FRP Poles: A State-of-the-Art-Review of Manufacturing, Testing, and Modeling

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Abstract: Fiber-reinforced polymers poles were on the increase because they were lightweight, have high strength-to-weight ratios, provide corrosion resistance, can be customized to meet strength and deflection requirements, and have a low life-cycle cost of construction and maintenance. This research presents a comprehensive review of all significant research and existing case studies to review the present knowledge concerning fiber-reinforced polymers poles. The main summary covers 70 works focusing on fiber poles to summarize recent activities on selected relevant topics and highlight possible future implementations. In this context, this study discusses fiber-reinforced polymers poles in six aspects: (i) introduction; (ii) methodology; (iii) Materials properties of FRP poles; (iv) manufacturing techniques of FRP poles; (v) testing of FRP poles (static and dynamic flexure test as cantilever beam); (vi) modeling of FRP poles. Therefore, this critical review will demonstrate an overview of FRP Poles manufacturing techniques (Pultrusion, filament winding, centrifugal process, and hand lay-up) and which Pultrusion technique is the best suited for FRP Poles. Static modeling was the most used of other techniques.

Keywords: FRP poles; manufacturing; testing; modeling; lightening poles; transmission poles; power line poles

1. Introduction
1.1. FRP Industry

Fiber-reinforced polymer was a composite material composed of a polymer matrix and fibers, engineered or natural composite materials comprising two or more component elements with vastly diverse physical or chemical properties that remained distinct and separate within the finished construction. The goal was to make a robust and rigid component with a low density. The rising use of composites in recent years has been fueled by the development of new advanced forms of FRP materials. Composite poles are rapidly gaining acceptance throughout the utility industry, mainly due to the main advantages of glass-fiber-reinforced polymer (GFRP) poles, such as exceptional strength-to-weight ratios, resistance to corrosion chemical attack, non-conductivity, and long lifespans. Because of its beneficial properties in concrete, bridge decks, modular structures, formwork, and external reinforcement for strengthening and seismic upgrades, FRP composites have been employed as reinforcement in new construction and strengthening of buildings. However, such a conclusion must be weighed against the potential benefits of adopting FRP composites in terms of factors such as cost and durability (higher strength, lighter weight, higher performance, longer-lasting, strengthening existing structures and extending their
life, seismic upgrades, defense systems, space systems, and ocean environments) [1]. Therefore, fiber-reinforced polymers (FRP) were generally categorized as advanced composite materials. Compared to conventional materials, where available products are limited to what industry can provide, the entire FRP manufacturing process can be closely engineered to fabricate a custom product for different operations. Furthermore, engineers can select various types of fibers, matrix materials, and geometrical properties in designing FRP structures to optimize the final product structurally and economically, as shown in Figure 1 [2]. Previous studies found that a few papers study the effect of cyclic load on a pole. It should be considered, and it was recommended to compare the different FE software on the accuracy of results. The effect of the FRP Pole fixation method must be considered in future research works.

![The manufacturing process of a glass fiber sheet.](image)

**Figure 1.** The manufacturing process of a glass fiber sheet.

1.2. Poles

Engineers were increasingly being charged with evaluating, developing, and running systems that leverage the concept of resiliency across many critical infrastructure sectors in the face of recurrent natural and man-made disasters. One example of critical infrastructure was electric poles and transmission networks. According to a recent study on the economic benefits of improving electric grid resilience to weather outages, the US economy lost USD 18 billion to USD 33 billion annually from 2003 to 2012. Several strategies were found to improve the country’s electric grid resiliency [3]. In the United States, most current electrical poles supplying electric distribution systems are made of wood. It was projected that over three million existing electric wood poles would need to be replaced yearly. Upgrading supporting structures and wooden electric poles with stronger materials that can withstand hurricane-force winds was a primary mitigation strategy [4]. The primary disadvantage of fiber-reinforced polymers (FRP) poles was their high manufacturing cost. However, as utility companies gained a better understanding of the advantages of FRP, it was projected that their usage would increase and their cost would decrease [5]. The lighting pole used in the street lighting system has various cross-sectional shapes such as circular, tubular, and octagonal. Materials used for manufacturing conventional lighting poles are cast iron, structural steel, and stainless steel. Recently, aluminum alloy lighting poles and FRP poles were also developed [6]. These poles were used in different applications such as street lighting, solar lighting, power transmission, traffic sign, and flag poles, as shown in Figure 2.
1.3. Research Objective

The objective of this study is to collect, sort, analyze and criticize the early published research regarding FRP poles for determining the current trends, figuring out the gap studies, and recommending future research. This study discusses fiber-reinforced polymers poles in six aspects: (i) introduction; (ii) Methodology; (iii) Materials properties of FRP poles; (iv) Manufacturing techniques of FRP poles; (v) Testing of FRP poles; and (vi) Modeling of FRP poles.

2. Methodology

2.1. Research Program

According to [7,8], the international journals were searched for relevant research papers. This review was based on articles from reputable academic journals published up through the end of April 2022 in fiber-reinforced plastics. The journals were chosen substantially impact fiber-reinforced polymers poles and were part of the Science Citation Index Expanded or Engineering Index databases. The paper search engines used were SCOPUS, Google Scholar, and Web of Science, and two rounds of searches were undertaken. In the initial round of searching, key terms such as fiber-reinforced polymers, pole strength, electric poles, transmission poles, civil engineering, and construction materials were used to find publications. Then, a second search round was performed based on the outcomes of the first search round, manually filtering publications linked to fiber-reinforced polymers poles in structural and construction engineering to exclude unnecessary papers. In addition, the authors should study the abstract of each research to check that the application of the article was within the structural and construction materials. As a result, many journal papers were chosen and grouped into six categories after two rounds of screening. Namely, (i) introduction; (ii) methodology; (iii) materials properties of FRP poles; (iv) manufacturing techniques of FRP poles; (v) testing of FRP poles; (vi) modeling of FRP poles. Figure 3 shows the number of chosen papers per year.
Figure 3. No. of published works per year.

2.2. Research Organization

Fiber-reinforced polymers: This section introduces research work discussing the fiber-reinforced polymer industry, fiber-reinforced polymer poles, and the research objective.

Materials properties of FRP poles: This section presents the different properties of fiber-reinforced polymer poles, such as physical, mechanical, and chemical. Further discuss the effect of these properties on poles and the different types of fibers (glass, carbon, and aramid).

Manufacturing techniques of FRP poles: Present a historical background on the manufacturing methods of fiber-reinforced polymer poles. This section reviews filament winding, Pultrusion, centrifugal casting, and hand lay-up techniques.

Testing of FRP poles: FRP composite poles were economically and industrially viable. However, this promising alternative technique became more generally accepted in practice and grew to become the future of pole construction. This section discusses the design codes and allowable limits, and background on the standard test procedures. It also includes an experimental program from previous research, as shown in Figure 4.

Modeling of FRP poles: This chapter introduces a finite element model of fiber-reinforced polymer poles with different applications presented by researchers. It includes simple linear static models, advanced static models, dynamic models, and fatigue/fracture mechanics/cyclic models. FE simulations used parameters such as fiber direction, layer number, and layer thickness. In addition, the deflection and bending strength characteristics of GFRP Poles were studied.
3. Material Properties

3.1. FRP Materials

The structural properties of FRPs, usually glass, carbon, aramid, or basalt, were predominantly determined by the fibers used in the product, as shown in Table 1. Figure 5 addresses the comparison between carbon fibers, aramid fibers, and glass fibers related to the various characteristics (tensile strength and modulus of elasticity) [2,7].

Table 1. Physical and mechanical properties of different FRPs, adapted from refs. [7,8].

| FRP Type               | Tensile Strength (GPa) | Density (t/m³) | Modulus of Elasticity (GPa) | Shear Modulus (GPa) | Poisson’s Ratio |
|------------------------|------------------------|----------------|-----------------------------|---------------------|-----------------|
| Electrical-resistant E-glass | 3.4                    | 2.5            | 40                          | 30                  | 0.22            |
| High-strength S-glass  | 4.5                    | 2.5            | 56                          | 35                  | 0.22            |
| Carbon (high-modulus)  | 4.8                    | 1.9            | 200                         | 23                  | 0.20            |
| Carbon (high-strength) | 2.7                    | 1.7            | 300                         | 27                  | 0.20            |
| Aramid                 | 3.4                    | 1.4            | 62                          | 21                  | 0.35            |

Figure 5. Comparison of design tensile strength and elasticity modulus of different types of fibers.
3.2. Physical, Mechanical, and Chemical Properties

The low cost of glass-fiber-reinforced polymers (GFRP) compared to other kinds of FRPs makes glass fibers the most used in the construction industry. However, low long-term strength, a relatively low deformation modulus, alkaline resistance, and low humidity are the main disadvantages of GFRP. On the other hand, carbon-fiber-reinforced polymers (CFRP) do not absorb water and have a high deformation modulus and fatigue strength. One of the significant drawbacks was the relatively high energy need for producing carbon fibers, which led to high costs. Anisotropy (lower radial strength) and potential galvanic corrosion in direct contact with steel are further disadvantages of these materials. Fiber-reinforced polymers using aramid (AFRP). High static and impact strengths characterize these fibers. However, their diminished long-term strength (stress rupture) and susceptibility to UV exposure limit their utilization. Aramid fibers also have the disadvantage of being challenging to cut and process [7]. According to the findings of the experimental investigation, which are displayed in Table 1, physical properties such as glass percentage and thickness and mechanical parameters such as longitudinal modulus and tensile strength were among the factors that most affected the tensile behavior of the poles in terms of stiffness and strength. According to the study, the production process resulted in a product with little tolerance regarding the testing values for the poles’ sizes and tensile properties. An effective stiffness was established to accurately describe the experimental tensile response and provide a design tool for the mechanical characteristics of the poles. This measurement appears to be a valuable tool for forecasting the structural reaction of the material since it directly contains the dependence on glass content and thickness values [7,8].

4. Manufacturing Techniques of FRP Poles

4.1. Filament Winding

The most common method for creating hollow tubular forms was filament winding. In this process, continuous fibers impregnated with resin are wound around a revolving mandrel. The fibers’ ability to be orientated to create the required mechanical characteristics specified by a designer, as seen in Figure 6, was a significant benefit of filament-winding. The fiber feeder’s linear velocity and the mandrel’s relative rotating speed be used to adjust this [9].

4.2. Pultrusion

Pultrusion was a continuous molding process in which predefined reinforcements were fed in predetermined quantities, and repeated creels were layered through a resin bath. The resin-impregnated reinforcement was drawn through a die that determined the product’s sectional geometry while controlling the reinforcement and resin content. In the heated portion of the die, the resin cure began. A puller mechanism drew the product through the die, then cut it to the desired length, as shown in Figure 6. Pultrusion could
be used for any extruded shape, but it was limited to prismatic members. Pultrusion was suitable for members of a uniform cross-section, such as tubes, rods, beams, and channels. Pultrusion involves pulling resin-impregnated fibers through a heated die formed to the desired cross-sectional geometry [9].

4.3. Centrifugal Casting

The centrifugal casting method was best for cylindrical shapes such as pipes, poles, and tubing. Glass fabric was placed in a hollow steel mold in a predetermined amount and configuration in this process. The resin was injected and distributed evenly around the reinforcement while the mold was rotated (spun) at high speeds. Centrifugal forces distributed and compacted the resin and reinforcement against the revolving mold’s wall. The product’s curing was accelerated using an external heat source, as shown in Figure 6 [5].

4.4. Hand Lay-Up

Hand lay-up requires mixing fiber reinforcement and a resin into two FRP semi-cylinders, curing them, and then combining the semi-cylinders with a resin adhesive to form a traditional FRP lighting pole. While the hand lay-up method may reduce the cost of producing standard FRP lighting poles by using a less expensive production machine, the structural strength of the conventional FRP lighting pole was insufficient. In addition, it can rend at the semi-cylinder, so combining interface. Table 2 shows the manufacturing steps of each technique [9–11].

Table 2. Different Techniques of Manufacturing FRP Poles.

| Technique               | Manufacturing Process                  |
|-------------------------|---------------------------------------|
| Centrifugal Process     | Fiber roving                          |
|                         | Rolling Sheets                        |
|                         | Rotating Die                          |
|                         | Resin injection                       |
| Pultrusion Process      | Fibers rolls                          |
|                         | Resin                                 |
|                         | Heated Die                            |
|                         | Puling Device                         |
|                         | Cut-off                               |
| Filament Winding Process| Creel                                 |
|                         | Continuous roving                     |
|                         | Resin bath                            |
|                         | Rotating Mandrel                      |
| Hand Lay-up Process     | Contact Mold                          |
|                         | Laminate                              |
|                         | Resin                                 |
|                         | Reinforcement                         |

5. Testing of FRP Poles

5.1. Design Codes and Allowable Limits

The pole manufacturer shall determine the shaft length based on specific embedment depth (where applicable) as shown in Figure 7 and luminaire mounting height. The total pole length shall be maintained within a tolerance of 61%. The pole manufacturer shall determine the pole weight that will meet the strength requirements of the user’s installation. Once the weight is established, the weight shall be at least 95% of the specified weight. The pole shall withstand at least one and one-half times the maximum bending moment induced by the wind when tested. The pole-top deflection induced by the wind acting on the pole and all accouterments attached shall not exceed 15% of the above-ground height, as shown in Table 3 [12,13].
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Table 3. Different standards of testing poles.

| Code   | Deflection under Max Wind Conditions | Deflection under Static Conditions | Load Point from Top (m) |
|--------|-------------------------------------|-----------------------------------|------------------------|
| ASTM   | Not exceed 15% pole height           | Not exceed 1% pole height         | 0.30                   |
| CSA    | Not exceed 20% pole height           | Not exceed 1% pole height         | 0.25                   |
| AASHTO | Not exceed 15% pole height           | Not exceed 1% pole height         | 0.30                   |

5.2. Standard Test Procedures

After marking the designed ground-line location on the pole, place the pole in saddles with the ground-line properly located. Rotate the pole so that the hand hole, with cover in place, is on the maximum compression surface, or, in the case of poles equipped with two opposed arms, oriented with maximum compression surface as it would be in an actual secure load line. Adjust the hoist position, so the load line is vertical (65°). Zero the deflection measuring device or take an initial reading that will be subtracted from subsequent measurements. Tare a load-indicating device or take an initial reading that will be subtracted from subsequent data. Apply the load at a uniform rate (N inches per minute) between increments until the pole fails or until a predetermined load is reached. Take deflection readings at load increments shown on the test data sheet and at failure or a predetermined load, as shown in Table 4 [12]. A concrete base with a diameter of 230 mm and 430 mm in height. The bottom of the specimen was filled from the inside with concrete. After the concrete hardened, the specimen was placed vertically into a concrete block. The load is applied horizontally, 140 mm from the top end, through a loading sleeve. The loading sleeve was attached to a tension bar with an electronic load cell mounted at mid-length to measure the applied load. The other end of the tension member was connected to a lever arm, and loading was applied to this lever arm at the bottom through a hydraulic jack. An electronic liner measurement transducer measured the lateral deflection at the load point [14]. The bridge crane was moved at a displacement rate of 12 mm/s, and a 225 KN load-capacity cell was employed. As illustrated in Figure 8, a draw wire transducer (DWT) was used to measure the deflection of the FRP poles at three different locations: hc/4, hc/2,
and under the load application point. Electrical strain gauges were installed around the hole, at \( hc/4, \) \( hc/2, \) and \( 3/4hc \) on the two faces close to the ground line support. The deformations in the longitudinal, circumferential, and at \( 45^\circ \) from the longitudinal axis of the pole were all observed using strain gauges. Two LVDTs (linear variable differential transducers) were placed against the test fixture or the lower wall to monitor displacement at the pole base [15,16].

| Working Load Applied (kg) | 25  | 50  | 75  | 100 | 125 | 150 | 175 | 200 |
|---------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| GRC pole                  |     |     |     |     |     |     |     |     |
| Sample average-Deflection %| 0.4 | 0.7 | 1.1 | 1.4 | 1.8 | 2.2 | 2.6 | 3.1 |
| FRP pole                  |     |     |     |     |     |     |     |     |
| Sample average-Deflection %| 2.1 | 3.6 | 5.2 | 6.8 | 8.4 | 10  | 11.4| 13.1|

Table 4. Deflection comparison—GRC vs FRP poles.

Figure 8. Test setup, adapted from ref. [16].

5.3. Previous Experimental Research Program

As cantilever beams, two poles made of glass-fiber-reinforced polymer were loaded to failure (NTUA). The experimental poles were created using the filament winding process. The experimental results comprised load-deflection data at the loading point and strain distribution at the fixed support. It was found that the fiber orientation has a significant effect on the critical load on FRP poles. An increase in the fiber angle results in a reduction of the critical ovalization load [17]. Sherif published results from cantilever bending experiments on full-scale tapered GFRP poles with a hollow circular cross-section in 2000. The poles were made utilizing a filament winding method with polyester resin reinforced with E-glass fibers. Twelve full-scale poles were bent to failure in cantilever bending tests. The number of layers and fiber orientation were among the test parameters [18]. In 2000, Ibrahim made twelve 2.5 m and twelve 6.1 m GFRP poles tested under lateral loading. The examples were created with various wall thicknesses, fiber orientations, and fiber arrangements in mind. The most common failure mode of the specimens studied was local buckling due to flexural failure [19]. Jiwon (2006) examined the load-deformation behavior of tapered steel and fiber-reinforced plastic bridge camera poles subjected to cantilever bending stresses experimentally and analytically. Three full-scale experiments were performed on tapered octagonal metal cross-sections and two FRP circular cross-section poles to establish their load-deformation properties [20]. FRP tubes offer a lot of promise for utility and light poles, according to Fam in 2007. The ultimate strength of hollow thin-walled FRP tubular poles subjected to bending was determined by the local buckling failure of the tubes on the compression side before reaching the maximum strength of FRP, according to research. Several poles of varying lengths of concrete fill were tested to determine the ideal length of the concrete fill. The ideal length was determined by achieving flexural material failure of the FRP tube at the base while also experiencing local buckling failure above the concrete fill. The ideal length of partial concrete fill of the tube
used in this study was 38 percent of the complete length, proven experimentally. Figure 9 shows the anchorage options for FRP light pole base [21,22].

Masmoudi (2007) developed and evaluated the flexural behavior of lightweight fiber-reinforced polymer poles at the University of Sherbrooke. Static flexural testing was conducted on 23 full-scale prototypes of FRP poles with lengths varying from 5 to 12 m. Experimental results show that using low linear density glass fibers could increase the ultimate load-carrying capacity up to 38% for some FRP poles. The epoxy resin reinforced with E-glass fibers FRP poles were made using the filament winding technique [23]. Torran, in 2009, completed the findings of an investigation into the bending strength and stiffness of full-size Eucalyptus Grandis poles from Argentina. With the growing demand for utility poles of this species and modern procedures aimed at achieving a reliable and cost-effective structural design, knowing the mechanical properties of this material has become increasingly important. For this purpose, the methodologies for cantilever bending tests specified by the American Standard ASTM D 1036 and the Argentinean Standard IRAM 9529 were used to test two samples containing new, green, untreated poles [24]. In 2010 Jeffrey conducted Flexure experiments on six glass-fiber-reinforced polymer cantilevered tubular poles. The prismatic tubes had a length of 3660 mm, a clamped length of 700 mm at the fixed end, an outer diameter of 220 mm, and a 4.15 mm wall thickness. Test results showed that flexural strength increases as the length of concrete fill increases until it reaches a plateau. Corresponding to about double the strength of the hollow tube when the concrete fill is about one-third of the clear length. Figure 10 shows the pole placed on the test setup [25,26].

Zhang (2011) investigated the durability of glass-fiber-reinforced-polymer (GFRP) poles and towers for power transmission in UV and extreme temperatures. The results reveal that UV and extreme temperatures impact GFRP material performance, with reduced strength and elastic modulus increasing, while Poisson’s ratio changes little [27]. Vazquez (2015) found that their use in structural engineering was growing every day because of the advantages of composite materials over traditional materials. In countries such as the United States, India, and China, structures for electric energy transmission made entirely of polymeric materials have been built. However, no experience with replacing metallic parts with composite elements has been documented on lattice power transmission towers. Therefore, lattice power transmission towers introduced a system for testing the feasibility of substituting metallic elements with composite members. Figure 11 shows the pole deflection [28,29].
In 2015, Jaafar explained that transmission systems such as transmission towers and poles were designed to withstand various acting forces. On the other hand, these current concrete and metal structures were heavyweight materials that were difficult to handle during assembly, repair, and reinstallation. Then there was the issue of vandalism on the transmission towers’ metallic bracing [30]. XIAO 2016 used a three-pole model to analyze the force situation of the pole in detail, and the five-pole model was built based on the former model. Furthermore, external factors such as height difference, span, wind angle, and line angle on the pole were investigated. The pole’s force situation hung the pole arrangement styles [31]. Mohamadi (2016), in his research, found that engineers were increasingly being asked to develop and operate systems that incorporate the resiliency philosophy across several critical infrastructure sectors. Essential sectors of infrastructure included electric distribution and transmission systems. Results indicate that pole boundaries may considerably impact the estimates of failure probabilities, especially when the extent of difference in the properties of adjacent spans is not negligible [32]. Vivek (2017) found that self-supported single poles were commonly used for electricity transmission in India’s rural areas. Several self-supported poles were severely tilted during recent windstorms in the Unnao district of Uttar Pradesh, India. The government and the company in charge of the poles’ construction and installation were concerned about the incident’s safety. Table 5 shows the specifications of composite poles [33,34].
Ahmed, 2020, explained that due to slow hardwood replenishment, high clearing rates in the 19th century, and occasional bushfires, it becomes difficult and expensive as a source of utility poles. Therefore, there was a serious need to find alternative wood species for timber poles [35]. Dionysius, in 2020, figured out why several major earthquakes have caused damage to light poles and utility poles mounted on elevated highways or railway bridges. They were mainly caused by excessive pole deformation, yielding-induced bending failure, pole buckling, and masts falling. Damages hampered functionality and slowed traffic, complicating post-earthquake recovery in the affected region. While the seismic resistance of elevated highway bridges has been assessed and updated in seismic codes, most light and utility poles were built for wind loads rather than earthquakes [36]. Sami was in charge of the analysis, design, and manufacture of a communication guyed tower in 2021, consisting of individual cells made of fiberglass matting joined together to form an equilateral triangle. First, the mechanical properties of the GFRP materials were determined by a series of experiments utilizing ASTM Standards. Then, a 9 m tower was built and put through its paces under static and dynamic stresses. Based on limit states design criteria, as defined in the current CSA-S37 Standard, various nonlinear finite element models were created and utilized to predict the size of the tower and the thickness of the cell walls. According to the finite element analysis, the tower was more flexible than the test specimen, which yielded results for deflections and stressed higher than the test results [37]. According to Jianhui 2022, The failure mode of a GFRP solid pole with a circular section under axial compression was the loss of stability of the extreme point, as shown in Figure 12, and the material in the middle of the specimen suffers axial and transverse tearing failures; when overall lateral buckling of the specimen occurs, a bearing capacity platform phenomenon appears; and when the ultimate deformation was reached, the specimen undergoes brittle failure [38].

![Figure 12. Pole failure.](image-url)
6. Modeling of FRP Poles
6.1. Simple Linear Static Models

Masmoudi, 2008, used the FE model to determine the performance of GFRP poles with service apertures (holes). FE simulations were performed with fiber direction, layer number, and layer thickness parameters. The deflection and bending strength of GFRP Poles (20, 33, 35, and 40 feet in height) were tested. For three zones and the height of the GFRP poles, ideal new designs were presented under equivalent wind loads. The ultimate load-carrying capacity and flexural stiffness were enhanced while a significant amount of weight was conserved with this design. Table 6 shows the FRP poles’ results different cross-sectionals [39,40].

| Material             | Stress (MPa) | Deformation (mm) |
|----------------------|--------------|------------------|
| Circular FRP pole    | 16           | 98               |
| Hexagonal FRP pole   | 19           | 124              |

Amir developed a finite element model and validated it in a companion study in 2008, which was used to analyze partial concrete filling of cantilever-type FRP tubular poles. The goal was to increase flexural strength while lowering the pole’s dead weight. By altering the length of the concrete fill, flexure was studied in tubes with various D/t ratios and laminate designs. The effects of lateral loading type and taper have also been considered. A simpler method has been created to determine the ideal concrete fill length [41]. Saboori (2011) performed a linear static analysis of tapered fiber-reinforced plastics transmission poles with circular thin-walled cross-sections using a second-order shell element and shear deformation theory of the first order (FSDT). The cross-section was processed as though it were an orthotropic laminate. A computer program was developed to examine typical poles using the MATHEMATICA software (Mathematica 6, Wolfram Research, Champaign, IL, USA). The numerical modeling results were confirmed by comparing the numerical modeling findings to analytical results or those produced from the commercial finite element program ANSYS 11.0 (ANSYS, “ANSYS Inc., ANSYS User’s Manual for Rev. 11.0”, ANSYS, USA, 2007). The influence of numerous parameters on the behavior of tapered FRP transmission poles was investigated, including fiber orientation and type, fiber volume fraction, number of layers, and form [42]. Mohamadi (2016) provided ABAQUS finite element calculations of tapered fiber poles and associated parametric investigations with determining the impact of various factors on the poles’ overall static and dynamic response. These properties are geometric parameters, fiber orientation, taper ratio, layer number, lamina thickness, and transverse load location. The suitability of three different general-purpose finite elements based on thick shell theory for modeling FRP poles was investigated. By using parametric analyses, trends in FRP poles’ static and dynamic study were identified. Shock spectrum research was provided for idealized impulsive loadings owing to wind gusts or loss of cable tension supported by FRP poles [43]. Mohamadi (2016) employed a finite element model to investigate the geometric characteristics, fiber orientation, layer number, and lamina thickness of FRP composite poles. Figure 13 shows the finite element meshing [32,44].

Plinio used the finite difference method to calculate the stiffness and maximum deflection in 2017. Buckling and failure were also analyzed at the global and local levels. Abaqus commercial finite element software was used to obtain the results [45]. In 2019, Omar used LS-DYNA software (LS-DYNA, LSTC (Ansys, Inc.), R10.1, USA) to conduct a finite element (FE) parametric research to explore the effects of the pole’s diameter, length, and wall thickness. In the FE parametric analysis, pole diameters ranged from 254 mm to 457.2 mm, and wall thicknesses from 3.175 mm to 12.70 mm [46]. Thomas (2020) used the Finite Element Method to analyze the static behavior of tapered poles made of glass-fiber-reinforced-polymer. The theoretical model built using the FEM was validated using...
an experimental method. The FEM results for specimen deflection and ultimate load were close to the experimental data [47].

![FE mesh of the pole.](image)

**Figure 13.** FE mesh of the pole.

### 6.2. Advanced Static Models

Son built a Finite Element (FE) model in 2008 to predict the flexural behavior of hollow and concrete-filled FRP tubes (CFFTs). Geometric and material nonlinearities were accounted for in the model. The plasticity and cracking of the concrete were also considered. The model can represent the in-walled hollow tubes’ ovalization and local buckling failure mechanisms. Using the Tsai–Wu failure criteria for thick-walled hollow tubes or CFFTs, the model can reliably identify the material failure of the FRP tube. The model was validated using experimental findings from various hollow GFRP tubes and CFFTs, including a wide range of laminate structures, diameters, wall thicknesses, concrete strengths, and failure modes. The load-deflection responses and ultimate strengths were found to be very well aligned. Different failure mechanisms were also predicted with a high degree of accuracy. The load-deflection responses and ultimate strengths showed excellent agreement. Other failure mechanisms were also indicated with a high degree of accuracy. The model was used in a parametric study to examine the impacts of cross-ply and angle-ply laminate structures and the diameter-to-thickness (D/t) ratio for hollow GFRP tubes [48].

In 2008, Amir investigated fiber-reinforced polymer tubular poles filled with concrete in flexure using a nonlinear finite element model. The partial filling was a low-cost alternative to employing thicker-walled tubes to increase flexural strength and stability. Tubes with varied diameter-to-thickness (D/t) ratios and laminate designs in cantilever-type monopoles were designed with the partial concrete fill length in mind. Figure 14 shows the FE model of the pole [49, 50].

According to Mohamed (2009), tapered GFRP poles were first used in overhead power lines and aerial distribution networks to substitute traditional materials such as wood, steel, and concrete. A full-scale tapered GFRP pole structure was used to undertake a finite element (FE) analysis of the nonlinear behavior of laterally loaded pole structures. The performance of GFRP poles with service holes was calculated using the FE model. Fiber direction, layer number, and layer thickness were used in various parameter combinations in FE simulations [43].

In 2009, Masmoudi released a finite element analysis of the nonlinear...
behavior of laterally loaded full-scale tapered GFRP pole structures. The FE model was used to determine the performance of GFRP poles with service holes. FE simulations were performed using parameters such as fiber direction, layer number, and layer thickness. Deflection and bending strength characteristics of GFRP Poles [20 and 33 ft] height were studied. For three zones and the height of the GFRP poles, ideal new designs were presented under equivalent wind loads. The ultimate load-carrying capacity and flexural stiffness increase with a substantial weight decrease. The new designs meet the ASTM, AASHTO LT S, and ANSI specifications for maximum permissible deflection and minimum ultimate moment capacity [51]. Jaafar used composite star software to model a laminate design of glass fiber samples to assess mechanical strength and reserve factor in 2015. The composite panels were designed to withstand a distributed load of 5 kN in longitudinal and transverse axis directions on samples with thicknesses ranging from 4 to 4.2 mm by varying the fiber direction [30].

![Wind Flow Direction](image)

**Figure 14.** FE model shows the wind flow direction on pole.

### 6.3. Dynamic Modes

Dimos, 2007, proposed a straightforward finite element approach for the dynamic analysis of tapered composite poles with hollow circular cross-sections. The tapered beam element was applied to cross-sections with any taper ratio, and cross-sections were constructed of standard materials. The finite element model was presented as a flexible joint model, which was then included. The qualities of the applied resin, its thickness, and the pole diameter at the joint position and the joint length all influence joint stiffness. As a result, a sufficiently robust and rigid joint may be developed and manufactured [52]. In 2010, Khalili investigated the transient dynamic analysis of tapered fiber-reinforced polymer (FRP) composite transmission poles with circular thin-walled cross-sections subjected to dynamic cable tension and vehicle impacts using a tapered beam finite element and precise time integration method. The wall’s cross-section laminate was symmetric or antisymmetric angle-ply, and the material behavior was linearly elastic. A dynamic study of FRP poles under the step, triangle, and sine pulses was used to investigate the effects of fiber type and orientation, pole geometry, and concentrated mass at the pole tip. The current method’s results were consistent with those obtained from poles modeled with ANSYS commercial finite element software and existing literature. In addition, the current technology has a significantly shorter run-time. According to the findings, the pole tip deflection does not
change beyond 10 layers of laminate with constant wall thickness. Figure 15 shows the cross-sectional shape of the guyed tower [52,53].

Wind gusts and cable unilateral failure induced dynamic cantilever bending in electricity transmission poles, according to Khalili (2010), which might be vulnerable to vehicle accidents. A combination of tapered beam finite element and precise time integration techniques was used to investigate the transient dynamic behavior of tapered (FRP) composite transmission poles with circular thin-walled cross-sections exposed to dynamic cable tension and vehicle impacts. The wall’s cross-section laminate was symmetric or antisymmetric angle-ply, and the material behavior was supposed to be linearly elastic. Fiber type, orientation, pole shape, and concentrated mass at the pole tip were examined using dynamic analysis of fiber poles under phase, triangle, and sine pulses [54]. Amir used a 3D finite element study in 2010 to estimate the lateral load-deflection responses under various axial loads and the axial load–bending moment interaction curves at ultimate. The model considered geometric nonlinearities and the composite laminate structure. According to the Tsai–Wu failure criterion or stability failure, material failure was utilized to characterize failure modes. The model was put to the test using the results of the experiments. On poles, the properties of various angle ply and cross-ply laminates, as well as the various diameter to thickness (D/t) and length to diameter (L/D) ratios, were investigated [55]. Jungate (2017) compared theoretical values and ratios for different cross-sections to the static buckling stress calculated by numerical simulations. According to the comparison, the results of the FE investigation were more conservative than the theoretical values in some circumstances. The model’s boundary conditions were particularly sensitive in the simulation of dynamic buckling loads. Local buckling occurs near the column’s base, according to the results of the horizontal loading simulation [54].
6.4. Fatigue/Fracture Mechanics/Cyclic Models

Pre-stressed concrete poles reinforced with carbon fiber polymer were a lightweight and durable alternative to steel-reinforced or pre-stressed concrete poles, stated Roberts (2012). In addition, CFRP tendons’ corrosion resistance can decrease maintenance costs and reduce the amount of concrete cover required. Wind loading was a significant load situation for lighting poles utilized in pedestrian or low-traffic regions. The wind was a passing gust of air that may blow in any direction. The output of CFRP pre-stressed lighting poles was thus studied under multiple cycle loads and/or load reversals [56]. In Yanbu Industrial City, Saudi Arabia, a simulation analysis was conducted by Omar (2019) on a fiber-reinforced polymer light pole that was in use. The light poles in this area were exposed to cyclic wind loads from the Red Sea. Under lateral load, a full-scale GFRP distribution pole was tested until it failed. The pole stood 10.5 m high, had a diameter of 254 mm, and a wall thickness of 6.35 mm. Figure 16 shows the mode of vibration [46,57].

![First Mode Vibration](attachment:image.png)

**Figure 16.** Sway mode of vibration, adapted from ref. [46].

7. Discussion

7.1. Advantages and Disadvantages of FRP Types

GFRP glass fibers are the most used FRP in the building sector due to their relatively inexpensive cost compared to other FRPs. However, the primary drawbacks of GFRP are a relatively low deformation modulus, low humidity, alkaline resistance, and low long-term strength because of stress rupture. In addition to not absorbing water, CFRP offers a high deformation modulus and fatigue strength. However, one of the main drawbacks is that producing carbon fibers requires a disproportionately large amount of energy, which drives up expenses. In addition, AFRP fibers possess high static and impact strengths. However, their diminished long-term strength (stress rupture) and susceptibility to UV exposure limit their utilization. Aramid fibers also have the disadvantage of being challenging to cut and process.

7.2. Advantages and Dis-Advantages of FRP Manufacturing Techniques

Manufacturing techniques of FRP poles have many advantages and disadvantages, as shown in Table 7.
Table 7. Comparison between fiber-reinforced polymer poles manufacture methods.

| Methods            | Advantages                                                                 | Disadvantages                                                                 |
|--------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Filament Winding   | • Economical. • Cross-section with large dimensions. • The fiber direction can be determined easily. • Experience. | • Specific cross-sections. • The outer surface of the product was not smooth. • A low viscosity resin should be used. • Voids. |
| Pultrusion         | • Fast produce. • Many shapes (L, T, U, and C) sections. • Long lengths. • Mechanical produce. | • Expensive. • Fixed dimension for one length. • Voids due to Heat curing. • Low experience. |
| Centrifugal Casting| • Economical. • The product does not need to be cured. • Reduces fiber volume ratio. • Reduces any voids. • The outer surface has an attractive appearance. • Larger length. | • Specific cross-sections. • Change mold after a specific number of rotations. |
| Hand Lay-up        | • Economical. • High experience.                                             | • Small length. • Not Mechanical produce. • Specific shapes. • The outer surface of the product was not smooth. |

7.3. Advantages and Disadvantages of FRP Modeling

FRP poles’ modeling has many advantages and disadvantages, as shown in Table 8.

Table 8. Advantages and disadvantages of each modeling technique.

| Model              | Advantages                                                                 | Disadvantages                                                                 |
|--------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Linear Static      | The solving process is relatively short compared to a nonlinear analysis on the same model. The maximum discrepancy of the maximum stress for the typical FRP pole concerning the ANSYS model was almost 10%. | Applicable only to structural problems where stresses remain in the linear elastic range of the used material. |
| Advanced Static    | The program accounts for the nonlinear behavior of the poles and gives a good prediction for the ultimate load at failure. | Nonlinear effects can originate from geometrical nonlinearity (large deformations), material nonlinearity (elastoplastic material), and contact. |
| Dynamic            | used to select more efficient cross sections for the compressive elements of the structure. It can be more critical than static loading for sheet pile members. | Numerical analysis is required to design the FRP columns with thin-walled parts. |
| Fatigue            | The downwards and upwards reversal of load direction in each cycle did not significantly change the overall behavior when compared with a solely downwards loading. | The deflections increase with the number of cycles, but most of this increase occurred within the first 50,000 cycles. |

8. Conclusions and Recommendations

This study aims to collect, sort, analyze and criticize the early published research regarding FRP poles for determining the current trends, illustrate previous studies of testing poles, figure out the gap studies, and recommend future research. In addition, This study discusses fiber-reinforced polymers poles in six aspects: (i) introduction; (ii) methodology; (iii) materials properties of FRP poles; (iv) manufacturing techniques of FRP poles; (v) testing of FRP poles; (vi) modeling of FRP poles. Fiber-reinforced polymers poles were an important alternative to traditional materials (steel, concrete, and wood). Based on the performed extensive analysis of literature sources, it can be concluded that:

- According to the comparison between the fiber-reinforced polymers poles manufacturing methods, the Pultrusion process was more accurate than others but more expensive. Therefore, the most suitable method was the centrifugal process due to its low cost.
The analysis indicates major differences in stiffness and strength when comparing fiber-reinforced polymers poles to standard metallic poles. According to the different types of fibers, glass fiber was the best choice for poles due to its low cost, UV resistance, electric insulation, and energy absorption. For the chosen sites, the pole load capabilities were determined to be between 0.95 and 1.48 times the design wind load. By increasing the footing dimension, the pole's capacity increases. According to FE studies, the maximum moment of the GFRP pole increased significantly as the diameter or wall thickness of the pole was increased. Local buckling was the most common mode of failure for GFRP poles, but it may change to rupture in tension when the wall thickness is high.

The FEM results for deflection and ultimate load of the specimens were very similar to the experimental results. Based on the results, the study concluded that the FEM could be used with trust in the research and design of GFRP structures such as utility poles and towers without the high cost of experimentation.

**Gap Studies:**

Previous studies found that a few papers study the effect of cyclic load on the pole, it should be considered, and it was recommended to compare the different FE software on the accuracy of results. Table 9 presents the gap studies for some published papers.

**Table 9. Summary of gaps study of fiber-reinforced polymers poles.**

| Authors and Year | Description and Contribution of the Research                                                                 | Gaps                                                                 |
|------------------|-------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------|
| [20]             | On full-scale poles, twelve bending tests were performed up to failure. The number of layers and fiber orientation were among the test parameters. The current findings show that the established theoretical model can accurately predict the ultimate capacity and behavior of GFRP poles. | Study the stacking sequence of the fibers among the test parameters. |
| [17]             | Composite materials’ permissible stress design theory under various stress states was employed to improve the available design techniques for fiber-reinforced polymer poles. The influence of these holes on the rapid reduction in the cross-sectional region of the poles was ignored by most design recommendations, which instead account for the effect of these holes on the abrupt decrease in the cross-sectional part of the poles. The accuracy of the established design techniques and current design approaches was confirmed compared to published test findings from the authors’ early experimental program. | Study the effect of the surface texture of the opening hole on the strength of FRP poles due to the stress concentration of this region. |
| [48]             | Under lateral load, a full-scale GFRP distribution pole was tested until it failed. The pole in issue stood 10.5 m high, had a diameter of 254 mm, and a wall thickness of 6.35 mm. With increasing the diameter or wall thickness of the GFRP pole, the maximum moment increased significantly. Local buckling was the most common mode of failure for GFRP poles | Study the effect of the pole fixation method on the maximum moment. |
| [49]             | As cantilever beams, two poles made of glass-fiber-reinforced polymer were loaded to failure (NTUA). The experimental poles were created using the filament winding process. The experimental results comprised load-deflection data at the loading point and strain distribution at the fixed support. | Compare the results of load-deflection among different pole manufacturing techniques. |
Recommendations for Future Work:

Fiber-reinforced polymers in poles had a significant impact. Still, we suggest that future studies investigate the effects of additional mass near the pole’s tip, such as cross arms used to carry electric wires or transformer equipment. It can be treated as lumped mass to evaluate the effect of the additional mass on the poles’ fundamental frequency. Frontal crash simulations of a vehicle against FRP poles can be studied with the Finite Element model’s full version to understand the contact-impact nonlinear dynamic response better. Future research may look at failure criteria to estimate the FRP poles’ ultimate ability using detailed ply stress calculations.

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