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Review

Characterization Specifications for FRP Pultruded Materials: From Constituents to Pultruded Profiles

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Abstract: Pultruded FRP composites have emerged as a promising alternative to traditional materials like concrete, steel, and timber, especially in corrosive environmental conditions. However, the unique properties of these composites necessitate careful consideration during their implementation, as they differ significantly from conventional materials. Proper testing and characterization of FRP pultruded materials is key for their efficient and safe implementation. However, the existing specifications are not unified, resulting in ambiguity among stakeholders. This paper aims to bridge this gap by thoroughly reviewing current destructive and non-destructive test methods for FRP pultruded materials, specifications, quality control, and health monitoring of FRP structures. Each subsection is further divided into subtopics, providing a comprehensive overview of the subject. By shedding light on these crucial aspects, this article aims to accelerate the adoption and utilization of these innovative materials in practical applications.

Keywords: FRP pultruded materials; pultrusion; test methods; specifications

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1. Introduction

Fiber-reinforced polymer (FRP) pultruded shapes and profiles have been manufactured for structural engineering purposes since the 1970s. The initial patents for these products were granted as early as the 1950s, notably to W.B. Goldsworthy [1]. Over the past five decades, leading pultrusion companies, often in collaboration with industry associations, have developed and manufactured a wide range of unique products tailored for use by structural engineers in construction projects, including buildings, bridges, and other infrastructure [2,3]. Pultruded profiles are made of longitudinally aligned fibers embedded in a resin matrix, and they are revolutionizing modern construction as a robust alternative to traditional materials like wood, steel, and concrete. These composites are formed by embedding high-strength and high-stiffness fibers within a continuous polymeric matrix of lower modulus through a continuous manufacturing process called pultrusion. The reinforcing fibers serve as the structural backbone of FRP composites, determining their strength and stiffness along the fiber direction. The resin acts as a glue or binder to hold the fibers in place and transfer stresses between them. Small quantities of coatings, pigments, and fillers may also be incorporated for various purposes [4]. An example of the pultruded grating system and structural profiles made of FRP materials are shown in Figure 1.

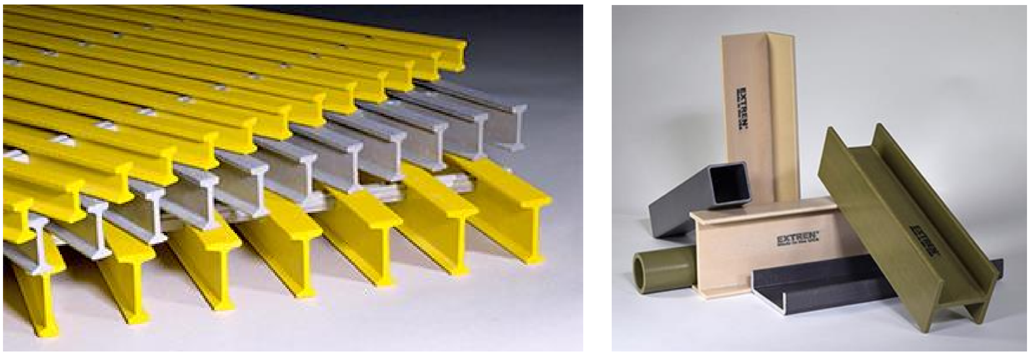

Figure 1. FRP gratings and FRP structural shapes (Image courtesy of Strongwell).

The widespread adoption of FRPs can be attributed to their exceptional qualities, such as high strength, design versatility, electrical and thermal insulation properties, and resistance to chemical corrosion, making them valuable in various sectors of building and infrastructure construction [5,6]. Their corrosion resistance prolongs service life in harsh environments, and UV resistance combined with coatings reduces maintenance needs. Their lightweight nature eases transportation, while a high strength-to-weight ratio supports efficient design. Customizable shapes and sizes provide design flexibility [4,7]. Additional benefits include electrical and thermal insulation, non-magnetic properties, and suitability for sensitive environments like MRI rooms. FRP's environmental compatibility and potential for recycling contribute to sustainability. These attributes make FRP pultruded components ideal for a range of infrastructure applications, from bridges to marine structures [4].

The expanding use of FRP pultruded profiles in modern construction (Figure 2) highlights the importance of standardized testing, specifications, and quality control to comply with industry standards and ensure safety, reliability, and long-term performance. Leading standard organizations worldwide, including ASTM International (ASTM) and the International Organization for Standardization (ISO), develop relevant test methods. While numerous standardized tests exist for constituent materials and lamina and laminate levels, limited standards apply to full-section FRP-pultruded components. However, some organizations like the American Concrete Institute (ACI), the Japan Society for Civil Engineers (JSCE), the European Committee for Standardization (CEN), and the Canadian Standards Association (CSA) have recently developed test standards for FRP-pultruded components [3]. Despite the absence of universal agreement among stakeholders on test methods, a range of tests assess FRP materials, reflecting the importance of physical and mechanical properties in design. Test method selection is typically at the discretion of material suppliers, composite producers, or pultruded manufacturers, leading to potential variations in interpretation regarding their relevance to structural engineering design. Material specifications for FRP pultruded composites in construction projects define test methods and material properties, often with specific minimum or limiting values, based on design assumptions, with guidelines found in model specifications like those from CEN or ANSI for pultruded profiles.

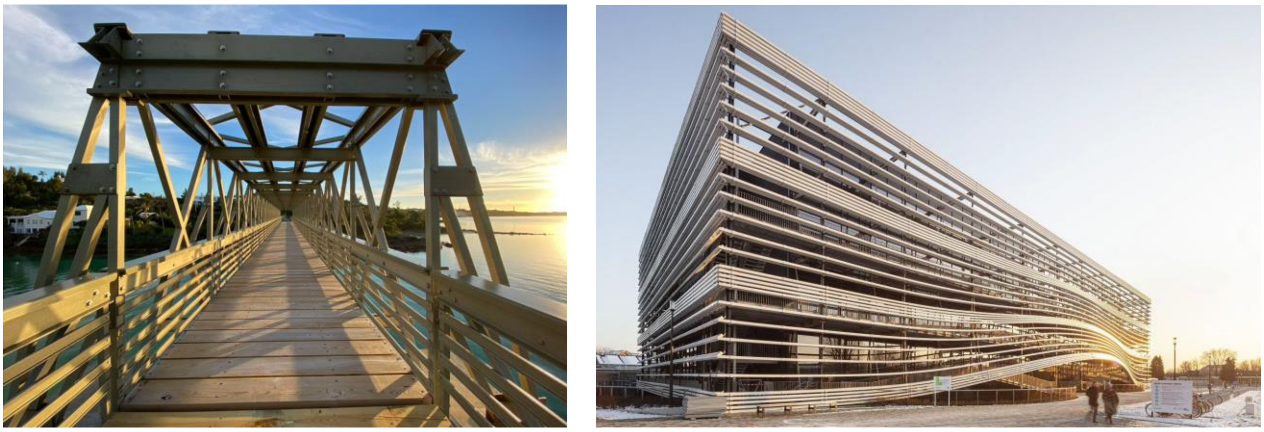

Figure 2. Composite pedestrian bridge in Bermuda (**left**) (Image courtesy of Creative Composites Group) and FRP profiles at the façade of a building on the University College Ghent's Schoonmeersen Campus (**right**) (Source: Open Oproep 2013).

In addition to the testing of materials prior to construction, it is also important to monitor and maintain a structure once built. Structures utilizing FRP pultruded profiles' long-term performance and safety are closely tied to effective maintenance and health monitoring practices. Regular inspections, condition assessments, and predictive maintenance strategies are essential to detect and address potential issues before they escalate. Advanced health monitoring techniques, such as non-destructive testing [8], can provide real-time insights into the structural integrity of FRP components, enabling timely interventions and extending the service life of the infrastructure. Integrating maintenance and health monitoring with quality control ensures that FRP pultruded profiles meet performance expectations and regulatory requirements throughout their lifecycle.

The objective of this paper is to categorize the existing specifications for FRP pultruded composites, covering aspects from constituent materials to the final pultruded profiles. The paper also discusses the governing specifications, quality control, and quality assurance practices for the safe use of these materials in construction applications. Emphasis is also placed on maintenance and health monitoring strategies, highlighting their critical role in ensuring the longevity and reliability of FRP-based structures.

2. Test Methods for FRP Pultruded Materials

A diverse array of testing methods exists to characterize FRP pultruded materials at distinct hierarchical tiers: the raw material level, composite level (lamina/laminate level), FRP pultruded element level, and full-scale testing level. These tailored approaches, including both destructive and non-destructive techniques, offer unique insights into the material's behavior and characteristics. A proper testing and characterization process is key for a comprehensive understanding of the behavior of FRP pultruded elements, enabling safe and efficient engineering designs and informed decision-making. This section delves into the existing test methods for these materials (refer to summary in Figure 3).

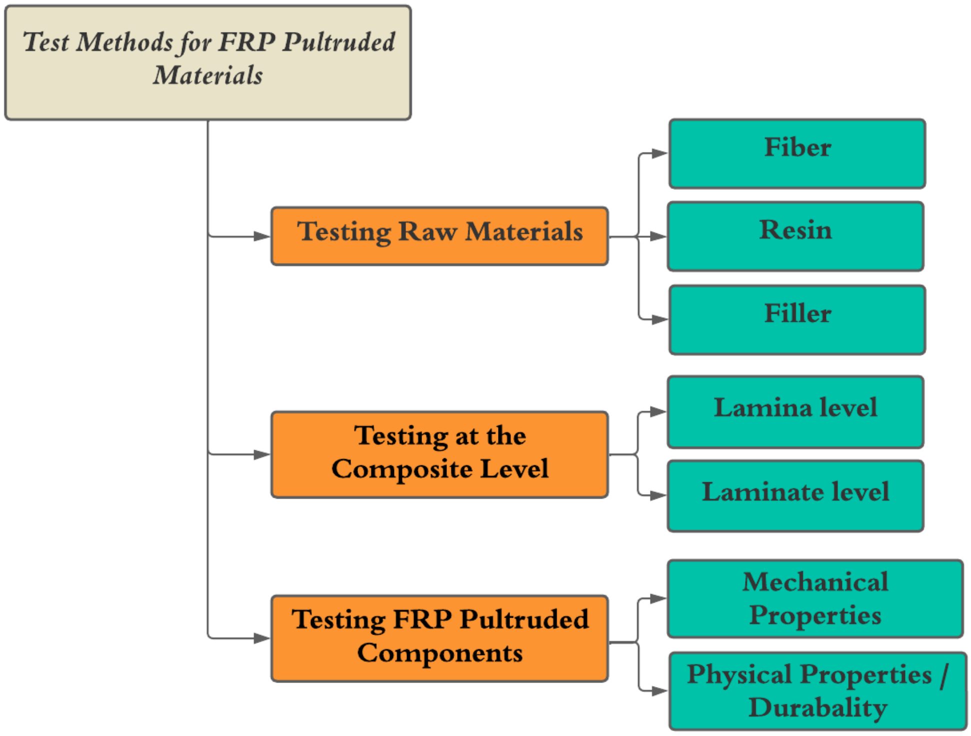

Figure 3. Test methods for FRP pultruded materials.

2.1. Raw Materials Testing

FRP composites are made of fibers embedded in a resin matrix that bonds the fibers. The reinforcing fibers, which are typically made of materials such as glass, carbon, basalt, or aramid, provide the composites with remarkable strength and stiffness. The choice of fiber type depends on the desired mechanical properties and the intended application. For instance, carbon fibers are favored in aerospace and high-performance applications for their exceptional strength-to-weight ratio, while glass fibers find extensive use in the construction and automotive industries due to their cost-effectiveness and corrosion resistance. The polymer matrix, also known as the resin, acts as a binding agent that holds the fibers together, transfers loads, and safeguards them from environmental factors. Epoxy, polyester, vinyl ester, and polyamide are some commonly used polymer matrices, each offering unique characteristics that cater to specific application requirements. Properly combining fibers and resin is crucial in designing FRP composites with tailored mechanical properties, making them versatile materials widely employed in industries seeking lightweight, high-strength solutions. Below, the most frequently used test methods to test and evaluate the performance of fibers, resin, and fillers are listed.

2.1.1. Fiber

Fiber-based tests are essential for FRP pultruded materials and are usually provided by the fiber supplier as part of the material certification documents. Testing can be conducted on single fibers using methods such as ASTM C1557 or ASTM D3379 to obtain the fundamental properties of the reinforcing fibers used in FRP composites. However, testing single fibers may not accurately represent the properties of the fibers when bundled or used in composite components. To address this, fiber manufacturers often report mechanical properties of fibers when they are impregnated with a commonly used resin and tested as an FRP composite. For example, glass and basalt fiber manufacturers commonly use ASTM D2343, while carbon fiber manufacturers employ ASTM D4018 to test the tensile properties of impregnated fibers. The properties of the bare fibers are then calculated using rule-of-mixtures approximations derived from the FRP composite test data. Other relevant ASTM test methods are listed in Table 1, including ASTM D1907 for measuring the linear density of yarn, ASTM D2256 for assessing the tensile properties of yarns, and ASTM D4963 for determining the ignition loss of glass fiber strands and fabrics. The characterization of fibers through these ASTM standards is critical to understanding the physio-mechanical properties of the final composite components. It ensures quality control and assurance in the manufacturing of FRP pultruded components. The strength of the fibers is a primary determinant of the overall strength of the FRP pultruded composite material, making these standards an integral part of the evaluation and certification process [3].

Table 1. Test methods for fibers and resins commonly used in pultruded materials.

Material	*Property*	*Test Standard*
Fiber	Density	ISO 1889 ISO 10119 ASTM D1577
	Thermal expansion coefficient	ISO 7991
	Tensile strength	ISO 5079 ISO 11566 ASTM C1557 ASTM D2343 ASTM D3379
	Tensile modulus	
	Tensile ultimate strain	
Resin	Density	ISO 1183 ASTM D1505
	Specific Gravity	D792
	Tensile Strength	ISO 527 ASTM D638
	Elongation	
	Tensile Elastic Modulus	
	Compressive Strength	D695
	Compressive Elastic Modulus	
	Flexural Strength	D790
	Flexural Elastic Modulus	
	Impact Strength	D256
	Hardness	D785
	Thermal Conductivity	C177
	Thermal Expansion	D696
	Water Absorption	D570
	Shrinkage during cure	D2566
	Heat Deflection Temperature	D648

2.1.2. Resin

Numerous standard test methods are available for obtaining the mechanical, physical, and chemical properties of polymer-based resins (also referred to as plastics) in both their liquid and hardened (cured) states. These methods, developed primarily by the plastics industry over the past 50 years, include those from ASTM, ISO (International Organization for Standardization), and DIN (Deutsches Institut für Normung). The properties of the polymer are typically derived from tests on resin samples that have undergone a specific post-cure protocol at elevated temperatures, which may differ from the curing protocol applied to FRP pultruded components during manufacturing [9]. These test methods measure various properties such as density, viscosity, gel time, tensile strength, deflection temperature, flexural properties, impact resistance, adhesion, and abrasion resistance. Selecting the appropriate test method is crucial, depending on the specific properties of the polymer resin and its intended application. These methods ensure the quality and performance of plastic products across various industries, including automotive, construction, aerospace, and electronics. Some commonly used ASTM test methods for resins are listed in Table 1, and they play a vital role in the standardization and quality control of polymer resins in their liquid and hardened states.

2.1.3. Fillers

Assessing the fillers incorporated into FRP composite materials does not rely on a singular test methods approach. Instead, the characterization of these fillers, including their morphology, size, shape, and surface charge, is commonly achieved through various techniques such as Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray photoelectron spectroscopy, wide-angle X-ray scattering, transmission electron microscopy, X-ray diffraction (XRD), and atomic force microscopy [10]. Fillers play a vital role in FRP formulation, serving multiple purposes such as reducing polymerization shrinkage, regulating compound plasticity, influencing fire resistance, enhancing mechanical strength, improving crack-resistance, and being extensively used in marine putty and the transportation industry due to their low-density [11,12]. Fillers are classified as coarse or fine based on their particle sizes, and the most commonly used fillers in FRP composite materials are provided in list below:

- *Alumina trihydrate (ATH):* Extender; flame retardant; smoke suppressant
- *Calcium carbonate:* Extender
- *Calcium sulfate:* Flame/smoke retardant
- *Carbon black:* Pigment and pacifier
- *Clay (kaolin):* Extender
- *Fumed silica:* Thixotrope
- *Glass fibers*: Higher strength; dimensional stability; heat and chemical resistance
- *Microspheres*: Weight reduction; stiffness improvement; impact resistance
- *Pigments:* Pigmentation; opacity
- *Talc*: Extender; stiffness enhancement; tensile strength; creep resistance

Inert fillers such as clay, calcium, or alumina tri-hydrate carbonate are used to reduce resin costs by substituting volume. These functional fillers impart specific properties to the resin and reinforcement combination, requiring careful selection tailored to specific design requirements. The rising use of inorganic fillers in composites reduces costs and enhances performance beyond reinforcement and resin alone. By utilizing fillers, essential properties like water resistance, stiffness, weathering resistance, surface smoothness, dimensional stability, and temperature resistance can be significantly improved [12].

2.2. Testing at the Composite Level (Lamina/Laminate)

In structural engineering applications, various tests are conducted on FRP pultruded composites. These tests often involve coupons taken from the original FRP pultruded component. When these tests are performed on coupons extracted from FRP pultruded composites consisting solely of unidirectional fibers, the testing focuses on the properties of a single direction ply, known as tests at the lamina level. Conversely, when the coupon is taken from an FRP composite that includes layers of multidirectional plies or mats (such as in many FRP profiles), the testing assesses the properties of a multidirectional plate, operating at the laminate level. Test coupons from the as-manufactured component must encompass the FRP material’s full thickness to obtain design-dependent properties accurately. In evaluating FRP pultruded composites, same standard test methods are often employed to determine properties at both the lamina and laminate levels. These tests are conducted at a macroscopic level, treating the coupon as a homogeneous material, irrespective of its unidirectional or multidirectional composition.

Common standard test methods for assessing strength, stiffness, and physical dependent properties are outlined in Table 2. It's critical to conduct these tests on samples taken from the fabricated FRP composite, not just the polymer matrix, as fibers can influence properties typically attributed to the resin alone, such as glass transition temperature, hardness, and flash ignition temperature. A standard guide, ASTM D4762, serves as a guide for testing FRP composite materials, including methods for evaluating fatigue, creep, and fracture properties. Additional guidance on testing unidirectional and multidirectional laminates can be found in the publication by Carlsson and Adams [9]. These tests are not only essential for assessing the inherent properties of FRP composites but are also utilized to evaluate durability after exposure to relevant environmental conditions or accelerated conditioning protocols.

Table 2. Standard Test Methods for FRP Composites at the Lamina and Laminate Level.

Ply or Laminate Property	*ASTM Test Method(s)*	*Test Required*
	Strength Properties	
Longitudinal tensile strength	D3039, D5083, D638, D3916	Unidirectional ply and multidirectional laminate
Longitudinal compressive strength	D3410, D695	
Longitudinal bearing strength	D953, D5961	
Longitudinal short beam shear strength	D2344, D4475	
In-plane shear strength	D5379, D3846	
Impact resistance	D256	
Transverse tensile strength	D3039, D5083, D638	Multidirectional laminate only
Transverse compressive strength	D3410, D695	
Transverse short beam shear strength	D2344	
Transverse bearing strength	D953, D5961	
	Stiffness Properties	
Longitudinal tensile modulus	D3039, D5083, D638, D3916	Unidirectional ply and multidirectional laminate
Longitudinal compressive modulus	D3410, D695	
Major (longitudinal) Poisson ratio	D3039, D5083, D638	
In-plane shear modulus	D5379	Multidirectional laminate only
Transverse tensile modulus	D3039, D5083, D638	
Transverse compressive modulus	D3410, D695	
	Physical Properties	
Fiber volume fraction	D3171, D2584	Unidirectional ply and multidirectional laminate
Density	D792	
Barcol hardness	D2583	
Glass transition temperature	E1356, E1640, D648, E2092	
Water absorbed when substantially saturated	D570	
Longitudinal coefficient of thermal expansion	E831, D696	
Transverse coefficient of thermal expansion	E831, D696	
Dielectric strength	D149	
Flash ignition temperature	D1929	
Flammability and smoke generation	E84, D635, E662	

2.2.1. Lamina Level

Structural engineers must consider a crucial distinction between testing unimpregnated dry fiber and impregnated roving at the lamina level in the design of FRP systems. Typically, two distinct methods are provided in guidelines for designing these systems. One method relies on the properties of the FRP composite, which are calculated using the measured gross area of the composite. The other method utilizes the properties of the fibers, determined based on the manufacturer-supplied area of the fibers within a dry sheet or fabric. However, certain design-oriented documents, such as ACI 440.3R-04, specify that the fiber properties should not be derived from individual single-fiber tests when employing the fiber area method. Regardless of the chosen design method, both the stiffness and longitudinal strength of either the FRP composite or the fibers are determined through testing at the ply level. This ensures that both approaches, despite their differing methodologies, result in consistent and identical designs. Careful selection between these methods and strict adherence to the relevant testing protocols are critical to achieving accurate and reliable design outcomes when applying FRP strengthening systems.

A single ply (or lamina), which consists of fibers aligned in a single direction within a planar FRP composite material, holds significant importance in characterizing the behavior of FRP composites in structural engineering. There are three key reasons for its significance: Firstly, numerous FRP products used in structural engineering, such as FRP sheets, FRP rebars, and FRP fabrics, are commonly utilized in their unidirectional form as the final FRP product. Secondly, when investigating the properties of FRP_composites, experimental testing often in volves unidirectional FRP materials, providing valuable data for analysis. Lastly, the unidirectional ply serves as the fundamental building block for calculating the properties of multidirectional FRP laminates. These laminates are frequently employed to represent the walls of pultruded profiles. Understanding and characterizing the behavior of the unidirectional ply is therefore crucial for accurate assessments and design considerations in various FRP applications in structural engineering [9]. Common tests for FRP laminas or laminates are provided in Table 2.

2.2.2. Laminate Level

The test methods used for multidirectional laminates are identical to those for unidirectional FRP composites (as shown in Table 2). However, two key differences arise when testing multidirectional composites. Firstly, while only longitudinal mechanical tests are conducted on the unidirectional ply, both transverse tests and longitudinal are required for the multidirectional laminate, with additional test directions evaluated based on application. Secondly, the ASTM standard test methods may not always fully apply due to the thickness and construction of the FRP component, especially when fabric-type composites are used. In such cases, where fabric-type composites tend to be thicker than traditional unidirectional composites, ASTM D6856 recommends modifying the standard test methods accordingly.

2.3. Testing of FRP Pultruded Components

FRP pultruded profiles are generally designed using properties derived from coupon tests and appropriate theoretical coefficients. However, sometimes the need exists of testing full-section tests on individual profiles or subassemblies to develop full-section properties. This approach is particularly useful when coupon property data cannot confidently predict complex details, or when intricate fiber architecture or composite construction is involved.

FRP pultruded profiles exhibit orthotropic behavior, and the orientation of the fibers influences their mechanical properties. The material behaves linearly and elastically until failure, and it requires five elastic constants to characterize its behavior fully: (i) Poisson ratio and Young's modulus parallel to the fibers (E_x and υ_{xy}), (ii) Poisson ratio and Young's modulus perpendicular to the fibers (E_y and υ_{yx}), and (iii) shear modulus (G). The assessment of elastic constants for FRP profiles on the entire element is challenging, and the reliability of extending coupon test results is limited [13]. The complexity of the problem and the lack of unified standardized testing procedures lead to the use of high safety factors in the design process (in some cases safety factors higher than four). Such high safety factors result in increased construction costs, underscoring the urgent need for rapid advancements in knowledge and improved quality control practices in the field of FRP profile applications [14,15].

The durability performance of FRP products is influenced by several factors, including the fiber volume fraction, manufacturing process, installation procedures, presence of matrix additives or fillers, short- and long-term loading, and exposure to various chemical and environmental conditions. These elements are critical in determining FRP materials' overall performance and durability. However, it's important to note that much of the available durability data has not been validated over long-term durations, such as 50 to 100 years in real field conditions. The reliability of the data on composite properties is influenced by the specific durability test methods used (including the type of exposure, the concentration of salts and alkali, exposure methods), the testing conditions (such as humidity, temperature, specimen type and dimensions, and the rate of testing), variations in the constituents (including resins, fibers, additives, and cure conditions), as well as manufacturing quality assurance and quality control (QA and QC) processes. Additionally, the complexity of the interplay between various environmental loads and the corresponding responses of the composite materials can sometimes lead to conflicting or controversial trends in the results of durability studies [4].

With the considerations mentioned above, there are two primary aspects to examine in the test methods related to FRP materials: one aspect emphasizes the strength of these materials, while the other is concerned with their durability. Figure 4 visually represents these two key areas.

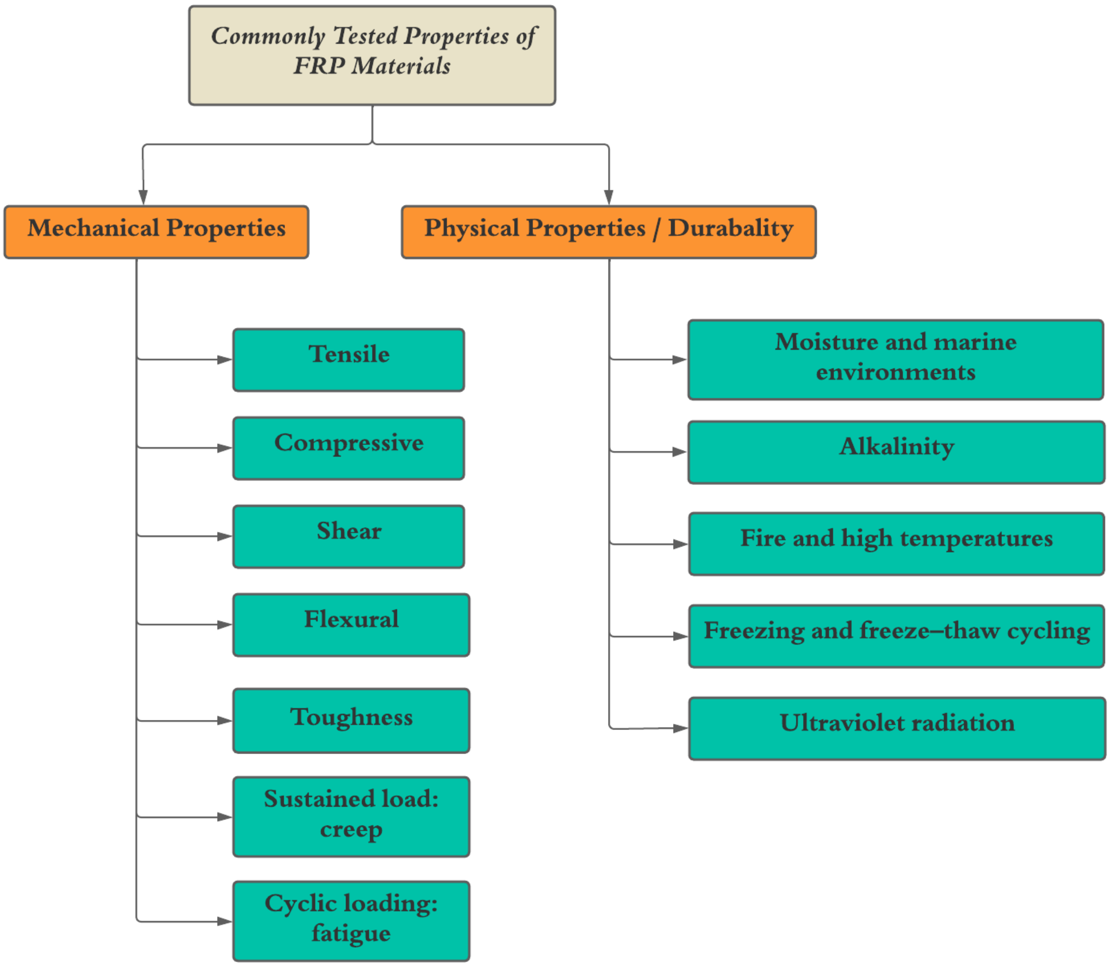

Figure 4. Commonly tested properties of FRP materials.

2.3.1. Density

The density of FRP materials is influenced by factors such as the type of fibers and resin used, void content, and manufacturing process. Voids within composites can significantly reduce density and affect mechanical characteristics, leading to reduced fatigue resistance, increased susceptibility to weathering, and varied strength properties [16]. Pultruded FRP materials generally have lower density than traditional construction materials like steel or concrete, contributing to their lightweight nature. The typical density range for FRP composite falls between 85 and 125 (lb/ft^3), which is equivalent to 1360 to 2002 (kg/m^3). This low density is considered an advantage in various applications. Standards such as ASTM D2734, ASTM D792, and ISO 1183 are commonly used to determine the density of FRP accurately. These standards enable precise calculations and adjustments in the formulation to achieve the desired composite properties, ensuring the quality and performance of the FRP materials.

2.3.2. Tensile Tests

Tensile properties are vital in evaluating composites for design, and their testing becomes more complex with material orthotropy [9]. The fiber type, volume, and orientation significantly influence these properties, including tensile and flexural strength. Tensile elongation at failure usually ranges from 1–2%, with shear elongation dependent on material and bonded interface quality [12]. Specific tensile tests, as described in standards like ASTM D3039 (Figure 5), ASTM D638, and ISO 3268, are employed to determine essential mechanical properties of materials, including Poisson's ratio, tensile modulus, tensile strength, and ultimate strains. When samples are tested with fibers oriented in the longitudinal direction, the primary modes of failure typically involve either fiber fracture or fiber pullout. Conversely, when fibers are tested in the transverse direction, the dominant failure modes typically involve either matrix or fiber-matrix interface failure. These standardized testing procedures and associated failure modes are crucial for assessing and characterizing the mechanical behavior of materials, particularly in understanding how they respond to tensile loads in different orientations [17].

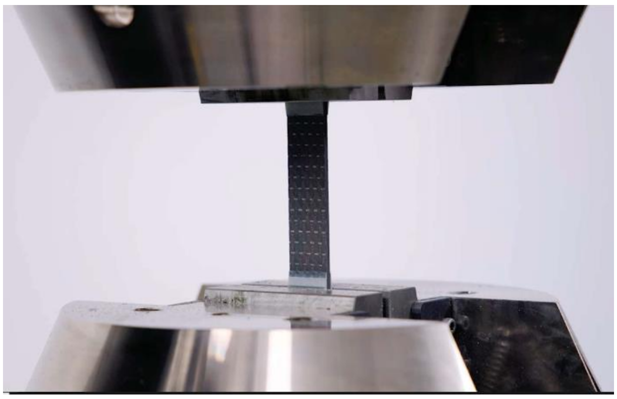

Figure 5. In-Plane Tensile ASTM D3039 (Image courtesy of Instron).

2.3.3. Compressive Tests

To determine compressive properties such as compressive modulus, compressive strength, Poisson's ratio, and ultimate compressive load-displacement, compressive strains tests are conducted following established standards such as ASTM D3410, ASTM D695, ASTM D6641 (Figure 6), ASTM D6484, or ISO 8515. These testing standards provide guidelines for obtaining reliable data on the material's behavior under compressive loads. Additionally, compressive tests can be performed on test specimens that have been previously subjected to impact loads. This helps assess the impact-induced delamination effect on the material's compressive properties, providing valuable insights into its behavior under combined loading conditions [17]. The compressive strength is influenced by the presence of local and global buckling phenomena, which are commonly observed in thin-walled pultruded profiles. These drawbacks are amplified by the orthotropic characteristics of FRP material, which are a consequence of the pultrusion manufacturing process. Another noteworthy factor is that manufacturing imperfections are responsive to the unregulated longitudinal distribution of fibers within the profile shape during production [18].

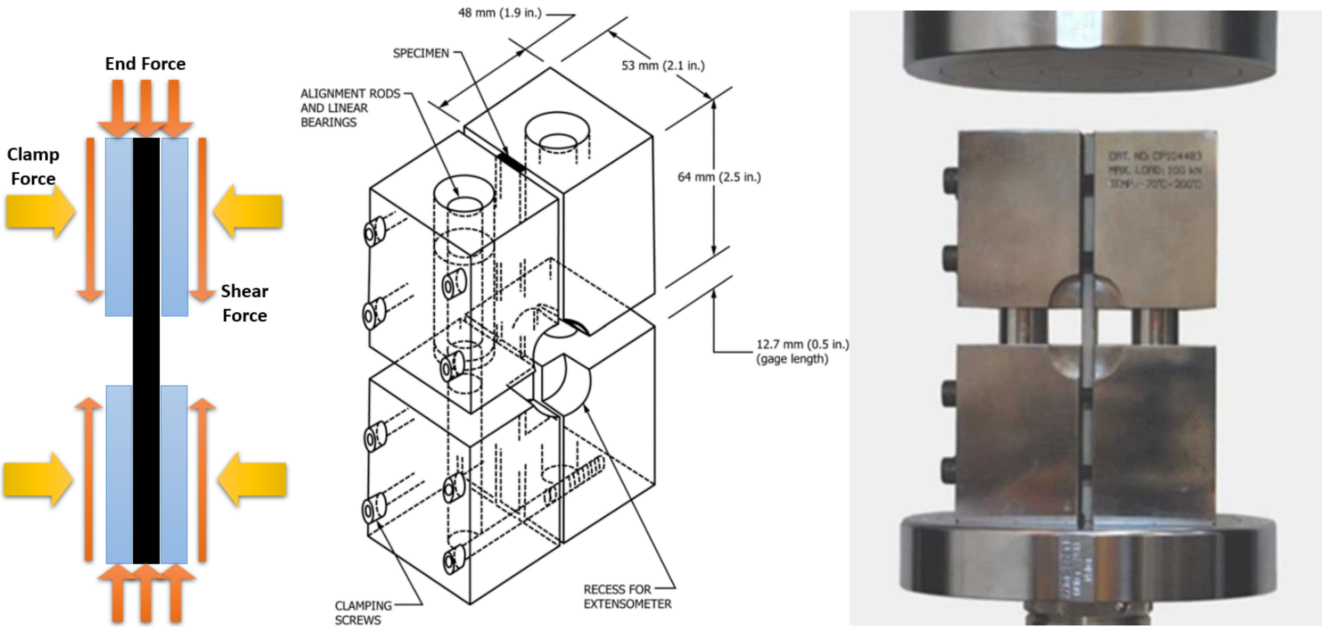

Figure 6. In-plane compression testing using combined loading unsupported gauge section per ASTM D6641 [19] (Right image courtesy of Instron).

Compressive loading in composites can lead to different failure modes, including fiber crushing, micro-buckling, shear splitting, and global buckling. The governing failure modes are determined through experimental evaluations, considering various design factors such as fiber and matrix combination, geometry, and reinforcement layer stacking. These factors can influence the in-plane or edgewise compressive strength, and global or local buckling may affect the composite's compression capacity [12].

2.3.4. Shear Tests

Shear stresses in composites are categorized as in-plane, through-thickness, or interlaminar, and their characterization depends on the chosen test method. In-plane shear properties are influenced by fiber orientation and stacking sequence, while transverse shear strength depends on reinforcement type and volume. Matrix properties and the matrix/fiber interface mainly influence interlaminar shear strength. Shear properties are essential for accurate design evaluations of composite structures [12]. Various tests, including the short-beam shear test (ASTM D2344, ISO 4585), are used to determine shear modulus, strength, and ultimate strains, and ISO 20337 is used for pure shear loading and large shear strains (>5%). The short-beam test is mainly used for quality control, while other tests like the double-notched shear test ASTM D5379, the double-cantilever beam test, and the rail shear test ASTM D4255 provide more specific evaluations of shear strengths [17] (Shown on Figure 7).

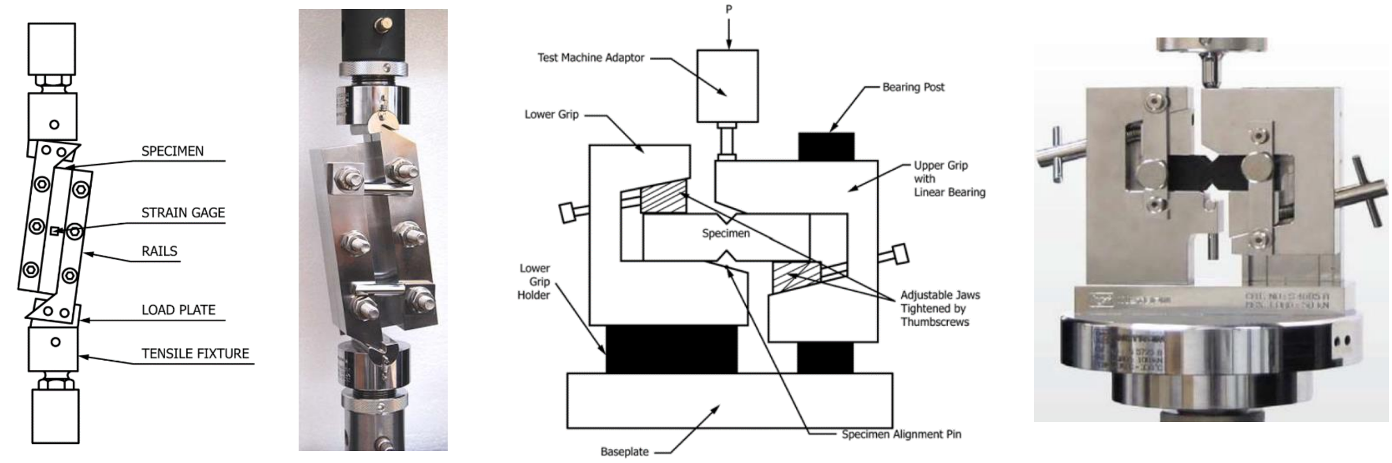

Figure 7. In-Plane Shear testing ASTM D4255 [20] and ASTM D5379 [21] (Image courtesy of Instron).

2.3.5. Flexure Tests

These tests are used to determine the flexural strength and modulus of the composite. The test is similar to the interlaminar shear test, carried out using a three- or four-point fixture ASTM D790 (Figure 8). The support span/thickness ratio in these tests is typically increased to minimize interlaminar shear deformation, ensuring that failure occurs in flexure. Extracting inherent properties from these tests can be challenging since flexural failure results from a combination of tensile and compressive forces. Therefore, they are often employed more as a quality control tool rather than a definitive measure of the material's characteristics [17].

Figure 8. Flexure testing ASTM D790 [22] (Image courtesy of Instron).

2.3.6. Toughness Tests

These tests serve various purposes, including quality control, the estimation of crack propagation, and the delamination characteristics of composite samples subjected to impact loads. The Izod and Charpy pendulum impact tests and the falling dart impact tests are commonly employed methods for evaluating composite materials' impact resistance and behavior. ASTM D256 outlines the procedures for determining the resistance of plastics to impact using the Izod pendulum impact test. The test measures the energy required to break a notched specimen under a single blow from a pendulum. The result is expressed in terms of energy absorbed per unit of thickness.

2.3.7. Fatigue

Fatigue is a critical mechanical-durability property that must be evaluated for FRP composites, particularly in applications where periodic loading and unloading cycles are applied. This can be coupled with environmental fatigue factors such as temperature cycles (hot–cold, freeze–thaw) and chemical cycles (moisture, seasonal road treatments, oxidation, NOx effects). Unlike metals, where crack growth behavior is observed, fatigue in composites is progressive and accumulative, leading to microcracking, delamination, fiber fracture, and fiber/matrix debonding. Composites with higher modulus fibers, such as carbon fibers, generally display greater fatigue resistance, exhibiting slower stiffness and strength degradation under fatigue. ASTM D 4762 outlines test methodologies for evaluating essential attributes like creep, fatigue, and fracture properties in Fiber Reinforced Polymer (FRP) composites, providing valuable insights for structural engineers and contributing to the understanding of these complex materials [17,18,23].

2.3.8. Creep and Relaxation

Over time, the moduli of a pultruded profile will experience a reduction when the profile is consistently subjected to loads. This phenomenon arises due to the viscoelastic nature of fiber-reinforced polymeric materials, causing them to undergo deformation under sustained loads, a behavior known as creep. While reinforced polymers exhibit less creep compared to unreinforced polymers, they can still show increased deflection over time without a proportionate increase in the applied load. Notably, reinforced polymers containing continuous fibers aligned in a specific direction exhibit less creep than those with randomly oriented reinforcement. Similarly, reinforced polymers characterized by higher volume fractions of fibers also display reduced susceptibility to creep [24]. ASTM D2990 and ISO 899 are standards that provide guidelines and procedures for conducting creep and creep-rupture testing on materials, including plastics and polymers. These tests are used to assess the behavior of materials under constant load over an extended period, which is important for understanding their long-term mechanical properties.

Thermoset composites, in comparison to thermoplastic FRP materials, display superior resistance to performance degradation from long-term loads. Creep studies emphasize the significant influence of the matrix material on these properties, with long-term axial-loaded columns and beams showing potential for creep-related strains and deformations, especially at high applied load levels. For safety, engineered FRP parts should be designed with working stresses well below ultimate stress levels. Moreover, some linear high-elongation cores may exhibit creep behavior, particularly in compression, unless density is increased to match the intended use. Furthermore, this creep effect primarily depends on the fiber type used. Creep in polymeric composites arises from a combination of bulk material strain and microflow initiation, influenced by the viscoelastic nature of the polymer. Different fibers have varying susceptibility to creep rupture at different stress levels, with aramid and glass fibers being more prone to creep than carbon fibers. Basalt fibers show better creep behavior than glass or aramid but are slightly lower than carbon. Under-cured composites are particularly vulnerable to creep and microcrack initiation during the early stages of service [25].

2.3.9. Fire Performance

Two standard tests are commonly used to assess the flammability of building products and plastic materials in devices and appliances: ASTM E84 and UL 94. While ASTM E84 evaluates surface burning characteristics, UL 94 determines a material's ability to extinguish or spread flames after ignition. When exposed to elevated temperatures, composite materials with softened resins and adhesives may exhibit an increased viscoelastic response. However, this can lead to reduced mechanical properties and faster moisture diffusion, accelerating polymer damage. Although some elevated temperature effects can be beneficial, such as the post-curing of resins, combining high temperatures and moisture immersion can negate the benefits, causing rapid deterioration. Moreover, when exposed to temperatures above 100 °C, the matrix of the composite softens, leading to distortion, buckling, and potential failure of load-bearing elements. At even higher temperatures (250–400 °C), close to the matrix's pyrolysis temperature, ignition of the composite becomes possible [17]. In fire-exposed conditions, the compressive properties of FRP materials displayed greater susceptibility to degradation in comparison to their corresponding tensile properties [26,27].

2.3.10. Moisture Properties

Moisture, particularly in the form of water, has the potential to cause harm to the fibers, the matrix, and the interface between fibers and the matrix. The resin matrix, a key component, absorbs water primarily from the surrounding environment. Water infiltration into the resin matrix occurs via diffusion and capillary action [28]. Subsequently, the absorbed water can lead to the expansion of the matrix and the spread of small cracks, consequently influencing the microstructure of the resin matrix [29]. According to research, inorganic fibers, such as carbon or glass fibers, do not absorb water. Nonetheless, surface microcracks can develop on these fibers, which may eventually lead to the breaking of the fibers. Conversely, organic fibers have a tendency to absorb water, resulting in more significant swelling and subsequent rupture [30,31]. Generally, the maximum moisture absorptions are limited to 1–2% for pultruded elementso ensure proper durability [32]. Different examinations, such as the assessment of water absorption as per ASTM standards D570 and D5229, are employed to ascertain the moisture characteristics of FRP materials.

2.3.11. Acid/Alkaline Exposure

FRP composites are widely used in applications that span the entire pH scale, from highly acidic to highly alkaline environments. To assess their performance under such conditions, tests are conducted using composites exposed to solutions with varying pH levels, even as high as 13.5 [33]. The impact of acidity or alkalinity on FRP composites depends on the specific matrix and fibers utilized. However, it's important to note that alkaline and acidic solutions could have distinct effects on the degradation process. Research indicates that alkaline solutions tend to exert a more severe influence on FRP materials' mechanical characteristics than acidic solutions [34]. Moreover, the detrimental impact caused by alkaline solutions becomes more pronounced as the alkalinity level increases. On the contrary, the effects of acidic solutions on FRP materials exhibit an unusual pattern [35].

Dry glass fibers are particularly vulnerable to alkaline attack, resulting in significant levels of irreversible damage. This damage is characterized by substantial fiber surface degradation and pitting. Additionally, exposure to alkaline environments can lead to leaching, where alkali ions diffuse out of the glass structure, essentially dissolving the fiber. This deterioration of glass fibers in alkaline environments poses a concern for FRP composites' durability and long-term performance. Both acidic and alkaline solutions can cause degradation of the resin and the interphase region in the composite. Therefore, it is essential to ensure that the formulation used in FRP composites is carefully chosen and validated to meet the specific durability requirements of the intended application [36]. ASTM D543 is a standard practice that provides guidelines for evaluating the resistance of plastics to various chemical reagents. This practice is used to assess how different chemicals may affect the physical and chemical properties of plastic materials. Other standards such as the ASTM D7705 for alkaline testing of FRP rebars also exist. By selecting appropriate materials and formulations, engineers and designers can enhance the resistance of FRP composites to the potentially damaging effects of acidic or alkaline environments, ensuring their suitability for a wide range of practical applications.

2.3.12. UV Radiation Exposure

Exposure to natural sunlight exposes FRP composites to ultraviolet (UV) radiation, which can affect polymeric materials. However, the UV degradation mainly occurs at the surface of the composite to a depth of about ten micrometers. The UV-induced cross-linking may alter the surface's aesthetic appearance but typically does not cause significant damage to the material [37]. In FRP composites, UV attack primarily impacts the surface layer and is confined to the surface veil material. Consequently, this effect is largely cosmetic and generally does not significantly impact the composite's structural performance, a characteristic commonly observed in the marine industry. In the initial stages of UV exposure, you may notice color changes, yellowing, and alterations in gloss, but these changes are typically aesthetic and do not compromise the composite's structural integrity [12]. Prolonged UV exposure can erode resin, expose fibers, allow moisture penetration, and induce matrix cracking, ultimately reducing the thermomechanical properties of composites. Carbon fibers are less susceptible to UV damage than glass or aramid fibers, and thin composites are more affected in strength and stiffness reduction than thick composites. ASTM D4329 and ISO 16474 are standards that provide guidance and procedures for conducting UV radiation exposure testing on materials, including plastics and composites.

To protect against UV radiation, FRP composites are formulated with UV-resistant resins or are coated with a gel coat or other protective layer that acts as a sacrificial barrier, shielding the FRP composite from direct UV exposure. However, these protective coatings require routine maintenance as they are not immune to UV radiation degradation [33].

A list of the main test methods used to characterize FRP pultruded materials is included in Table 3, categorized per physio-mechanical property. Also, as a reference, Table 4 includes the minimum criteria for the characteristic mechanical properties of pultruded FRP composite structural members as per the pre-standard ASCE-74 [38]. It's important to note that these properties listed in Table 4 tend to be conservative and often fall below the actual strength and stiffness values observed in experiments for various structural FRP profiles and plates.

Table 3. Tests to determine physio-mechanical properties of FRP components.

Mechanical Properties	*Method*	Lap Shear Strength	ASTM D3164
Density	ASTM D2734	Bearing Load	ASTM D1602
	ASTM D792	Short Beam Strength	ASTM D2344
	ISO 1183	Izod Impact	ASTM D256
Compressive Strength and Modulus	ASTM D695	Charpy Impact	ASTM D256
	ASTM D6641	Flexural Strength and Modulus	ASTM D790
	ASTM D3410		ASTM D6272
	ASTM C365	Bearing Strength	ASTM D953
	ISO 8515		ASTM D5961
	ISO 844	*Fire*	*Method*
Tensile Strength	ASTM D638	Surface Burning Characteristics	ASTM E84
	ASTM D3039		ASTM D162
	ASTM D5083	Oxygen Index	ASTM D2863
	ASTM C297	NBS Smoke Test	ASTM E662
	DIN 53455	Multi-Story Building Test	NFPA 285
	ISO 3268	Room Corner Test	NFPA 286
Tensile Modulus	ASTM D638	Ignitability by Radiant Panel	NFPA 268
	ASTM D3039	Potential Heat of Building Materials	NFPA 259
	ASTM C297	Cone Calorimeter	ASTM E1354
	DIN 53457	*Surface Testing*	*Method*

	ASTM D638	Gravelometer	SAE J-400
% Elongation	ASTM D3039	Gardener Gloss Meter	GARDNER
	ISO 1922	Stain Resistance	ANSI Z124
	ASTM C393	Bracol Hardness	ASTM D2583
Flexural Strength and Stiffness	ASTM D7249	***Physical Properties***	***Method***
	ASTM D7250	Specific Gravity	ASTM D792
	ASTM D3518	Water Absorption	ASTM D570
	ASTM D3846	Moisture Absorption	ASTM D5229
	ASTM D3914	Glass Transition	ASTM D7028
	ASTM D5379	CTE	ASTM E289
In-Plane Shear Strength and Modulus	ASTM D4255	Heat Distortion	ASTM D648
	ASTM D2344	***Material Properties***	***Method***
	ASTM D7078	Brookfield Viscosity	ASTM D2196
	ASTM C273	Ignition Loss of Cured Reinforced Resins	ASTM D2584
	ASTM C393	Gel Time	ASTM D2471
	ISO 4585	Glass Fiber Strands	ASTM D578
	ISO 1922	Punch Shear Test	ASTM D732
Creep and Relaxation	ASTM D2990	Chemical Reagents	ASTM D543
	ISO 899	Alkaline Resistance of FRP rebars	ASTM 7705

Table 4. Minimum required mechanical properties for FRP composite per ASCE-74.

Mechanical Property	*ASTM Test Method*	*Minimum Requirement (psi)*	
		Profiles	***Plates***
Longitudinal tensile strength	D638	30,000	20,000
Transverse tensile strength	D638	7000	7000
Longitudinal tensile modulus	D638	3,000,000	1,800,000
Transverse tensile modulus	D638	800,000	700,000
Longitudinal compressive strength	D6641	30,000	24,000
Longitudinal compressive modulus	D6641	3,000,000	-
Transverse compressive modulus	D6641	1,000,000	15,500
In-plane shear strength	D5379	8000	6000
In-plane shear modulus	D5379	400,000	400,000
Interlaminar shear strength	D2344	3500	3500
Longitudinal pin-bearing strength	D953	21,000	21,000
Transverse pin-bearing strength	D953	18,000	13,000

All things considered, the testing methods for FRP pultruded components highlight the intricate relationship between material design, behavior, and their implications in structural engineering. Although coupon tests provide initial insights, the complexity of fiber orientation and composite construction often necessitates full-section assessments, presenting challenges in the precise determination of the mechanical properties of FRP pultruded materials. The significant safety factors currently in use, which result in increased construction costs, emphasize an urgent need for refined knowledge and enhanced quality assurance practices in the field. Durability remains a critical aspect and is influenced by various factors. However, much of the durability data has yet to be validated over long-term durations in actual field conditions.

2.4. Non-Destructive Testing

Non-destructive testing (NDT) methods are integral to the evaluation of FRP composites, particularly when traditional testing is inadequate for detecting potential defects.

This section explores the most frequently used NDT techniques, highlighting their significance in the condition assessment of FRP structures, quality assurance, health-monitoring, and in-service inspections. The application of NDT in civil structures is an expanding field; Table 5 summarizes available NDT methods and their primary applications for detecting various deterioration or damage in FRP composites. It's important to note that no single NDT method is suitable for all failure modes, and multiple methods may be required for a thorough assessment. These technologies mainly identify local defects without determining strength or durability, but they are crucial for enhancing construction quality and aiding in repairing and renovating aging composite structures. The ongoing advancement of NDT technologies promises to further refine the understanding and utilization of FRP composites in civil infrastructure.

Table 5. Summary of NDE technologies and their typical applications [17].

Technique	Moisture Absorption	UV Damage	Fibrillation Unraveling and Broken Fibers	Fiber Breakage	Loss of Mechanical Properties	Debonding Between Composite Layers	Bond Strength
Visual inspection	✓	✓	✓				
Sounding testing						✓	
Ultrasonic testing			✓		✓	✓	
Vibrational testing			✓		✓	✓	✓
Infrared Thermography						✓	
Acoustic emission			✓		✓	✓	
Acoustic-ultrasonic			✓	✓	✓	✓	

2.4.1. Visual Inspection Testing

Visual Inspection is a fundamental Non-Destructive Testing (NDT) technique utilized for assessing damage in materials, including FRP pultruded structures [8]. It offers quick, cost-effective, and flexible examination but is restricted to surface evaluation and cannot detect subsurface damage. Despite its simplicity and low cost, it requires standardized training to identify and document specific deterioration modes like unraveling and UV damage. Sounding may be employed to enhance inspection, and certified inspectors are often needed for thorough assessments. While offering several benefits, visual inspection also has limitations such as subjective interpretation and unsuitability for certain environments [39].

2.4.2. Sounding Testing

The mechanical sounding method is a straightforward technique used to detect delamination and deboned areas in composite materials. It involves tapping the surface of the composite with a metal or plastic hammer-like object and listening to the resulting sound. Delaminated regions are often identifiable by their distinct hollow tone. This method has been widely adopted in aerospace structures, where a quarter is commonly used, earning it the "coin-tap test". For deeper defects, a larger mass is employed to ensure the tapping excites the material's depth. Although the use of hammers allows the detection of features further from the surface, near-surface issues like delamination between layers of FRP composite may not be as easily identifiable using this method [40].

2.4.3. Ultrasonic Testing

The ultrasonic Testing technique is a prominent method for inspecting the internal structure of FRP composite materials, utilizing high-frequency sound waves transmitted through a transducer [41]. These waves travel through the material until they encounter a boundary, reflecting predictably. Thickness measurements are made by calculating the round-trip transit time of the sound pulse, while flaw detection involves analyzing echoes and comparing patterns. Variations in the echo pattern can reveal internal structural changes, such as voids or cracks. The inhomogeneous nature of composites may cause scatter noise reflections, but trained operators can recognize strong localized indications from cracks [42]. This technology offers valuable insights for both pre-delivery inspection and routine assessment of FRP structures, contributing to quality assurance in composite materials. However, one limitation of ultrasonic thermography is that it is primarily employed for the localized detection of defects and small cracks, making them unsuitable for rapid overall assessment or global evaluation of the entire structure [43–45].

2.4.4. Vibrational (Modal) Testing

Vibrational testing is a method to detect defects in FRP composite materials by analyzing their natural frequency and modal characteristics. While other frequently used local methods like ultrasonic testing tend to be time-consuming when applied to large components, vibrational-based techniques offer a solution to this limitation by adopting a more comprehensive approach. For vibrational testing, [20] the composite part is subjected to excitation using an impact hammer or automated shaker, and accelerations are recorded and converted into mode shapes and a natural frequency spectrum. By comparing these with defect-free reference data, defects can be identified through qualitative analysis of the vibrational characteristics [18]. Well-placed accelerometers record information over the entire surface and both reference and actual vibrational characteristics are processed by automated NDT algorithms, allowing precise localization and quantification of defects [17,46]. Vibration approaches are especially well-suited for slender one-dimensional structures with minor cracks or imperfections. Among these approaches, methods based on natural frequencies are frequently employed to detect and pinpoint damage [47,48].

2.4.5. Infrared Thermographic Testing

This inspection method utilizes thermal diffusion to detect defects in FRP pultruded composites. The composite is subjected to surface heat using a high-intensity flash heat impulse or gradual heating. Different materials' heat diffusion rates vary based on density, and defects like air voids or uncured resin create hot or cold spots. A thermographic camera records these thermal gradients, identifying defects as variations in the thermal pattern. Image processing software pinpoints the defect's location and severity. Though the resolution may be lower than other inspection methods, the portability and ease of use make it valuable for quality control in FRP composite production. [17].

2.4.6. Acoustic Emission Testing

Acoustic emission techniques are employed to monitor debonding in FRP-strengthened structures under service loads. These techniques detect high-energy stress waves emitted during fracture, such as debonding or fiber fractures within the matrix. Piezoelectric sensors, attached at various locations, detect these emissions, and the location of active debonding can be determined through suitable equipment. This method is being developed for on-site use, transitioning from a laboratory tool [42]. While it can detect defects in FRP composites by analyzing sound propagation during mechanical or thermal stress, quantifying the location and severity of defects, especially in a factory setting, remains a challenge.

2.4.7. Acoustic-Ultrasonic Testing

This NDT test integrates acoustic and ultrasonic testing to evaluate internal inconsistencies and imperfections in FRP composites. It facilitates the identification and assessment of non-critical defects and the indication of cumulative damage resulting from fatigue loading or impact. However, this method has its drawbacks, including the necessity for setup and pre-calculations before testing. Moreover, it is not well-suited for detecting significant individual flaws such as delamination or voids [8].

Overall, NDT methods present a comprehensive toolkit for assessing the health and quality of FRP composites, especially as they become more integral to civil infrastructure. Each method offers its unique strengths and potential limitations, emphasizing the need for a multi-pronged approach for thorough evaluations. While visual inspection provides a basic surface overview, deeper insights are obtained through technologies like ultrasonic and infrared thermography. As the field of NDT for FRP structures continues to evolve, it remains essential for practitioners to stay updated on these advancements. This will ensure that the application of these technologies is optimized, meeting the demands of quality assurance, in-service assessments, and overall safety of FRP-reinforced structures.

3. Specifications for FRP Pultruded Materials

Material specifications for FRP pultruded elements are integral to the quality and performance of these materials in various applications. These specifications define the essential characteristics and standards that the FRP pultruded materials must meet, including properties such as tensile strength, stiffness, thermal resistance, and chemical compatibility. By defining the criteria for raw materials, manufacturing processes, testing methods, and quality assurance, material specifications ensure that the FRP pultruded elements are consistent, reliable, and fit for their intended purpose. They also facilitate communication and understanding among suppliers, manufacturers, engineers, and regulators, providing a common language and reference point. This section delves into the existing material specifications for FRP pultruded elements defining their role in guiding the production, evaluation, and utilization of these advanced composite materials in the construction industry and beyond.

3.1. Specifications for the Raw Materials

These specifications detail the tests for various physio-mechanical, chemical, and other properties of raw materials utilized in the manufacturing of pultruded FRP components. Their role is three-fold: (i) manufacturers may use these specifications to establish supplier requirements, (ii) design guides may reference them to define specific materials for relevant applications, or (iii) they may be incorporated within other component-based specifications.

Among the specifications for fibers, two of the most common are ASTM D578, "Specification for Glass Fiber Strands," which sets requirements for glass fiber in FRP products, and ASTM D8448, "Specification for Basalt Fiber Strands," outlining requirements for basalt fiber. Resin manufacturers often develop resin-based specifications due to the wide range of performance requirements that can be obtained from different resin formulations. Standard examples include ISO 3673–1, "Plastics—Epoxy Resins—Part 1", ASTM D1763, "Standard Specification for Epoxy Resins", ASTM D1755, "Standard Specification for Poly(Vinyl Chloride) Resins" and ASTM D4690, "Standard Specification for Urea-Formaldehyde Resin Adhesives".

3.2. Specifications for FRP Components

Though relatively limited in scope, these specifications establish the minimum requirements for specific FRP pultruded components. They often reference testing and particular performance-based criteria for a given FRP component in a specific application or define a particular parameter for FRP components. Notable examples include ASTM

F3059, "Standard Specification for Fiber-Reinforced Polymer (FRP) Gratings Used in Marine Construction and Shipbuilding", ASTM D3917, "Standard Specification for Dimensional Tolerance of Thermosetting Glass-Reinforced Plastic Pultruded Shapes" and ASTM D8505, "Standard Specification for Basalt and Glass Fiber Reinforced Polymer (FRP) Bars for Concrete Reinforcement".

The primary objective of these specifications is to ensure a certain quality level for acceptance in a specific FRP application, effectively setting the acceptance criteria for the use of the FRP component. These specifications may encompass various types of requirements, extending beyond physical, mechanical, and durability considerations to include application-specific needs.

3.3. Construction/Project Specifications

Since FRP pultruded components are a relatively new material solution in the built infrastructure, limited development exists of well-established standard specifications that cover the diverse and varied applications and needs of the construction industry. To address this gap, project and construction specifications are often developed by various stakeholders (such as owners, developers, architects, engineers, contractors, etc.) to define the requirements for a specific project. Where possible, these specifications will include other specifications, but they typically reference test standards, such as ASTM D8019, "Standard Test Methods for Determining the Full Section Flexural Modulus and Bending Strength of Fiber Reinforced Polymer Crossarms Assembled with Center Mount Brackets," and other project and construction specifications. Manufacturers of FRP often contribute to the formulation of these specifications, ensuring alignment with current solutions and performance requirements. Early engagement with knowledgeable manufacturers or experts is crucial for crafting logical and applicable specifications for a particular project.

As stated in Section 2, several full-scale FRP component test methods, but these only provide the method to test, not the performance requirements. A project or construction specification will reference such test methods and include the applicable performance requirements for that specific project. It's not uncommon to see specifications that reference generic or non-FRP specific test methods, such as ASTM D1036, "Standard Test Methods of Static Tests of Wood Poles", which, though a test method for wood piles, is generally used in project specifications for FRP utility poles.

3.4. Specification Gaps for FRP Pultruded Elements

In the fast-expanding FRP pultruded materials industry, several critical specifications gaps are hindering optimal growth and application. The absence of specific performance requirements for different FRP applications often leads to ambiguity in material selection and underutilization of FRP's benefits. There is also a lack of specifications that cover critical aspects for the durability and long-term safety of structures built with FRP pultruded sections, such as, UV radiation resistance, environmental durability, or fire reaction. Furthermore, the absence of unified standards across all these aspects such as physical/mechanical properties, durability, and fire reaction creates challenges in ensuring consistent quality. Addressing these gaps by developing comprehensive and unified standards is vital for the industry's continued growth, ensuring safety, quality, and fostering innovation in the use of FRP pultruded materials in construction and other fields.

4. Quality Control and Quality Assurance of FRP Pultruded Elements

Manufacturing FRP pultruded composites requires meticulous attention to mechanical characteristics, surface appearance, production process, equipment quality, and inspection methods. Quality control and quality assurance (QC/QA) are integral to this process, ensuring consistent, high-quality components. QC/QA is implemented in three main steps [17,49]. The first step involves validating critical design, geometric, material, and manufacturing parameters, comparing them with the manufacturing plant's constraints, and optimizing design and manufacturing methodology. The second step focuses on verifying tooling and mold dimensional tolerances, equipment calibrations, assembly stability, and fabrication processes, including specific tests for vibroacoustic, aerodynamics, mechanical, and thermal loading conditions. The third step emphasizes quality control of the manufactured component through inspections and destructive/nondestructive testing. This includes validating and characterizing constituent materials, monitoring the curing process, and validating the physical and mechanical properties of the finished composite. Techniques such as visual inspection, mechanical testing, numerical simulation, and nondestructive evaluation are employed to detect defects, verify design dimensions, and ensure that the part consistently meets design specifications. Adhering to these quality control measures is essential for obtaining ISO 9000 certification and plays a vital role in the growing industry of FRP pultruded composites, ensuring that the products are reliable, safe, and meet the required performance standards [17,49]. Finally, it is worth mentioning that QC is mainly the inspection component of quality management; quality assurance is more concerned with how a process is carried out or how a product is manufactured. In other words, QC is the operational methods and actions implemented to satisfy quality requirements (See Figure 9).

Figure 9. Venn diagram showing the overlaps of quality assurance and quality control [49].

Quality control and quality assurance (QC/QA) for FRP pultruded components can be established following recognized quality control schemes and documented through a certificate of conformity. This certification may encompass essential properties mandated by a specific standard (e.g., EN 13706–2,3 [50]) as well as additional properties agreed upon with the customer. In this stage, QC/QA should, at a minimum, address the following aspects: visual defects, dimensional tolerances, and mechanical properties relevant to the application. The visual inspection for defects such as blister, crack, delamination, and more, are defined in EN 13706–2 and ASTM D4385. These standards also detail acceptance levels and inspection requirements for different product grades. Dimensional tolerances for parameters like wall thickness, profile height, and twist are specified in standards like ASTM D3917 and EN 13706–2 [50]. In terms of cross-section geometry, EN 13706–2 [50] and ASTM D3917 specify dimensional tolerances for various parameters, ensuring consistency in wall thickness, flatness, profile height, flange width, angle size, straightness, and twist. Mechanical characterization tests may also be conducted in the laboratory facilities of pultrusion companies. EN 13706–3 defines two grades of FRP pultruded profiles, with minimum material property values and corresponding test methods. For certain applications, especially in industries like petroleum and natural gas, stricter requirements may be imposed, including considerations related to fire reaction and fire resistance behavior (e.g., NBR 15708–1 [51]). These measures collectively guarantee consistent quality and performance of pultruded products.

5. Maintenance/Health Monitoring

As for any new structure, a proper maintenance/health monitoring process is essential for the durability and safety of the structure. Ideally, appropriate maintenance strategies should be in place to reduce repairs. However, when the structure suffers damage during its lifespan, it is imperative to explore potential repair strategies and to establish evaluation and diagnostic tools to facilitate informed decisions regarding repair approaches. Nonetheless, the existing knowledge concerning the maintenance and inspection of these systems is quite limited.

Maintenance/health monitoring inspection processes can be categorized into three distinct groups:

1. Construction inspection, which occurs both during and promptly after the construction process.
2. Routine inspection carried out throughout the operational lifespan of the structure.
3. Post-incident inspection, applicable in situations such as after an earthquake or an impact accident.

Each of the previously mentioned inspection types necessitates a unique approach. Inspections can take the form of visual assessments or be enhanced with the use of specialized instruments. Visual inspections frequently center around identifying discoloration or cracks on the surface of the FRP, but they may not offer insights into the overall integrity of the pultruded materials.

Two distinct Non-Destructive Evaluation (NDE) types can be conceptualized: continuous health monitoring and frequent/regular monitoring. Continuous health monitoring is commonly conducted by using surface-mounted gauges. These gauges must be strategically positioned at critical points to monitor axial and transverse strains in pultruded FRP elements. Different types of gauges are frequently used: electrical resistance-type gauges, fiber optic sensors, or vibrating wire gauges. Among these options, electrical resistance-type gauges are the most economical. However, they are prone to drift from the reference point over time. Hence, a more suitable choice would be either vibrating wire gauges or fiber optic sensors. Vibrating wire gauges are frequently characterized by their bulkiness. In contrast, fiber optic sensors are better suited for FRP fabrication and can potentially be seamlessly integrated into the manufacturing process of the FRP form. Moreover, the monitoring process could be automated, allowing for early alerts if any of the strain measurements surpass their pre-defined threshold values [52].

Frequent/regular monitoring, however, involves the presence of a qualified inspector who assesses the structure at a determined frequency. Most of the health monitoring tests are non-destructive (NDT). Depending on the purpose of the inspection, different NDTs are applied. Although multiple NDT test exists as detailed in Section 2.4, visual inspection is the most commonly used NDT for FRP pultruded profiles; if, after visually inspecting, a specific damage is detected, additional NDT techniques will be used to further assess the damage. Also, if needed, non-destructive testing of sample coupons taken from the structure is conducted.

Many techniques exist for detection and localization of damages in pultruded members. For example, Boscato et al., (2021) proposed TGP (Tree-structured Gaussian Process) approach with a particular focus on thin-walled pultruded members that exhibit orthotropic behavior along the fibers and isotropy in the cross-section [45]. The method uses numerical and experimental data to identify and assess the impact of damage on the performance of Glass Fiber Reinforced Polymer (GFRP) members. TGP combines Gaussian Process (GP) regression with Bayesian CARTs (Classification and Regression Trees) to detect discontinuities in mode shapes, particularly incongruences between numerical and experimental data for damaged structures. The approach was initially tested on numerically simulated cases with well-defined slots and later applied to experimental data from a pultruded GFRP beam with increasing damage levels.

6. Conclusions

FRP composites have gained increasing attention as a viable alternative to traditional construction materials like concrete, steel, and timber, particularly in environments prone to corrosion. However, the unique characteristics of FRP materials require meticulous evaluation for effective and safe application. This paper is a comprehensive guide, reviewing destructive and non-destructive test methods, specifications, quality control measures, and health monitoring protocols for FRP pultruded materials.

Despite the advancements in the field, several critical gaps in existing specifications continue to hinder the optimal growth and application of FRP pultruded materials. One of the main issues is the lack of specific performance requirements tailored to the diverse range of FRP applications. This gap often leads to ambiguity during the material selection process, resulting in suboptimal choices that fail to leverage the full potential of FRP materials. Additionally, the industry faces a significant shortfall in guidelines that address long-term durability and safety factors. For instance, limited standards specifically cover UV radiation resistance, environmental durability, and fire reaction, which are crucial for the longevity and safety of FRP-based structures.

The absence of unified standards across different aspects—from physical and mechanical properties to durability and fire safety—adds another layer of complexity to ensuring consistent quality. This fragmentation in standards creates challenges for engineers, material suppliers, and regulatory bodies alike, making it difficult to achieve a consensus on quality benchmarks. It is imperative to develop comprehensive and unified standards to propel the industry forward and maximize the benefits of FRP pultruded materials. Such an initiative would require a collaborative effort involving industry stakeholders, academic researchers, and regulatory agencies. Addressing these gaps will not only ensure the safety and quality of FRP-based structures but also foster innovation by providing a stable framework for developing and applying these materials across construction and other industries.

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