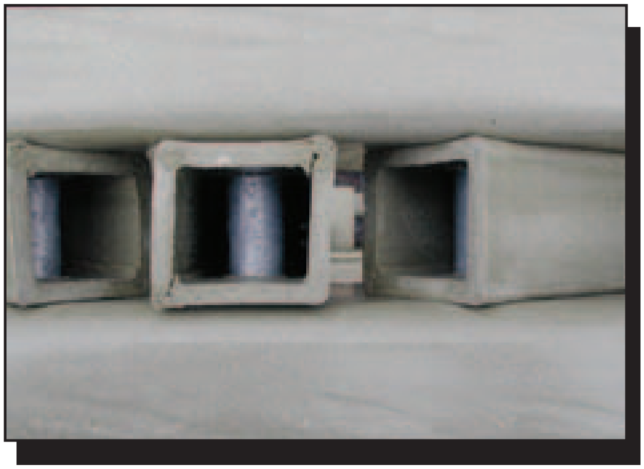

Figure 47— This joint at the top of a vertical post was damaged when bolts were overtightened.

cracks at the upper chord joints. The Medicine Bow-Routt Bridge has large cracks in the bottom chord at the bolt connections (see figure 32) that may have been caused by dynamic loads from ATV traffic, by bolts that were overtightened, or by overloading.

Environmental Problems

Environmental problems can be caused by heat, wind abrasion, and sunlight. One of the five bridges inspected no longer had UV protective coating. The side-truss bridges (figure 48) on the Tahoe National Forest show the problems of UV degradation. The 20-foot-long by 5-foot-wide bridge was built in 1994. The sides of the bridges exposed to full sun have lost their UV protective coating (see figure 30). Wind abrasion from blowing sand and debris can wear away the sealant that provides UV protection. For optimal protection, the members could be recoated with UV protective sealant about every 5 years. If the members are not sealed, the fibers could eventually be exposed, allowing water to wick into the material. As the water freezes and thaws, the member could deteriorate over time.

Figure 48—A side-truss FRP bridge in the Tahoe National Forest.

The two bridges tested at the Forest Products Laboratory had a constant deflection under a sustained load, but the deflection increased dramatically when the temperature rose above 80 degrees Fahrenheit. Consider anticipated maximum temperatures when deciding whether an FRP bridge is the proper choice for large, sustained loads in areas of prolonged extreme heat. For more information, see the test data in appendix D.

FRP Trail Bridge Failures

This section discusses three FRP bridge or catwalk failures and the lessons learned from them. Using a new material with limited knowledge of its long-term behavior can lead to unexpected results. Studying the two trail bridge failures has helped us learn more about FRP material behavior. This information was provided by the National Park Service and by Eric Johansen of E.T. Techtonics, Inc., the supplier of both bridges. Experience has shown that while FRP is not always equivalent to standard materials, sometimes it may be superior.

Redwood National Park

This bridge was the first of two 80-foot-long by 5-foot-wide FRP bridges to be constructed at Redwood National Park. It was designed for pedestrians and stock, but not for pack trains. When a team of mules carrying bags of concrete was 10 to 15 feet onto the bridge, the bridge (see figure 27) began to bounce. The cadence of the mules hit the fundamental frequency of the bridge. The mule train could not back up, so the wrangler started to run the mules across the bridge. When the last mule was halfway across the bridge, one abutment failed and the bridge truss broke. Fortunately, neither the stock nor the packer was injured. The abutment that was well anchored held; the second unanchored abutment did not hold. Crews repaired the abutment and replaced the structure.

This example shows the importance of designing for the correct live loads, determining the fundamental frequency of the bridge, and designing abutments properly. A variety of load conditions and their frequencies should be analyzed and considered in the design. The mule train produced different load patterns and different resonances than those produced by a single horse or mule. The bridge had the same horizontal and vertical fundamental frequencies, so when the fundamental frequency was obtained, the horizontal and vertical vibrations accentuated each other. Proper abutment design and an understanding of abutment conditions can help ensure that the bridge-to-abutment connections will provide the needed strength and support.

The proposed *Guide Specifications for Design of FRP Pedestrian Bridges* (appendix B) recommends that bridges be designed with different vertical and horizontal natural frequencies to minimize any potential amplification of stresses when the two frequencies are combined.

Olympic National Park

During the construction of the Staircase Rapids Trail Bridge in Olympic National Park, the bridge was installed with some out-of-plane bowing of the top chord (compression) in one side truss (see figure 28). Heavy snows 5 years later collapsed four steel bridges and this FRP bridge. Although snow loads far above design snow loads were the catalyst, failure probably was caused by a creep-buckling failure of the initially bowed side truss. Even in its failed state with 3 feet of deflection, this trail bridge was used by pedestrians for several months.

This bridge was only specified for a 35-pound-per-square-foot snow load, not the 85 pound-per-square-foot minimum live load recommended by AASHTO and the Forest Service. The time-dependent properties of FRP materials will tend to slowly increase any buckling caused by construction problems, overloads, or impacts.

During assembly, make sure that all members are in alignment. The design should ensure that all bays have outriggers to help alleviate compression effects in the top chord. Snow loads greater than 150 pounds per square foot require specialized design by experienced designers.

Aquarium of the Americas

A catwalk collapsed in New Orleans, LA, on August 7, 2002, at the Aquarium of the Americas. Ten aquarium members on a special tour fell into a tank of sharks. Sharks and visitors survived the collapse.

A team of experts determined that the catwalk collapsed when an angle bracket connected to a diagonal brace failed. The failed angle bracket was used inappropriately. The live load was about 82 percent of the design live load called for in the plans. This failure highlights the importance of connection design and the consequences of poor designs. This catwalk does not represent a design typically used in trail bridges.

Recommendations

More FRP trail bridges are being constructed on national forest lands. The pros and cons of FRP bridges need to be considered when deciding the type of bridge that best suits the needs.

Selection Considerations

When deciding whether to use FRP materials for a trail bridge, consider the following:

- How does the overall durability of the material compare to concrete, steel, or timber?
- How does the cost of the FRP structure compare to a similar structure of concrete, steel, or timber?
- How difficult is site access and construction?
- Will the temperatures be above 100 degrees Fahrenheit during peak load periods? If so, FRP bridges should be avoided because they lose strength and become more flexible at high temperatures.
- What is the likelihood of impacts from flood debris or collisions?
- How would a collision compromise the structure?
- Could the structure be repaired easily?
- How much would repairs cost and how would the repairs affect the overall strength of the member?
- Does the appearance of FRP trail bridges concern wilderness land managers?

Materials, Testing, Specifications, and Standardization

Researchers and developers in the bridge-building industry seem to be focusing on material testing. Because of the unfamiliarity of FRP composites in this industry, a great deal of materials testing needs to be done and standards need to be established. Methods need to be developed so material properties can be predicted over the long term. Analytical methods that can predict structural behavior also are needed.

A database needs to be developed recording the long-term performance of existing bridges. The performance data can be used to develop much-needed material specifications, leading to new and improved design methods and procedures.

Other barriers to the widespread use of FRP materials include:

- The high initial cost of FRP materials compared to timber

- The lack of design codes, standards, and guidelines

- The lack of proven inspection methods for FRP composites

- The lack of proven inservice durability data

Establishing guidelines and minimum performance requirements is essential before FRP can become a common material for Forest Service trail bridges.

In some ways, manufacturers make it more difficult to overcome these barriers. FRP composites are engineered materials, meaning that the composition of the material is adjusted to produce particular performance characteristics. Each manufacturer sells different products. These products are proprietary, and manufacturers have been unwilling to make their specific fiber architecture (precise material proportions and fiber orientation) available. This makes it difficult to produce standard tests, general design procedures, and specifications. The proprietary nature of the materials also makes it difficult to assure quality control during their manufacture. The industry may have to loosen its hold on information about the materials if it wishes to develop a broad market in the bridge industry.

The results of the initial testing suggest that the methods used to model the load-carrying capacity of the 44-foot bridge tested at the Forest Products Laboratory were very accurate. When the actual performance of the tested bridges is considered as well, the design procedures described in appendix H appear to provide a good basis for a thorough, reliable design of an FRP composite truss bridge. However, these procedures represent only a beginning and will need to be adapted as materials and our understanding of their behavior advance.

FRP composite bridges are not yet a practical solution for bridges designed to meet AASHTO and similar codes. Further study and testing are needed to better understand the material and its uses. However, FRP materials have the potential to meet an important need for lightweight, strong, low-maintenance, attractive trail bridges in remote locations.

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Appendix A—Glossary

Source: "Glossary of Terms," *Composites for Infrastructure, A Guide for Civil Engineers*, S. Bassett, V.P. McConnell, D. Dawson, editors, Ray Publishing Inc. (publishers of *High-Performance Composites* and *Composites Technology* magazines and the *SOURCEBOOK* directory), 1998. Visit Ray Publishing's Web site at: *http://www.compositesworld.com*.

Ablative—Material that absorbs heat through a decom-position process called pyrolysis at or near the exposed surface.

Accelerator—Chemical additive that hastens cure or chemical reaction.

Acoustic Emission—A measure of integrity of a material, as determined by sound emission when a material is stressed. Ideally, emissions can be correlated with defects and/or incipient failure.

Additive—Ingredients mixed into resin to improve properties. Examples include plasticizers, initiators, light stabilizers and flame retardants.

Adhesive—Substance applied to mating surfaces to bond them together by surface attachment. An adhesive can be in liquid, film or paste form.

Anisotropic—Fiber directionality where different properties are exhibited when tested along axes in different directions.

Antimony Trioxide—Fire retardant additive for use with resins.

Aramid—High-strength, high-stiffness aromatic polya-mide fibers, such as DuPont's Kevlar.

Areal Weight—Weight of a fiber reinforcement per unit area (width times length) of tape or fabric.

Aspect Ratio—The ratio of length to diameter of a fiber.

Axial Winding—Filament winding wherein the filaments are parallel to the axis.

Bag Molding—An airtight film used to apply atmospheric force to a laminate.

Balanced Laminate—A laminate in which all laminae except those at 0/90 degrees are placed in plus/minus pairs (not necessarily adjacent) symmetrically around the lay-up centerline.

Basket Weave—Woven reinforcement where two or more warp threads go over and under two or more filling threads in a repeat pattern. This weave is less stable than the plain weave but produces a flatter, stronger, more pliable fabric.

Batch (or Lot)—Material made with the same process at the same time having identical characteristics throughout.

Bias Fabric—A fabric in which warp and fill fibers are at an angle to the length.

Biaxial Winding—Filament winding wherein helical bands are laid in sequence, side by side, with no gaps or overlap between the fiber.

Bidirectional Laminate—A laminate with fibers oriented in more than one direction on the same plane.

Bismaleimide (BMI)—A type of polyimide that cures by an additional reaction to avoid formation of volatiles. BMIs exhibit temperature capabilities between those of epoxy and polyimide.

Bleeder Cloth—A layer of woven or nonwoven material, not a part of the composite, that allows excess gas and resin to escape during cure.

Bleedout—Excess liquid resin appearing at the surface, primarily occurring during filament winding.

Blister—A rounded elevation of the pultruded surface with boundaries that may be more or less sharply defined.

Blooming, Fiber—A pultrusion surface condition exhibiting a fiber prominence or fiber show that usually has a white or bleached color and a sparkling appearance.

Bond Strength—As measured by load/bond area, the stress required to separate a layer of material from another material to which it is bonded. The amount of adhesion between bonded surfaces.

Boron Fiber—A fiber usually of a tungsten-filament core with elemental boron vapor deposited on it to impart strength and stiffness.

Braid—Woven tubular shape used instead of a flat fabric for composite reinforcement.

Breakout—Separation or breakage of fibers when the edges of a composite part are drilled or cut.

Broadgoods—Fibers woven or stitched into fabrics that may or may not be impregnated with resin; usually furnished in rolls.

B-Stage—Intermediate stage in the polymerization reaction of thermosets. After B-stage, material softens with heat and is plastic and fusible. Also called resistal. The resin of an uncured prepreg or premix is usually B-stage. See A-stage, C-stage.

Buckling—A failure mode usually characterized by fiber deflection rather than breaking because of compressive action.

Cable—A ropelike, multistrand assembly of composite rods or steel wire or fiber.

CAD/CAM—Computer-aided design/computer-aided manufacturing.

Carbon Fiber—Reinforcing fiber known for its light weight, high strength and high stiffness. Fibers are produced by high temperature treatment of an organic precursor fiber based on PAN (polyacrylonitrile), rayon or pitch in an inert atmosphere at temperatures above 1,800 degrees Fahrenheit. Fibers can be graphitized by removing still more of the non-carbon atoms by heat treating above 3,000 degrees Fahrenheit.

Carbon/Carbon—A composite of carbon fiber in a carbon matrix.

Catalyst—A substance that promotes or controls curing of a compound without being consumed in the reaction.

Centipoise (cps)—Unit of measure used to designate a fluid's viscosity. At 70 degrees Fahrenheit, water is 1 cps; peanut butter is 250,000 cps.

Centrifugal Casting—A processing technique for fabricating cylindrical structures, in which the composite material is positioned inside a hollow mandrel designed to be heated and rotated as resin is cured.

Ceramic-Matrix Composites (CMC)—Materials consisting of a ceramic or carbon fiber surrounded by a ceramic matrix, usually silicon carbide.

Chopped Strand—Continuous roving that is chopped into short lengths and then used in mats, spray-up or molding compounds.

Circumferential Winding—The process of winding filaments perpendicular to the axis during filament winding.

Cocured—Cured and simultaneously bonded to another prepared surface.

Coefficient of Expansion (COE)—Measure of the change in length or volume of an object.

Coefficient of Thermal Expansion (CTE)—A material's fractional change in length corresponding to for a given unit change of temperature.

Cohesion—Tendency of a single substance to adhere to itself. Also, the force holding a single substance together.

Composite—A material that combines fiber and a binding matrix to maximize specific performance properties. Neither element merges completely with the other. Advanced composites use only continuous, oriented fibers in polymer, metal and ceramic matrices.

Compression Molding—A technique for molding thermoset plastics in which a part is shaped by placing the fiber and resin into an open mold cavity, closing the mold, and applying heat and pressure until the material has cured or achieved its final form.

Compressive Modulus—A mechanical property description which measures the compression of a sample at a specified load. Described in the ASTM standard, D-695.

Compressive Strength—Resistance to a crushing or buckling force. The maximum compressive load a specimen sustains divided by its original cross-sectional area.

Compressive Strength—The stress that a given material can withstand when compressed. Described in ASTM D-695.

Condensation Polymerization—A polymerization reaction in which simple byproducts (for example, water) are formed.

Consolidation—A processing step that compresses fiber and matrix to remove excess resin, reduce voids, and achieve a particular density.

Contaminant—Impurity or foreign substance that affects one or more properties of composite material, particularly adhesion.

Continuous Filament—An individual, small-diameter reinforcement that is flexible and indefinite in length.

Continuous Roving—Parallel filaments coated with sizing, gathered together into single or multiple strands, and wound into a cylindrical package. It may be used to provide continuous reinforcement in woven roving, filament winding, pultrusion, prepregs, or high-strength molding compounds, or it may be used chopped.

Core—In sandwich construction, the central component to which inner and outer skins are attached. Foam, honeycomb, paper, and wood are all commonly used as core material.

Core Orientation—Used on a honeycomb core to line up the ribbon direction, thickness of the cell depth, cell size and transverse direction.

Core Splicing—Joining two core segments by bonding them together.

Corrosion Resistance—The ability of a material to withstand contact with ambient natural factors or those of a particular artificially created atmosphere, without degradation or change in properties. For metals, corrosion can cause pitting or rusting; for composites, corrosion can cause crazing.

Cowoven Fabric—A reinforcement fabric woven with two different types of fibers in individual yarns. For example, thermoplastic fibers woven side by side with carbon fibers.

Crack—A visual separation that occurs internally or penetrates down from the pultruded surface to the equivalent of one full ply or more of reinforcement.

Crazing—Select region of fine cracks that may develop on or under a resin surface.

Creel—A device for holding the required number of roving spools.

Creep—Dimensional change over time the material of a finished part that is under physical load, beyond instantaneous elastic deformation.

Crimp—A fiber's waviness, which determines its capacity to cohere.

Critical Length—The minimum length of a fiber necessary for matrix shear loading to develop fiber ultimate strength by a matrix.

Cross Laminated—Material laminated so that some of the layers are oriented at various angles to the other layers with respect to the laminate grain. A cross-ply laminate usually has plies oriented only at 0/90 degrees (see *Fiber Architecture*).

Cross-Linking—The chemical bonding of molecules during polymerization that occurs during curing as the resin transitions from a liquid to a solid.

Crystallinity—The quality of having a molecular structure in which the atoms are arranged in an orderly, three-dimensional pattern.

C-Stage—Final step in the cure of a thermoset resin, resulting in irreversible hardening and insolubility.

Cure—To irreversibly change the molecular structure and physical properties of a thermosetting resin by chemical reaction via heat and catalysts alone or in combination, with or without pressure.

Cure Temperature—The temperature at which a material attains final cure.

Curing Agent—A catalytic or reactive agent that brings about polymerization when added to a resin. Also called *hardener*.

Damage Tolerance—A measure of the ability of structures to retain load-carrying capability after exposure to sudden loads (e.g., ballistic impact).

Damping—Diminishing the intensity of vibrations.

Debond—An unplanned nonadhered or unbonded region in a structure.

Deformation—Projections or indentations on rebar that are designed to increase mechanical bonding.

Delaminate—The separation of ply layers because of adhesive failure. This also includes the separation of layers of fabric from the core structure. A delamination may be associated with bridging, drilling and trimming.

Delamination—In-plane separation of a laminate ply or plies due to adhesive failure. For pultruded composites, the separation of two or more layers or plies of reinforc-ing material within a pultrusion.

Denier—A numbering system for yarn and filament in which yarn number is equal to weight in grams of 9,000 meters of yarn.

Design Allowable—A limiting value for a material property that can be used to design a structural or mechanical system to a specified level of success with 95-percent statistical confidence.

Dielectric—Nonconductor of electricity; the ability of a material to resist the flow of an electrical current.

Dielectric Constant—The property of a material that determines the relative speed that an electrical signal will travel through that material. A low dielectric constant will result in a high signal propagation speed. A high dielectric constant will result in a much slower signal propagation speed. Signal speed is roughly inversely proportional to the square root of the dielectric constant.

Dielectric Strength—Voltage required to penetrate insulating material. Material with high dielectric strength offers excellent electrical insulating properties.

Doubler—Extra layers of reinforcement for added stiffness or strength where fasteners or other abrupt load transfers occur.

Drape—The ability of fabric (or prepreg) to conform to the shape of a contoured surface.

Dry Fiber—A condition in which fibers are not fully encapsulated by resin during pultrusion.

Dry Winding—A filament winding operation in which resin is not used.

Ductility—The ability of a material to be plastically deformed by elongation, without fracture.

E-Glass—Stands for *electrical glass* and refers to boro-silicate glass fibers most often used in conventional polymer matrix composites.

Elastic Limit—The greatest stress a material is capable of sustaining without permanent deformation remaining after complete release of the stress.

Elastic Modulus—See *Modulus of Elasticity.*

Elasticity—The property of materials allowing them to recover their original size and shape after deformation.

Elastomer—A material that substantially recovers its original shape and size at room temperature after removal of a deforming force.

Elongation—The fractional increase in length of a material stressed in tension. When expressed as a percentage of the original length, it is called percent elongation.

End—A strand of roving consisting of a given number of filaments gathered together. The group of filaments is considered an *end* or strand before twisting.

End Count—An exact number of strands contained in a roving.

Epoxy Resin—A polymer resin characterized by epoxide molecule groups.

Exothermic—Term used for a chemical reaction that releases heat.

Extenders—Low-cost materials used to dilute or extend high-cost resins without extensive lessening of proper-ties.

Fabric, Nonwoven—A material formed from fibers or yarns without interlacing (for example, stitched non-woven broadgoods).

Fabric, Woven—A material constructed of interlaced yarns, fibers or filaments.

Fabrication—The process of making a composite part or tool.

Fatigue—The failure of a material's mechanical proper-ties as a result of repeated stress over time.

Fatigue Life—The number of cycles of deformation require to fail a test specimen under a given set of oscillating stresses and strains.

Fatigue Limit—The stress level below which a material can be stressed cyclically for an infinite number of times without failure.

Fatigue Strength—Maximum cyclical stress withstood for a given number of cycles before a material fails.

FEA—Finite element analysis.

Fiber—A general term used to refer to filamentary materials. Often, fiber is used synonymously with filament.

Fiber Architecture—The design of a fibrous part in which the fibers are arranged in a particular orientation to achieve the desired result. This may include braided, stitched or woven fabrics, mats, rovings or carbon tows.

Fiber Bridging—Reinforcing fiber material that is found bridging across an inside radius of a pultruded product.

Fiber Content—Amount of fiber in a composite expressed as a ratio to the matrix. Strength generally increases as the fiber content ratio increases.

Fiber Orientation—Direction of fiber alignment in a nonwoven or mat laminate wherein most of the fibers are placed in the same direction to afford higher strength in that direction.

Fiber Placement—A continuous process for fabricating composite shapes with complex contours and/or cutouts by means of a device that lays preimpregnated fibers (in tow form) onto a nonuniform mandrel or tool. It differs from filament winding in several ways: there is no limit on fiber angles; compaction takes place online by heat, pressure, or both; and fibers can be added and dropped as necessary. The process produces more complex shapes and permits a faster putdown rate than filament winding.

Fiber Prominence—A visible and measurable pattern of the reinforcing material on the surface of pultruded product.

Fiber Show—Strands or bundles of fibers that are not covered by resin and that are at or above the surface of a reinforced plastic pultrusion.

Fiber-Reinforced Plastics (FRP)—A general term for a composite material or part that consists of a resin matrix containing reinforcing fibers, such as glass or carbon, having greater strength or stiffness than the resin. FRP is most often used to denote glass fiber-reinforced plastics; the term “advanced composite” usually denotes high-performance aramid or carbon fiber-reinforced plastics.

Filament Winding—An automated process for fabricating composites in which continuous roving or tows, either preimpregnated with resin or drawn through a resin bath, are wound around a rotating mandrel.

Filaments—Individual fibers of indefinite length used in tows, yarns or roving.

Fill Threads—Also known as the weft. These are the crosswise fibers woven at 90 degrees to the warp fibers.

Filler—Material added to the mixed resin to increase viscosity, improve appearance, and/or lower the density and cost.

Film Adhesive—An adhesive in the form of a thin, dry resin film with or without a carrier; commonly used for adhesion between laminate layers.

Finish—Material applied to fibers (after sizing is removed) to improve bonding between resin and fiber.

Fish Eye—The effect of surface contamination which causes a circular separation of a paint or gel coat.

Flexural Modulus—An engineering measurement that determines how much a sample will bend when a given load is applied (ASTM D-790).

Flexural Strength—The strength of a material in bending expressed as the stress of a bent test sample at the instant of failure. Usually expressed in force per unit area.

Folded Reinforcement—An unintentional or unspecified misalignment of mat or fabric reinforcing material in relation to the contour of a pultruded section.

Fracture—Cracks, crazing, or delamination, or a combination thereof, resulting from physical damage.

Gel Coat—Pigmented or clear coating resins applied to a mold or part to produce a smooth, more impervious finish on the part.

Gel Time—Period of time from initial mixing of liquid reactants to the point when gelation occurs as defined by a specific test method.

Glass Fiber—Reinforcing fiber made by drawing molten glass through bushings. The predominant reinforcement for polymer matrix composites, it is known for its good strength, processability and low cost.

Glassiness—A glassy, marbleized, streaked appearance at the pultruded surface.

Glass-Transition Temperature (Tg)—Approximate temperature above which increased molecular mobility causes a material to become rubbery rather than brittle. The measured value of Tg can vary, depending on the test method.

Graphitization—The process of pyrolization at very high temperatures (up to 5,400 degrees Fahrenheit) that converts carbon to its crystalline allotropic form.

Grooving—Long narrow grooves or depressions in a surface of a pultrusion running parallel to its length.

Hand Lay-up—A fabrication method in which reinforcement layers—preimpregnated or coated afterward—are placed in a mold or on a structure by hand, then cured to the formed shape.

Hardener—Substance that reacts with resin to promote or control curing action.

Heat—Term used colloquially to indicate any tempera-ture above ambient (room) temperature, to which a part or material is or will be subjected.

Heat-Distortion Temperature (HDT)—Temperature at which a test bar deflects a certain amount under specified temperature and stated load.

Helical—Ply laid onto a mandrel at an angle, often a 45-degree angle.

Honeycomb—Lightweight cellular structure made from either metallic sheet materials or non-metallic materials (for example, resin-impregnated paper or woven fabric) and formed into hexagonal nested cells, similar in appearance to the cross section of a beehive.

Hoop—Ply laid onto a mandrel at a 90-degree angle.

Hoop Stress—Circumferential stress in a cylindrically shaped part as a result of internal or external pressure.

Hybrid Composite—A composite made with two or more types of reinforcing fibers.

Hygroscopy—A material's readiness to absorb or retain moisture.

Impact Strength—A material's ability to withstand shock loading as measured by fracturing a specimen.

Impregnate—To saturate the voids and interstices of a reinforcement with a resin.

Impregnated Fabric—See *Prepreg*.

Inclusion—Any foreign matter or particles that are either encapsulated or embedded in the pultrusion.

Inhibitor—Chemical additive that slows or delays cure cycle.

Injection Molding—Method of forming a plastic to the desired shape by forcibly injecting the polymer into a mold.

Interface—Surface between two materials: in glass fibers, for instance, the area at which the glass and sizing meet; in a laminate, the area at which the reinforcement and laminating resin meet.

Interlaminar—Existing or occurring between two or more adjacent laminae.

Interlaminar Shear—Shearing force that produces displacement between two laminae along the plane of their interface.

Internal Shrinkage Cracks—Longitudinal cracks in the pultrusion that are found within sections of roving reinforcement.

Intumescent—A fire-retardant technology which causes an otherwise flammable material to foam, forming an insulating barrier when exposed to heat.

Isophthalic—A polyester resin based on isophthalic acid, generally higher in properties than a general purpose or orthophthalic polyester resin.

Isotropic—Fiber directionality with uniform properties in all directions, independent of the direction of applied load.

Kevlar—Strong, lightweight aramid fiber trademarked by DuPont, used as a reinforcing fiber.

Laminate—The structure resulting from bonding multiple plies of reinforcing fiber or fabric.

Laminate Ply—One fabric/resin or fiber/resin layer that is bonded to adjacent layers in the curing process.

Lay-up—Placement of layers of reinforcement in a mold.

Liquid-Crystal Polymers (LCP)—High-performance melt-processible thermoplastic with improved tensile strength and high-temperature capability.

Mandrel—Elongated mold around which resin-impregnated fiber, tape or filaments are wound to form structural shapes or tubes.

Mat—A fibrous reinforcing material composed of chopped filaments (for chopped-strand mat) or swirled filaments (for continuous-strand mat) with a binder applied to maintain form; available in blankets of various widths, weights, thicknesses and lengths.

Matrix—Binder material in which reinforcing fiber of a composite is embedded; the binder is usually a polymer, but may also be metal or a ceramic.

Mil—The unit used in measuring the diameter of glass fiber strands, wire and so forth (1 mil = 0.001 inch).

Milled Fiber—Continuous glass or carbon strands hammer milled into very short fibers.

Modulus—The physical measurement of stiffness in a material, which equals the ratio of applied load (stress) to the resultant deformation of a material, such as elasticity or shear. A high modulus indicates a stiff material.

Modulus of Elasticity—An engineering term used to describe a material's ability to bend without losing its ability to return to its original physical properties.

Moisture Absorption—Assimilation of water vapor from air by a material. Refers to vapor withdrawn from the air only, as distinguished from water absorption, which is weight gain due to absorption of water by immersion.

Mold—The cavity into or on which resin/fiber material is placed, and from which a finished part takes form.

Monomer—A single molecule that can react with like or unlike molecules to form a polymer.

Multifilament—A yarn consisting of many continuous filaments.

Nomex—Trademark of DuPont for nylon paper-treated material that is made into honeycomb core.

Nondestructive Inspection (NDI)—Determining material or part characteristics without permanently altering the test subject. Nondestructive testing (NDT) and nondestructive evaluation (NDE) are broadly considered synonymous with NDI.

Nonwoven Roving—A reinforcement composed of continuous fiber strands loosely gathered together.

One-Part Resin—A resin system in which the neat resin and catalyst are mixed together by the material supplier as part of the resin production operation, thereby eliminating the mix step during composite fabrication.

Outgassing—Release of solvents and moisture from composite parts under a vacuum.

Out-Time—Period of time in which a prepreg remains handleable with properties intact outside a specified storage environment (a freezer, in the case of thermoset prepregs).

PAN—See *Polyacrylonitrile.*

Peel Ply—Layer of material applied to a prepreg lay-up surface that is removed from the cured laminate prior to bonding operations leaving a clean, resin-rich surface ready for bonding.

Peel Strength—Strength of an adhesive bond obtained by stress that is applied "in a peeling mode."

Phenolic Resin—Thermosetting resin produced by condensation of an aromatic alcohol with an aldehyde, particularly phenol with formaldehyde.

Planar Winding—Filament winding in which the filament path lies on a plane that intersects with the winding surface.

Plastic—A high molecular weight thermoplastic or thermosetting polymer that can be molded, cast, extruded or laminated into objects. A major advantage of plastics is that they can deform significantly without rupturing.

Ply—One of the layers that makes up a laminate. Also, the number of single yarns twisted together to form a plied yarn.

Ply Schedule—Lay-up of individual plies or layers to build an FRP laminate. Plies may be arranged (scheduled) in alternating fiber orientation to produce in a multidirectional strength laminate (see *Fiber Architecture*).

Polar Winding—Filament winding in which the filament path passes tangent to the polar opening at one end of the chamber and tangent to the opposite side of the polar opening at the other end of the chamber.

Polyacrylonitrile (PAN)—Base material in the manufacture of some carbon fibers.

Polymer—Large molecule formed by combining many smaller molecules or monomers in a regular pattern.

Polymerization—Chemical reaction that links monomers together to form polymers.

Porosity—The presence of numerous pits or pin holes on or beneath the pultruded surface.

Postcure—An additional elevated temperature exposure often performed without tooling or pressure to improve mechanical properties.

Post-Tension—To compress cast concrete beams or other structural members to impart the characteristics of prestressed concrete.

Pot Life—Length of time in which a catalyzed thermosetting resin retains sufficiently low viscosity for processing.

Precursor—For carbon fibers, the rayon, PAN, or pitch fibers from which carbon fibers are made.

Prepreg—Resin-impregnated cloth, mat, or filaments in flat form that can be stored for later use in molds or hand lay-up. The resin is often partially cured to a tack-free state called B-staging. Additives such as catalysts, inhibitors, flame retardants, and others can be added to obtain specific end-use properties and improve processing, storage and handling characteristics.

Prestress—To apply a force to a structure to condition it to withstand its working load more effectively or with less deflection.

Pretension—Precasting concrete beams with tension elements embedded in them.

Promoter—See *Accelerator.*

Puckers—Local areas on prepreg where material has blistered and pulled away from the separator film or release paper.

Pultrusion—An automated, continuous process for manufacturing composite rods, tubes and structural shapes having a constant cross section. Roving and/or tows are saturated with resin and continuously pulled through a heated die, where the part is formed and cured. The cured part is then cut to length.

Pyrolysis—Decomposition or chemical transformation of a compound caused by heat.

Quasi-isotropic—Approximating isotropy by orienting plies in several directions.

Ramping—Gradual programmed increase/decrease in temperature or pressure to control cure or cooling of composite parts.

Reinforcement—Key element added to matrix to provide the required properties (primarily strength and stiffness); ranges from short fibers and continuous fibers through complex textile forms.

Release Agent—Used to prevent cured matrix material from bonding to molds or forms. It is usually sprayed or painted on mold.

Release Film—An impermeable film layer that does not bond to the composite during cure.

Resin—Polymer with indefinite and often high molecular weight and a softening or melting range that exhibits a tendency to flow when subjected to stress. As composite matrices, resins bind together reinforcement fibers.

Resin Starved—Localized areas lacking sufficient resin for fiber wetout.

Resin Transfer Molding (RTM)—A molding process in which catalyzed resin is pumped into a two-sided, matched mold where a fibrous reinforcement has been placed. The mold and/or resin may or may not be heated.

Resin-Rich Area—Localized area filled with excess resin as compared to consistent resin/fiber ratio. A resin-rich area is beneficial when the composite is exposed to a corrosive environment, as long as sufficient reinforcement is present to carry structural loads.

Ribbon Direction—On a honeycomb core, the way the honeycomb can be separated. The direction of one continuous ribbon.

Rod—A thin, round bar made of composites or metal.

Roving—A collection of bundles of continuous filaments either as untwisted strands or as twisted yarn.

Sandwich Structure—Composite composed of light-weight core material (usually honeycomb or foam) to which two relatively thin, dense, high-strength, functional or decorative skins are adhered.

Scale—A condition wherein resin plates or particles are on the surface of a pultrusion.

Sealant—Applied to a joint in paste or liquid form that hardens in place to form a seal.

Secondary Bonding—The joining together, by the process of adhesive bonding, of two or more already cured composite parts.

S-Glass—Stands for *structural glass*, and refers to magnesia/alumina/silicate glass reinforcement designed to provide very high tensile strength. Commonly used in applications requiring an exceptionally high strength and low weight.

Shear—An action or stress resulting from applied forces that causes or tends to cause two contiguous parts of a body to slide relative to each other.

Shelf Life—Length of time in which a material can be stored and continue to meet specification requirements, remaining suitable for its intended use.

Silicon Carbide Fiber—Reinforcing fiber with high strength and modulus; its density is equal to that of aluminum. Used in organic metal-matrix composites.

Sizing—A solution of chemical additives used to coat filaments. The additives protect the filaments from water absorption and abrasion. They also lubricate the filaments and reduce static electricity.

Skin—A layer of relatively dense material used in a sandwich structure on the surface of the core.

Sluffing—A condition wherein scales peel off or become loose, either partially or entirely, from the pultrusion.

Specific Gravity—Density (mass per unit volume) of a material divided by that of water at a standard temperature.

Specification—The properties, characteristics or requirements a particular material or part must have to be acceptable to a potential user of the material or part.

Spray-Up—Technique in which continuous strand roving is fed into a chopper gun, which chops the roving into predetermined lengths. The gun sprays the chopped fiber, along with a measured amount of resin and catalyst, onto an open mold.

Stiffness—A material's ability to resist bending. Relationship of load to deformation for a particular material.

Stop Mark—A band, either dull or glossy, on the surface of a pultrusion, approximately ½ to 3 inches wide and extending around the periphery of a pultruded shape.

Storage Life—Amount of time a material can be stored and retain specific properties.

Strain—Elastic deformation resulting from stress.

Strand—One of a number of steel or composite wires twisted together to form a wire rope or cable.

Stress—Internal resistance to change in size or shape, expressed in force per unit area.

Stress Concentration—The magnification of applied stress in the region of a notch, void, hole or inclusion.

Stress Corrosion—Preferential attack of areas under stress in a corrosive environment, where such an environment alone would not have caused corrosion.

Stress Crack—External or internal cracks in a composite caused by tensile stresses; cracking may be present internally, externally, or in combination.

Structural Adhesive—An adhesive used to transfer loads between two or more adherents.

Structural Bond—A bond joining load-bearing components of a structure.

Substrate—A material on which an adhesive-containing substance is spread for any purpose, such as bonding or coating.

Surfacing Veil—Used with other reinforcing mats and fabrics to enhance the quality of the surface finish. Designed to block out the fiber patterns of the under-lying reinforcements and often adds ultraviolet protection to the structure.

Tack—Stickiness of an uncured prepreg.

Tape—Thin unidirectional prepreg in widths up to 12 inches.

Tendon—Broadly, any prestressing element, including one or more steel or composite seven-wire strands, composite rods or steel threaded bars.

Tensile Strength—Maximum stress sustained by a composite specimen before it fails in a tension test.

Thermal Conductivity—Ability to transfer heat.

Thermoplastic—A composite matrix capable of being repeatedly softened by an increase of temperature and hardened by a decrease in temperature.

Thermoset—Composite matrix cured by heat and pressure or with a catalyst into an infusible and insoluble material. Once cured, a thermoset cannot be returned to the uncured state.

Thixotropic—Materials that are gel-like at rest, but fluid when agitated. Having high static shear strength and low dynamic shear strength at the same time. Losing viscosity under stress.

Toughness—A measure of the ability of a material to absorb energy.

Tow—An untwisted bundle of continuous filaments, usually designated by a number followed by K, indicating multiplication by 1,000 (for example, 12K tow has 12,000 filaments.)

Twist—A condition of longitudinal progressive rotation found in pultruded parts.

Two-Part Resin—A resin, typically epoxy, that requires addition of a hardening agent before it will cure.

Unidirectional—Reinforcing fibers that are oriented in the same direction, such as unidirectional fabric, tape, or laminate.

Vacuum Bag Molding—Molding technique wherein the part is cured inside a layer of film from which entrapped air is removed by vacuum.

Vacuum-Assisted Resin Transfer Molding (VARTM)—An infusion process where a vacuum draws resin into a one-sided mold; a cover, either rigid or flexible, is placed over the top to form a vacuum-tight seal.

Viscosity—Tendency of a material to resist flow. As temperature increases, the viscosity of most materials decreases.

Void—A pocket of entrapped gas that have been cured into a laminate. In a composite that has been cured properly, void content is usually less than one percent.

Volatile Organic Compounds (VOCs)—Carbon-containing chemical compounds (for example, solvents and styrene) that evaporate readily at ambient temperatures. Environmental, safety and health regulations often limit exposure to these compounds, so low VOC content is preferable.

Volatiles—Materials in a sizing or resin that can be vaporized at room or slightly elevated temperature.

Warp—Yarns running lengthwise and perpendicular to the narrow edge of woven fabric.

Warpage—Dimensional distortion in a composite part.

Water Absorption—Ratio of weight of water absorbed by a material to the weight of dry material.

Weave—Pattern by which a fabric is formed from interlacing yarns. In plain weave, warp and fill fibers alternate to make both fabric faces identical. In satin weave, pattern produces a satin appearance with the warp yarn over several fill yarns and under the next one (for example, eight-harness satin would have one warp yarn over seven fill yarns and under the eighth).

Weft—Yarns running perpendicular to the warp in a woven fabric. Also called woof.

Wet Lay-Up—Fabrication step involving application of a resin to dry reinforcement.

Wet Winding—Filament winding wherein fiber strands are impregnated with resin immediately before they contact the surface of the winding.

Wetout—Saturation with resin of all voids between strands and filaments.

Wetting Agent—A surface-active agent that promotes wetting by decreasing the cohesion within a liquid.

Wind Angle—The measure in degrees between the direction parallel to the filaments and an established reference line.

Winding Pattern—Regularly recurring pattern of the filament path in a filament winding after a certain number of mandrel revolutions.

Wire Mesh—Fine wire screen used to increase electrical conductivity. Typically used to dissipate the electrical charge from lightning.

Woven Roving—Heavy, coarse fabric produced by weaving continuous roving bundles.

X-Axis—The axis in the plane of the laminate used as 0-degree reference. The Y-axis is the axis in the plane of the laminate perpendicular to the X-axis. The Z-axis is the reference axis normal to the laminate plane.

Yarn—Continuously twisted fibers or strands that are suitable for weaving into fabrics.

Y-Axis—See *X-axis*.

Yield Point—The first stress in a material, less than the maximum attainable stress, at which the strain increases at a higher rate than the stress. The point at which permanent deformation of a stressed specimen begins to take place. Only materials that exhibit yielding have a yield point.

Yield Strength—The stress at the yield point. The stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain.

Young's Modulus—Ratio of normal stress to the corresponding strain for tensile or compressive stresses less than the proportional limit of the material.

Z-Axis—See *X-axis*.

Glossary References

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Standard Terminology Relating to Reinforced Plastic Pultruded Products, ASTM D 3918-96, American Society for Testing and Materials (W. Conshohocken, PA), 1996.

McGraw-Hill Dictionary of Scientific and Technical Terms (4th Ed.), McGraw-Hill (New York), 1993.

Handbook of Composites, George Lubin, editor, Van Nostrand Reinhold Co. (New York), 1982.

Whittington's Dictionary of Plastics (3rd Ed.), James F. Carley, editor, Technomics (Lancaster, PA), 1993.

Appendix B—Proposed Guide Specifications for the Design of FRP Pedestrian Bridges

The following specification is a proposed AASHTO FRP Pedestrian Bridge Specification written by E.T. Techtonics, Inc. The proposed guideline has been submitted to the AASHTO T-6 Committee for evaluation and approval.

GUIDE SPECIFICATIONS FOR DESIGN OF FRP PEDESTRIAN BRIDGES

Table of Contents

Guide Specifications For Design of FRP Pedestrian Bridges

1.1 GENERAL

These Guide Specifications shall apply to FRP composite bridges intended to carry primarily pedestrian and/or bicycle traffic. Unless amended herein, the existing provisions of the AASHTO *Standard Specifications for Highway Bridges,* 16th Edition, shall apply when using these Guide Specifications. The AASHTO LRFD *Bridge Design Specifications* in conjunction with the *Design and Construction Specifications for FRP Bridge Decks* (Constructed Facilities Center at West Virginia University) and *A Model Specification for Composites for Civil Engineering Structures* (Lawrence C. Bank at the University of Wisconsin) should be used. In lieu of this approach, a Service Design Load Approach can be used for particular applications.

1.2 DESIGN LOADS

1.2.1 Live Loads

1.2.1.1 Pedestrian Live Load

Main Members: Main supporting members, including girders, trusses, and arches, shall be designed for a pedestrian live load of 85 lb/sq ft (psf) (4.07 KPa) of bridge walkway area. The pedestrian live load shall be applied to those areas of the walkway so as to produce maximum stress in the member being designed.

If the bridge walkway area to which the pedestrian live load is applied (deck influence area) exceeds 400 sq ft (37.16 m^2), the pedestrian live load may be reduced by the following equation:

$$w = 85\ (0.25 + (15/\sqrt{\qquad}\ )\ )$$

w = design pedestrian load (psf)
Al = deck influence area (sq ft)

In no case shall the pedestrian live load be less than 65 psf (3.11 KPa).

Secondary Members: Bridge decks and supporting floor systems, including secondary stringers, floor beams, and their connections to main supporting members, shall be designed for a live load of 85 psf (4.07 KPa), with no reduction allowed.

1.2.1.2 Vehicle Load

Pedestrian/bicycle bridges should be designed for an occasional single maintenance vehicle load provided vehicular access is not physically prevented. A specified vehicle configuration determined by the operating agency may be used for this design vehicle.

If an Agency design vehicle is not specified, the following loads conforming to the AASHTO Standard H-Truck shall be used. In all cases, a single truck positioned to produce the maximum load effect shall be used:

Clear deck width from 6 to 10 ft:	10,000 lb (44.48 kN) (H-5 Truck)
Clear deck width over 10 ft:	20,000 lb (88.96 kN) (H-10 Truck)

The maintenance vehicle live load shall not be placed in combination with the pedestrian live load.

A vehicle impact allowance is not required.

1.2.2 Wind Loads

A wind load of the following intensity shall be applied horizontally at right angles to the longitudinal axis of the structure. The wind load shall be applied to the projected vertical area of all superstructure elements, including exposed truss members on the leeward truss.

For trusses and arches: 75 psf (3.59 KPa)
For girders and beams: 50 psf (2.39 KPa)

For open truss bridges, where wind can readily pass through the trusses, bridges may be designed for a minimum horizontal load of 35 psf (1.68 KPa) on the full vertical projected area of the bridge, as if enclosed.

A wind overturning force shall be applied according to Article 3.15.3 of the *Standard Specifications for Highway Bridges*.

1.2.3 Combination of Loads

The load combinations, i.e., allowable stress percentages for service load design and load factors for load factor design as specified in table 3.22.1A of the *Standard Specifications for Highway Bridges*, shall be used with the following modifications:

Wind on live load, WL, shall equal zero
Longitudinal force, LF, shall equal zero

1.3 DESIGN DETAILS

1.3.1 Deflection

Members should be designed so that the deflection due to the service pedestrian live load does not exceed $^1/_{400}$ of the length of the span.

The deflection of cantilever arms due to the service pedestrian live load should be limited to $^1/_{200}$ of the cantilever arm.

The horizontal deflection due to lateral wind load shall not exceed $^1/_{400}$ of the length of the span.

1.3.2 Vibrations

The fundamental frequency of the pedestrian bridge (in the vertical direction) without live load should be greater than 5.0 hertz (Hz) to avoid any issues associated with the first and second harmonics. If the second harmonic is a concern, a dynamic computer analysis should be preformed.

The fundamental frequency of the pedestrian bridge (in the horizontal direction) without live load should be greater than 3.0 hertz (Hz) to avoid any issues due to side to side motion involving the first and second harmonics.

The fundamental frequencies of the pedestrian bridge in the vertical and horizontal directions should be different to avoid potential adverse effects associated with the combined effects from the first and second harmonics in these directions.

1.3.3 Allowable Fatigue Stress

Standard fatigue provisions do not apply to FRP composite pedestrian bridge live load stresses as heavy pedestrian loads are infrequent and FRP composite pedestrian bridge design is generally governed by deflection criteria. Wind load concerns are also governed by deflection criteria.

1.3.4 Minimum Thickness of FRP

Minimum thickness of closed structural tubular members shall be 0.25 inch (6.4 mm)

Minimum thickness of open structural FRP members shall be 0.375 inch (9.6 mm)

Plate connections also require a minimum thickness of 0.375 inch (9.6 mm)

1.3.5 Connections

Under this specification, bolted connections shall be used for all main and secondary members. Use only galvanized or stainless steel bolts based on approval by the owner. Adhesive bonding can be used in conjunction with bolted connections for all main members and secondary members. Non-structural members can be either bolted/screwed or adhesively bonded.

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1.3.6 Half-Through Truss Spans

1.3.6.1 The vertical truss members of the floor beams and their connections in half-through truss spans shall be proportioned to resist a lateral force applied at the top of the truss verticals that is not less than 0.01/K times the average design compressive force in the two adjacent top chord members where K is the design effective length factor for the individual top chord members supported between the truss verticals. In no case shall the value for 0.01/K be less than 0.003 when determining the minimum lateral force, regardless of the K-value used to determine the compressive capacity of the top chord. This lateral force shall be applied concurrently with these members' primary forces. End posts shall be designed as a simple cantilever to carry its applied axial load combined with a lateral load of 1.0% of the axial load, applied at the upper end.

1.3.6.2 The top chord shall be considered as a column with elastic lateral supports at the panel points. The critical buckling force of the column so determined shall be based on using not less than 2.0 times the maximum design group loading in any panel in the top chord.[1] Maximum design group loading is based on the design loads (not sustained) specified in *Section 1.2—Design Loads* in this Specification.

1.3.6.3 For sustained snow loads (duration of load a minimum of 3 days) greater than 65 psf (3.11 KPa), the critical buckling force of the column so determined shall be based on using not less than 3.0 times the maximum design group loading in any panel in the top chord. This increased factor will account for any adverse viscoelastic behavior (creep buckling) that potentially could occur in the bridge system.

Commentary

1.1 GENERAL

This guide specification is intended to apply to pedestrian and pedestrian/bicycle bridges that are part of highway facilities, and provide standards that ensure structural safety and durability comparable to highway bridges designed in conformance with the AASHTO *Standard Specifications for Highway Bridges*. This specification applies to all bridge types, but specifically to fiber reinforced polymer (FRP) composite construction materials.

The term *primarily pedestrian and/or bicycle traffic* implies that the bridge does not carry a public highway or vehicular roadway. A bridge designed by these specifications could allow the passage of an occasional maintenance or service vehicle.

This specification allows the use of the methodologies provided by AASHTO LRFD *Bridge Design Specifications* in conjunction with the *Design and Construction Specifications for FRP Bridge Decks* (Constructed Facilities Center at West Virginia University) and *A Model Specification for Composites for Civil Engineering Structures* (Lawrence C. Bank at the University of Wisconsin). In lieu of this approach, a Service Load Design Approach can be used for particular applications where vehicle loading conditions are restricted to an H-5 truck. Manufacturer's recommended ultimate stresses with factors of safety not less than 3 and modulus of elasticity will provide conservative results. For a discussion of the Service Load Design Approach for FRP Composite Pedestrian Bridges, see *Design of Falls Creek Trail Bridge: A Fiber Reinforced Polymer Composite Bridge* by Scott Wallace of the Eastern Federal Lands Highway Division of FHWA in conjunction with E.T. Techtonics, Inc., and the USDA Forest Service, Transportation Record No. 1652, Vol. 1, Transportation Research Board, National Academy Press, Washington, DC, 1999.

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[1] For a discussion of half-through truss designs, refer to Galambos, T.V., *Guide to Stability Design Criteria for Metal Structures*, 4th Ed., 1988, New York: John Wiley and Sons, Inc., pp. 515–529.

1.2 DESIGN LOADS

1.2.1 Live Loads

1.2.1.1 Pedestrian Live Load

The 85 psf (4.07 KPa) pedestrian load, which represents an average person occupying 2 square feet (0.186 m2) of bridge deck area, is considered a reasonably conservative service live load that is difficult to exceed with pedestrian traffic. When applied with the AASHTO LRFD *Bridge Design Specifications*, or a Service Load Design Approach, an ample overload capacity is provided.

Reduction of live loads for deck influence areas exceeding 400 square feet (37.16 m2) is consistent with the provisions of ASCE 7-89, *Minimum Design Loads for Buildings and Other Structures*, and is intended to account for the reduced probability of large influence areas being simultaneous maximum loaded.

For typical bridges, a single design live load value may be computed based on the full deck influence area and applied to all the main member subcomponents.

The 65 psf (3.11 KPa) minimum load limit is used to provide a measure of strength consistency with the LRFD Specifications.

Requiring an 85 psf (4.07 KPa) live load for decks and secondary members recognizes the higher probability of attaining maximum loads on small influence areas. Designing decks for a small concentrated load (for example 1 kip) (4.48 kN) is also recommended to account for possible equestrian use or snowmobiles.

1.2.1.2 Vehicle Load

The proposed AASHTO vehicle loads are intended as default values in cases where the Operating Agency does not specify a design vehicle. H-Truck configurations are used for design simplicity and to conservatively represent the specified weights.

1.2.2 Wind Loads

The AASHTO wind pressure on the superstructure elements is specified, except that the AASHTO minimum wind load per foot of superstructure is omitted. The 35 psf (1.68 KPa) value applied to the vertical projected area of an open truss bridge is offered for design simplicity, in lieu of computing forces on the individual truss members. The specified wind pressures are for a base wind velocity of 100 miles per hour and may be modified based on a maximum probable site-specific wind velocity in accordance with AASHTO Article 3.15.

1.2.3 Combination of Loads

The AASHTO wind on live load force combination seems unrealistic to apply to pedestrian loads and is also excessive to apply to the occasional maintenance vehicle, which is typically smaller than a design highway vehicle. The longitudinal braking force for pedestrians is also neglected as being unrealistic.

The AASHTO Group Loadings are retained to be consistent with applying the AASHTO LRFD *Bridge Design Specifications* in conjunction with the *Design and Construction Specifications for FRP Bridge Decks* (Constructed Facilities at West Virginia University) and *A Model Specification for Composites for Civil Engineering Structures* (Lawrence C. Bank at the University of Wisconsin) and the Service Load Design Approach without modification.

1.3 DESIGN DETAILS

1.3.1 Deflection

The specified deflection values are more liberal than the AASHTO highway bridge values, recognizing that, unlike highway vehicle loads, the actual live load needed to approach or achieve the maximum deflection will be infrequent. Pedestrian loads are also applied much more gradually than vehicular loads. The AASHTO value of span/1000 is intended for deflections caused by highway traffic on bridges that also carry pedestrians. In the AASHTO *Guide Specifications for Design of Pedestrian Bridges* (steel, concrete, wood, and aluminum), deflection due to the service pedestrian live load does not exceed $^1/_{500}$ of the length of the span. Deflection of cantilever arms due to the service pedestrian live load is limited to $^1/_{300}$ of the cantilever arm. The horizontal deflection due to lateral wind shall not exceed $^1/_{500}$ of the length of the span. For FRP composite bridges, the specified deflection values are more liberal due to the high strength, but low stiffness (modulus of elasticity) characteristics of the material. Because of the low modulus, FRP composite bridges tend to be at very low levels of stress (in comparison to other materials) at the above deflection limits. Allowing the deflection due to the service pedestrian live load to not exceed $^1/_{400}$ of the length of the span, deflection of cantilever arms due to the service pedestrian live load limit to $^1/_{200}$ of the cantilever arm, and the horizontal deflection due to lateral wind load to not exceed $^1/_{400}$ of the length of the span, FRP composite bridges are at more reasonable levels of stress in conjunction with the serviceability criteria. This allows better use of the material while maintaining a high factor of safety.

1.3.2 Vibrations

Pedestrian bridges have on occasion exhibited unacceptable performance due to vibration caused by people walking or running on them. The potential for significant response due to the dynamic action of walking or running has been recognized by several analyses of problem bridges and is provided for in other design codes such as the Ontario Bridge Code. Research into this phenomenon has resulted in the conclusion that, in addition to stiffness, damping and mass are key considerations in the dynamic response of a pedestrian bridge to ensure acceptable design. The range of the first through the third harmonic of people walking/running across pedestrian bridges is 2 to 8 Hertz (Hz) with the fundamental frequency being from 1.6 to 2.4 Hz. Therefore, bridges with fundamental frequencies below 3 Hz (in the vertical direction) should be avoided.

For pedestrian bridges with low stiffness, damping and mass, such as bridges with shallow depth, lightweight (such as FRP), etc., and in areas where running and jumping are expected to occur on the bridges, the design should be tuned to have a minimum fundamental frequency of 5 Hz (in the vertical direction) to avoid the second harmonic. If the structural frequencies cannot be economically shifted, stiffening handrails, vibrations absorbers, or dampers could be used effectively to reduce vibration problems.

In recent years, there have been several pedestrian bridge cases (a classic example is the Millennium Bridge in London), which have exhibited extreme vibration issues in the horizontal direction due to walking and/or running. This problem has been attributed to the high aspect ration (length/width) of the bridges, which results in relatively low stiffness to the structure in the horizontal direction. Because FRP composite bridge designs are lightweight in nature, fundamental frequencies below 3 Hz (in the horizontal direction) should be avoided. Aspect rations greater than 20 should also be avoided.

When a pedestrian bridge is expected to have frequencies in the range of possible resonance (in either the vertical or horizontal directions) with people walking and/or running, the acceleration levels are dealt with to limit dynamic stresses and deflections. The basic intrinsic damping available in pedestrian bridges using conventional materials (steel, wood, concrete, and aluminum) is low and fairly narrow in range, with 1 percent damping being representative of most pedestrian bridges using these materials. For FRP composite bridges, 1% damping is considered very conservative. In general, due to the bolted nature of the connections used in FRP bridge structures, 2% to 5% damping is considered a more representative range for design.

It is suggested that the vertical and horizontal fundamental frequencies be different in value to minimize any potential amplification of stresses when combined together. In particular, this type of behavior can occur under equestrian loading conditions.

The design limits given in the Guide Specifications are based on D.E. Allen and T.M. Murray, *Design Criterion for Vibrations due to Walking*, ASCE Journal, fourth quarter, 1993. Additional information is contained in H. Bachmann, *Case Studies of Structures with Man-Induced Vibrations*, ASCE Journal of Structural Engineering, Vol. 118, No. 3, March 1992.

1.3.3 Allowable Fatigue Stress

Fatigue issues, which are critical in steel design, do not apply to FRP composite bridges. This is due to the low modulus of elasticity, which results in bridge structures designed to meet serviceability requirements while exhibiting low levels of stress.

1.3.4 Minimum Thickness of FRP

The 0.25-inch (6.2-mm) minimum thickness value for closed structural tubular members minimizes potential fiber-blooming and ultraviolet degradation of the material.

The 0.375 inch (9.6 mm) minimum thickness value for open structural members and plates minimizes potential fiber-blooming and ultraviolet degradation of the material. It also minimizes any localized buckling effects that can potentially occur in the flanges and the webs of the shapes. It also helps in providing additional strength in the Z-direction of these members, which is relying on the strength of the resin in this direction.

1.3.5 Connections

Bolted connections have been extensively tested and documented for FRP composite structures. Adhesive bonding alone (though possible) is not recommended due to the lack of testing done to date in this area. Adhesive bonding can be used in conjunction with bolted connections for all main members and secondary members to provide additional redundancy within the bridge system. Nonstructural members, which include intermediate railings, toe plates, rub rails, etc., can be either bolted/screwed or adhesively bonded.

1.3.6 Half-Through Truss Spans

This article modifies the provisions of AASHTO Article 10.16.12.1 by replacing the 300 pounds per linear foot (4.41 kN/m) design requirements for truss verticals with provisions based on research by Holt and others. These provisions establish the minimum lateral strength of the verticals based on the degree of elastic lateral support necessary for the top chord to resist the maximum design compressive force.

The use of 2.0 times the maximum top chord design load to determine the critical buckling force in the top chord is in recognition that under maximum uniform loads, maximum compressive stresses in the to chord may occur simultaneously over many consecutive panels. For a discussion on this, refer to T.V. Galambos' *Guide to Stability Design Criteria for Metal Structures*.

For sustained snow load conditions (duration of load a minimum of 3 days) greater than 65 psf (3.11 KPa), it is recommended that 3.0 times the maximum top chord design load be used to determine the critical buckling force in the top chord. Adverse viscoelastic behavior (creep buckling) could potentially occur in the top chord. This conservative criteria is based on *Creep Bending and Buckling of Linearly Viscoelastic Columns* by Joseph Kempner, National Advisory Committee for Aeronautics, Technical Note 3136, Washington, 1954. The research addresses the viscoelastic problems associated with compression members, which exhibit initial curvature. This initial curvature can result from manufacturing tolerances, fabrication issues, and/or assembly procedures. Once this curvature is built into the system, adverse viscoelastic behavior can occur if the bridge structure is subjected to unaccounted for sustained load conditions.

Appendix C—CSI Specifications for FRP Pedestrian Bridges

The following CSI specification is a sample for a Pedestrian Bridge Specification written by E.T. Techtonics, Inc.

FRP PREFABRICATED BRIDGE SPECIFICATIONS

1.0 GENERAL

1.1 Scope

These specifications are for a fully engineered clear span bridge of fiber-reinforced polymer (FRP) composite construction and shall be regarded as minimum standards for design and construction as manufactured by E.T. Techtonics, Inc.; P.O. Box 40060; Philadelphia, PA 19106; phone 215-592-7620; or approved equal.

1.2 Qualified Suppliers

The bridge manufacturer shall have been in the business of design and fabrication of bridges for a minimum of 5 years and provide a list of five successful bridge projects, of similar construction, each of which has been in service at least 3 years. List the location, bridge size, owner, and contact reference for each bridge.

2.0 GENERAL FEATURES OF DESIGN

2.1 Span

Bridge span will be xxx' xx" (straight line dimension) and shall be measured from each end of the bridge structure.

2.2 Width

Bridge width shall be xx' xx" and shall be measured from the inside face of structural elements at deck level.

2.3 Bridge System Type

Bridges must be designed as a FRP Composite Truss Span or FRP Composite Cable Span.

2.4 Member Components

All members shall be fabricated from pultruded FRP composite profiles and structural shapes as required.

2.5 Camber

Bridges can be precambered to eliminate initial dead load deflections. Cambers of 1% of the total span length can be provided on request.

3.0 ENGINEERING

Structural design of the bridge structure(s) shall be performed by or under the direct supervision of a licensed professional engineer and done in accordance with recognized engineering practices and principles.

3.1 Uniform Live Load

Bridges spanning less than 50'0" will be designed for 85 psf. Bridges spanning greater than 50'0" will be designed for 60 psf unless otherwise specified.

3.2 Vehicle Load (as required)

A specified vehicle configuration determined by the operating agency may be used for the design vehicle. If an agency design vehicle is not specified, the loads conforming to the AASHTO Standard H-Truck is used. The maintenance vehicle live load shall not be placed in combination with the pedestrian live load. A vehicle impact allowance is not required.

3.3 Wind Load

All bridges shall be designed for a minimum wind load of 25 psf. The wind is calculated on the entire vertical surface of the bridge as if fully enclosed.

3.4 Seismic Load

Seismic loads shall be determined according to the criteria specified in the standard building codes (IBC 2002, ASCE 7-02, BOCA, SBC or UBC) unless otherwise requested. Response Spectrum Analysis shall be performed in those designs that require complex seismic investigation. All necessary response spectra information will be provided by the client for evaluation.

3.5 Allowable Stress Design Approach

An Allowable Stress Design (ASD) approach is used for the design of all structural members. Factors of safety used by E.T. Techtonics, Inc. in the design of FRP bridges are as follows unless otherwise specified (based on the Ultimate Strength of the FRP material):

Tension:	2.5	Bending:	2.5
Compression:	2.5	End bearing:	2.5
Shear:	2.5	Connections:	3.0

Above information is based on E.T. Techtonics, Inc.'s 5-year test program funded by the National Science Foundation.

3.6 Serviceability Criteria

Service loads are used for the design of all structural members when addressing deflection and vibration issues. Criteria used by E.T. Techtonics, Inc. in the design of FRP bridges are as follows:

Deflection:
Live load (LL) deflection = L/240

Vertical frequency (fn): = 5.0 Hz

The fundamental frequency of the pedestrian bridge (in the vertical direction) without live load should be greater than 5.0 Hz to avoid any issues with the first and second harmonics.

Horizontal frequency (fn): = 3.0 Hz

The fundamental frequency of the pedestrian bridge (in the horizontal direction) without live load should be greater than 3.0 hertz (Hz) to avoid any issues due to side to side motion involving the first and second harmonics.

3.7 Snow Load

Sustained snow load conditions shall be evaluated for time dependent effects (creep and relaxation) and expected recovery behavior.

4.0 MATERIALS

4.1 FRP Composites

FRP bridges shall be fabricated from high-strength E-glass and isophthalic polyester resin unless otherwise specified.

Weathering and ultraviolet light protection shall be provided by addition of a veil to the laminate construction. Minimum material strengths and properties are as follows:

Tension:	33,000 psi	Bending:	33,000 psi
Compression:	33,000 psi	Young’s Modulus:	2,800,000 psi
Shear:	4,500 psi		

The minimum thickness of FRP Composite shapes shall be as follows unless otherwise specified: Square-tube members (closed-type shape) shall be 0.25 in. Wide-flange beams, channel sections, and angles (open-type shapes) shall be a minimum thickness of 0.25 in. Standard plate shall be a minimum thickness of 0.25 in.

4.2 Decking

Wood decking is No. 2 southern yellow pine treated according to the American Wood Preservers Bureau. The standard 2- by 10-in planks are provided for pedestrian and bicycle type loading conditions. Standard 3- by 12-in planks can be provided for equestrian and light vehicle type loading conditions as required. High-strength, E-glass/isophthalic polyester resin planks or recycled plastic deck planks can also be provided as required.

4.3 Hardware

Bolted connections shall be A307 hot-dipped galvanized steel unless otherwise specified. Mounting devices shall be galvanized or stainless steel.

5.0 SUBMITTALS

5.1 Submittal Drawings

Schematic drawings and diagrams shall be submitted to the client for their review after receipt of order. As required, all drawings shall be signed and sealed by a licensed professional engineer.

5.2 Submittal Calculations

As required, structural calculations shall be submitted to the client. All calculations will be signed and sealed by a licensed professional engineer.

6.0 FABRICATION

6.1 Tolerances

All cutting and drilling fabrication to be done by experienced fiberglass workers using carbide or diamond-tipped tooling to a tolerance of $^{1}/_{16}$". No material deviations beyond industry standards are accepted. All cut edges to be cleaned and sealed.

7.0 RAILINGS

7.1 Railings for pedestrian and equestrian use should be a minimum of 42" above the floor deck and bicycle use should be a minimum of 54" above the floor deck.

7.2 Safety Rails

Continuous horizontal midrails shall be located on the inside of the trusses. Maximum opening between the midrails shall be available as required, but should not be greater than 9". If preferred, vertical pickets can be provided upon request.

7.3 Toeplates (Optional)

Park and trail bridge toeplates (if required) are 3" green channels. Industrial catwalks use standard 4" yellow toeplate shapes unless otherwise specified.

8.0 FINISHING

Bridge color shall be determined by client with green, grey, beige, and safety yellow as standard. No painting is required as the color is added during the manufacturing process. Green is recommended for park and trail bridge applications. Grey, beige, and safety yellow for industrial catwalk applications. Custom colors can be provided upon request.

9.0 DELIVERY AND ERECTION

Delivery is made by truck to a location nearest the site accessible by roads. E.T. Techtonics, Inc. will notify the client in advance of the expected time of arrival at the site. Bridges are usually shipped to the site in component parts or partially assembled depending on site requirements. The spans can then be completely assembled using standard hand tools. Upon request, bridges can also be shipped totally assembled to the site. Unloading, splicing (if required) and placement of the bridge will be the responsibility of the client.

9.1 Erection Direction

For bridges shipped in component parts or partially assembled, E.T. Techtonics, Inc. shall provide assembly drawings and a recommended assembly procedure for building the bridge. Temporary supports or rigging equipment, if needed, is the responsibility of the client. For bridges shipped assembled, E.T. Techtonics, Inc. shall advise the client of the actual lifting weights, attachment points and all necessary information to install the bridge.

9.2 Site Issues and Foundation Design

The client shall procure all necessary information about the site and soil conditions. Soil tests shall be procured by the client. The engineering design and construction of the bridge abutments, piers and/or footing shall be by the client. E.T. Techtonics, Inc. will provide the necessary information pertaining to the bridge support reactions. The client shall install the anchor bolts in accordance with E.T. Techtonics, Inc's anchor bolt spacing dimensions.

10.0 WARRANTY

E.T. Techtonics, Inc. shall warrant the structural integrity of all FRP materials, design and workmanship for 15 years.

This warranty shall not cover defects in the bridge caused by foundation failures, abuse, misuse, overloading, accident, faulty construction or alteration, or other cause not the result of defective materials or workmanship.

This warranty shall be limited to the repair or replacement of structural defects, and shall not include liability for consequential or incidental damages.

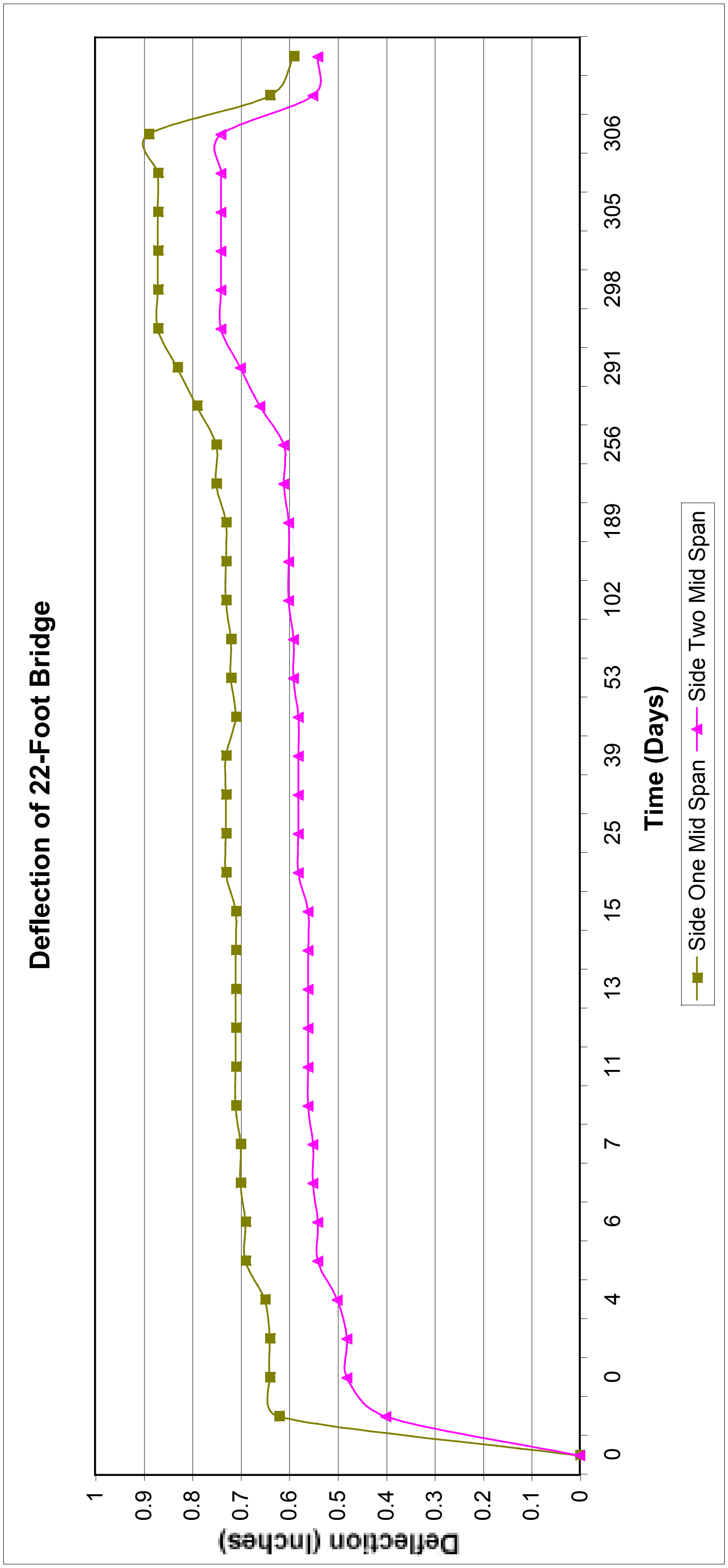
E.T. Techtonics, Inc.
P.O. Box 40060
Philadelphia, PA 19106
Phone and fax: 215-592-7620

Appendix D—Test Data for Bridges at the Forest Products Laboratory

The bridge was loaded on September 24, 1998. Deflection was measured at midspan. Temperature (Temp) was measured in degrees Fahrenheit. The *actual reading* is the *bridge reading* at a particular time minus the initial unloaded bridge reading. After testing at the Forest Products Laboratory, this bridge was dismantled and installed at Peavine Creek in the Wallowa-Whitman National Forest.

22-Foot Walk Bridge

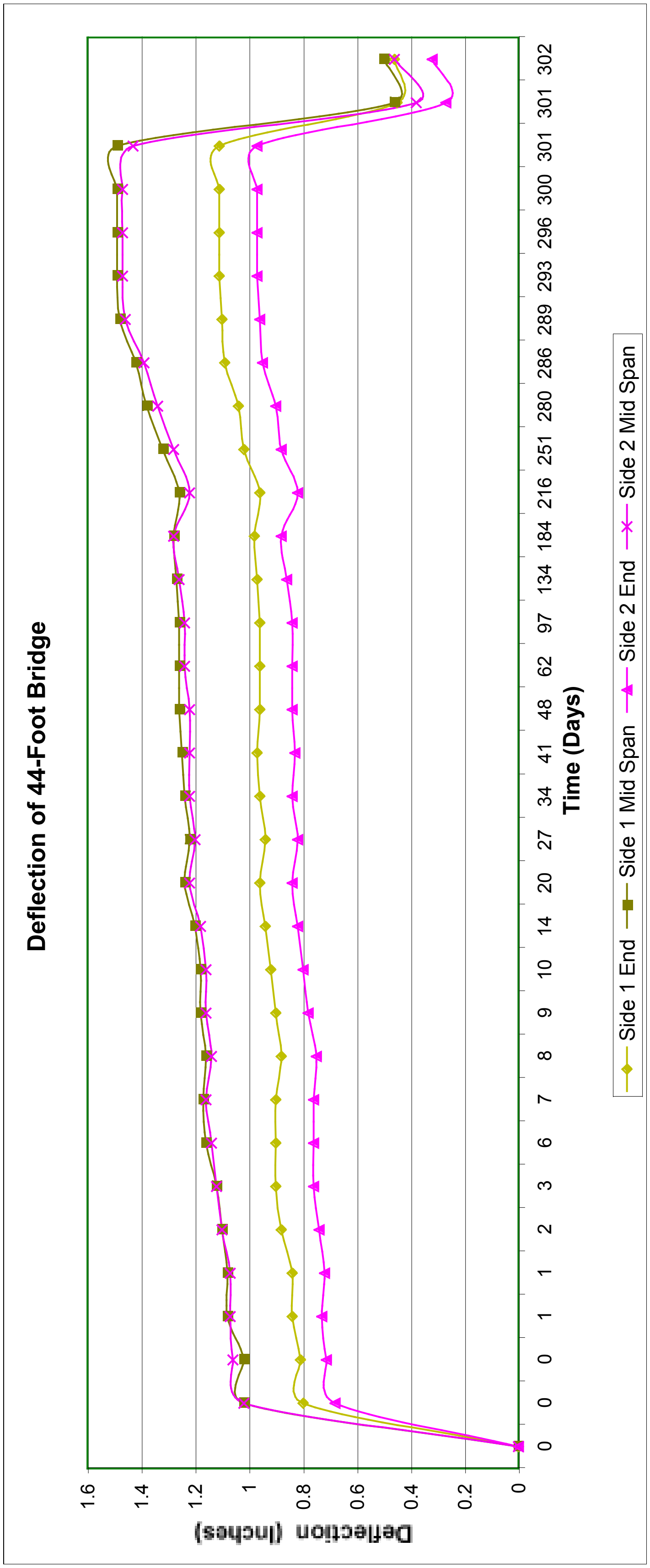
			Actual reading		Bridge reading			
Time	**Date**	**Total time (days)**	**Side 1 deflection**	**Side 2 deflection**	**Side 1 deflection**	**Side 2 deflection**	**Temp**	**Comments**
2:30	9/24/98	0.00	0.00	0.00	0.25	3.10	65	No Load
3:15	9/24/98	0.03	0.62	0.40	0.87	3.50	65	Loaded, side 2 wire moved
3:30	9/24/98	0.04	0.64	0.48	0.89	3.58	65	
4:15	9/24/98	0.08	0.64	0.48	0.89	3.58	65	
7:45	9/25/98	1.00	0.65	0.50	0.90	3.60		
7:45	9/28/98	4.00	0.69	0.54	0.94	3.64		
7:45	9/29/98	5.00	0.69	0.54	0.94	3.64	70	Light rain
7:45	9/30/98	6.00	0.70	0.55	0.95	3.65	63	
2:30	9/30/98	6.00	0.70	0.55	0.95	3.65	63	After rain
8:00	10/1/98	7.00	0.71	0.56	0.96	3.66	50	
8:00	10/2/98	8.00	0.71	0.56	0.96	3.66	55	Rain, cloudy
10:00	10/5/98	11.00	0.71	0.56	0.96	3.66	60	Rain
8:00	10/6/98	12.00	0.71	0.56	0.96	3.66	55	Rain
9:30	10/7/98	13.00	0.71	0.56	0.96	3.66	60	Clearing
8:30	10/8/98	14.00	0.71	0.56	0.96	3.66	55	Sunny
8:00	10/9/98	15.00	0.73	0.58	0.98	3.68	51	Sunny
9:00	10/13/98	19.00	0.73	0.58	0.98	3.68	42	Sunny
8:00	10/19/98	25.00	0.73	0.58	0.98	3.68	45	Sunny
8:00	10/26/98	32.00	0.73	0.58	0.98	3.68	54	Sunny
8:00	11/2/98	39.00	0.71	0.58	0.96	3.68	42	Overcast
8:00	11/9/98	46.00	0.72	0.59	0.97	3.69	34	Overcast
8:00	11/16/98	53.00	0.72	0.59	0.97	3.69	40	Sunny after rain
8:00	11/30/98	67.00	0.73	0.60	0.98	3.70	50	Rainy
8:00	1/4/99	102.00	0.73	0.60	0.98	3.70	4	After 2 days of snow
8:00	2/10/99	139.00	0.73	0.60	0.98	3.70	50	After spring melt
8:00	4/1/99	189.00	0.75	0.61	1.00	3.71	58	Overcast
8:00	5/3/99	221.00	0.75	0.61	1.00	3.71	78	Sunny
8:00	6/7/99	256.00	0.79	0.66	1.04	3.76	88	Sunny
11:00	7/6/99	285.00	0.83	0.70	1.08	3.80	96	Sunny
8:00	7/12/99	291.00	0.87	0.74	1.12	3.84	80	Sunny
8:00	7/15/99	294.00	0.87	0.74	1.12	3.84	72	Sunny
8:00	7/19/99	298.00	0.87	0.74	1.12	3.84	73	Sunny
8:00	7/22/99	301.00	0.87	0.74	1.12	3.84	72	Sunny
8:00	7/26/99	305.00	0.87	0.74	1.12	3.84	84	Rainy
8:00	7/27/99	306.00	0.89	0.74	1.14	3.84	83	Before unload, sunny
9:30	7/27/99	306.00	0.64	0.55	0.89	3.65	84	Unload, sunny
8:00	7/28/99	307.00	0.59	0.54	0.84	3.64	73	Sunny


Deflection of 22-Foot Bridge
Deflection (Inches)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time (Days)
0
0
4
6
7
11
13
15
25
39
53
102
189
256
291
298
305
306
Side One Mid Span
Side Two Mid Span

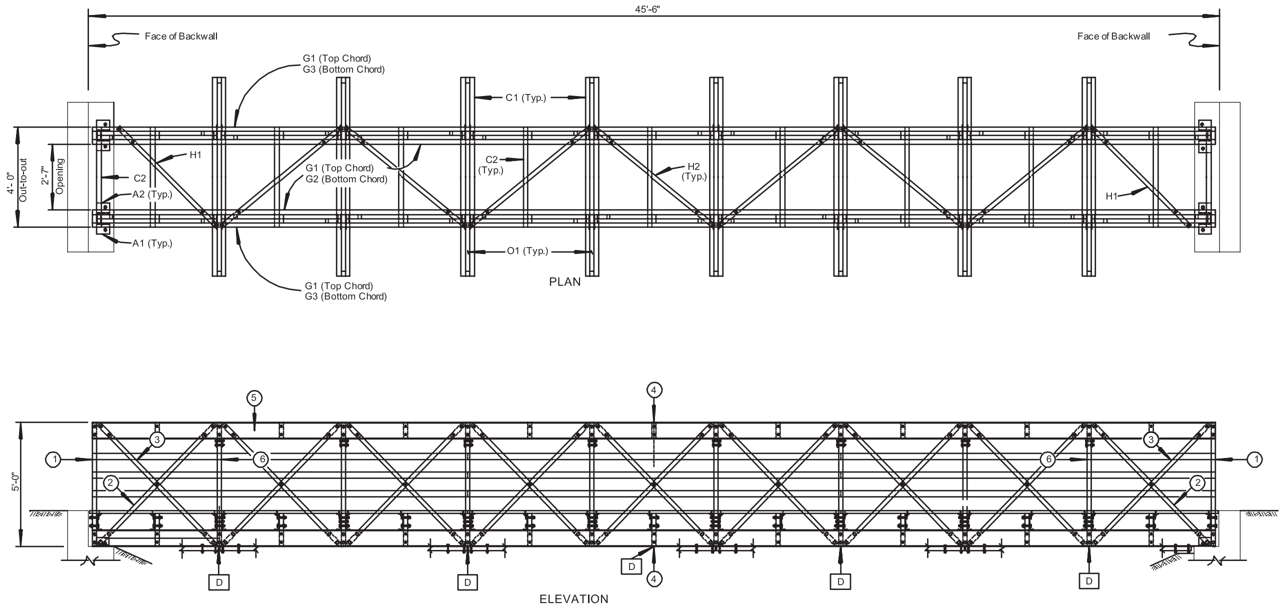
The bridge was loaded on September 29, 1998. Temperature (Temp) was measured in degrees Fahrenheit. The *actual deflection* is the *bridge readings* at a particular time minus the initial unloaded bridge reading. After testing at the Forest Products Laboratory, this bridge was dismantled and reinstalled at Falls Creek in the Gifford-Pinchot National Forest.

44-Foot Walk Bridge

			Actual deflection				Bridge readings					
			Side 1		Side 2		Side 1		Side 2			
Time	Date	Total time (days)	End	Mid	End	Mid	End	Mid	End	Mid	Temp	Comments
1:00	9/29/1998	0.00	0.00	0.00	0.00	0.00	6.50	4.38	9.14	0.44	70	Zero load
3:15	9/29/1998	0.08	0.80	1.02	0.68	1.02	7.30	5.40	9.82	1.46	70	1 hr after loading
4:45	9/29/1998	0.16	0.81	1.02	0.71	1.06	7.31	5.40	9.85	1.50	70	Sunny
7:45	9/30/1998	0.80	0.84	1.08	0.73	1.07	7.34	5.46	9.87	1.51	70	Sunny
2:30	9/30/1998	1.00	0.84	1.08	0.72	1.07	7.34	5.46	9.86	1.51	70	Sunny
8:00	10/1/1998	2.00	0.88	1.10	0.74	1.10	7.38	5.48	9.88	1.54	50	Sunny
8:00	10/2/1998	3.00	0.90	1.12	0.76	1.12	7.40	5.50	9.90	1.56	55	Rain, cloudy
10:00	10/5/1998	6.00	0.90	1.16	0.76	1.14	7.40	5.54	9.90	1.58	60	Rainy
8:00	10/6/1998	7.00	0.90	1.17	0.76	1.16	7.40	5.55	9.90	1.60	55	Rainy
9:30	10/7/1998	8.00	0.88	1.16	0.75	1.14	7.38	5.54	9.89	1.58	60	Clearing
8:30	10/8/1998	9.00	0.90	1.18	0.78	1.16	7.40	5.56	9.92	1.60	55	Sunny
8:00	10/9/1998	10.00	0.92	1.18	0.80	1.16	7.42	5.56	9.94	1.60	51	Sunny
9:00	10/13/1998	14.00	0.94	1.20	0.82	1.18	7.44	5.58	9.96	1.62	41	Sunny
8:00	10/19/1998	20.00	0.96	1.24	0.84	1.22	7.46	5.62	9.98	1.66	45	Sunny, after 2 days rain
8:00	10/26/1998	27.00	0.94	1.22	0.82	1.20	7.44	5.60	9.96	1.64	54	Sunny
8:00	11/2/1998	34.00	0.96	1.24	0.84	1.22	7.46	5.62	9.98	1.66	42	Overcast
8:00	11/9/1998	41.00	0.97	1.25	0.83	1.22	7.47	5.63	9.97	1.66	34	Overcast
8:00	11/16/1998	48.00	0.96	1.26	0.84	1.22	7.46	5.64	9.98	1.66	40	Sunny after rain
8:00	11/30/1998	62.00	0.96	1.26	0.84	1.24	7.46	5.64	9.98	1.68	50	Rainy
8:00	1/4/1999	97.00	0.96	1.26	0.84	1.24	7.46	5.64	9.98	1.68	4	After 2 days of snow
8:00	2/10/1999	134.00	0.97	1.27	0.86	1.26	7.47	5.65	10.00	1.70	50	After spring melt
8:00	4/1/1999	184.00	0.98	1.28	0.88	1.28	7.48	5.66	10.02	1.72	59	Overcast
8:00	5/3/1999	216.00	0.96	1.26	0.82	1.22	7.46	5.64	9.96	1.66	78	Sunny
8:00	6/7/1999	251.00	1.02	1.32	0.88	1.28	7.52	5.70	10.02	1.72	88	Sunny
11:00	7/6/1999	280.00	1.04	1.38	0.90	1.34	7.54	5.76	10.04	1.78	96	Sunny
8:00	7/12/1999	286.00	1.09	1.42	0.95	1.39	7.59	5.80	10.09	1.83	80	Sunny
7:00	7/15/1999	289.00	1.10	1.48	0.96	1.46	7.60	5.86	10.10	1.90	72	Sunny
7:00	7/19/1999	293.00	1.11	1.49	0.97	1.47	7.61	5.87	10.11	1.91	73	Sunny
7:00	7/22/1999	296.00	1.11	1.49	0.97	1.47	7.61	5.87	10.11	1.91	76	Sunny
10:00	7/26/1999	300.00	1.11	1.49	0.97	1.47	7.61	5.87	10.11	1.91	84	Rainy
8:00	7/27/1999	301.00	1.11	1.49	0.97	1.43	7.61	5.87	10.11	1.87	90	Before unload, sunny
12:00	7/27/1999	301.00	0.45	0.46	0.27	0.38	6.95	4.84	9.41	0.82	92	Unload, sunny
7:00	7/28/1999	302.00	0.46	0.50	0.32	0.46	6.96	4.88	9.46	0.90	73	Sunny


Deflection of 44-Foot Bridge
Deflection (inches)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Time (Days)
0
0
0
1
1
2
3
6
7
8
9
10
14
20
27
34
41
48
62
97
134
184
216
251
280
286
289
293
296
300
301
301
302
Side 1 End
Side 1 Mid Span
Side 2 End
Side 2 Mid Span

REGION	STATE	PROJECT	SHEET NO.	TOTAL SHEETS



Suggested Strain Gauge Locations

1. The strain gauges on the vertical end posts are located 18" from top of the post. They are centered on all four faces and oriented along the longitudinal axis of the members. There are four gauges per post for a total of sixteen gauges.
2. The strain gauges on the compression diagonals are located 15" from the center of the bolt connecting the diagonals in each panel. They are centered on the outside faces of the top and bottom flanges and are oriented along the longitudinal axis of the members. There are two gauges per diagonal for a total of eight gauges.
3. The strain gauges on the tension diagonals are located 15" from the center of the bolt connecting the diagonals in each panel. They are centered on the outside faces of the top and bottom flanges and are oriented along the longitudinal axis of the members. There are two gauges per diagonal for a total of eight gauges.
4. The strain gauges at midspan are located on the top and bottom chords at the center of the bridge. They are centered on the outside faces of the top and bottom flanges and are oriented along the longitudinal axis of the members. There are two gauges per channel or four gauges per chord for a total of 16 gauges.
5. The strain gauges on the top chord near the first interior post are located 1' from the post. They are centered on the outside face of each channel web and are oriented along the longitudinal axis of the top chord. There is one gauge on each channel of both top chords at only one location on each truss for a total of four gauges.
6. The strain gauges on the first interior posts are located 18" from the top of the post. They are centered on all four faces and are oriented along the longitudinal axis of the posts. There are four gauges per post for a total of sixteen gauges.

Notes:
1. Strain gauges at locations 1 - 5 are placed on both trusses.
2. Strain gauges at location 6 are placed near one post on both trusses.
3. Deflection gauges should be on the bottom flange of the bottom chord of both trusses as indicated.

Key:
④ Strain gauge location number
D Deflection gauge

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
EASTERN FEDERAL LANDS HIGHWAY DIVISION

GIFFORD PINCHOT NATIONAL FOREST
FALLS CREEK TRAIL BRIDGE

STRAIN GAUGE LOCATIONS

NO.	DATE	BY	REVISIONS	NO.	DATE	BY	REVISIONS	DESIGNED BY	DRAWN BY	CHECKED BY	SCALE	PROJECT TEAM LEADER	BRIDGE DRAWING	DATE	DRAWING NO.
								Scott Wallace	Scott Wallace	Johansen\Wilson E.T.Techtonics		Gary Jakovich	1 of 1	March, 1998	

Figure 1—Locations of the strain and deflection gauges for the Falls Creek Trail Bridge.

Appendix E—FRP Trail Bridges in the United States

(Courtesy of the American Composites Association in 2000.)

FRP Trail Bridges in the United States

Bridge name	Location	Year built	Length (feet)	Width (feet)	System provider or FRP manufacturer
Will Rogers State Park	Temescal Canyon Pacific Palisades, CA	1994	20	4	E.T. Techtonics, Inc.
San Luis Obispo (1)	San Luis Obispo, CA	1994	25	4	E.T. Techtonics, Inc.
San Luis Obispo (2)	San Luis Obispo, CA	1994	30	4	E.T. Techtonics, Inc.
San Luis Obispo (3)	San Luis Obispo, CA	1994	30	4	E.T. Techtonics, Inc.
San Luis Obispo (4)	San Luis Obispo, CA	1994	35	4	E.T. Techtonics, Inc.
San Luis Obispo (5)	San Luis Obispo, CA	1994	35	4	E.T. Techtonics, Inc.
San Luis Obispo (6)	San Luis Obispo, CA	1994	40	4	E.T. Techtonics, Inc.
Sierra Madre	Sierra Madre, CA	1994	40	4	E.T. Techtonics, Inc.
Malibu Creek State Park (1)	Malibu, CA	1994	40	5	E.T. Techtonics, Inc.
Malibu Creek State Park (2)	Malibu, CA	1994	20	5	E.T. Techtonics, Inc.
Tahoe National Forest Bridge	Grass Valley, CA	1994	20	5	E.T. Techtonics, Inc.
Deukmejain Wilderness Park (1)	Glendale, CA	1994	15	4	E.T. Techtonics, Inc.
Deukmejain Wilderness Park (2)	Glendale, CA	1994	20	4	E.T. Techtonics, Inc.
Deukmejain Wilderness Park (3)	Glendale, CA	1994	25	4	E.T. Techtonics, Inc.
Deukmejain Wilderness Park (4)	Glendale, CA	1994	25	4	E.T. Techtonics, Inc.
Will Rogers State Park	Malibu, CA	1994	40	5	E.T. Techtonics, Inc.
Point Bonita Lighthouse (1)	San Francisco, CA	1995	35	4	E.T. Techtonics, Inc.
Point Bonita Lighthouse (2)	San Francisco, CA	1995	70	4	E.T. Techtonics, Inc.
Pardee Dam Bridge	Valley Springs, CA	1995	25	5	E.T. Techtonics, Inc.
San Dieguito River Park	San Diego, CA	1996	70	8	E.T. Techtonics, Inc.
City of Glendora Bridge (1)	Glendora, CA	1996	18	6	E.T. Techtonics, Inc.
City of Glendora Bridge (2)	Glendora, CA	1996	22	6	E.T. Techtonics, Inc.
Grant Cty Park Bridge (1)	San Jose, CA	1997	20	5	E.T. Techtonics, Inc.
Grant Cty Park Bridge (2)	San Jose, CA	1997	35	5	E.T. Techtonics, Inc.
Grant Cty Park Bridge (3)	San Jose, CA	1997	40	5	E.T. Techtonics, Inc.
Grant Cty Park Bridge (4)	San Jose, CA	1997	40	5	E.T. Techtonics, Inc.
Grant Cty Park Bridge (5)	San Jose, CA	1997	50	5	E.T. Techtonics, Inc.
Santa Monica National Park	Calabasas, CA	1998	40	5	E.T. Techtonics, Inc.
Redwoods Natl Park (1)	Orick, CA	1999	80	5	E.T. Techtonics, Inc.
Redwoods Natl Park (2)	Orick, CA	1999	80	5	E.T. Techtonics, Inc.
Muir Beach Bridge (1)	Muir Beach, CA	1999	50	4	E.T. Techtonics, Inc.
Muir Beach Bridge (2)	Muir Beach, CA	1999	70	5	E.T. Techtonics, Inc.
Audubon Canyon Ranch Nature Preserve	Marshall, CA	1999	96	6	E.T. Techtonics, Inc.
City of Glendora Bridge	Glendora, CA	1999	28	6	E.T. Techtonics, Inc.
Santa Monica Bridge	Topanga, CA	2000	60	6	E.T. Techtonics, Inc.
Prairie Creek Redwoods State Park Bridge	Orick, CA	2000	46	5	E.T. Techtonics, Inc.
Santa Monica Bridge (1)	Calabasas, CA	2000	30	6	E.T. Techtonics, Inc.
Santa Monica Bridge (2)	Calabasas, CA	2000	75	6	E.T. Techtonics, Inc.
Rodeo Beach Pier	Sausalito, CA	2000	180	5	E.T. Techtonics, Inc.

Continued ⤳

FRP Trail Bridges in the United States

Bridge name	Location	Year built	Length (feet)	Width (feet)	System provider or FRP manufacturer
Alameda County Bridge	Castro Valley, CA	2000	18	4	E.T. Techtonics, Inc.
Humboldt State Park Bridge	Weott, CA	2000	40	4	E.T. Techtonics, Inc.
Golden Gate National Recreation Area (1)	Sausalito, CA	2001	25	5	E.T. Techtonics, Inc.
Golden Gate National Recreation Area (2)	Sausalito, CA	2001	25	5	E.T. Techtonics, Inc.
Topanga Canyon Bridge	Topanga, CA	2002	18	6	E.T. Techtonics, Inc.
Petaluma Bridge	Petaluma, CA	2002	40	6	E.T. Techtonics, Inc.
Boulder County Bridge	Boulder, CO	1994	35	6	E.T. Techtonics, Inc.
Heil Ranch Bridge	Boulder, CO	2000	45	6	E.T. Techtonics, Inc.
O’Fallon Park Bridge (1)	Denver, CO	2002	100	22	Strongwell
O’Fallon Park Bridge (2)	Denver, CO	2002	42	19	Strongwell
Sachem Yacht Club	Guilford, CN	2001	54	6	E.T. Techtonics, Inc.
Greensbranch - Pedestrian	Smyrna, DE	1999	32	6	Hardcore Composites
Catholic University Access Bridge	Washington, DC	1995	35	4	E.T. Techtonics, Inc.
Haleakala National Park (1)	Maui, HI	1995	40	4	E.T. Techtonics, Inc.
Haleakala National Park (2)	Maui, HI	1995	80	4	E.T. Techtonics, Inc.
Sealife Park Dolphin Bridge	Oahu, HI	2001	36	3	Strongwell
LaSalle Street Pedestrian Walkway	Chicago, IL	1995	220	12	Strongwell
Antioch Composite Pedestrian Bridge	Antioch, IL	1995	45	10	E.T. Techtonics, Inc.
Clear Creek Bridge (Daniel Boone National Forest)	Bath County, KY	1996	60	6	Strongwell
Levisa Fork of the Big Sandy River Footbridge	Johnson County, KY	1999	420	4	Strongwell
Bar Harbor Yacht Club Pier	Bar Harbor, ME	1995	124	5	Strongwell
Montgomery Cty Dept. of Park & Planning (1)	Silver Spring, MD	2000	23	6	E.T. Techtonics, Inc.
Montgomery Cty Dept. of Park & Planning (2)	Silver Spring, MD	2000	26	6	E.T. Techtonics, Inc.
Montgomery Cty Dept. of Park & Planning (3)	Silver Spring, MD	2000	30	6	E.T. Techtonics, Inc.
Montgomery Cty Dept. of Park & Planning (4)	Silver Spring, MD	2000	32	6	E.T. Techtonic
Montgomery Cty Dept. of Park & Planning (5)	Silver Spring, MD	2000	32	6	E.T. Techtonics, Inc.
Montgomery Cty Dept. of Park & Planning (6)	Silver Spring, MD	2000	40	6	E.T. Techtonics, Inc.
Becca Lily Park Bridge	Takoma Park, MD	2000	30	6	E.T. Techtonics, Inc.
Montgomery Cty Dept. of Park & Planning (1)	Clarksburg , MD	2002	20	6	E.T. Techtonics, Inc.
Montgomery Cty Dept. of Park & Planning (2)	Clarksburg, MD	2002	40	6	E.T. Techtonics, Inc.

FRP Trail Bridges in the United States

Bridge name	Location	Year built	Length (feet)	Width (feet)	System provider or FRP manufacturer
Montgomery Cty Dept. of Park & Planning (3)	Clarksburg, MD	2002	50	6	E.T. Techtonics, Inc.
Montgomery Cty Dept. of Park & Planning (4)	Clarksburg, MD	2002	60	6	E.T. Techtonics, Inc.
Tanner Creek/Weco Beach Bridge	Bridgman, MI	1999	33	6	E.T. Techtonics, Inc.
Aurora Pedestrian Bridge	Aurora, NE	2001	100	10	Kansas Structural
Composites, Inc.					
Homestead Bridge	Los Alamos, NM	1997	54	4	E.T. Techtonics, Inc.
City of Los Alamos (1)	Los Alamos, NM	1999	50	4	E.T. Techtonics, Inc.
City of Los Alamos (2)	Los Alamos, NM	1999	25	6	E.T. Techtonics, Inc.
City of Los Alamos (3)	Los Alamos, NM	1999	12	6	E.T. Techtonics, Inc.
Los Alamos National Laboratory Bridge (1)	Los Alamos, NM	2001	40	3	E.T. Techtonics, Inc.
Los Alamos National Laboratory Bridge (2)	Los Alamos, NM	2001	60	3	E.T. Techtonics, Inc.
City of Los Alamos (1)	Los Alamos, NM	2001	16	4	E.T. Techtonics, Inc.
City of Los Alamos (2)	Los Alamos, NM	2001	35	4	E.T. Techtonics, Inc.
City of Los Alamos (3)	Los Alamos, NM	2001	12	4	E.T. Techtonics, Inc.
Tiffany Street Pier	Bronx, NY	1998	410	49	Seaward International
Lemon Creek Park Bridge	New York, NY	1998	85	5	Seaward International
Barclay Avenue Bridge	Staten Island, NY	2001	32	6	E.T. Techtonics, Inc.
Scenic Hudson Bridge	Tuxedo, NY	2002	35	4	E.T. Techtonics, Inc.
Popolopen Creek Bridge	New York, NY	2003	N/A	N/A	Strongwell
Powell Park Bridge	Raleigh, NC	1997	15	4	E.T. Techtonics, Inc.
Blue Ridge Parkway Bridge	Spruce Pine, NC	2001	30	4	E.T. Techtonics, Inc.
Mt. Hood National Forest Bridge (1)	Sandy, OR	1997	30	3	E.T. Techtonics, Inc.
Mt. Hood National Forest Bridge (2)	Sandy, OR	1997	30	3	E.T. Techtonics, Inc.
Peavine Creek Bridge	Wallowa-Whitman National Forest, OR	1998	22	6	E.T. Techtonics, Inc.
Devil’s Pool / Fairmount Park (1)	Philadelphia, PA	1991	20	4	E.T. Techtonics, Inc.
Devil’s Pool / Fairmount Park (2)	Philadelphia, PA	1991	32	4	E.T. Techtonics, Inc.
Devil’s Pool / Fairmount Park	Philadelphia, PA	1992	50	5	E.T. Techtonics, Inc.
Philadelphia Zoo	Philadelphia, PA	1994	100	10	Creative Pultrusion, Inc.
Dingman Falls Bridge (1)	Bushkill, PA	1996	70	6	E.T. Techtonics, Inc.
Dingman Falls Bridge (2)	Bushkill, PA	1996	80	6	E.T. Techtonics, Inc.
McDade Trail Bridge (1)	Bushkill, PA	2002	25	6	E.T. Techtonics, Inc.
McDade Trail Bridge (2)	Bushkill, PA	2002	40	6	E.T. Techtonics, Inc.
McDade Trail Bridge (3)	Bushkill, Pennsylvania	2002	40	6	E.T. Techtonics, Inc.
Clemson Experimental Trail Bridge	Clemson, SC	2001	30	6	E.T. Techtonics, Inc.
Francis Marion National Forest	McClellanville, SC	2002	60	6	E.T. Techtonics, Inc.
Las Rusias Military Highway	Texas	1997	45	4	Hughes Bros., Inc.
Lake Jackson Bridge	Lake Jackson, TX	2003	90	6	N/A

Continued

FRP Trail Bridges in the United States					
Bridge name	**Location**	**Year built**	**Length (feet)**	**Width (feet)**	**System provider or FRP manufacturer**
Unknown	Charlottesville, VA	1978	16	7	N/A
Girl Scout Council of Colonial Coast Bridge	Chesapeake, VA	1999	50	8	E.T. Techtonics, Inc.
Blue Ridge Parkway Bridge (1)	Floyd, VA	1999	24	4	E.T. Techtonics, Inc.
Blue Ridge Parkway Bridge (2)	Floyd, VA	1999	34	4	E.T. Techtonics, Inc.
Blue Ridge Parkway Bridge (1)	Floyd, VA	2001	28	4	E.T. Techtonics, Inc.
Blue Ridge Parkway Bridge (2)	Floyd, VA	2001	34	4	E.T. Techtonics, Inc.
George Washington & Jefferson National Forest	Edinburg, VA	2001	35	6	E.T. Techtonics, Inc.
Staircase Rapids (1) (Hoodsport)	Olympic National Park, WA	1994	40	4	E.T. Techtonics, Inc.
Staircase Rapids (2) (Hoodsport)	Olympic National Park, WA	1994	50	4	E.T. Techtonics, Inc.
Staircase Rapids (3) (Hoodsport)	Olympic National Park, WA	1994	80	4	E.T. Techtonics, Inc.
Bovee Meadows Trail Bridge	Lake Crescent, WA	1995	75	6	E.T. Techtonics, Inc.
Falls Creek Trail Bridge	Gifford Pinchot National Forest, WA	1997	45	3	Creative Pultrusion, Inc.
Ohio River Bridge	Wheeling, WV	1999	1000	4	Hardcore Composites
Medicine Bow National Forest	Medicine Bow, WY	1995	20	5	E.T. Techtonics, Inc.

Appendix F—Web Sites

FRP Bridge Inspections

AEA Technology
Engineering Solutions—CPD4D Project Number AH9/124 Non-Destructive Evaluation of Composite Components (CPD4D) Web site: *http://www.aeat.co.uk/ndt/cpd4d /cpd4dsum.html*

Identification of Fiber Breakage in Fiber Reinforced Plastic by Low-Amplitude Filtering of Acoustic Emission Data. Web site: *http://www.kluweronline.com/article.asp?PIPS=491177&PDF=1*

Long-Term In-Service Evaluation of Two Bridges Designed with Fiber-Reinforced Polymer Girders. Bernard Leonard Kassner. Web site: *http://scholar.lib.vt.edu/theses/available/etd-09062004-152133/unrestricted/Kassner_Thesis.pdf*

Thermal Infrared Inspection of FRP Bridge Decks for Health Monitoring. Marybeth Miceli, Lucius Pitkin, Inc. (USA); John C. Duke and Michael Horne, Virginia Polytechnic Institute and State University (USA). Web site: *http://spiedl.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=PSISDG00507300000100032800000 1&idtype=cvips&gifs=yes*

Transportation Research Board—NCHRP Project 10/64 Panel on Field Inspection of In-Service FRP Bridge Decks. Web site: *http://trb.org/directory/comm_detail.asp?id= 2879*

University of Delaware—Nondestructive Inspection of FRP Composite Bridge Using Vibration Techniques Web site: *http://www.ccm.udel.edu/Pubs/posters02/P_posters/P167.pdf*

General Information

Composites in Construction Pultruded Profiles. Reference and Bibliography Database. Compiler: Dr J.T. Mottram. Web site: *http://www.eng.warwick.ac.uk/staff/jtm/pfrp_latest.pdf*

Composites World. Web site: *http://www.compositesworld.com/*

Polymer Composites III 2004. Transportation Infra-structure, Defense and Novel Applications of Composites. Proceedings, March 30–April 1, 2004. West Virginia University, Morgantown, WV. Editors: Robert C. Creese and Hota GangaRao. Web site: *http://www.destechpub. com/pageview.asp?pageid=15104*

United States Department of Transportation Federal Highway Administration—FRP Library. Web site: *http://www.fhwa.dot.gov/bridge/frp/frppaper.htm*

Pedestrian Bridges

Antioch Composite Pedestrian Bridge, Antioch, IL (1996). Web site: *http://www.iti.northwestern.edu/research/completed/composites/antioch.html*

Homestead Bridge, Los Alamos, NM (1997). Web site: *http://composite.about.com/library/weekly/aa102797.htm*

LaSalle St. Composite Pedestrian Walkway (1994). Web site: *http://www.iti.northwestern.edu/research/completed/composites/lasalle.html*

Preliminary Design and Analysis of a Pedestrian FRP Bridge Deck. Lulea University of Technology, licentiate thesis by Patrice Godonou. Web site: *http://epubl.luth.se/1402-1757/2002/18/index-en.html*

Appendix G—FRP Suppliers, Designers, and Associations

American Composites Manufacturers Association
1010 North Glebe Rd.
Arlington, VA 22201
Phone: 703–525–0511
Fax: 703–525–0743
Email: *info@acmanet.org*
Web site: *http://www.mdacomposites.org/*

Bedford Reinforced Plastics, Inc.
R.D. 2, Box 225
Bedford, PA 15522
Phone: 814–623–8125, 800–FRP–3280
Fax: 814–623–6032
Web site: *http://www.bedfordplastics.com*

Creative Pultrusions, Inc.
214 Industrial Lane
Alum Bank, PA 15521
Phone: 814–839–4186
Fax: 814–839–4276
Web site: *http://www.pultrude.com/*

E.T. Techtonics, Inc.
P.O. Box 40060
Philadelphia, PA 19106
Phone: 215–592–7620
Fax: 215–592–7620
Email: *info@ettechtonics.com*
Web site: *http://www.ettechtonics.com/*

Fibergrate Composite Structures, Inc.
5151 Beltline Rd., Suite 700
Dallas, TX 75254
Phone: 972–250–1633
Fax: 972–250–1530
Web site: *http://www.fibergrate.com*

Hardcore Composites
618 Lambsons Lane
New Castle, DE 19720
Phone: 302–442–5900
Fax: 302–442–5901
Email: *sales@hardcorecomposites.com*
Web site: *http://www.compositesworld.com*

Infrastructure Composites International, Inc.
7550 Trade St.
San Diego, CA 92121
Phone: 858–537–0715
Fax: 858–537–3465, 858–537–3465
Web site: *http://www.infracomp.com*

Liberty Pultrusions East & West
1575 Lebanon School Rd.
Pittsburgh, PA 15122
Phone: 412–466–8611
Fax: 412–466–8640
Web site: *http://www.libertypultrusions.com*

Kansas Structural Composites, Inc.
553 S. Front St.
Russell, KS 67665
Phone: 785–483–2589
Fax: 785–483–5321
Email: *ksci@ksci.com*
Web site: *http://www.ksci.com*

Peabody Engineering
13465 Estelle St.
Corona, CA 92879
Phone: 800–473–2263
Fax: 310–324–7247
Web site: *http://www.etanks.com*

San Diego Plastics, Inc.
2220 McKinley Ave.
National City, CA 91950
Phone: 800–925–4855, 619–477–4855
Fax: 619–477–4874
Web site: *http://www.sdplastics.com/*

Seasafe, Inc.
209 Glaser Dr.
Lafayette, LA 70508
Phone: 800–326–8842
Fax: 337–406–8880
Web site: *http://www.seasafe.com*

Seaward International, Inc.
3470 Martinsburg Pike
Clearbrook, VA 22624
Phone: 540–667–5191
Fax: 540–667–7987
Web site: *http://www.seaward.com/*

Structural Fiberglass, Inc.
4766 Business Route 220 North
Bedford, PA 15522
Phone: 814–623–0458
Fax: 814–623–0978
Web site: *http://www.structuralfiberglass.com*

Strongwell
400 Commonwealth Ave.; P.O. Box 580
Bristol, VA 24203–0580
Phone: 276–645–8000
Fax: 276–645–8132
Email: *webmaster@strongwell.com*
Web site: *http://www.strongwell.com/*

Appendix H—Design of the Falls Creek Trail Bridge

DESIGN OF THE FALLS CREEK TRAIL BRIDGE

A Fiber Reinforced Polymer Composite Bridge

Scott Wallace, P.E.
Eastern Federal Lands Highway Division
Federal Highway Administration

INTRODUCTION

The design of the Falls Creek Trail Bridge, a 13.9-m- (45-ft 6-in-) long single-span, fiber-reinforced composite (FRP) bridge, was borne out of an old need and new technology. Lightweight, low maintenance structures that can be hauled into remote locations have been needed for a long time. However, applying fiber reinforced polymer (FRP) composites to such needs is a recent development driven by efforts of FRP composite manufacturers to enter the bridge industry. The Bridge Design office in the Eastern Federal Lands Highway Division (EFLHD) of the Federal Highway Administration (FHWA) became interested in developing a design approach for FRP bridges after seeing a presentation given by E.T. Techtonics, Inc., which highlighted the potential of the material. One of EFLHD's primary clients, the USDA Forest Service, had a large need for lightweight, low maintenance bridges for their trail system, and FRP bridges appeared to be an ideal solution.

In May 1997, EFLHD met with representatives of the Forest Service, E.T. Techtonics, Inc., and GHL, Inc. The objective of the meeting was to bring together one of EFLHD's client agencies (Forest Service) with experts in the FRP composite industry to explore the possibility of making a lightweight, low maintenance bridge. E.T. Techtonics, Inc., one of the leading experts in the country on the use of FRP composites in pedestrian bridges and GHL, Inc., were working to increase the use of FRP composites in government projects.

EFLHD wanted to acquire the ability to design, specify, and produce plans for FRP composite pedestrian bridges. The Forest Service wanted a bridge that could be "packed" into remote locations and easily constructed onsite. The FRP industry wanted to expand the application of their products to include the bridge industry. All three parties also wanted to test the finished bridge extensively and disseminate the results to other agencies.

GENERAL FEATURES

A Pratt truss was chosen for this bridge (see figures 1 and 2), based on many of its intrinsic characteristics that fit well with characteristics of FRP composite structural shapes. These same characteristics are ideal for pedestrian bridges.

A truss is really a deep beam with unnecessary portions of the web removed. It optimizes the placement of the structural sections in order to get the most advantage out of them. The result is a large top and bottom chord with a minimal web in between them. It also places the individual sections such that they carry uniaxial loads along their length.

FRP composite sections are well suited for this type of use. Because of their fiber orientation, they are much stronger along their longitudinal axis than transverse to it. They are also readily available in structural shapes, such as tubes and channels, that have been traditionally used in trusses, making assembly easier.

The combination of a structural type that minimizes the amount of material needed and an extremely lightweight material provides an excellent structure for pedestrian bridge applications. Using the Pratt truss approach also provides a ready-made pedestrian rail on each side of the bridge with the top chord of each truss serving as the handrail.

The Forest Service needed a bridge that was not only lightweight and required little maintenance, but one that could carry considerable loads as well. In recent years they had experienced some very extreme snowfalls in the Pacific Northwest. Some of their pedestrian bridges which were designed for a 7.182 kPa (150 psf) snow load failed due to the weight of the snow. Because of this and the unfamiliarity with the FRP composite material, they requested that a design snow load of 11.97 kPa (250 psf) be used. This is equivalent to a wall of wet snow piled over 6 m (20 ft) high. The loading actually models a bank of snow that “mushrooms” out over the handrails, thus significantly increasing the load per unit surface area of the deck. The bridge superstructure was also designed to resist a design wind load based on 45 m/s (100 mph) winds.

Along with lightweight, low maintenance characteristics, and the ability to carry these extreme loads, the Forest Service wanted a bridge made of readily available components with a repeatable design so that it could be duplicated. FRP composites seemed to have the potential to meet all of their criteria.

MATERIALS

FRP composites are composed of a resin matrix binder that has been reinforced with fibers. The fibers provide tensile strength along their length and may be oriented in more than one direction. The resin binder holds the fibers together and in the proper orientation while transferring loads between fibers. It also provides all of the interlaminar shear strength for the member. Together, they combine in a working relationship much like that between reinforcing steel and concrete.

The structural sections making up the trusses on the Falls Creek Trail Bridge are manufactured by Strongwell and came from their EXTREN line (1). They contain glass fibers embedded in an isophthalic polyester resin. The fibers consist of continuous strand roving composed of thousands of fiber filaments running along the length of the member and continuous strand mat composed of long intertwined glass fibers running in different directions. The roving provides the strength along the longitudinal axis of each member and the mat provides the multidirectional strength properties. Each member also includes a surfacing veil composed of polyester nonwoven fabric and resin on the outside of the section to provide ultraviolet and corrosion protection.

The decking is also a Strongwell product and includes a 6-mm ($^1/_4$-in) EXTREN sheet with a gritted surface on top of DURAGRID I-7000 25-mm (1-in) grating. The grating is similar in composition to the structural shapes except that it contained a vinyl ester resin binder.

All of the FRP composite sections were manufactured using a pultrusion process. The process involves pulling continuous lengths of glass mat and roving through a resin bath and then into a heated die. The heat initiates the gelation (or hardening) of the resin and the cured profile is formed matching the shape of the die.

Only two other materials were used in the superstructure of this bridge. The sections were connected with galvanized bolts conforming to ASTM A307. And the superstructure was attached to the foundations by steel anchor bolt clip angles conforming to ASTM A36.

DESIGN

The design of the Falls Creek Trail bridge was performed in accordance with the American Association of State Highway and Transportation Officials’ (AASHTO) *Standard Specifications for Highway Bridges* (2) and *Guide Specifications for Design of Pedestrian Bridges* (3). Both specifications were needed in that while the standard specification provided good general bridge design guidance, the guide specification provided specific guidance relating to the unique characteristics of pedestrian bridges, which tend to be smaller, lighter, more flexible structures than standard highway bridges.

Neither specification, however, deals with FRP composites. Therefore, additional guidance and design techniques were developed from sources in the FRP composite industry. The *Design Manual for EXTREN Fiberglass Structural Shapes* (1) developed by Strongwell was a good source of information relating to the individual structural shapes of which the bridge was comprised. In addition, E.T. Techtonics, Inc., provided assistance in interpreting and modifying existing information; provided test data pertaining to connection capacity and other details; and reviewed the final design and details.

Because of the FRP composite sections being patterned after shapes common to the steel industry, some guidance and design techniques were developed based on the *Manual of Steel Construction* from the American Institute of Steel Construction (AISC) (4) as well.

It was necessary to design each structural member of the bridge with respect to allowable tension, allowable compression, allowable bending stresses, combined stresses due to axial forces and moments acting together, and shear. The design forces and moments used were the maximum values generated by an analysis of the structure with fixed joints, one pinned support, and one roller support.

Whenever a member was exposed to a bending moment in conjunction with an axial compression force in excess of 15 percent of the allowable axial compression, it was assumed that a secondary moment was generated. To account for this, a secondary moment amplification factor was employed. It was unnecessary to apply the same design approach to tensile members (4). This will be discussed further in the *Combined Axial Load and Bending* portion of this section of the report.

The bridge is loaded primarily with dead load (self-weight and snow) and wind load. By observation, it was determined that the most conservative AASHTO load group designation was load group II (2). Members designed with this design load group are permitted a 25-percent increase in allowable unit stresses. Similarly, AISC allows a 33-percent increase in allowable stresses based on Euler's equation if the wind load causes a stress increase of over 33 percent in all members (4), which occurred on this bridge. Therefore, since the critical design loads were caused by wind load and dead load, a 25-percent increase in allowable stresses and allowable Euler stresses was incorporated into the design. However, due to unfamiliarity with the equations from the Strongwell design manual, no allowable stress increase was applied to them.

Tension Members

Designing an FRP composite section to carry tensile loads is a very straightforward process. The allowable tensile stress for the sections used in the Falls Creek Trail Bridge is simply the ultimate tensile stress divided by a factor of safety regardless of the structural shape being designed.

In this bridge, the bottom chord, interior vertical posts, diagonal tension members, and horizontal bracing all experienced some tension. However, none of them were stressed to more than 40 percent of their allowable tensile stress.

Compression Members

As should be expected, designing an FRP composite section to resist compressive loads is more complex. The allowable compressive stress is a function of local, member, and Euler buckling characteristics, as well as structural shape and end conditions.

The structural channels and tubes that made up this bridge were all comprised of plate elements such as flanges and webs. These elements may develop wave formations when they are compressed; this is called *local buckling*. The stress at which local buckling occurs is a function of many factors. In typical structural members the primary factors are element slenderness (width/thickness ratio), aspect ratio (length/width ratio) and edge support conditions.

A constant (k) is used to adjust the calculated critical stress at which local buckling occurs to account for differing edge conditions. When both unloaded edges are fixed, as in the case of webs, $k = 7$. When one unloaded edge is fixed and one is free, as in the case of channel flanges, $k = 1.33$. The Strongwell column equations take this into account. For W and I shapes the equations are based on local buckling of the flange because their sections are proportioned such that the flanges will buckle before the webs. Therefore, in order to extend the use of these formulas to channels, shapes for which they do not provide column equations, it was necessary to examine local buckling in both the web and the flanges. The element that had a lower critical stress at which local buckling occurred, and therefore a higher width/thickness ratio, controlled the design. However, the web width/thickness ratio had to first be modified to allow for its edge conditions being different than those on which the formulas were based. Simply put, the width/thickness ratio for the web was replaced with an adjusted web width/thickness ratio equivalent to 1.33/7 times its actual ratio. The larger of the flange or adjusted web width/thickness ratios for each compressive member was then used in the appropriate Strongwell equation (Equations 1 or 2) to determine the short column mode ultimate compressive stress based on local buckling.

For square and rectangular structural tubes, the equations were applied without adjustments. The empirically derived Strongwell equations follow; ultimate compressive stress column equations, short column mode:

W and I shapes:

$$F'_u = \frac{0.5E}{\left(\frac{b}{t}\right)^{1.5}} \qquad (1)$$

Square and rectangular tubes:

$$F'_u = \frac{E}{16\left(\frac{b}{t}\right)^{0.85}} \qquad (2)$$

where

F'_u = ultimate compressive stress (kPa)
b = element width (mm)
E = modulus of elasticity (kPa)
t= element thickness (mm)

Even if a compression member does not fail due to local buckling of one of its elements, the entire member could fail due to member buckling. This type of failure is a function of modulus of elasticity, end conditions, and member slenderness ratio. In order to design for member buckling, two equations were applied to each member. The appropriate Strongwell equation (Equations 4 or 5) for long column mode failures in W and I shapes or in tubes was first applied. These formulas, along with the short column formulas (Equations 1 and 2), are based on Strongwell's extensive testing of fiberglass shapes and are pertinent only to their EXTREN products. The general column formula developed in 1744 by Swiss mathematician Leonard Euler (5) was also applied to both the channels and the tubes. The more conservative results were used for determining the ultimate compressive stress based on member failure. In every member of this bridge, the Euler equation proved to be more restrictive. However, in some cases when the 25-percent increase in allowable Euler stress was taken into consideration the Strongwell equations controlled. Following are the ultimate compressive stress column equations, long column mode:

W and I shape:

$$F'_u = \frac{4.9E}{\left(\frac{Kl}{r}\right)^{2}} \qquad (3)$$

Square and rectangular tubes:

$$F'_u = \frac{1.3E}{\left(\frac{Kl}{r}\right)^{1.5}} \qquad (4)$$

Euler equation:

$$F'_u = \frac{\pi^2 E}{\left(\frac{Kl}{r}\right)^2}\,1.25 \qquad (5)$$

where

E = modulus of elasticity (kPa)
l = column length (m)
K = effective length factor
r = radius of gyration (m)

As the primary compressive load carrying member on this bridge, the top chord presented some interesting problems. It was sufficiently restrained in the vertical direction by the posts to reduce it to a column braced at intervals equal to the distance between posts, 1.5 m (5 ft) when designing against buckling in the vertical plane. The posts also provided restraint against buckling in the horizontal plane. However, the degree of restraint provided was dependent upon the stiffness of the transverse U-shaped frame composed of two posts and their interconnecting crosspiece. For this condition, the top chord was modeled as a column braced at intervals equal to the post spacing by elastic springs whose spring constants correspond to the stiffness of the transverse U-shaped frames restraining it (4) as shown in figure 3.

The transverse frame spring constant (C) upon which the effective length factor is based can be calculated according to the following formula:

Transverse frame spring constant:

$$C = \frac{E_{chord}}{h^2\left(\left(\frac{h}{3I_p}\right)-\left(\frac{b}{2I_c}\right)\right)} \tag{6}$$

E_{chord} = modulus of elasticity of top chord
I_p = moment of inertia of vertical posts
h = effective height of vertical posts
I_c = moment of inertia of crosspiece
b = span of crosspiece between trusses

AASHTO provides an appendix to their pedestrian bridge guide specification (3) that includes a table for relating the transverse frame spring constant to an effective length factor for trusses with different numbers of panels. Neglecting the outriggers, the Falls Creek Trail Bridge had a transverse frame spring constant: C = 0.423. Based on this and taking into account its nine panels, the resultant effective length factor was K = 2.8.

If the top chord of this bridge was supported such that K = 2.8 it would only be able to carry approximately 3.5 kips of compression. Therefore, it was necessary to employ outriggers at every interior post. The outriggers sufficiently stiffen the transverse frame such that the effective length factor becomes K = 1. By increasing the stiffness of the transverse frame through the use of outriggers, and thereby increasing the stiffness of the elastic spring supports, the top chord's compression carrying capability was increased approximately 800 percent.

Having established the support conditions for the top chord it was important to then determine how the top chord would carry the axial compression applied to it. Because it is composed of two channels the top chord will function as two separate compression members acting individually between points where the two channels are attached to each other. If the channels were attached to each other only at the post connections, each would function as a compression member across a length of 1.5 m (5 ft). However, by fastening them together at the midpoint between the posts, their slenderness ratios were reduced by 75 percent and their ability to carry compressive forces individually was increased 400 percent. If the Strongwell long-column mode equation had controlled the design instead of the Euler equation, their allowable load would have increased 325 percent instead of 400 percent. Due to this significant increase in load carrying capability, the channels were bolted together with spacer blocks made of 51- by 102-mm (2- by 4-in) FRP composite tubes placed between them at the midpoint between the vertical posts.

The top chord will also try to carry the compressive loads as a single member with both channels working together. In an effort to maximize the load carrying capability of the top chord, the channels were placed four inches apart from each other. This was accomplished by using 51- by 102-mm (2- by 4-in) structural tubes as vertical posts and attaching the channels to the outside of the posts. By doing this the section modulus was increased substantially resulting in a much more laterally rigid member. This stiffer member carried compressive loads across an unsupported length equal to the distance between the posts. The Strongwell long column mode formula (Equation 3) and the Euler equation (Equation 5) were again employed, but the entire member was taken into consideration rather than just the individual channel.

It should be noted that when designing the top chord, AASHTO requires that the design load used for the determination of the critical buckling force should not be less than two times the maximum design load that any panel would experience. This requirement is in recognition of the fact that under uniform loading the maximum compressive stresses may occur simultaneously over consecutive panels (3). The use of what is basically a minimum factor of safety (FS) of two, seems wise in that there are a number of secondary factors and uncertainties involved in the analysis of top chord compression members that at present have not been quantified into an easily performed design procedure. These include torsional stiffness of the chord, lateral support contributed by the diagonals, initial crookedness of the chord, eccentricity of the axial load and uneven displacement of the posts as a moving load crosses the bridge. A factor of safety of three was employed for the design of all members of the Falls Creek Trail Bridge, thereby requiring no adjustment to meet this criteria.

Structural tubing also served as compression members on this bridge. The vertical end posts in particular carried a considerable amount of compression. By examining the Strongwell and Euler equations it can readily be noted that under axial compression loads the 51- by 102-mm (2- by 4-in) tubes, whose walls measure 51 by 6 mm (2 by $^1/_4$ in) and 102 by 3 mm (4 by $^1/_8$ in) respectively, tend to buckle in the plane of the truss. Both the width/thickness ratio and the slenderness ratio are higher in this direction, thereby causing the stress levels at which local buckling, member buckling, and Euler buckling take place to be lower. Although using the larger, rectangular tubes in place of 51- by 51-mm (2- by 2-in) square tubes (which have been used on other bridges) did not improve the buckling characteristics of the end posts, it did provide other advantages. As mentioned previously, the larger posts further separated the two channels comprising the top chord and resulted in an approximately 250-percent increase in member buckling resistance capacity in the horizontal direction for the top chord. They also provided increased lateral support to the top chord at each post and increased the overall lateral stiffness of the bridge. In addition, enough room was provided for the diagonals to cross between posts without intersecting each other. That is, if the vertical posts were made from 51- by 51-mm (2- by 2-in) tubes the diagonals would intersect each other, creating connection and stiffness difficulties.

Two diagonals were incorporated into each panel of the bridge trusses. As is common in Pratt trusses, one of the diagonals slopes upward toward the center of the span and is in compression while the other slopes downward toward the center of the span and is in tension. The exception to this occurred in the center panel where both diagonals experienced a small amount of tension. The tension diagonals were made of 51- by 51-mm (2- by 2-in) FRP composite structural tubes. The ends were filled with 44- by 44-mm (1$^3/_4$- by 1$^3/_4$-in) FRP composite solids to improve the connections. The compression diagonals were also made of 51- by 51-mm (2- by 2-in) FRP composite structural tubes but were filled from end to end with the solids in order to improve their compression carrying capability. The same local (Equation 2), member (Equation 4), and Euler (Equation 5) buckling equations mentioned previously were applied to the compression diagonals. Because the diagonals are connected at their centers they are assumed to be supported there and their unsupported length is equal to 50 percent of their actual length. The compression diagonals in the outside panels experienced the greatest loads and were stressed to approximately 35 percent of their allowable limit.

Bending

For Pratt truss bridges similar in size to the Falls Creek Trail Bridge, bending stresses generally will not control the design of the members. The multiple members attaching to each connection tend to adequately distribute the moment such that no single member experiences a large moment. However, two situations merit mentioning:

- If the supports are fixed, the moment in the bottom chord increases considerably.

- By applying a lateral force equivalent to 0.01/K times the average design compressive force in the two adjacent top chord members to the top of the vertical posts, as specified in the AASHTO guide specification (3), a large moment is generated in the posts.

Although the supports on the Falls Creek Trail Bridge were not designed as fixed, they did possess some degree of fixity. It was therefore important to examine the effects on the structure of fixing the supports. An analysis was performed under two loading conditions. One condition included full loading, while the other removed the snow load but included a 38-degrees Celsius (100-degrees Fahrenheit) temperature rise. The results revealed that the bottom chord was transformed from a tensile member with small bending moments to a compression member with much larger bending moments in the plane of the truss near the supports. In this region the bottom chord experienced approximately 89 kN (20 k) of compression while subject to a 8 kN-m (70 k-in) bending moment. Because the bottom chord is identical in section to the top chord but better supported laterally by the crosspieces, it was able to resist buckling at stress levels that were about 50 percent of the allowable compressive stress and 30 percent of the allowable bending stress.

The AASHTO guide specification takes a new approach to designing vertical posts. Instead of applying a minimum 4.378 kN/m (300 plf) force to the tops of the posts as required by the standard specification, it establishes a minimum lateral strength based on the degree of elastic lateral support provided by the post necessary for the top chord to resist its maximum design compressive force. It requires that a lateral force equivalent to 0.01/K times the average design compressive forces in the two adjacent top chord members be applied to the top of the verticals concurrently with all other design loads. Applying this design criteria effectively increased the design lateral bending stress in the interior vertical posts of this bridge by approximately 450 percent over that which the analysis produced. However, the bending stress level was approximately 65 percent of that which was allowed.

No member of the Falls Creek Trail Bridge was stressed beyond 65 percent of its allowable bending stress. However, each member also had to be proportioned to resist the combined effects of axial load and bending moment acting together. In order to consider these combined effects, the AISC combined stress equations were employed (4).

Combined Axial Load and Bending

Whenever a bending moment is applied to an axially loaded member, a secondary moment equal to the product of the eccentricity caused by the moment and the applied axial load is generated. Because any secondary moment caused by axial tension is opposite in sense to the primary, applied moment, the secondary moment will diminish rather than amplify the effects of the primary moment. Also, when the axial compression force is not in excess of 15 percent of the allowable axial compression, the effects of any secondary moment caused by the axial load are minor enough to be neglected. Therefore, when a member is exposed to either of these conditions, the secondary moment can be ignored. However, whenever a member is exposed to a bending moment in conjunction with an axial compression force in excess of 15 percent of the allowable axial compression, it should be assumed that a secondary moment is generated and its effects should be considered. To take the effects of the secondary moment into consideration, a secondary moment amplification factor is applied to the bending stress portion of the general combined stress equation.

For each member, the applicable following equations (7 to 10) must be satisfied. They are based on equations used by the steel industry (4) and are used as a check to assure that the combined effects of axial and bending stresses do not go beyond acceptable limits.

Axial tension and bending:

$$\frac{f_a}{F_t} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1 \qquad (7)$$

Axial compression and bending (f_a / F_a < 0.15):

$$\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1 \qquad (8)$$

Axial compression and bending (Equation 1):

$$\frac{f_a}{F_a} + \left(\frac{C_{mx}}{\left(1 - \frac{f_a}{F'_{ex}}\right)}\right)\frac{f_{bx}}{F_{bx}} + \left(\frac{C_{my}}{\left(1 - \frac{f_a}{F'_{ey}}\right)}\right)\frac{f_{by}}{F_{by}} \leq 1 \qquad (9)$$

Axial compression and bending (Equation 2):

$$\frac{f_a}{0.6\,F_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1 \qquad (10)$$

Secondary moment amplification factor:

$$\left(\frac{C_{m}}{\left(1 - \frac{f_a}{F'_e}\right)}\right) \qquad (11)$$

Euler stress (divided by FS):

$$F'_e = \frac{\pi^2 E}{3\left(\frac{Kl}{r}\right)^2} \quad 1.25 \tag{12}$$

where

E = modulus of elasticity (kPa)
F'_e = Euler stress divided by a FS (kPa)
C_m = Secondary moment reduction factor
F_y = Specified minimum yield stress (kPa)
F_a = Allowable axial stress (kPa)
f_a = Computed axial stress (kPa)
F_b = Allowable bending stress (kPa)
f_b = Computed bending stress (kPa)

Shear

The FRP composite structural shapes are fabricated in such a manner that they have an inherent resistance to shear. Because the roving fibers are primarily oriented such that they run longitudinally through each member, they are strategically located to resist the shear. The crosspieces in the Falls Creek Trail Bridge were the only members that were subjected to substantial shear forces. As they transfer the loads from the deck to the trusses they develop their highest shear stresses at the point at which they connect to the vertical posts. Unfortunately, this is also the point at which holes were drilled in the webs of the crosspieces to attach them to the posts. The result of the applied loads and the reduced web section were stress levels of approximately 40 percent of the allowable shear stress for channels.

Bearing

All of the members of the Falls Creek Trail Bridge were bolted together. Even though the crosspieces rest on the top flange of the bottom chord, they are fastened to the vertical posts such that they do not transfer their loads to the trusses through bearing. Only two areas of the bridge transfer loads by means of bearing on another member. The FRP composite deck bears directly on the top flange of the crosspieces and the bottom chord bears directly on the grade beams at both ends of the bridge. In the case of the top flange of the crosspieces, the deck transfers its load through 18 bearing bars which sufficiently spread the load along the crosspiece such that bearing is not an issue. It is only the last 10 inches of the bottom flange of the channels making up the bottom chord that needed to be investigated.

Testing by E.T. Techtonics, Inc., has shown that a 3-in length of Strongwell's EXTREN C203 by 56 by 10 mm (C8 by $2^3/_{16}$ by $^3/_8$ in) can carry 35.586 kN (8 k) in bearing. Based on this data it was determined that the ultimate bearing capacity of the bottom chords was 222.411 kN (50 k) per chord, on each end of the bridge. The maximum reaction occurred on the leeward side of the bridge when fully loaded, and only amounted to approximately 62 kN (14 k). Therefore, a maximum bearing stress level of less than 30 percent was reached.

Connections

Approximately 2.25 kN (500 lb) of ASTM A307 galvanized bolts, nuts, and washers were used to connect all of the members together. The primary load carrying connections consisted of two 19-mm- ($^3/_4$-in-) diameter bolts spaced 100 mm (4 in) apart, with a 50-mm (2-in) edge distance at the end of the member. Tests have shown that the EXTREN structural tubes used in this bridge can carry ultimate tensile or compressive loads in excess of 62 kN (14 k) when connected in this manner. The configuration of the bolts also meets the general guidelines given in *Composites for Infrastructure, A Guide for Civil Engineers* (6). When filled, the compression diagonals have an ultimate compressive load capacity of over 220 kN (50 k). It is interesting to note that these same tests have shown that the ultimate capacity of these connections varies greatly depending on resin type and manufacturer. It is also interesting to note that the filled 102- by 102-mm (2- by 2-in) structural tubes used for compression diagonals gained very little tensile capacity by being filled. Evidently, the fiber orientation of the solids used to fill the tubes is such that it provides little additional tensile strength.

Other less critical connections used 13-mm- ($^1/_2$-in-) diameter bolts. All connections consisted of at least one bolt with a standard washer under its head and a nut with a standard washer and lock washer under it. It is important to include the standard washers in order to spread the forces coming from the bolt over a larger area of the member. The lock washer performs two important functions. It prevents the nut from working itself loose due to vibrations and shifting of the members, and also serves as a direct tension indicator. Each nut was tightened until its corresponding lock washer compressed to a flat position.

Vibrations

The potential for significant responses due to the dynamic action of walking or running can be a problem on pedestrian bridges, especially those bridges that have low stiffness, little damping, and little mass. The Falls Creek Trail Bridge is just such a bridge. Studies have shown that the range of the first through third harmonic of people walking or running across a pedestrian bridge is 2 to 8 Hz, with the fundamental frequency occurring between 1.6 and 2.4 Hz. Therefore, AASHTO recommends that bridges such as this one be tuned to have a fundamental frequency larger than 5 Hz (3). They also provide guidance for estimating the fundamental frequency and checking that the bridge is properly proportioned to avoid excessive excitation:

$$f = 0.18\sqrt{g/\Delta_{DL}} \qquad (13)$$

where

f = estimated fundamental frequency (Hz)
g = acceleration due to gravity (m/s2)
Δ_{DL} = deflection due to dead load (m)

AASHTO recommends first estimating the fundamental frequency by considering the truss as a simply supported uniform beam. The calculation is based on the stiffness of the truss. For this bridge the estimated fundamental frequency produced by the AASHTO equation (Equation 13) was 11.8 Hz. The SAP90 analysis of the same structure produced a fundamental frequency of 11.6 Hz. Therefore, the estimate proved to be an excellent one for the given bridge. If the fundamental frequency cannot satisfy the minimum fundamental frequency criteria, or if the second harmonic is a concern, the guide specification provides a check of the proportioning of the superstructure to ensure that a minimum superstructure weight with respect to the fundamental frequency is present. Theoretically, the fundamental frequency can be increased by increasing the stiffness of the superstructure or decreasing its weight. The minimum allowable weight of the superstructure can be established using the following equation:

$$W = 180e^{-0.35f} \qquad (14)$$

where

W = minimum allowable weight of superstructure (kN)
e = natural log base
f = estimated fundamental frequency (Hz)

This check, in effect, is a prohibition against overly reducing the weight of the superstructure. The Falls Creek Trail Bridge superstructure weighed in at approximately 18 kN (4 k), which was 25 percent heavier than the calculated minimum.

TESTING

In June 1998, the bridge was assembled at the USDA Forest Products Laboratory in Madison, WI. Later, it was instrumented with 16 strain gauges and 4 devices for measuring deflections. In September 1998, it was subjected to a 12 kPa (250 psf) loading and left exposed to the Wisconsin weather. The monitoring began and is expected to continue for up to a year. Data will be continuously gathered by Forest Service personnel concerning deflection, strain, and temperature. A close study of the connections will also be performed. The points at which the vertical posts and diagonals all attach to the chords present an eccentrically loaded connection that will be closely examined.

The initial load testing data show that the actual deflections at the center of the span are approximately 30 mm (1.16 in). The amount of deflection recorded corresponds very closely with that which was anticipated. Design calculations predicted an initial deflection of 32 mm ($1\frac{1}{4}$ in).

During the same period of time another bridge is being tested next to this one. It is a 6.50-m- (21-ft 6-in-) long, 1.83-m (6-ft-) wide FRP composite truss bridge designed to carry pack stock and a snow load of 6 kPa (125 psf). Because it will be used by pack animals it will be closely monitored for deflection and lateral stability characteristics.

CONSTRUCTION

The bridge is scheduled to be constructed over a 2-day period in June 1999. It will be packed into the backcountry near Mt. Hood and installed on the Falls Creek Trail in the Gifford Pinchot National Forest. It will be constructed by Forest Service personnel with the assistance of FHWA. No heavy equipment or power tools will be required.

CONCLUSIONS

Many benefits of using FRP composites to construct a trail bridge were uncovered through the work on the Falls Creek Trail Bridge. The bridge is lightweight with its heaviest component weighing approximately 0.67 kN (150 lb). The assembled bridge weighs approximately 1.4 kPa (30 psf), based on area of deck, for a total of approximately 18 kN (2 tons). Yet, it still has a very high load carrying capacity. It can easily be constructed in just a few days using general maintenance personnel and without the aid of heavy equipment. It is also composed completely of off-the-shelf fiberglass structural shapes that are readily available from fabricators. When constructed it is virtually maintenance-free and looks identical to a small steel truss bridge. Also, the design is flexible and can easily be adjusted for bridges of different lengths up to spans of 18.29 m (60 ft). Depending on the loading conditions, the length can be adjusted in 1.524-m (5-ft) increments by adding or removing panels. Ultimately, however, the testing and inservice performance will largely determine the long-range viability of the Falls Creek Trail Bridge and others like it.

Currently, research and development efforts in the bridge building industry seem to be focusing on material testing. Because of the unfamiliarity of FRP composites in this industry, a great deal of work needs to be done to develop means to adequately test these materials. This information can then be used to develop much needed material specifications and will likely lead to new and improved design methods and procedures. At the same time, other barriers must be overcome including the high initial cost of the material, the lack of design codes and inspection methods for FRP composites, and the lack of proven inservice durability data.

In some ways, overcoming these barriers is made even more difficult by the manufacturers. Because FRP composites are engineered materials, meaning that the composition of the material is adjusted to produce particular performance characteristics, each manufacturer sells an entirely different product. These products are proprietary and are protected by their owners, who are currently unwilling to make their specific fiber architecture (precise material proportions and fiber orientation) available. This makes producing standard tests, general design procedures, and specifications extremely difficult. The industry may have to loosen their hold on this type of information if they desire a market in the bridge industry.

The results of the initial load testing suggest that the analysis methods used to model the load carrying capacity of this bridge were very accurate. When the actual performance of the bridge to date is considered as well, the design procedures described in this report appear to provide a good basis for a thorough, reliable design of an FRP composite truss bridge. However, the procedures represent the latest scholarship in a growing and changing field and will need to be adapted as materials and our understanding of their behavior advance. Also, some of the procedures shown here apply only to bridges made out of components from Strongwell's EXTREN line. They would need to be modified in order to be used to design with other products.

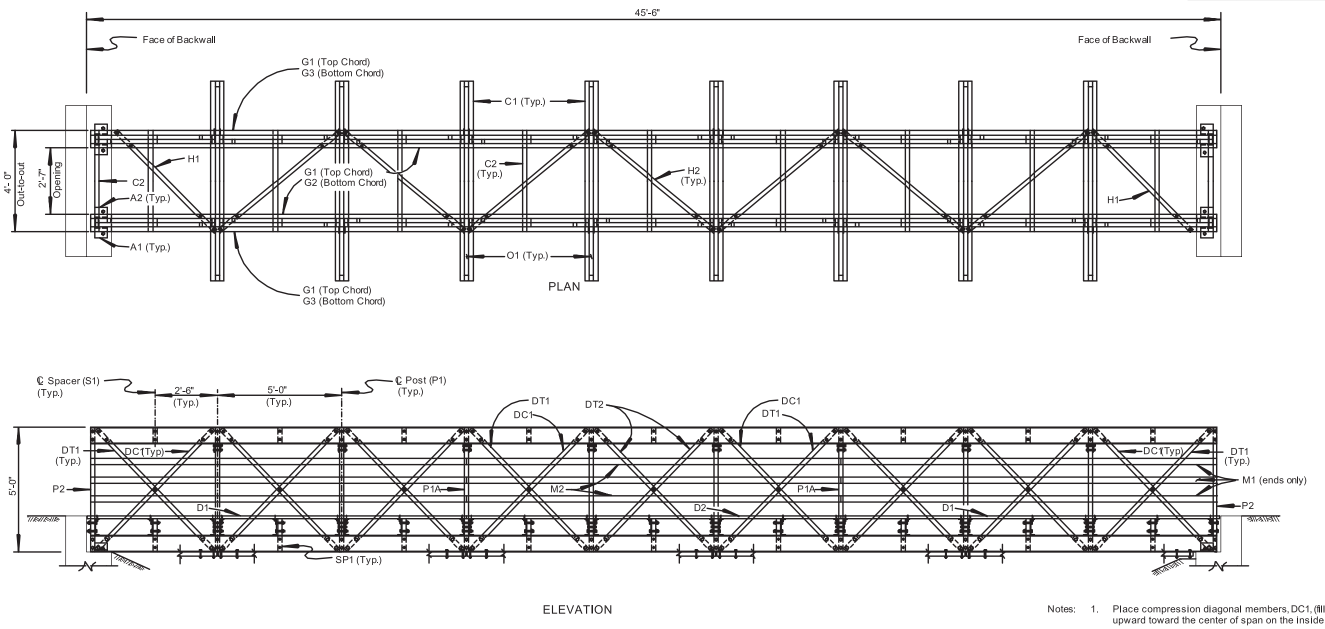
FRP composite bridges are not currently a practical solution for most bridge needs. Further study and testing are needed to gain a better understanding of the material and its uses. However, they do appear to have the potential to uniquely meet an important need for lightweight, strong, low maintenance, attractive trail bridges in remote locations.

Acknowledgments—The work presented in this report is the result of a partnership between the Eastern Federal Lands Highway Division of the Federal Highway Administration, the USDA Forest Service, and E.T. Techtonics, Inc. The author acknowledges the valuable instruction and advice provided by Mr. G. Eric Johansen and Mr. Roy Wilson of E.T. Techtonics, Inc.; and Mr. Merv Eriksson of the Forest Service.

References—

1) *Design Manual for EXTREN Fiberglass Structural Shapes*, Strongwell, Bristol, VA
2) *Standard Specifications for Highway Bridges,* Sixteenth Edition, AASHTO, Washington, DC
3) *Guide Specifications for Design of Pedestrian Bridges*, AASHTO, Washington, DC
4) American Institute of Steel Construction. *Manual of Steel Construction Allowable Stress Design*, Ninth Edition, Chicago, IL
5) Galambos, T.V. *Guide to Stability Design Criteria for Metal Structures*. John Wiley and Sons, Inc., New York, NY, 1988
6) *Composites for Infrastructure—A Guide for Civil Engineers*, Ray Publishing, Inc., Wheat Ridge, CO

REGION	STATE	PROJECT	SHEET NO.	TOTAL SHEETS



Notes:

1. Place compression diagonal members, DC1, (filled 2"x 2"x 1/4" tubes) sloping upward toward the center of span on the inside face of each truss.
2. Place tension diagonal members, DT1, (2"x 2"x 1/4" tubes) sloping downward toward the center of span on the outside face of each truss.
3. In center panel of each truss place one DT2 on each face irrespective of direction of slope.
4. Deck and most bolts not shown in Plan view.

GENERAL NOTES

SPECIFICATIONS:

DESIGN:
Standard Specifications for Highway Bridges, AASHTO 1996 and Guide Specifications for Design of Pedestrian Bridges, AASHTO 1998

DESIGN LOADING:
Snow load: 250 psf

FOUNDATION LOADING:
Grade beam: 2000 psf

ULTIMATE DESIGN STRESSES:
FRP Composite channels and tubes:
Min. Ultimate Strength = 30 ksi (tension and compression)
Min. Ultimate Strength = 30 ksi (bending)
Min. Ultimate Strength = 3.5 ksi (bearing on bottom flange of channel)
Min. Ultimate Strength = 4.5 ksi (shear)
Factor of Safety = 3.0

FRP COMPOSITE SECTIONS:

FRP Composite sections have minimum moduli of elasticity of E=3000 ksi (channels), E=2500 ksi (tubes) and E=6000 ksi (solids). The filled tubes have an effective modulus of elasticity of E=4000 ksi. All sections contain polyester resin and are green in color. Wall dimensions of all 2"x 4" sections are 2"x 1/4" and 4"x 1/8" respectively. Fill all cut edges and holes with the resin matrix used in the structural shape.

BOLTED CONNECTIONS:

Bolted connections are bearing type. FRP Composite sections must be capable of resisting ultimate tensile and compressive loads of 14 k at the connections. Bolts conform to ASTM A307, galvanized. All bolted connections include a washer under the bolt head and a nut with a washer and lock washer. Anchor bolts have a nut, washer, and lock washer on the exposed ends. Tighten all nuts until lock washers are compressed to a flat position. Do not over tighten.

DECKING:

FRP Composite decking is Strongwell DURAGRID I-7000 1" grating with a 1/4" EXTREN sheet or approved equal. The grating contains vinyl ester resin and is grey in color. The sheet contains polyester resin, has a non-slip, gritted surface and matches the other FRP composite sections in color and appearance.

STRUCTURAL STEEL:

Structural steel anchor bolt clip angles conform to AASHTO M270, Gr. 36. Paint clip angles with an approved zinc-based paint system as per ASTM A 780.

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
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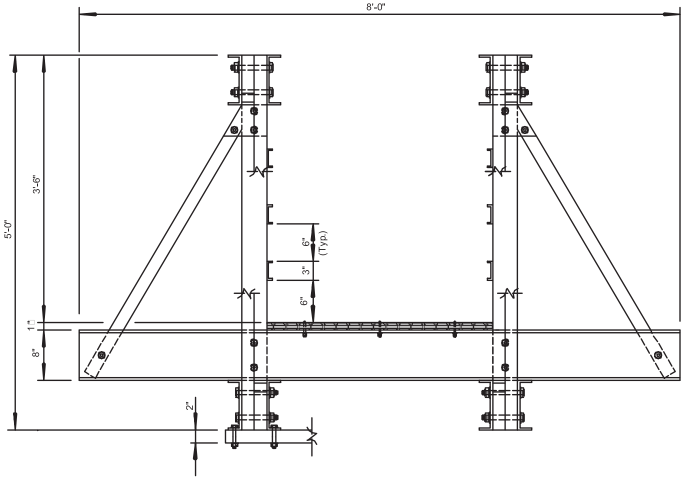
GIFFORD PINCHOT NATIONAL FOREST
FALLS CREEK TRAIL BRIDGE

PLAN AND ELEVATION

NO.	DATE	BY	REVISIONS	NO.	DATE	BY	REVISIONS	DESIGNED BY	DRAWN BY	CHECKED BY	SCALE	PROJECT TEAM LEADER	BRIDGE DRAWING	DATE	DRAWING NO.
								Scott Wallace	Scott Wallace	Johansen\Wilson E.T.Techtonics		Gary Jakovich	1 of 7	March, 1998	

Figure 1—Falls Creek Trail Bridge plan and elevation sheet.

REGION	STATE	PROJECT	SHEET NO.	TOTAL SHEETS



U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
EASTERN FEDERAL LANDS HIGHWAY DIVISION

GIFFORD PINCHOT NATIONAL FOREST
FALLS CREEK TRAIL BRIDGE

TYPICAL SECTION

NO.	DATE	BY	REVISIONS	NO.	DATE	BY	REVISIONS	DESIGNED BY	DRAWN BY	CHECKED BY	SCALE	PROJECT TEAM LEADER	BRIDGE DRAWING	DATE	DRAWING NO.
								Scott Wallace	Scott Wallace	Johansen\Wilson E.T.Techtonics		Gary Jakovich	2 of 7	March, 1998	

Figure 2—Falls Creek Trail Bridge typical section sheet.

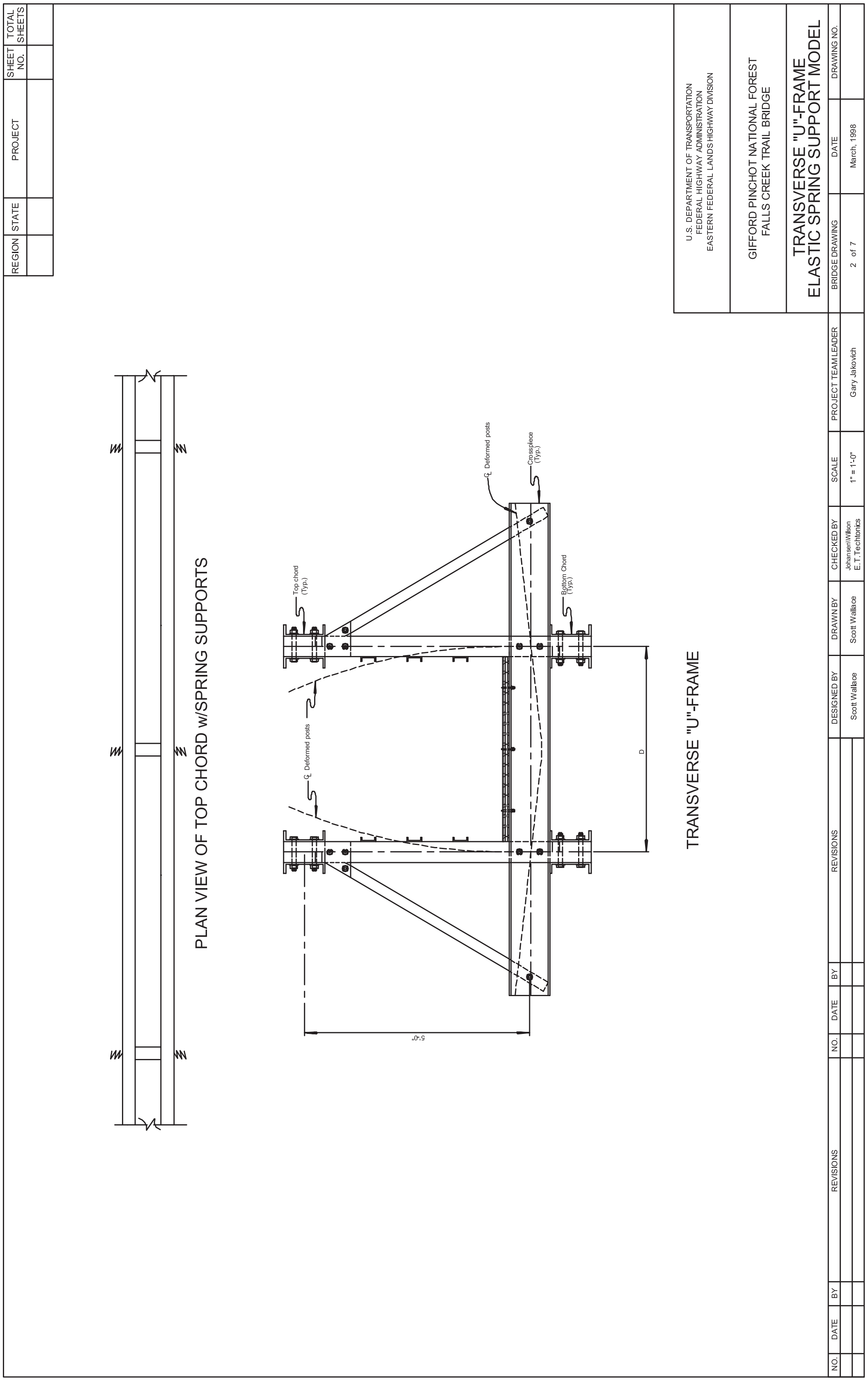
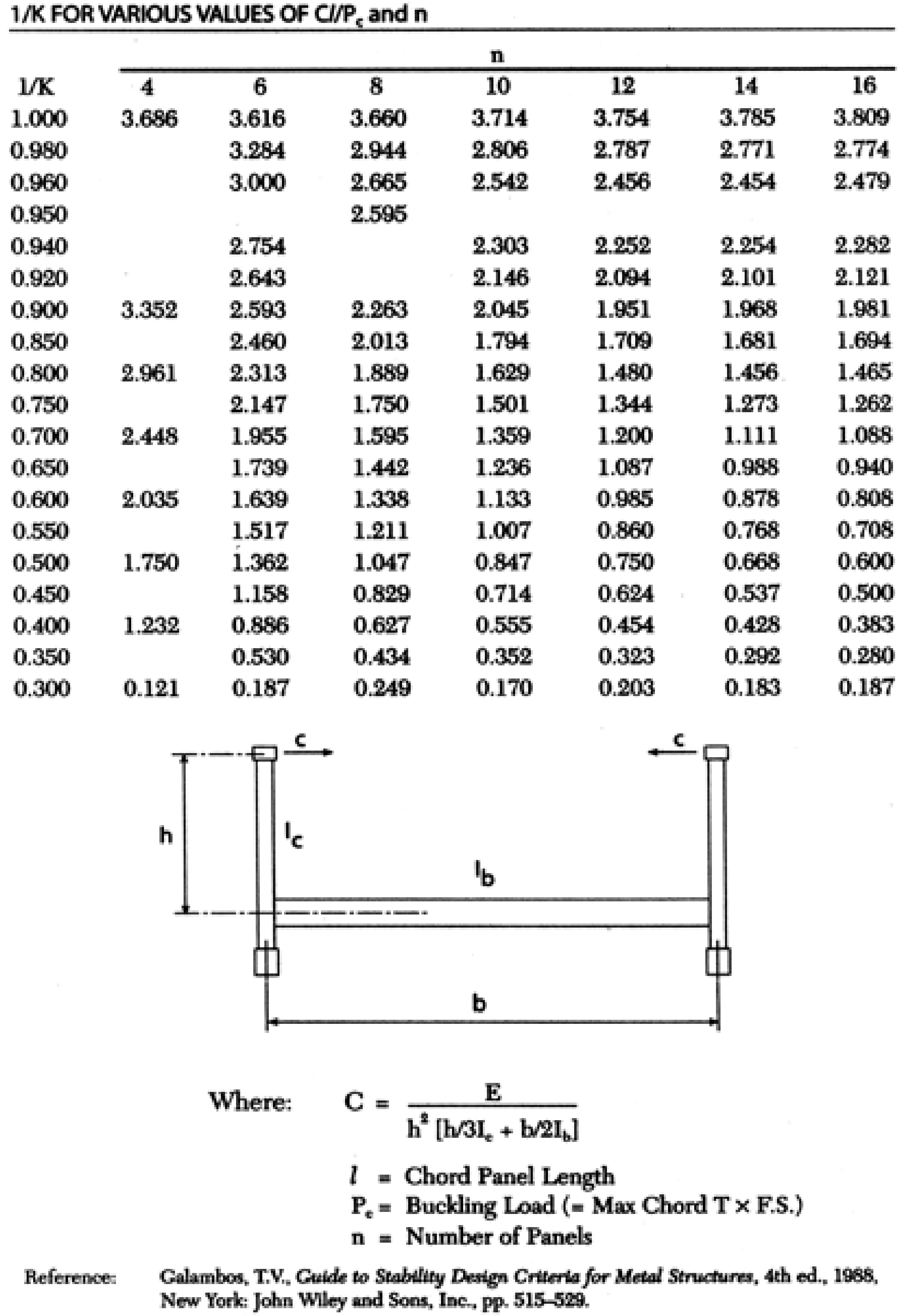


Figure 3—Transverse U-frame elastic spring support model.



1/K FOR VARIOUS VALUES OF Cl/P_c and n

	n						
1/K	4	6	8	10	12	14	16
1.000	3.686	3.616	3.660	3.714	3.754	3.785	3.809
0.980		3.284	2.944	2.806	2.787	2.771	2.774
0.960		3.000	2.665	2.542	2.456	2.454	2.479
0.950			2.595				
0.940		2.754		2.303	2.252	2.254	2.282
0.920		2.643		2.146	2.094	2.101	2.121
0.900	3.352	2.593	2.263	2.045	1.951	1.968	1.981
0.850		2.460	2.013	1.794	1.709	1.681	1.694
0.800	2.961	2.313	1.889	1.629	1.480	1.456	1.465
0.750		2.147	1.750	1.501	1.344	1.273	1.262
0.700	2.448	1.955	1.595	1.359	1.200	1.111	1.088
0.650		1.739	1.442	1.236	1.087	0.988	0.940
0.600	2.035	1.639	1.338	1.133	0.985	0.878	0.808
0.550		1.517	1.211	1.007	0.860	0.768	0.708
0.500	1.750	1.362	1.047	0.847	0.750	0.668	0.600
0.450		1.158	0.829	0.714	0.624	0.537	0.500
0.400	1.232	0.886	0.627	0.555	0.454	0.428	0.383
0.350		0.530	0.434	0.352	0.323	0.292	0.280
0.300	0.121	0.187	0.249	0.170	0.203	0.183	0.187

Where: $$C = \frac{E}{h^2\,[h/3I_c + b/2I_b]}$$

l = Chord Panel Length

P_c = Buckling Load (= Max Chord T × F.S.)

n = Number of Panels

Reference: Galambos, T.V., *Guide to Stability Design Criteria for Metal Structures*, 4th ed., 1988, New York: John Wiley and Sons, Inc., pp. 515–529.

Figure 4—Transverse frame spring constant table for pedestrian bridges.—*From* Guide Specifications for Design of Pedestrian Bridges *Copyright 1997, by the American Association of State Highway and Transportation Officials, Washington, DC. Used by permission. Documents may be purchased from the AASHTO bookstore at 800-231-3475 or online at* http://bookstore.transportation.org.

Appendix I—Example Installation Instructions

Example installation instructions for the Falls Creek Trail Bridge.

Falls Creek Trail Bridge
45-Foot Bridge Assembly Instructions

(Gifford Pinchot National Forest)

GENERAL NOTES

After examining all parts and reviewing all documentation, be sure to account for each part that is listed under the parts list and shown in the plans. Also, verify that all necessary tools listed under *Tools Required* are available. Before beginning assembly operations, note the following:

1. Assembly Instructions assume the use of ¾-in bolts unless otherwise noted.

2. Use drift pins to align holes during assembly. When necessary, a rat-tail file may be used to slightly enlarge holes.

3. Each connection consists of a bolt with a flat washer under the head and a flat washer, lock washer, and nut on the threaded end.

4. All bolt heads are on the inside face of the members except those attaching to the bottom chord. The bottom chord bolt heads are on the outside of the chords. If desired, the bottom chord bolts can also have their heads on the inside face.

5. Generally all components should first be installed with the connections made "finger tight." After all parts are assembled and proper alignment is obtained, tighten all bolts securely. Tighten all nuts until lock washers are compressed to a flat position. ***Do not over tighten.***

6. Bottom chords (G2 and G3) have occasional holes in the bottom flange only. The chords must be installed with the holes on the bottom to facilitate the attachment of the horizontal bracing.

7. Vertical posts (P1, P1A, and P2) have pilot holes in their inside face only. The posts must be installed with the holes facing inward to facilitate the attachment of the midrails.

8. Crosspieces (C1 and C2) have holes in their top flange only. The crosspieces must be installed with the holes on the top to facilitate the attachment of the decking.

9. Compression diagonals (DC1) are installed sloping upward toward the center of the span and placed against the inside channel of each chord.

10. Tension diagonals (DT1) are installed sloping downward toward the center of the span and placed against the outside channel of each chord. The Tension Diagonals in the center span (DT2) can slope in either direction and can be installed against either channel.

11. Whenever possible, orient the members such that any labels or other marking on them is hidden by connections with other members.

To assure proper alignment of connections, it is critical that sufficient support and alignment be maintained during assembly operations. All temporary supports must be level from side to side and at the proper elevation so as not to introduce a twist or a wiggle into the structure. Regularly sight along the chords during assembly operations to ensure the alignment conforms to a reasonable degree of straightness. Shims should be used at as many points along the bottom chord as is convenient to adjust the alignment. They can also be used to provide the camber that is built into the span. The following measurements should be used to set the proper camber. They are measured from a straight line connecting the abutments to the bottom of the bottom chord. At each post starting at either end they are: 0 in, ½ in, ⅞ in, 1⅛ in, 1¼ in, 1⅛ in, ⅞ in, ½ in, 0 in.

ASSEMBLY STEPS

1. Construct temporary supports at two or three locations. Temporary supports at the quarter-points of the span or two supports centered 5 ft from the center of the span should suffice. Construct all supports wide enough to accommodate the span (4 ft minimum) and strong enough to carry the weight of the bridge in addition to workers. The supports must be placed and erected in such a manner as to not interfere with the assembly operations. *Note:* The horizontal bracing will be attached after the supports are removed.

2. Lay out bottom chord girders (G2 and G3) in correct pairs on supports. Note: flanges with holes in them go on bottom. Also, holes in bottom flange of outside girders (G3) are spaced closer together than those on the inside girders (G2).

3. Attach stub posts (SP1) and bottom chord girders using ½- by 6-in hex bolts. Note: The stub posts should be oriented such that the plugged end is on top and the girders are 4 in apart. Finger tighten nuts. Loosely attach the steel anchor clip angles (A1 and A2) using one ¾- by 7-in bolt per angle. *Note:* Place the 4-in leg of the clip angles to the bottom chord and the slot in the 5-in leg over the anchor bolts. Bottom chords can remain upright on the supports on their own at this point.

Align bottom chords on supports. Shim to level if necessary and also to provide proper camber (See *General Notes*).

4. Attach four vertical posts (two P1A at midrail splices, and two P2 at ends) per truss to bottom chord by sliding between the channels and connecting with ¾- by 6-in hex bolts. Finger tighten nuts. *Note:* Orient posts such that the ends with two sets of 13⁄16-in-diameter holes are at the bottom, the plugged ends are at the top, and the pilot holes are facing toward the deck. Individual bottom chords may not be particularly stable until the next step is completed.

5. Attach the crosspieces (C1) to the vertical posts (P1A) and end crosspieces (C2) to the end vertical posts (P2) using ¾- by 4-in hex bolts. Finger tighten nuts. *Note:* Point the bolt heads toward the nearest end of the bridge and orient them so that the holes are all in the top flanges. Structure now should be somewhat stable.

Adjust alignment horizontally and vertically. *Note:* Adjustments are easier to make before additional weight is added.

6. Attach horizontal bracing (H1 and H2) to the bottom chords wherever accessible with ½- by 3¾-in hex bolts with the nuts on the underside. Finger tighten nuts. *Note:* H2 braces are interchangeable, but H1 braces must be installed at the ends. If difficult to access, some bracing can be attached later.

7. Attach the intermediate crosspieces (C2) to the stub posts using ¾- by 4-in hex bolts. Finger tighten nuts. *Note:* Point the flanges and the bolt heads toward the nearest end of the bridge. Examine the center decking panel (D2) to determine which side of the center stub posts to put the center Intermediate crosspiece. The connection holes are slightly to one side of center and the intermediate crosspiece must be installed on the corresponding side of the stub post. Also, orient the intermediate crosspieces so that the flange holes are in the top flange.

8. Attach remaining vertical posts (P1) to bottom chord by sliding between the channels and connecting with ¾- by 6-in hex bolts. Finger tighten nuts. *Note:* Orient posts so that the ends with two sets of 13⁄16-in-diameter holes are at the bottom, the plugged ends are at the top, and the pilot holes are facing toward the deck.

9. Attach remaining crosspieces (C1) to the vertical posts (P1) using ¾- by 4-in hex bolts. Finger tighten nuts. *Note:* Point the bolt heads toward the nearest end of the bridge and orient such that the holes are all in the top flanges.

Adjust alignment horizontally and vertically. Make sure camber is set correctly.

10. Temporarily lay enough decking (D1 and D2) to provide a working platform for accessing the top chord. *Note:* Careful placement of the decking panels now will prevent the need to remove and reinstall them later. Orient end decking panels (D1) such that the holes that are $4\frac{11}{16}$ in from the end are directly over the end crosspieces. Place the center decking panel (D2) so that the holes near the center of the panel are aligned with the center intermediate crosspiece (C2). Temporarily attach the decking with a minimum of $4\frac{1}{4}$- by $2\frac{1}{2}$-in truss head machine screws. Finger tighten nuts.

Adjust alignment horizontally and vertically. Make sure camber is set correctly.

11. Lay out top chord girders (G1) in correct pairs on deck. Attach top chords by installing girder (G1) on both sides of vertical posts (P1, P1A, and P2) as follows:

A. Hang inside channel of top chord (G1) from one pin at each end vertical post (P2).

B. Attach inside channel of top chord to each end vertical post (P2) using a $\frac{3}{4}$- by 6-in hex bolt. Finger tighten nut. *Note:* Place bolt heads on inside face of channel.

C. Attach inside channel of top chord to center vertical posts (P1) using $2\frac{3}{4}$- by 6-in hex bolts each. Finger tighten nuts. *Note:* Place bolt heads on inside face of channel.

D. Remove nuts at each end of top chord and hang outside channel of top chord (G1) from one pin at each end vertical post (P2).

E. Attach outside channel of top chord to each end vertical post (P2) using a $\frac{3}{4}$- by 6-in hex bolt. Finger tighten nut. *Note:* Place bolt heads on inside face of channel.

F. Remove nuts at center vertical posts (P1) and attach outside channel of top chord to center vertical posts (P1) using $2\frac{3}{4}$" x 6" hex bolts each. Finger tighten nuts. *Note:* Place bolt heads on inside face of channel.

Verify that all holes in the top chord for the attachment of the diagonals are aligned properly before continuing to attach the top chord.

G. Continue attaching top chord by attaching to all vertical posts (P1, P2, and P3) using $2\frac{3}{4}$- by 6-in hex bolts per post. Finger tighten nuts.

12. Attach top chord spacers (S1) using $2\frac{1}{2}$- by 6-in hex bolts per spacer. Finger tighten nuts. *Note:* Plugged ends are at top of spacers.

Adjust alignment horizontally and vertically. Make sure camber is set correctly.

13. Attach tension diagonals (DT2) in center bay of span using $\frac{3}{4}$- by 6-in hex bolts as follows:

A. Attach bottom end of diagonals and finger tighten nuts. *Note:* Place bolt heads on the outside face of the outside channel.

B. Attach top end of diagonals by first inserting a drift pin into one hole in the top chord and working the second hole into alignment. Install the bolt into the second hole and remove drift pin. Install bolt into first hole. Finger tighten nuts. *Note*: Place bolt heads on inside face of the inside channel.

C. Attach diagonals to each other where they intersect using $\frac{3}{4}$- by $5\frac{1}{2}$-in hex bolt. Finger tighten nuts. *Note:* Place bolt heads on inside face of the inside channel.

14. Attach remaining tension diagonals (DT1) and all compression diagonals (DC1) using ¾- by 6-in hex bolts. Attach on tension diagonal (DT1) and one compression diagonal (DC1) in each bay progressing from the center of the bridge toward the ends in both directions in both trusses simultaneously. *Note:* Tension diagonals (DT1) are filled only at the ends and slope downward toward the center of the bridge when installed. They are attached on the outside of the compression diagonals. Compres-sion diagonals (DC1) are filled from end to end and slope upward toward the center of the span. Perform the work as follows:

A. Attach bottom end of diagonals and finger tighten nuts. *Note:* Place bolt heads on the outside face of the outside channel.

B. Attach top end of diagonals by first inserting a drift pin into one hole in the top chord and working the second hole into alignment. Install the bolt into the second hole and remove drift pin. Install bolt into first hole. Finger tighten nuts. *Note:* Place bolt heads on inside face of the inside channel.

C. Attach diagonals to each other where they intersect using ¾- by 5½-in hex bolt. Finger tighten nuts. *Note:* Place bolt heads on inside face of the inside channel.

Proper alignment of the holes in the diagonals is dependent upon how carefully the span has been supported and assembled. It may be necessary to lift or lower the span slightly using wedges or jacks at different locations to properly align the holes. If necessary, a rat-tail file can be used to slightly enlarge the holes. Bolts can be driven with a mallet, but care must be taken to not splinter the FRP sections.

15. Attach outrigger plates (OP1) to each side of vertical posts (P1, P1A, and P2) using ½- by 3¾-in hex bolts. Finger tighten nuts. *Note:* The long edge of the plate is on the bottom and points outward away from the deck.

16. Attach all outriggers (O1) to outrigger plates (OP1) and crosspieces (C1) using ½- by 3¾-in hex bolts. Finger tighten nuts. *Note:* Place bolt heads toward nearest end of bridge.

Adjust alignment horizontally and vertically. Make sure camber is set correctly before tightening bolts. Also, verify that all bolts are in place and have a washer under each end and a lock washer and nut on the threaded end.

17. Tighten all bolts in bottom chord, horizontal bracing, and those that connect the crosspieces to the posts. Progress systematically from center toward ends of bridge. *Note:* Tighten all nuts until lock washers are compressed to a flat position. ***Do not overtighten.***

18. Tighten all bolts in outrigger plates and connections between outriggers and crosspieces. Progress systematically from one end of bridge to the other. *Note:* Trans-verse vertical alignment of posts and horizontal alignment of top chord must be correct before tightening outrigger connections. Tighten all nuts until lock washers are compressed to a flat position. ***Do not overtighten***.

19. Tighten all bolts in top chord and those at the intersections of the diagonals. Progress systematically from center toward end of bridge. *Note:* Tighten all nuts until lock washers are compressed to a flat position. ***Do not overtighten.***

20. Remove temporary supports as necessary to attach the remaining horizontal bracing (H2). *Note:* Tighten all nuts until lock washers are compressed to a flat position. ***Do not overtighten.***

21. Finish placing and attaching decking panels (D1 and D2) as needed. *Note:* Tighten all nuts until lock washers are compressed to a flat position. ***Do not overtighten.***

22. Verify that all bolts are properly tightened. System-atically progress from one end of bridge to the other. *Note:* All lock washers should be compressed to a flat position.

23. Remove all temporary supports.

24. Install midrails (M1 and M2) using No. 10–1-in ss pan head sheet metal screws. *Note:* Install midrail (M1) such that the end with the screw hole located 1 in from end of section is at the end of the bridge. Orient flanges to point inward toward the deck.

BRIDGE ASSEMBLY IS COMPLETE

Tools required:

1 Level (2 or 4 ft)
1 Carpenter's square
2 Open-end $1\frac{1}{8}$-in wrenches (for $\frac{3}{4}$-in nuts)
2 Open-end $\frac{3}{4}$-in wrenches (for ½-in nuts)
2 Ratchets equipped with $1\frac{1}{8}$- and $\frac{3}{4}$-in sockets
1 Small ratchet set
2 Drift pins
1 Rubber head hammer
2 Carpenter's hammers
1 Medium round (rat-tail) file
1 Crowbar
2 Phillips-head screwdrivers
1 Knife and 1 shear (for unpacking)
1 Tape measure
1 Battery-powered drill with Phillips-head bit and $\frac{1}{16}$-or $\frac{3}{32}$-in standard steel drill bit (optional)
1 String line
Miscellaneous material for shims (under bottom chord on top of each temporary support)

NOTES

About the Authors

James Scott Groenier, professional engineer, began working for MTDC as a project leader in 2003. Groenier earned a bachelor's degree in civil and environmental engineering from the University of Wisconsin at Madison and a master's degree in civil engineering from Montana State University. He worked for the Wisconsin and Illinois State Departments of Transportation and with an engineering consulting firm before joining the Forest Service in 1992. He worked as the east zone structural engineer for the Eastern Region and as a civil engineer for the Ashley and Tongass National Forests before coming to MTDC.

Merv Eriksson has a bachelor's degree in civil engineering from the University of North Dakota. Eriksson worked as a highway and bridge engineer with the U.S. Department of Transportation Federal Highway Administration before joining the Forest Service's Northern Region in 1979 as a structural engineer. Erikssson was the leader of the bridge design and construction group from 1986 until 1997. He joined MTDC where he served as the technical coordinator for the Wood in Transportation Program and managed a number of projects for the Technology and Development Program and the Forest Products Laboratory. Eriksson served as the regional bridge engineer for the Pacific Northwest Region before becoming the deputy director of engineering for the Intermountain Region in 2005.

Sharon Kosmalski worked for the Forest Service for 14 years in bridge design, construction, and inspection. She now lives in Willow, AK, where she works for the State of Alaska in water system design and approval. She has a degree in civil engineering from the University of Minnesota's Institute of Technology.

Library Card

Groenier, James Scott; Eriksson, Merv; Kosmalski, Sharon. 2006. A guide to fiber-reinforced polymer bridges. Tech. Rep. 0623–2824P–MTDC. Missoula, MT: U.S. Department of Agriculture Forest Service, Missoula Technology and Development Center. 98 p.

Discusses the benefits and problems encountered with the use of lightweight, low-maintenance, easily constructed fiber-reinforced polymer (FRP) trail bridges in remote areas where the weight of conventional bridge-building materials such as steel, concrete, or timber make their use impractical. Beginning in 1997, the U.S. Department of Transportation, Federal Highway Administration Recreational Trails Program and the USDA Forest Service Missoula Technology and Development Center funded the design, testing, and construction of two trail bridges made of FRP composite members. This report discusses the background of FRP composites, how they are manufactured, and the applicability of FRP products to trail bridges, along with their benefits and shortcomings. Case histories of five FRP bridges in national forests and discussions of their performance are included, as is information about the installation and testing of two FRP bridges, along with guidance on design, installation, maintenance, and inspection. The qualifications required for persons who design FRP bridges for the Forest Service are outlined. A list of current suppliers of FRP trail bridges is included.

Keywords: Case studies, composites, construction, damage, E.T. Techtonics, Inc., failures, Federal Highway Administration, fiberglass, inspections, maintenance, polymers, testing

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Electronic copies of MTDC's documents are available on the Internet at:
http://www.fs.fed.us/eng/pubs

For additional information about fiber-reinforced polymer bridges, contact MTDC.
Phone: 406–329–3900
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Forest Service and Bureau of Land Management employees can search MTDC's documents, videos, and CDs on their internal computer networks at:
http://fsweb.mtdc.wo.fs.fed.us/search.

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