the necessary hardware connections for the expected loads. Manufacturer tests of hardware connections and pole wall compatibility should also be used in analysis-recommended connections and hardware. Vertical shear and pullout checks should be made for all fasteners and connectors, with allowances for the nonuniform load distribution owing to the curvature of a pole wall.

Being engineered products, FRP structures and their properties and performance are typically predictable and consistent. However, the degree of automation used to manufacture an FRP product can greatly affect performance consistency and predictability. In general, FRP structures can be designed and analyzed using classical structural theory, provided fiber directional properties are considered. Composite structures are made from engineered products generally with high reliability and a low variability in strength, with similar performance to steel poles. Provided the modulus of elasticity (MOE) and ultimate fiber strength (modulus of rupture [MOR]) of the FRP pole, crossarm, or cross brace are derived from full-scale testing, then design computations should be based on manufacturer-stated 5% lower-exclusion limit (LEL) values. The test articles should be similar in geometry, produced from the same materials, and made by the same manufacturer as will be used for the components being designed. Because of the variation of input materials and manufacturing methods, both the MOE and the MOR will vary from manufacturer to manufacturer.

One of the key positive attributes in designing with FRP materials is the designer's ability to use the anisotropic characteristics to tailor the properties in the desired direction, similar to the way prestressing strands are used in concrete poles to improve their longitudinal tensile strength. For example, an FRP pole can be designed to provide more strength and stiffness in the axial direction than in the transverse direction, thus tailoring it to more optimally meet the actual structural performance requirements.

Because of the geometry and shape characteristics of FRP poles, crossarms, and cross braces, it is common for the structural elements to be hollow and thin-walled poles, box beams, or channel sections. The designer should understand that analysis of the FRP structure capacity in tension, compression (local buckling and crushing), bending, and vertical load-bearing capacity (e.g., through bolts for attachments) is key for the design. FRP members, especially pultruded shapes, should be analyzed as orthotropic (anisotropic), unlike steel, which is isotropic.

FRP structures have a high degree of load-deflection linearity and a very low permanent set. The deflections of FRP structures stay very nearly linear throughout their loading sequence (e.g., elastic range) even as loads approach the ultimate strength of the structure. For FRP structures, at maximum design loading, there is no appreciable creep over the long term. In addition, as FRP structures are unloaded, they will return to within 1% to 2% of their original position.

Note that the ASCE "Pre-Standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures" (ASCE 2010) should also be reviewed for pultruded members' design considerations.

4.3 POLES

4.3.1 Mechanical Properties

All strength requirements described herein shall be based on mechanical properties that have been established using a 5% LEL value. Information on calculating 5% LEL strength value can be found in ASCE 111, "Reliability-Based Design of Utility Pole Structures" (ASCE 2006). Chapter 5 provides suggested guidelines for performance-based tests to establish mechanical properties for FRP products. It is important that test articles be manufactured as close as possible to the final structure being designed.

The following engineering elastic properties are critical for structural design analysis and should be supplied by the FRP component manufacturer:

- MOE,
- Bending stiffness,
- Ultimate moment capacity,
- Failure stress,
- Pin-bearing strength (axial and transverse), and
- Washer pull/push-through strength.

Table 4-1 contains material property descriptions and provides an example of a range of FRP pole characteristics. The ranges in the table may be larger than expected; however, this demonstrates the vast range in material properties that can result from the combination of different manufacturing techniques, fiber layup schedule, and raw material inputs (e.g, resin, fillers).

The following properties are beneficial but not as critical as those in the previous list:

- Poisson's ratio,
- Modulus of shear,
- Ultimate shear capacity,
- Flexural strength, and
- Compression strength.

Table 4-1. Sample Range of Material Properties for an FRP Pole

Material property	Value range
MOE	2×10^6 psi (13.8 GPa)—5×10^6 psi (34.5 GPa)
Bending stiffness	1.18×10^9 lb•in.^{2} (345×10^9 kg•mm^2)—4.04×10^9 lb•in.^{2} (118×10^{10} kg•mm^2)
Ultimate moment capacity	166,591 ft-lb (226 kN-m)—388,752 ft-lb (526 kN-m)
Failure stress	1×10^4 psi (2.7579×10^7 Pa)—5×10^4 psi (3.44738×10^8 Pa)
Pin-bearing strength (axial)	12,000 psi (82.7 MPa)—25,000 psi (172.4 MPa)
Pin-bearing strength (transverse)	9,000 psi (62.1 MPa)—14,000 (96.5 MPa)
Washer push/pull-through strength (6 in. [150 mm] washer)	8 kip (3,629 kg)—20 kip (9,072 kg)

4.3.2 Bending Strength

FRP poles should meet the same specified bending performance criteria applied to poles made of other materials. FRP poles must also meet all bending-strength and deflection requirements dictated by the specific application, including any combined bending-loading conditions produced by guying the pole at one height to resist a load at another height. In this case the localized loads on the pole cross section need to be carefully analyzed to avoid premature failure caused by localized overloading.

4.3.3 Local Buckling Strength

Local buckling needs to be considered because FRP pole designs typically use relatively thin-wall construction. FRP poles may be polygonal, hexagonal, round, or oval and may or may not include internal stiffeners or foam to increase their local buckling capacity. Being thin-wall tubes, bending results in a flattening or ovalizing of the pole's cross-section as it bends, which causes a reduction in the cross section moment of inertia along its length. This distortion is most pronounced in the higher-stressed areas, such as at the ground line, and less pronounced where the stress decreases, such as where there may be localized ring reinforcement or double pole walls in slip joint overlap areas of modular poles.

Diameter/thickness (D/T) ratio limits are a consideration for local wall buckling analysis and are most important for round steel tubes because of the limited elongation of steel before yielding. Although there are some D/T limits in certain design codes, applicability to FRP tubes may be limited. The FRP manufacturer should confirm any applicable D/T ratio limits.

4.3.4 Axial Strength

The axial material strength of a pole must be sufficient to meet all axial load (compression and tension) requirements in all sections of the pole. The material strength data for FRP poles made by various manufacturers will likely differ because of the differences in wall thickness, materials used, fiber reinforcement orientation, and manufacturing processes used. Generally, axial material allowable strength is on the order of 20,000 psi to 40,000 psi (138 MPa to 276 MPa) for both compression and tension.

The allowable stress data for a specific pole should be provided by the structure designer. Axial strength is rarely a controlling design factor for nonguyed structures. For guyed structures in line-angle and dead-end applications, however, axial strength and column buckling are often the controlling design factors and should be checked as an integral part of the structural analysis.

The column-buckling capacity of an FRP pole must meet or exceed the maximum axial load requirements. In determining the column-buckling strength of an FRP structure, consideration should be given to burial depth, elevation of guy wire attachment point(s), and structure taper rate. For constant cross section poles, the bending stiffness (EI) calculation is straightforward. For tapered FRP poles, the bending stiffness decreases from the ground up because of both material and geometric nonlinearities. Tapered poles should be analyzed using appropriate nonlinear structural analysis software.

Calculations on global buckling from Gere and Carter's "Critical Buckling Loads for Tapered Columns" (Gere and Carter 1962) and RUS *Bull. 1724E-153* (RUS 2001) are the standard. Additionally, full-scale testing has verified that global buckling considerations are accurately and conservatively predicted by finite element software packages like PLS-POLE.

4.3.5 Pull-Through Strength

Pull-through strength requirements need to be assessed at points where loads are being introduced to the pole, such as at through bolt or single-wall attachment locations. Pull-through strength is dependent on the wall thickness, material, manufacturing process, and pole geometry used. Large washers or cleat-free gain plates shall be used to evenly distribute the load and reduce the stress caused by these concentrated loads. The structure designer is responsible for ensuring that all pull-through strength requirements are met, and the FRP pole manufacturer should provide test data on pull-though characteristics.

4.3.6 Hoop Strength

Hoop strength in FRP poles is an important consideration for loads resulting from pole transport and handling and through bolt installation. The maximum through bolt torque allowed is a function of the pole design and manufacturing process used. Because of fiber orientation, filament-wound FRP poles will have higher comparative hoop strength than pultruded FRP poles. Within the same manufacturing process, thicker-walled poles will typically have higher hoop strength than thinner-walled poles. Because this is process and thickness dependent, for each pole design the structure manufacturer must be responsible for supplying allowable maximum values for bolt torque.

Insufficient hoop strength can lead to a failure mechanism known as unzipping, wherein a crack initiates and propagates from the bottom edge of the top module in a slip joint as a result of high vertical and/or transverse loads. The FRP pole manufacturer should provide information on fiber reinforcement orientation, hole spacing requirements in the slip joint area, and maximum values for axial and transverse loads.

Historical data show that fully cured thermoset resin FRP poles do not result in significant creep that would allow for hoop strength load relaxation over time in the presence of load attachments such as through bolts.

4.3.7 Torsional Strength

For closed-section geometries, such as are typically used for an FRP pole, torsional strength and stability are generally not a design issue. However, different FRP materials and processes provide different torsional capability. The structure designer must be responsible for ensuring that any torsional strength requirements are met.

4.3.8 Fatigue Strength

FRP materials in general have superior fatigue strength at maximum allowable stress. Structures can be cyclically loaded to maximum operating load without showing any evidence of appreciable long-term creep or fatigue failure. FRP component manufacturers should be able to supply test reports demonstrating fatigue resiliency and creep resistance.

4.3.9 Deflection

Structural deflections are an important factor in a pole's performance. The line designer must specify any maximum deflection requirements for the structure, otherwise known as serviceability equivalency (see Section 3.9). However, these requirements should not be more restrictive than necessary to ensure adequate performance. And, provided that deflection is considered in the scope of a new line, it is possible not to impose limits, provided that right-of-way and ground clearances are considered. FRP structures can be engineered to meet almost any deflection requirements, and the structure manufacturer should be able to provide this information.

The load-deflection relationship of FRP structures is essentially linear, and elastic analysis and design methods are appropriate for most applications. For an exact structural analysis and deflection estimate, the line designer must use a nonlinear finite element analysis (FEA) design methodology. FEA modeling should include consideration of the thin-wall nature of the FRP pole design and account for the reduction in cross section structural moments of inertia along the pole length as bending occurs.

4.4 CROSSARMS

FRP distribution crossarms are used extensively for tangent and dead-end applications for grid hardening and to increase lineman safety. FRP crossarms are also increasingly being used for transmission applications. The inherent high dielectric structural strengths and resistance to corrosion and rot are attributes sought by utility planners and owners seeking to decrease both storm outages and future capital expenditures.

FRP crossarms were first used in distribution applications. To enable the continued use of standard hardware, common FRP crossarms dimensions are the same as the wood counterpart they are replacing, with the most popular size being a 3-5/8 in. × 4-5/8 in. (92 mm × 117 mm) box channel. Other FRP crossarm box channel sizes are used, both larger and smaller than the standard size, depending on the strength required for the application. Different FRP cross-sections, in addition to standard box channels, are also used. These shapes include C-channels and box channels with convex surfaces, among others.

Regarding length, following wood crossarms, standard FRP crossarms include 4 ft (1.2 m), 6 ft (1.8 m), 8 ft (2.4 m) and 12 ft (3.7 m) lengths, according to RUS *Bull. 1724E-151*, "Mechanical Loading on Wooden Distribution Crossarms" (RUS 2002). For transmission crossarms, custom lengths are typically used.

For connections to the pole, through bolted examples, which are the most popular, are shown in Chapter 3, Figures 3-16, 3-18, 3-20, 3-24, 3-29, and

3-44. Increasingly common, and the standard for FRP crossarms, is the use of a two-bolt shelf-style gain base with a smooth backing surface, which will not damage the FRP pole. In distribution applications, a supporting V-brace may commonly be used, providing a second through bolt attachment if only a single bolt is used to attach the crossarm.

4.4.1 Mechanical Properties

The mechanical properties of the tangent and dead-end arms, including the mount and phase hardware, are critical elements necessary for the standards and structural engineers to properly specify the correct arm for the application. The mechanical properties must be developed based on full-section testing of assembled arms based on ASTM D8019-15, "Standard Test Methods for Determining the Full Section Flexural Modulus and Bending Strength of Fiber Reinforced Polymer Crossarms Assembled with Center Mount Brackets" (ASTM 2015). The mechanical design values should be published based on a 5% LEL.

4.4.2 Bending and Shear Strength

The full-section bending strength should be determined based on full-section testing of assembled crossarms with the commercial hardware attached. The bending strength should be reported in terms of the ultimate phase load at failure and in terms of the shear and compression strength. Short- and long-span crossarms should be tested to determine the influence of length on the failure mode. The 5% LEL shear and compression stresses at failure should be used to determine the strength capacity of crossarms not represented in the actual test. Examples include different phase locations, additional phases, and unbalanced loading of crossarms.

4.4.3 Deflections

FRP crossarms exhibit high strength with moderate stiffness. Therefore, serviceability deflection calculations should be performed during the line design process. The utility should impose a satisfactory deflection limitation based on fitness for use. In some instances, similar to FRP poles, deflection limits can govern the capacity of the crossarm because of the high strength-to-stiffness ratio. However, similar to FRP poles, provided that the crossarm deflection is quantified and clearances adjust accordingly, it is possible that serviceability equivalency may not be mandated.

CHAPTER 5

SUGGESTED GUIDELINES FOR PERFORMANCE-BASED TESTS

5.1 INTRODUCTION

Although several standard tests are cited in this chapter, these tests are typically not designed specifically for FRP overhead line structures but rather for components of all material types and are generally aligned with the tests outlined in the American National Standards Institute (ANSI) approved American Composites Manufacturing Association's (ACMA) "Standard Specification for FRP Composite Utility Poles." Where appropriate, using industry standard tests not only better quantifies the range of composite component performance characteristics from different manufacturers but also baselines FRP component performance to other material types—like wood, steel, and concrete—that employ the same test methods.

The user must specify what types of load testing the manufacturer will need to do to adequately demonstrate the structural capacity of the pole and crossarm. Each manufacturer of FRP components will typically have performed a number of tests to be certain of the global and local structural performance characteristics of their particular products. Such tests may include full-scale static load and deflection tests, component or section static load tests, full-scale dynamic load testing, cross-sectional hoop strength testing, wall pull-through or punching testing, step bolt/climbing load/deflection testing, and others. A full-scale destructive test (ultimate load) is sometimes performed to validate the ultimate strength and stiffness (deflection/serviceability) characteristics of the pole/structure. This may be a single component test or a test of a sampling of components that will determine statistical significance of the potential variability. During a production run, scheduled nondestructive full-scale design load tests may be performed to ensure consistent quality in all structures. The manufacturer should be able to certify that the required tests were done and provide a copy of the documentation of the required tests to the user on request.

Note that with some anisotropic materials, like FRP laminates, coupon-level testing may not be representative of global component (e.g., full pole or full crossarm) performance. As a result, full-scale testing is recommended to avoid any data correlation inconsistencies.

5.2 RECOMMENDED MECHANICAL TESTS

The following tests are recommended for FRP poles and crossarms.

5.2.1 Static Bending (Horizontal Loading) Test

5.2.1.1 Poles A static bending test or horizontal loading test should be performed following the procedures specified in ASTM D1036-98, "Standard Test Methods of Static Tests of Wood Poles" (ASTM 1998). This test assumes a standard burial depth of 10% of the pole length, plus 2 ft (0.6 m). It also provides that the load be applied 2 ft (0.6 m) from the pole tip and that deflection be measured at the pole tip (Figure 5-1). Practical consider-

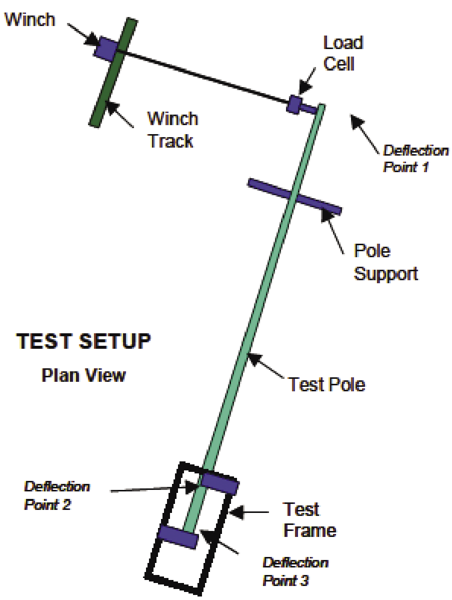

Figure 5-1. Typical test setup for pole bending test.
Source: Courtesy of EDM International, Inc.

Figure 5-2. Vertical full-scale test fixture based on ASTM D1036-98 principles. Source: Courtesy of RS Technologies Inc.

ations allow that a pole be tested in the horizontal position. These tests should be conducted with the pole clamped or strapped in the test fixture to simulate direct embedment. Ultimate capacity must be no less than the manufacturer's load rating. During the test, the pole should be oriented such that the majority of holes and openings in the pole are on the extreme compression and tension faces. This orientation will result in the maximum reduction in section modulus owing to these holes.

Using the ASTM D1036-98 principles of embedment and load attachment geometry, some FRP pole manufacturers are testing poles in the vertical position to simulate actual installed orientation, better measure P-Delta effect, and remove any complications in the results from the pole support required in horizontally oriented tests (Figure 5-2).

One manufacturer has started to evaluate poles in its vertical full-scale tester to correlate the results with its extensive library of horizontal full-scale test results. The manufacturer included in its test reports the calculated equivalent horizontal load, taking into account the weight of the pole, cabling, and attachment hardware and the angle the load was applied at. Figures 5-3 and 5-4 provide a detailed breakdown of these calculations for a 45 ft (13.7 m) pole.

Force calculations at loading point:

$$\theta^1 = 0.13 \text{ rad } (7.5^\circ) \tag{5-1}$$