THE USE OF PULTRUDED GLASS FIBER REINFORCED POLYMER PROFILES IN STRUCTURES

by

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Abstract

Pultruded fiber reinforced polymer (FRP) shapes are gaining popularity in the construction industry. Pultruded FRP profiles introduce a new world of construction that could prove to be a viable option to traditional structural materials. The use of pultruded FRP profiles in structures is discussed in this report. First a brief history of FRPs and their applications are addressed before explaining in detail the two main components of FRP; fibers and resin. The manufacturing process known as pultrusion and how two separate materials become one structural member is examined. As a result of pultrusion, engineers and designers can create structural profiles in customizable shapes, sizes, and strengths to suit any project and price. Theoretically, a pultruded FRP profile can be customized to different strengths within the geometrical and material bounds of the profile; however, many manufacturers publish data regarding mechanical and thermal properties along with allowable loads for their nominal profiles. Currently, there are no governing codes or guidelines for pultruded FRPs but there are design manuals and handbooks published by various committees and manufacturers so the design of pultruded FRP profiles is discussed. Ultimate and serviceability limit states are design concerns that engineers always deal with but concerns of heat or fire, chemical or corrosion, and moisture affect pultruded FRPs differently than steel or wood. Pultruded FRPs pose interesting design concerns because increased customizability and workability means the member can be tailored to meet the needs for that project but that would counter the benefit of mass-produced nominal sizes. A lack of uniform codes and standards inhibits the growth of the pultrusion industry in the United States but codes developed in Europe along with the development of specialized agencies and organizations could help gain a foothold. Lastly, a set of beams varying in length and load exhibit a side-by-side comparison to examine how pultruded FRPs match up next to traditional building materials. Although wood, steel, and reinforced concrete have been the preferred materials of construction, pultruded FRP structural shapes are gaining popularity for its economical and physical advantages, and advances in manufacturing and technology stand to usher in the widespread use of pultruded FRP profiles.

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Dedication

I'd like to dedicate this paper to my loving parents, Bamdad and Hilda, whose guidance and support have undoubtedly helped me accomplish my goals. The amount of gratitude I owe to them is incalculable.

CHAPTER 1 - Introduction

Many different materials are used to create structures. Traditional materials like wood, steel, concrete, and masonry have been the preferred materials for many years because their strengths, weaknesses, and behaviors under stress are all well understood. The primary concern in designing a structure is the safety of the structure's occupants. With this in mind, engineers must fully understand the materials used in a structure with regards to how it reacts under loading and whether it is capable of resisting the forces during the life-span of the structure. All the traditional materials mentioned above have withstood the test of time and proven themselves to be reliable and efficient, but not without some trial and error. Only after research, analysis, and testing of any new structural material can it be regarded safe to use for the public.

The ongoing search for more efficient and economical materials for construction has led to the application of reinforced plastics used in structures. As intriguing as it may be to have an entirely synthetic material become commonplace in construction, plastics must undergo the same rigorous gauntlet of testing and analysis before becoming a viable option.

Plastics

In 2007, the plastics industry was the third largest manufacturing industry in the United States. (Society of the Plastics Industry, 2009) The term plastics can cover a wide range of materials. All plastics have common characteristics that classify them as a single group of materials:

1.) They soften and can be formed into desired solid shapes with or without the use of heat or pressure. This behavior is known as a plastic behavior.
2.) Their molecular structure is made of polymers. A polymer is a repetitive chain of molecules, called monomers, which are bonded together.
3.) They are synthetic materials. This means they are man-made and do not occur in nature.

Plastics are used in almost every industry and market sector. The past 100 years of research, experimentation, and analysis, has enhanced plastics to better suit any application. As more time is spent studying and altering plastics it will become more economically feasible to incorporate them in the construction industry.

From formwork used during construction to baseboards and moldings for aesthetic purposes; plastics play an expansive role in structures. The versatility of plastic provides a unique material suitable for almost every application. This paper will focus on the plastics used for structural purposes; namely pultruded fiber reinforced polymers profiles.

Current Applications of Fiber Reinforced Polymers

In the recent decades, fiber reinforced polymers (FRP) have gained popularity in structural applications for their many advantages over traditional construction materials. The aerospace and automotive industries have taken advantage of FRP's high strength to weight ratio by designing entire chassis, fuselages, and wing structures using FRP. Advancements in the technology and capabilities of manufacturing have increased the availability and feasibility of FRP components that are better geared toward serving a specific purpose in a structure's design. FRP's have been used as strips and wraps to strengthen pre-existing structures, and reinforcing bars used to replace steel as the reinforcement in concrete or masonry. Similarly, the building construction industry has utilized FRP's advantages and identified a need for FRPs to be used in structures.

Nonstructural elements, such as electrical cable trays, pipe supports, and cladding/facades, are commonly made of FRP because of they can be easily customized to accommodate any shape or size economically. FRP structural shapes are typically used in structures that would be problematic for other construction materials. Extremely corrosive environments such as marine/off-shore structures, water treatment facilities, power generation cooling structures, and petro-chemical facilities require careful design and constant maintenance to ensure a long and profitable life-span of the structure. FRP structures are highly resistive to chemical corrosion in acidic environments whereas steel is susceptible to corrosion and wood lacks the strength and resistance necessary for these structures. Electrical and communication towers utilize FRP's electrical non-conductivity and impede in radio transmissions less than a steel structure would. Structures such as walkways, pedestrian bridges, and platforms benefit from FRP's low thermal conductivity as compared to steel's and the resistance to decay, rot, and insects unlike wood's. The market for FRP structures is constantly growing as engineers, designers, and manufacturers become more comfortable with FRPs.

CHAPTER 2 - Background of FRP

The concept of composite materials can date back to ancient times when straw and twigs were used to reinforce clay bricks. Separately, clay bricks and small limbs from plants used as building materials have advantages and disadvantages. However, early humans learned that combining the two materials creates a composite material that out-performs each separate material. Steel reinforced concrete is one of the more successful and widely used composite structural materials. More recently, the composite material industry has focused on composites that are comprised of a polymeric resin and a fibrous reinforcement. In the early- to mid-1900s, chemists and researchers began developing polymers that could be used in laminates for semi-structural applications, such as the marine and aviation industries. These polymeric resins were often layered with paper or cloth to create structural laminates used in these various applications. Since then many types of resins with different chemical, thermal, and mechanical properties have been created. In 1930, glass-fiber research was initiated by the Owens-Illinois and Corning Glass Works (later becoming Owens-Corning Fiberglass Corporation) after a molten glass rod being used to apply lettering on a glass milk bottle created a fine glass fiber, and 9 years later, the Owens-Corning Fiberglass Corporation commercialized fiberglass to be used as insulation. (Lubin, 1982) It wasn't until the 1940s and World War II that fiberglass and polymeric resins would be combined.

Figure 2-1 WWII Aircraft FRP Radome

The need for electromagnetically transparent radomes (domes that protected radar antennae) sparked the combining of glass fibers and polymeric resin in the 1940s. The FRP manufacturing industry gained significant notoriety during World War II when the government issued contracts to fabricate semi-structural components for aircrafts made from resin and cotton fibers. (Lubin, 1982) By the end of the war FRPs were successfully used in structural applications in aircrafts, automobiles, and boats. In the 1950s, the Corvette sports car featured a fiberglass reinforced body that boasted lightweight agility coupled with structural stability and strength. (Lubin, 1982) FRPs are now used in everyday household items such as bathtubs, furniture, ladders, and tools. Prosthetics and other medical equipment also utilize FRP's high strength to weight ratio. FRPs are also used in recreational and sporting equipment such as, tennis rackets, bicycles, golf clubs, skiing equipment, and fishing rods mostly due to the inexpensive material costs. Many FRP manufacturing processes have been developed throughout the years. Initially, the only method of manufacturing FRPs was by hand lay-up where a resin coated mold of the desired product is layered with chopped fiberglass strands, mats, or fabric and rolled to compact the material and remove entrapped air. This method was extremely labor intensive, required a skilled technician, and had a low production rate. As technology advanced, the manufacturing methods became more automated. Resin injection molds and pre-form molding became popular because hardly any resin was wasted and efficiency was improved. In the 1950s, W. Brant Goldsworthy developed a method known as pultrusion that manufactures continuous lengths of an FRP member simply by mechanically pulling it through a heated die. (Starr & Ketel, 2000)The versatility of FRPs is ever expanding, but one area in which it has not gained wide spread popularity is in the construction industry.

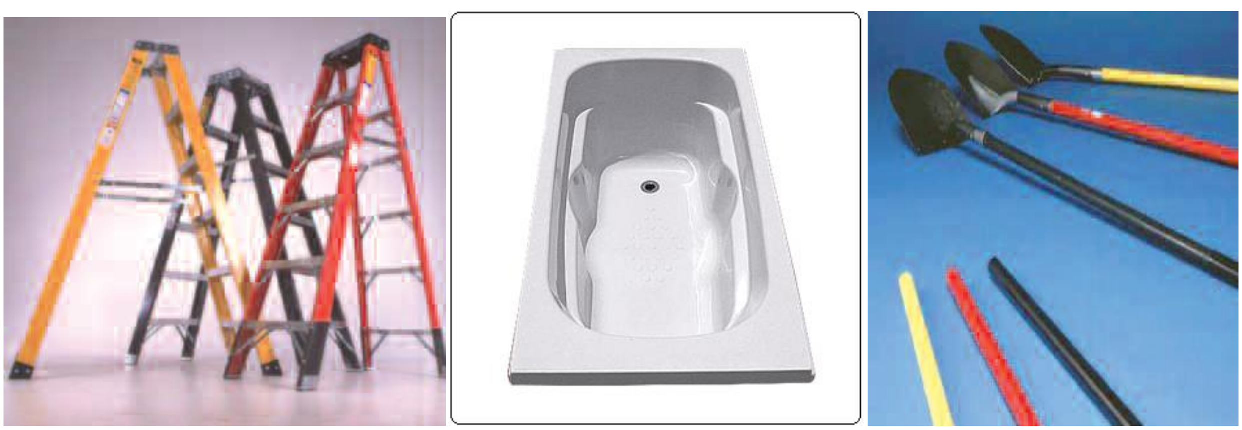


Figure 2-2 Typical household fiber reinforced polymer products

As mentioned in the previous chapter, FRPs have been used in the construction industry as reinforcing bars, wraps, and strips in concrete and masonry structures. The high tensile strength and corrosion resistance give FRPs and advantage over the traditional steel reinforcement used in these types of structures because improved durability and lower maintenance cost result in a more economical structure without compromising strength and stability. Pultruded FRP structural profiles have become more accepted within the recent decades due to increased understanding and evaluation of the characteristics of FRPs along with the increased automation and access of raw materials required for economical FRP production. Infrastructure, marine, electrical/communications, and petro-chemical processing structures are a few of the applications that have benefitted from pultruded FRP members.

What is FRP?

FRPs typically consist of two man-made components; fibers and a polymeric resin. In FRP members, synthetic reinforcing fibers are immersed in a polymeric resin and molded together in a specific shape. The resulting matrix hardens by curing, often by heat, in the desired configuration. FRP members can be manufactured in a variety of nominal or custom shapes and sizes depending on the mold or die. This flexibility in the manufacturing process makes FRPs an increasingly desirable structural material. Some benefits of having structural members comprised of all synthetic materials are the availability of infinite customizable configurations/sizes, and easily attainable design properties rather than the nominal run of the mill sizes and shapes.

Fibers

The fibers in FRPs provide the tensile strength throughout the member section, and can be comprised of fiberglass, aromatic polyamide (aramid), or graphite (carbon) fibers. While fiberglass is the most common fiber reinforcement used in pultruded FRP members, carbon and aramid fibers are a high strength alternative. Carbon fibers are typically used in relatively small structural applications that require high strength and stiffness. (Lubin, 1982) Aerospace and automotive sectors utilize carbon fiber as well as recreational items such as fishing poles, tennis rackets, and golf clubs. Aramid fibers, more commonly known as Kevlar, were originally created by DuPont. (Lubin, 1982) Aramid is more commonly used in aerospace and military transports as well as armor due to its high impact resistance. Carbon and aramid fibers are significantly stronger than fiberglass, but they are also 10 to 30 times more expensive. (Gutowski, 1997) While carbon and aramid fibers are used in smaller and more specialized FRP applications, large scale production of pultruded FRP members tend to be more economically feasible when fiberglass is used as the fiber reinforcement. The scope of this paper will focus on solely fiberglass as the method of reinforcement in pultruded FRP members.

The fiber reinforcement in FRPs exhibit strong tensile properties, but they are very weak when loaded transversely. An FRP member is strong in resisting all directions of loading when the reinforcing fibers span the member, both, longitudinally and transversely. For this reason FRP members are anisotropic, which means that they exhibit unique characteristics depending on the direction of loading. The direction of the reinforcing fibers is partially responsible for the FRP member's overall stability and strength.

All fiberglass reinforcement is comprised of silica (SiO_2) but by itself SiO_2 requires extremely high temperatures to liquefy so modifiers are added to adjust the liquefying temperature and control the characteristic properties. Precise proportions of modifiers, such as aluminum oxide (Al_2O_3), boron oxide (B_2O_3), calcium oxide (CaO), magnesium oxide (MgO), and sodium oxide (NaO) are heated to around 2,370°F (1,300°C), fused together, and drawn through dies to form fiberglass filaments ranging in diameters from 1.5×10^{-4} inches (3.8 µm) to 94.5×10^{-4} inches (24 µm). (Bank, 2006) Different proportions of these chemical compounds result in varying thermal and corrosion resistance properties.

Table 2-1 shows the percent weight of various chemical compounds in the different grades of fiberglass.

The most common composition of fiberglass is high-alkali glass (A-glass). It provides good chemical resistance, but struggles with electro-magnetic transparency. (Lubin, 1982) A-glass can interfere with radio and electromagnetic waves such as cell-phone reception, which could prove to be problematic for the occupants of a building. Low-alkali glass was developed to improve electrical insulation in fiberglass and was therefore named E-glass. (Lubin, 1982) E-glass exhibits most of the same properties of A-glass except much less electrical interference. For extremely corrosive environments, C-glass was developed. C-glass behaves similar to A- and E-glass, but provides unmatched resistance against chemical attack. Finally, S-glass was developed for high-strength applications. The tensile strength in S-glass is 40% higher than that of E-glass; therefore it is most widely used in special applications, such as the aircraft/aerospace industry. (Lubin, 1982) Of all the grades of fiberglass available, E-glass is the grade most commonly used in pultruded FRP profiles. It provides the best all-around performance and durability.

FIBERGLASS COMPOSITIONS (% wt.)				
COMPONENTS	GRADE OF GLASS			
	A (HIGH ALKALI)	C (CHEMICAL)	E (ELECTRICAL)	S (HIGH STRENGTH)
Silicon oxide	72.00	64.60	54.30	64.20
Aluminum oxide	0.60	4.10	15.20	24.80
Ferrous oxide	-	-	-	0.21
Calcium oxide	10.00	13.20	17.20	0.01
Magnesium oxide	2.50	3.30	4.70	10.27
Sodium oxide	14.20	7.70	0.60	0.27
Potassium oxide	-	1.70	-	-
Boron oxide	-	4.70	8.00	0.01
Barium oxide	-	0.90	-	0.20
Miscellaneous	0.70	-	-	-

Table 2-1 Fiberglass Composition by percent weight (Lubin, 1982)

After the fiberglass is made it can be spun into yarns, made into fabrics or mats, or chopped into strands and shipped off to suit any number of purposes. Since Owen-Cornings' first commercially manufactured fiberglass in 1939, researchers and manufacturers have developed grades of fiberglass with different properties each suited for different applications and environments. **Figure** 2-3 illustrates the fiberglass manufacturing process.

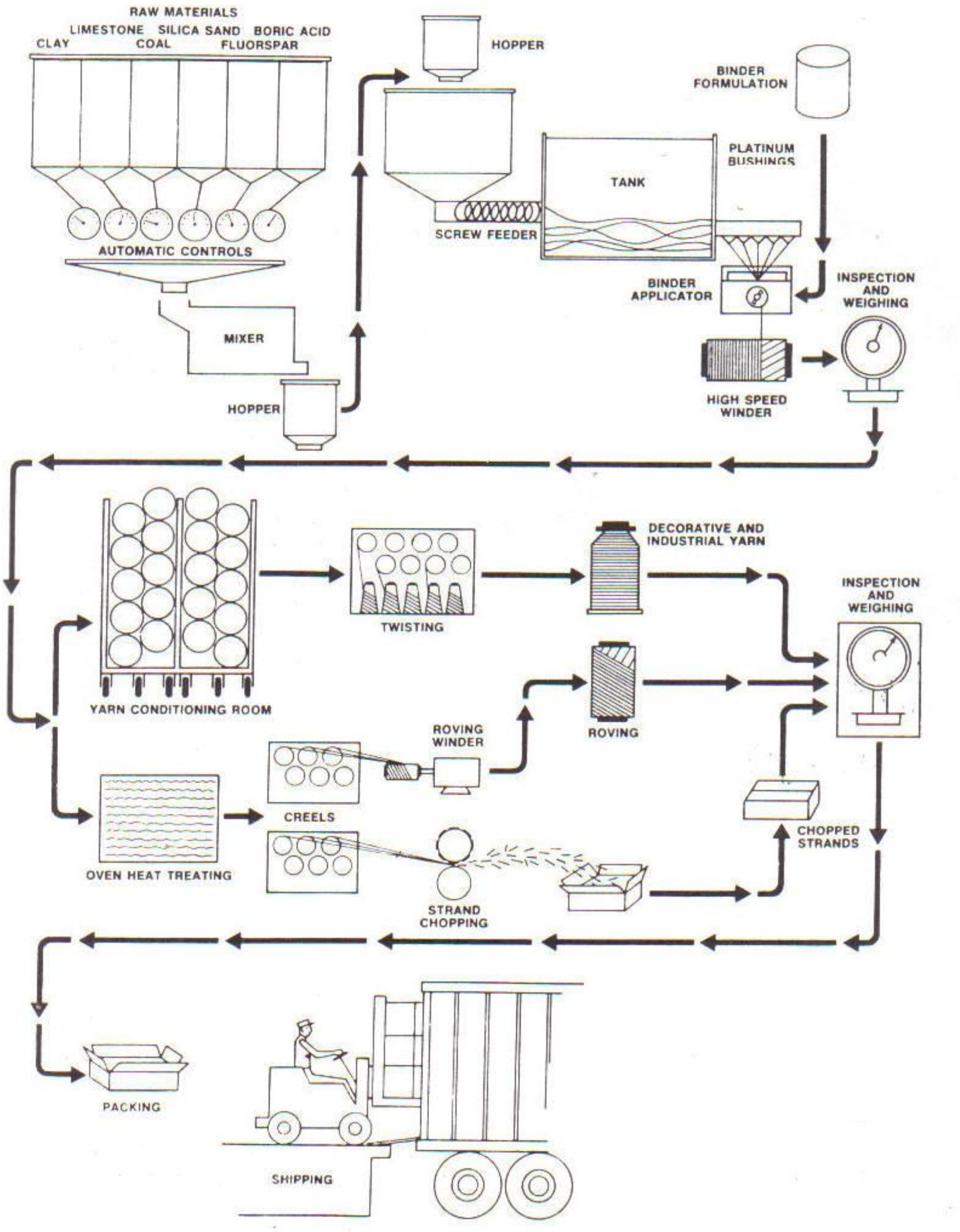


Figure 2-3 Fiberglass Manufacturing Process (Lubin, 1982)

Figure 2-4 Fiberglass roving

Fiberglass filaments are the initial result of the fiberglass manufacturing process. The thin glass filaments are spun into fiber strands, known as roving (**Figure** 2-4), and placed unidirectionally to provide strength in one direction. In a pultruded shape, roving typically spans the member longitudinally. The fiber filaments can also be woven or matted together to provide strength in multiple directions. These are typically applied to the edges of a laminate or plate to provide rigidity along the transverse axis of a member. Among the different fiber reinforcements available in FRP members, fiberglass provides the most versatility because of its diverse chemical make-up. The roving comprises 50% to 70% of the fiber content in the pultruded member depending on the manufacturer and design specifications. (Bedford Reinforced Plastics, Inc., 2009) Each roving filament is continuous throughout the member and provides the tensile strength experienced when bending occurs. Due to the low transverse strength of fiberglass filaments and the low shear modulus of the resin in pultruded members chopped or continuous strand mats must be used to resist the shear and torsion forces.

a) **b)**

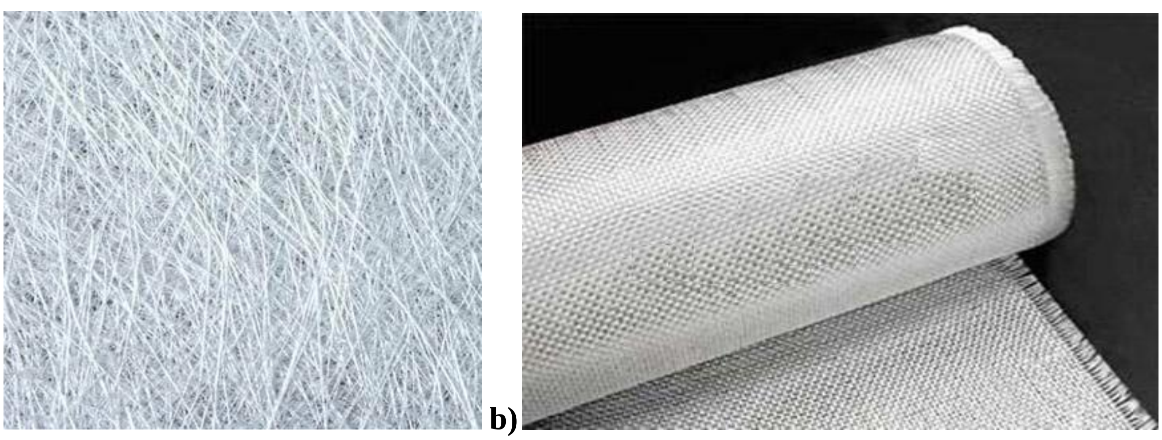


Figure 2-5 a) Fiberglass chopped strand mat; b) Fiberglass woven fabric

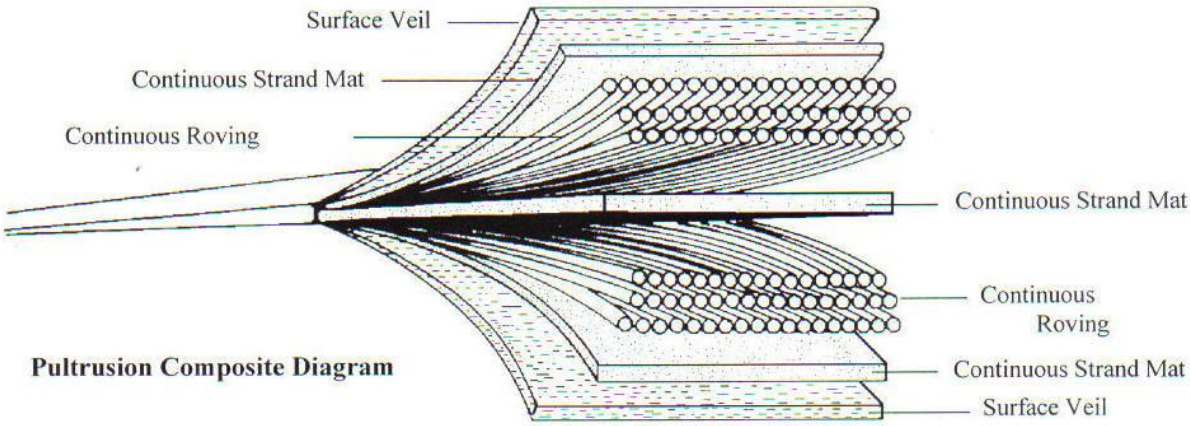
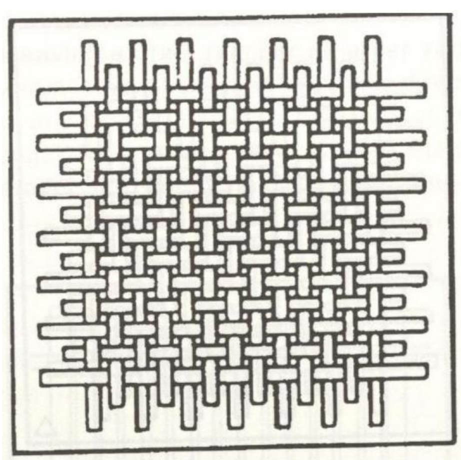
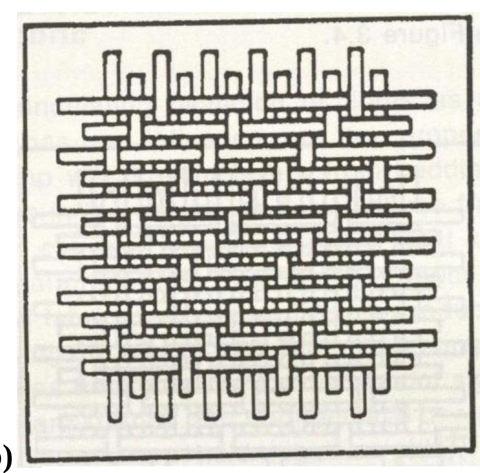


Figure 2-6 FRP Cross Section (Creative Pultrusions, Inc., 2002)

Continuous strand mats and/or fabrics are layered in the laminated plates, and provide the resistance for loads in the transverse direction such as shear and torsion due to buckling. Chopped strand mats are non-woven glass fiber strands that are chopped into short lengths and fairly evenly distributed and randomly oriented. The random strand direction of chopped strand mats ensure load transfer throughout the resin but provide little resistance to transverse loading of the member. Fabrics, however, can provide the required resistance to transverse loads because of the woven and interlocking orientation of the fibers. Fabrics can be woven into different styles to achieve specific strengths in multiple directions. **Figure** 2-7 shows the plain weave, twill weave, satin weave, and unidirectional weave used for fiberglass fabrics.

a)  **b)** 

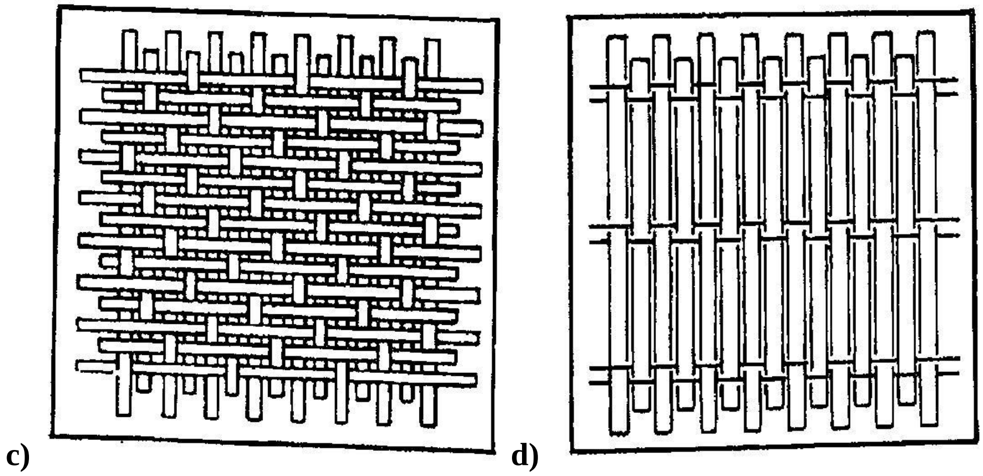


Figure 2-7 Fabric Styles a) plain, b) twill, c) satin, d) unidirectional. (Structural Design of Polymer Composites: EUROCOMP Design Code and Handbook, 1996)

Resins

Resins can be divided into two categories: thermoplastics and thermosets. Thermoplastics are resins that can be repeatedly softened and hardened by heating and cooling the material. This behavior is due to the chemical bond between polymers. Thermosets are resins that cannot be softened after they have been hardened, or cured. This behavior is due to an irreversible chemical process that occurs when the thermoset is cured.

Many resin mixtures can be utilized in an FRP pultruded structural member. Each resin has unique characteristics or properties that may make it more suitable than other resins. Fire, chemical, and environmental resistance are all factors that play a role in deciding which resin to use when manufacturing an FRP pultruded structural member. All polymeric resin mixtures vary in proportions of polymers, fillers, and additives. Typical resins include unsaturated polyesters, vinyl esters, and epoxies. Each type of resin provides unique thermal, corrosion, and mechanical properties that make them ideal in a certain application.

The most common polymer used in resins is unsaturated polyesters. Unsaturated polyesters are used in 75% of the resins used in the United States of America mostly because they are used in a variety of commercial products such as boats, bathtubs, ski poles, water slides, and prefabricated paneling and floors. (Tang, 2010) Overall, unsaturated polyesters provide the best value for performance and strength. Unsaturated polyesters possess properties that are very well suited for the pultrusion process. Low viscosity promotes workability and thorough wetting of the reinforcement, and high polymerization reactivity allows for quick but controllable curing within the pultrusion die. (Bogner, Breitigam, Woodward, & Forsdyke, 2000) Chemical and additive alterations can be easily made with unsaturated polyesters, which can improve mechanical properties and behavioral characteristics of pultruded FRP members.

Vinyl esters exhibit similar characteristics of unsaturated polyesters but are nearly 40% more expensive. (Gutowski, 1997) However, vinyl esters provide better chemical resistance than unsaturated polyesters. (Bogner, Breitigam, Woodward, & Forsdyke, 2000) Normally unsaturated polyester would be the resin of choice for regular construction purposes (i.e. typical commercial or residential building) but if the member is located in highly corrosive surroundings, whether it is chemical, fire or environmental, then vinyl esters might be the best decision. Vinyl esters are used in the same applications as unsaturated polyesters except with higher concentrations and exposures to the aforementioned corrosive surroundings.

Epoxy resins are used for high-performance applications and not as common in pultruded FRP members as polyesters and vinyl esters. They provide the highest level of strength, durability, and fatigue and creep resistance Epoxy resins are almost exclusively used in aerospace or defense applications with aramid or carbon fiber reinforcements due to its chemical and thermal properties as well as its ability to adhere well to other materials. (Bogner, Breitigam, Woodward, & Forsdyke, 2000) Epoxy resins, however, can cost 10 to 30 times the cost of unsaturated polyester resins (Gutowski, 1997).

Fillers & Additives

Fillers and additives are mixed into the resin matrix to enhance or provide additional properties. They can comprise of up to 30% of the weight of a structural member. (Structural Design of Polymer Composites: EUROCOMP Design Code and Handbook, 1996) Fillers and additives are designed to reduce material costs and peak exothermic temperature generated during curing, lower shrinkage, increase resistance to environmental and fire exposure, increase some properties (i.e. modulus of elasticity, hardness, etc.), enhance electrical transparency, and alter the appearance (i.e. color, surface finish). Some common fillers and additives and their respective roles are: clays and carbonates (shrinkage during curing), zinc oxide (pigment), aluminum trihydrate, zinc borate (fire resistance), silanes and silicon-based chemicals (bonding to reinforcement fibers). All fillers and additives are precisely portioned by the manufacturer to achieve a specified product.

Benefits & Weaknesses

When new materials immerge into the market it is important for them to prove to be durable, economical and user friendly. These qualities will undoubtedly determine the amount of success for any new material introduced. Structural engineers often select one type of material over another for certain applications because they obtain characteristics, properties, or behaviors that make them more suitable than other materials, however, ease of design and constructability play an important role in the decision making process. The benefits and rewards of choosing a relatively new material in structures must adequately justify the amount of work and effort put into the design of the structure as engineers are hesitant to change. In order to effectively determine whether a material is more suitable and desirable for a certain job the material's properties must be known and compared to other materials'. It is in this manner that the most economical and structurally sound materials are chosen.

Fiber reinforced polymers have recently been gaining popularity among designers and engineers for multiple reasons. Much of this popularity is due to the astonishing strength-to-weight ratio of the FRP members. Pultruded FRP members are half as strong, but weigh 80% less than their structural steel counterparts. (Strongwell Corporation, 2008) This could translate to less dead load throughout the entire structure, which may help with reducing the member size of the lateral force resisting system (LFRS) used to resist wind and seismic forces. Another benefit of pultruded FRPs is the nonconductive nature of the material. Similarly to wood, FRPs do not interfere with radio frequencies or electromagnetic waves. Steel and concrete are much more dense and reflective of these waves, so cellular phone reception and radio frequencies are not transmitted throughout a structure as easily. Electromagnetic transparency can be beneficial when there needs to be an open channel of communication between many floors or walls. In an FRP structure, a cellular device in the basement would be able to have great signal, whereas, in a concrete or steel structure it may have difficulty getting a good signal. Corrosion resistance is another advantage of using FRPs. Pultruded FRP profiles are extremely resilient in corrosive environments. Pultruded FRP shapes with a vinyl ester or epoxy resin system are resistant to most acidic and basic environments. Structures that contain volatile chemicals like chemical and water treatment plants can benefit from pultruded FRP shapes because of the minimal maintenance required in these harsh environments. One other benefit to pultruded FRP shapes is the similar coefficient of thermal expansion to its steel counterparts. Extreme cold or hot surroundings shrink or expand structural members, so it is important to account for these tolerances and make sure they are allowable for the design of the structure. Aesthetics aren't usually at the forefront of a structural engineer's concern, but it is still an important factor that goes into selecting a structural material for a building. Pultruded FRPs are extremely customizable with the selection of the proper die during the pultrusion process. Of course a thorough structural analysis of how the custom shape will resist load will be in order, but the option of creating unique structural shapes is within reach. FRPs can also be manufactured in any color with the addition of the appropriate dye at the beginning of the pultrusion manufacturing process.

Pultruded FRPs show many advantages in being a formidable material in structures, but there are some drawbacks to selecting them. While there is no flawless structural material, engineers and designers cope with materials' weaknesses by designing to avoid them while emphasizing their strengths. Similar to wood, FRPs are extremely susceptible to fire damage and other prolonged exposure to heat. Engineers and designers must account for situations that may arise and properly design structures with the safety of the occupant in mind. A unique quality of FRPs is its ability to extinguish itself in the event of a fire, whereas, wood is an extremely combustible material and burns very easily. Another drawback of FRP composites is the mode of failure. The reinforcing fibers and polymeric resins are extremely brittle. They tend to fail very quickly and with little visible strain or yielding unlike steel. The application of safety factors to design stresses ensures that pultruded FRPs will deform or buckle before rupture occurs. Engineers safeguard against catastrophic failures by designing structural members to show some form of warning to provide adequate time for evacuation. In steel design, the strain hardening phase of the stress-strain diagram allows for noticeable deformation in the member to make the occupants aware that the member is overstressed. The selection of structural material is an important decision never to be overlooked. Engineers and designers must always make choices based on facts and what they know is economically feasible and practical. When choosing a material of construction they must know the benefits and detriments of their selection.

CHAPTER 3 - The Pultrusion Process

The process known as pultrusion is an efficient method of manufacturing specified lengths of FRP composites. The process requires very little labor and utilizes almost 100% of the raw material required. The first pultrusion machines were invented in the 1950s as an efficient method of manufacturing fishing and kite rods, tool handles, sign posts, tent poles, and other solid rod blanks. (Starr & Ketel, 2000) Today pultrusion is the preferred method for manufacturing everyday household items; ladders and window sills, to structural components; wide-flanged beams, box columns, and floor grates. **Figure** 3-1 illustrates the pultrusion process.

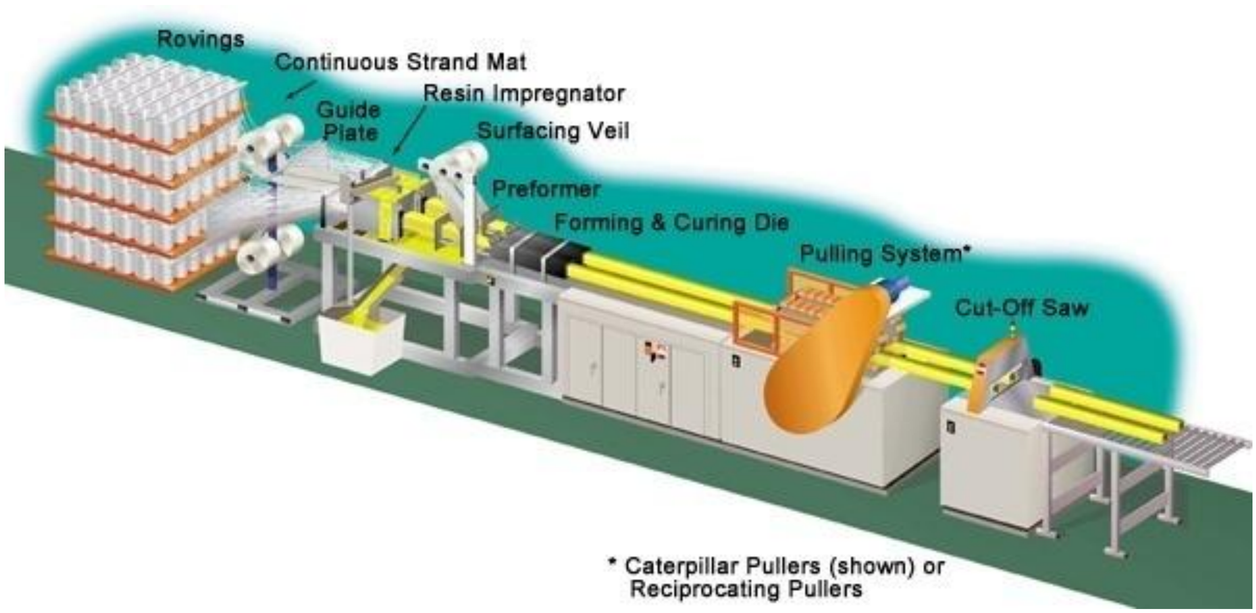


Figure 3-1 Pultrusion Manufacturing Process of FRP Structural Member, (Strongwell Corporation, 2008)

The pultrusion process starts with a collection of reinforcing fiber creels, often fiberglass, called roving. As mentioned earlier in this report, the roving comprises 50% to 70% of the fiberglass content of a pultruded member depending on the manufacturer’s specifications. Continuous mat strands and fabrics are guided into their proper locations before the entire system is immersed in a resin matrix. This occurs by either resin bath or resin impregnation system. The resin matrix consists of the proper proportions of resin, fillers, and additives specified by the manufacturer. Complete immersion of the fibers in the resin, or “wet out”, is required in order for uniformity and the absence of any defects throughout the matrix. The matrix is then drawn through a heated die where polymerization occurs, and the thermosetting resin begins to cure.

The curing process is carefully monitored with sensors and controls because it is the most crucial part of pultrusion. Any defects result in a faulty unusable product. Once the pultruded member has cured it is pulled along the line and cut into desired lengths. All of this occurs at an average line speed of 3.3 ft (1 m) per minute. (Bogner, Breitigam, Woodward, & Forsdyke, 2000) Pultrusion provides an effective and economical method of manufacturing a product with consistent properties and a multitude of customizable options.

Environmental impact is out of the scope of this report but it is still a pertinent issue with the manufacturing of building materials. Steel, wood, concrete, and masonry require different amounts of resources and energy during the manufacturing process. Past research and analysis has provided cost-benefit analyses for traditional materials that help engineers and designers in the decision of a specific material for construction. The same must be done for pultruded FRP profiles in order to justify the growth of the industry. Currently, initial costs of pultruded FRPs are much higher than any other traditional structural material, but a life-cycle cost would take into account the reduced cost of maintenance and protection in harsh environments. As pultruded FRPs gain popularity life-cycle cost and cost-benefit analyses can provide more results regarding the environmental impact of FRPs.

CHAPTER 4 - Material Properties

All structural materials possess properties and strengths attainable from testing and analysis. These unique properties are mostly a result of the interaction within the composition of the material. The homogeneity of a material plays an important role in what properties it exhibits. Structural steel, for instance, may contain many metallic alloys that alter certain properties but the overall composition is homogenous, and, therefore, exhibits the same properties throughout the entire member. Structural timber naturally provides a variety of properties. The properties of different wood species have been understood for quite some time because wood was one of the first building materials used in construction. Engineers and designers know that certain species of wood are stronger than others, but for every species the strength is dependent on the direction of the applied load and configuration of the member. Similar to pultruded FRP members, wood is anisotropic so the relation of the direction of loading to the direction of the wood grain affects the strength of the member. Wood members exhibit different properties perpendicular and parallel to grain. FRP members are similar to wood because the direction of the fiber reinforcement plays a key role in providing strength throughout the pultruded member. This chapter will discuss the properties of pultruded FRP members and compare them to the properties of steel and timber.

Strength is a critical property of any material used in structures. A material's strength must be known in order to ensure the safety of the occupants inside a structure. Ideally, engineers try to avoid designing structures with members that push the limit of rupture or failure. Typical steel members have a flexural strength of 60,000 psi (414 MPa) and modulus of elasticity of 29,000 ksi (200 GPa). Since steel is homogenous these properties pertain to a member in its entirety. Wood, however, has varying strengths associated with the direction of loading relative to the member. Douglas Fir-Larch, a common species of wood used in timber construction, has an allowable flexural strength ranging from 525 psi to 1,500 psi (3.6 MPa to 10.3 MPa) depending on the grade of the species. (American Forest & Paper Association & American Wood Council, 2005) The modulus of elasticity of Douglas Fir-Larch also varies with species selection and is averages from 1,300 ksi to 1,900 ksi (9 GPa to 13 GPa) (American Forest & Paper Association & American Wood Council, 2005). Since FRPs are a composite material the strength of the member depends on the components of the composite (i.e. fiberglass and resin).

Table 4-1 and **Table** 4-2 show the inherent properties of different resins and grades of fiberglass. The combined properties result in a range of possibilities for pultruded FRPs dependent on the ratio of fiber to resin in the member.

FIBERGLASS PROPERTIES					
Property	Units	Grade of Fiberglass			
		A	C	E	S
Specific Gravity	-	2.50	2.49	2.54	2.48
Tensile Strength	psi x 10^3	440	440	500	665
	MPa	3,033	3,033	3,448	4,585
Tensile Modulus	psi x 10^6	-	10	10.5	12.4
	GPa	-	69.0	72.4	85.5
Elongation	%	-	4.8	4.8	5.7
Coeff. of Thermal Expansion	(in./in./°F) x 10^{-6}	4.8	4.0	2.8	3.1
	(mm/mm/°C) x 10^{-6}	8.6	7.2	5.0	5.6

Table 4-1 Fiberglass Properties (Lubin, 1982)

RESIN PROPERTIES				
Property	Units	Resin Types		
		Polyester	Vinyl Ester	Epoxy
Tensile Strength	psi x 10^3	11.2	11.8	11.0
	MPa	77	82	76
Elongation	%	4.5	5.0	6.3
Flexural Strength	psi x 10^3	17.8	20.0	16.7
	MPa	123	138	110
Flexural Modulus	psi x 10^6	0.43	0.54	0.47
	GPa	3.0	3.7	3.2
Heat Distortion Temperature	°F	160	220	330
	°C	71	104	166

Table 4-2 Resin Properties (Creative Pultrusions, Inc., 2002)

Separately, fiberglass and resin make an inadequate structural material, but together they can combine their strengths and prove to be a viable option in the construction industry. The effectiveness of any FRP member relies on strand orientation and fiber content. The fiberglass is primarily responsible for resisting force so the ratio of fiber to resin affects strength and strand orientation affects stability. Pultruded FRP structural members typically have a tensile strength of 30,000 psi (207 MPa) and a modulus of elasticity of 2,500 ksi (17.2 GPa). Of course, this value can vary but in order for mass production to be feasible manufacturers must provide a product with consistent properties. **Table** 4-3 compares the mechanical properties of three different manufacturers' products. The discrepancies between each of the manufacturers' values can be attested to the proprietary design of their products. One manufacturer may use more resin or fiber than another manufacturer therefore creating a product with alternate mechanical properties. This exhibits the extremely customizable nature of pultruded FRP profiles.

PULTRUDED FRP PROFILE PROPERTIES				
PROPERTY	UNITS	MANUFACTURER		
		Creative Pultrusions, Inc.	Strongwell	Bedford Reinforced Plastics
Flexural Strength	10^3 psi	35	30	30
	MPa	241	207	207
Bearing Strength	10^3 psi	32	32	32
	MPa	220	220	220
Modulus of Elasticity (LW)	10^6 psi	3.90	2.60	2.80
	GPa	27	18	19
Modulus of Elasticity (CW)	10^6 psi	1.10	1.30	1.40
	GPa	8	9	10
Modulus of Rigidity	10^6 psi	0.5	0.425	0.450
	GPa	3	3	3
Tensile Strength (LW)	10^3 psi	20	20	24
	MPa	138	138	165
Tensile Strength (CW)	10^3 psi	10	10	10
	MPa	69	69	69
Compressive Strength (LW)	10^3 psi	24	24	24
	MPa	165	165	165
Compressive Strength (CW)	10^3 psi	16	20	16.5
	MPa	110	138	114
Poisson's Ratio (LW)	-	0.35	0.31	-
Poisson's Ratio (CW)	-	0.25	0.29	-

LW - Lengthwise (Longitudinally), CW - Crosswise (Transversely)

Creative Pultrusions, Inc.: 1500, 1525 Series Pultrex® **SuperStructural** Profiles; (Creative Pultrusions, Inc., 2002)

Strongwell: **EXTREN®** Series 500/525 Profiles; (Strongwell Corporation, 2008)

Bedford Reinforced Plastics: Pultruded Structural Profiles; (Bedford Reinforced Plastics Inc., 2009)

Table 4-3 Properties of Various Pultruded FRP Profiles

Engineers and designers must pay attention to load direction when designing pultruded FRPs. The strength of pultruded FRP profiles heavily relies on whether the location and quantity of the fiber reinforcement meets the demand. As previously mentioned in Chapter 2, roving provides longitudinal resistance and chopped strand mats and fabrics provide the transverse resistance and stability. Manufacturers create pultruded profiles with ranging amounts of roving and fabric so strength and stability may slightly vary for each product. Similar to steel and wood entities, organizations and agencies involved with pultruded FRPs may dictate certain criteria (fiberglass and resin grade, resin-fiber ratio, etc.) and minimum standards (flexural strength, longitudinal and transverse moduli of elasticity, etc.) acceptable for mass production to help develop a unifying code and progress the widespread use and design of pultruded FRP profiles. Figure 4-1, Figure 4-2, and Figure 4-3 illustrate the stress-strain curves for steel, wood, and pultruded FRP members. Steel has an elastic limit (yielding) stress and an ultimate limit stress whereas wood and FRPs resist loading until rupture occurs after relatively little deformation due to the brittle nature of wood and FRP.

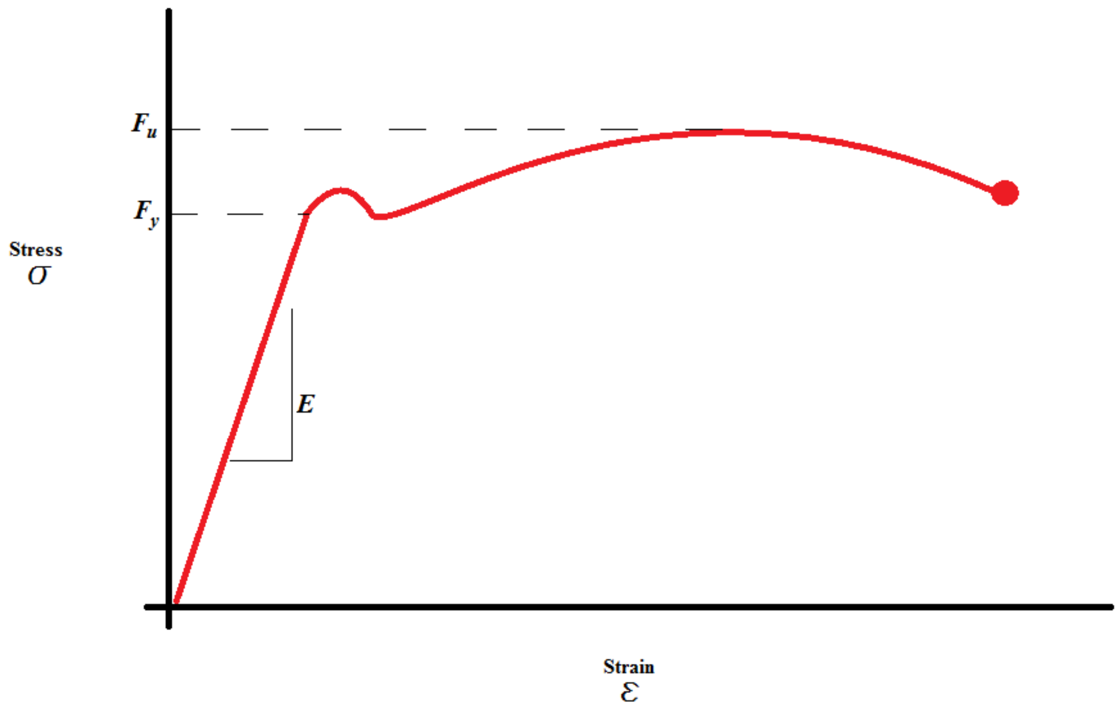


Figure 4-1 Stress-Strain Curve for Steel

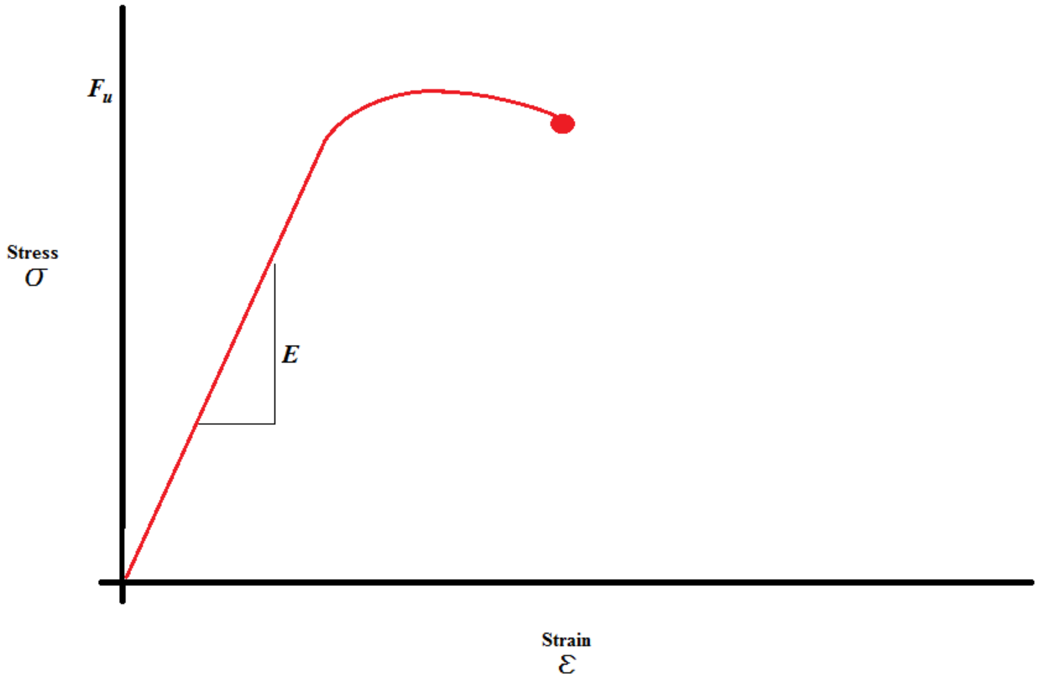


Figure 4-2 Stress-Strain Curve for Wood

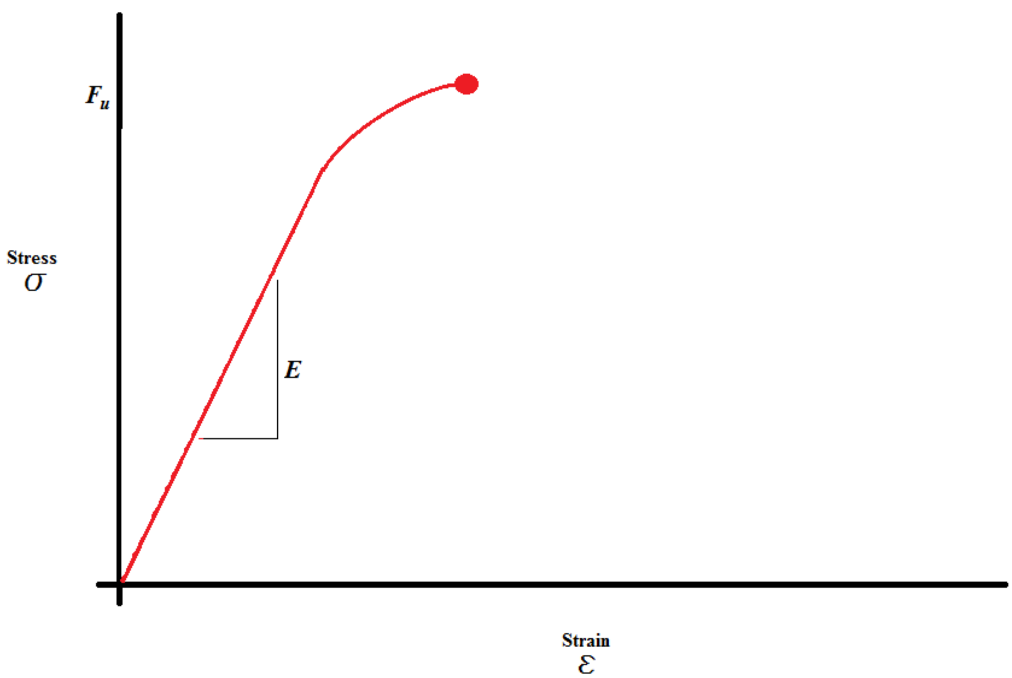


Figure 4-3 Stress-Strain Curve for Typical Pultruded FRP

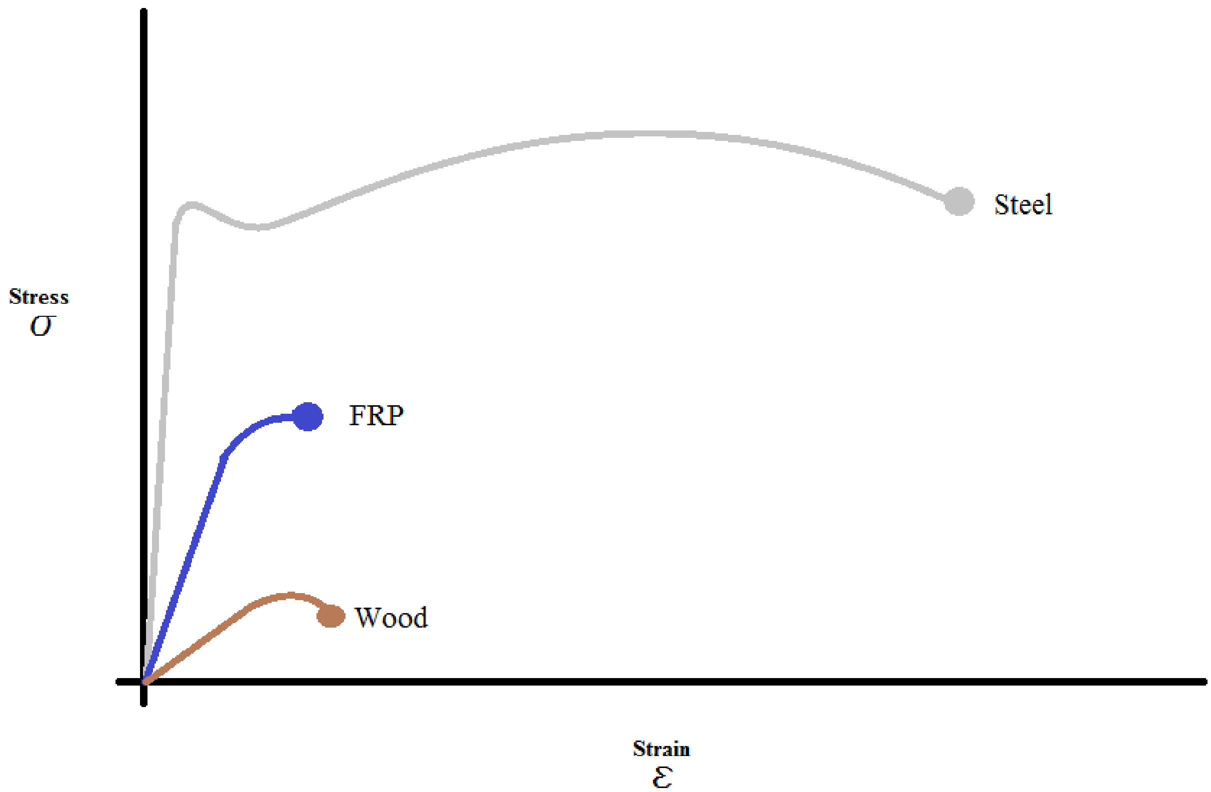


Figure 4-4 Stress-Strain Curve Comparisons

Although the tensile strength of fiberglass (see Table 4-1) is considerably higher than steel's, the pultruded FRP beam is a composite comprising of resin and fiberglass so the mechanical properties of the beam are a result of both of the components' properties. The resin and fiberglass content affect the properties. Exact values of strengths and stresses are proprietary information depending on the manufacturer's specification.

CHAPTER 5 - Design Considerations of FRP Shapes

With the emergence of pultruded FRP shapes in structures, the need for a design standard in the United States has increased. As FRP shapes become more readily available architects, engineers, and contractors must have guidelines of how to design, specify, and construct structures using FRP members. They cannot be creatively and technically confined by the various manufacturers' design handbooks and design methods. A uniform code that can be widely accepted is the best method of expanding the growth of pultruded FRP shapes.

In order to create codes and standards, a full understanding of how the material acts under loading must be achieved. This understanding is obtained through testing and, also, trial and error. Codes and standards are constantly being modified and updated as the material becomes more widely used. This chapter will focus on the design considerations of pultruded FRP shapes.

Composite Action

FRP structures are unique in their design because, unlike steel structures, they are not considered a homogenous material. Pultruded FRP shapes utilize the strengths of two separate materials; the tensile strength and low unit weight of the fibers and the stiffness and corrosion resistance of the resin and this is why they are considered composite materials. Composite action refers to the interaction and utilization of the properties of the separate materials. Reinforced concrete is considered a composite material because the combination of the tensile and confining strength of the reinforcing steel and the compressive strength of the concrete work together to effectively resist loads better than unreinforced concrete.

Composite action is important to understand in FRP design because both elements, the fibers and the resin, depend upon each other. Resins commonly used in pultruded FRP shapes provide a strong bond with the reinforcing fibers, which allows the transfer of stresses throughout the pultruded shape to be dispersed evenly with relatively low plastic deformation and creep resistance. (Erhard, 2006). The success of a pultruded FRP member depends on the load transfer between the fiber reinforcing, both longitudinal and transverse, and the resin.

Limit States

Every material acts in a specific manner when experiencing a load. This behavior can sometimes determine whether the material is suitable for a certain design application. A material’s characteristic properties determine how that material will behave when loaded. A material’s mode of failure is dependent on the geometric shape, size, and mechanical properties characteristic of that material; modulus of elasticity (*E*), the modulus of rigidity (*G*), and ultimate strength. Structural materials fail when a limit state, a state when the structure no longer satisfies its design requirements, has been reached. There are two types of limit states: ultimate limit state and serviceability limit state.

Ultimate Limit States

Ultimate limit states result from the behavior of the member under excessive loading. Ultimate limit states are normally associated with collapse, rupture, or other structural failures that may endanger the equilibrium of the structure or the safety of the occupants. A material’s mechanical properties determine whether the ultimate limit states are easily exceeded. Engineers try to avoid ultimate limit states that occur abruptly by designing structures to exhibit warning signs (deformations, cracking, and delaminations) to allow the occupant adequate time to exit the structure. By selecting the appropriate sizes and configurations of structural members that can effectively resist loads and avoid reaching these limit states.

Bending, Shear, & Bearing

A structural member will resist as much force within its capabilities until one of the limit states is reached then it will begin to fail. Engineers must know how, when, and where a structural member will fail in order to design a structure with the safety of the occupant in mind. Factors that affect a structural member’s behavior under loading are inherent mechanical properties (i.e. modulus of elasticity, rigidity, ultimate strength), loading conditions (i.e. distributed or point loads), and geometric configuration (i.e. wide-flanged beam, angle, channel, square or rectangular box). **Figure** 5-1 shows typical beam loading and end conditions and the corresponding maximum shear, moment, and deflections. Pultruded FRP profiles take advantage of their high strength and geometric configurations to effectively resist loads.

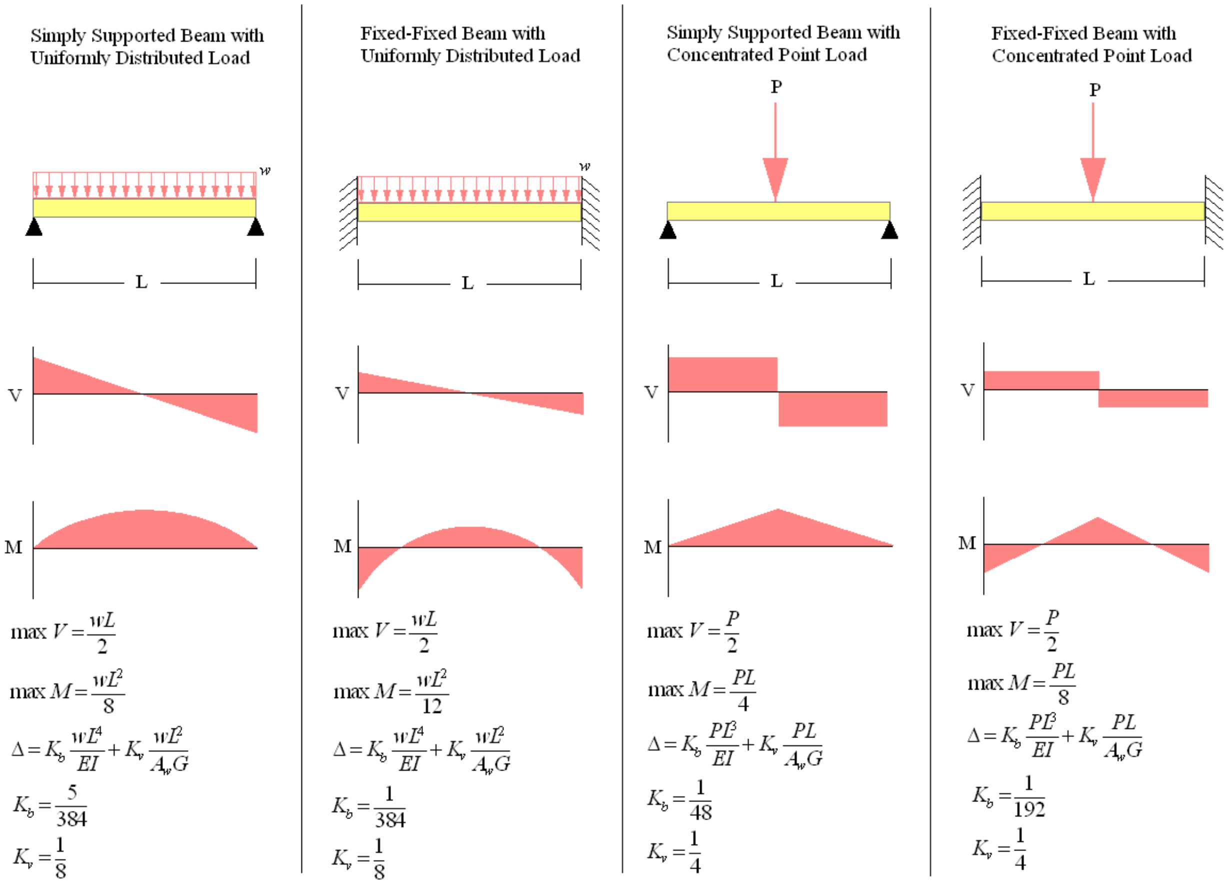


Figure 5-1 Beam Loading and End Conditions

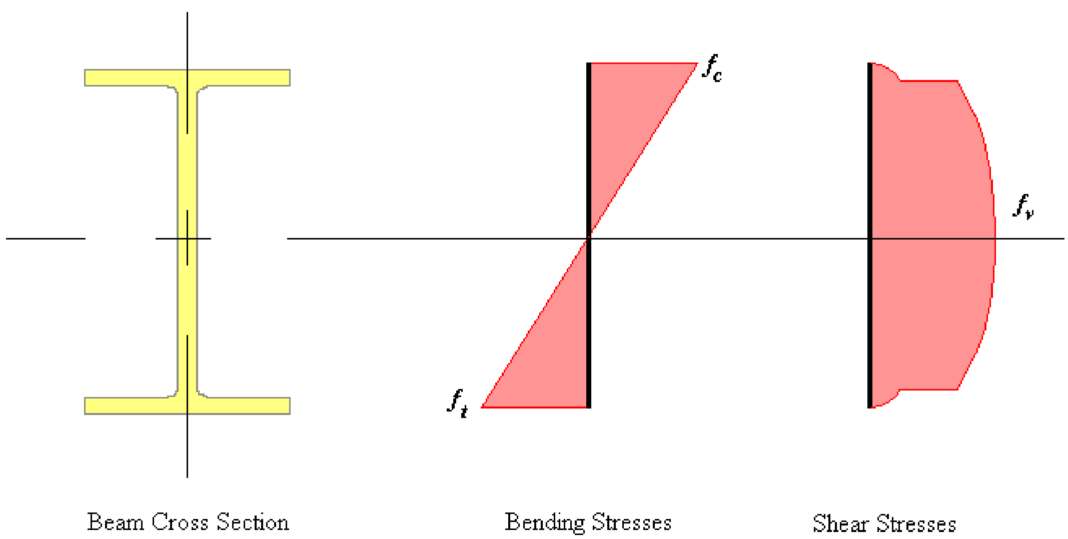


Figure 5-2 Beam Stresses

The primary purpose of a beam is to resist bending forces. A bending stress involves a compression stress, typically at the top section of a profile, and a tensile stress at the bottom as shown in **Figure** 5-2. The actual bending stress (f_b) is a result of the load applied to the beam. The allowable bending stress (F'_b) is the bending stress that a specific member can resist. For pultruded FRP, manufacturers and industry organizations apply a safety factor of 2.5 to the allowable bending stress to safely ensure that limit is never exceeded otherwise an accidental catastrophic failure could occur. (Structural Design of Polymer Composites: EUROCOMP Design Code and Handbook, 1996) The allowable bending stress is designed to be greater than the actual bending stress.

Equation 5 - 1	**Equation 5 - 2**	**Equation 5 - 3**
$f_b = \frac{M}{S}$	$f_v = \frac{V}{A_w}$	$f_{c\perp} = \frac{R}{A_b}$
M : Moment (lbs.-in.)	V : Shear (lbs.)	R : Reaction at support (lbs.)
S : Section Modulus (in.^{3})	A_w : Area of the web (in.^{2})	A_b : Bearing Area (in.^{2})

Shear stresses involve tearing of a structural material in opposite directions. Beams experience shear as a result of the resisted loads. The web element of I-beams resist shear. Actual shear stress (f_v) is the result of the reaction at each support with the loading on the member. The maximum shear on a member generally occurs at one of the supports. The allowable shear stress (F'_v) must exceed the allowed shear stress. A safety factor of 3.0 is typically applied to the design shear stress because shear abruptly fails and provides no visual indication of failure to notify the occupants. (Creative Pultrusions, Inc., 2002) The modulus of rigidity (G) measures a material's ability to resist shear.

Bearing stresses involve crushing of the surface of the member due to high concentrated loads. This normally occurs at the supports of a simply supported beam. The bearing area and compressive strength of a material are critical to calculating the allowed bearing stress (F'_c). A larger bearing area results in a larger F'_c. A safety factor of 2.0 is applied to the F'_c. (Creative Pultrusions, Inc., 2002) The actual bearing stress (f_c) involves the reaction at the support as a result of the loaded beam.

The first and foremost main objective of a structural member is to resist load, and the manner in which it accomplishes this correlates with the magnitude and intensity of the load, the mechanical properties inherent to that member, and the geometric configuration. However, in the design of pultruded FRP shapes, the ability to resist load may not be the prevalent issue due to the high strength of the material. Buckling, excessive deflections, minor cracking, local failures, and aesthetics usually play a governing role in the design.

Buckling

Buckling is the limit state of sudden failure of a structural member or element due to high compressive stresses. Dimensional stability is a key component of a structural member's ability to resist buckling. The stiffness and configuration of a beam's elements determine its strong and weak axes. A wide-flange is an ideal member for beams, girders, and other flexural members because the flanges effectively resist the high compressive and tensile forces associated with flexure and the web resists shear. However, a member's rigidity also plays a significant role. The modulus of elasticity (*E*) measures how well a material can deform and return to its normal state after a force has been applied and removed. Steel has a relatively high modulus of elasticity of 29,000 ksi (200 GPa), while wood has a lower modulus of elasticity of approximately 1,000 ksi (7 GPa). A pultruded FRP member has a modulus of elasticity of 3,000 ksi (20 GPa) longitudinally and 100 ksi (7.5 GPa) transversely (See

PULTRUDED FRP PROFILE PROPERTIES				
PROPERTY	UNITS	MANUFACTURER		
		Creative Pultrusions, Inc.	Strongwell	Bedford Reinforced Plastics
Flexural Strength	10^3 psi	35	30	30
	MPa	241	207	207
Bearing Strength	10^3 psi	32	32	32
	MPa	220	220	220
Modulus of Elasticity (LW)	10^6 psi	3.90	2.60	2.80
	GPa	27	18	19
Modulus of Elasticity (CW)	10^6 psi	1.10	1.30	1.40
	GPa	8	9	10
Modulus of Rigidity	10^6 psi	0.5	0.425	0.450
	GPa	3	3	3
Tensile Strength (LW)	10^3 psi	20	20	24
	MPa	138	138	165
Tensile Strength (CW)	10^3 psi	10	10	10
	MPa	69	69	69
Compressive Strength (LW)	10^3 psi	24	24	24
	MPa	165	165	165
Compressive Strength (CW)	10^3 psi	16	20	16.5
	MPa	110	138	114
Poisson's Ratio (LW)	-	0.35	0.31	-
Poisson's Ratio (CW)	-	0.25	0.29	-

LW - Lengthwise (Longitudinally), CW - Crosswise (Transversely)

Creative Pultrusions, Inc.: 1500, 1525 Series Pultrex® **SuperStructural** Profiles; (Creative Pultrusions, Inc., 2002)

Strongwell: **EXTREN**® Series 500/525 Profiles; (Strongwell Corporation, 2008)

Bedford Reinforced Plastics: Pultruded Structural Profiles; (Bedford Reinforced Plastics Inc., 2009)

Table 4-3). The anisotropy of pultruded FRP shapes provides strong and weak axes that must be taken into consideration when determining bracing length. Typically the weak axis is braced more frequently than the strong axis to utilize more strength in the member. **Figure** 5-3 shows the geometric strong and weak axes. **Figure** 5-4 provides examples for local flange buckling, local web buckling, and lateral-torsional buckling. **Figure** 5-5 illustrates the strong and weak axes in regards to bending.

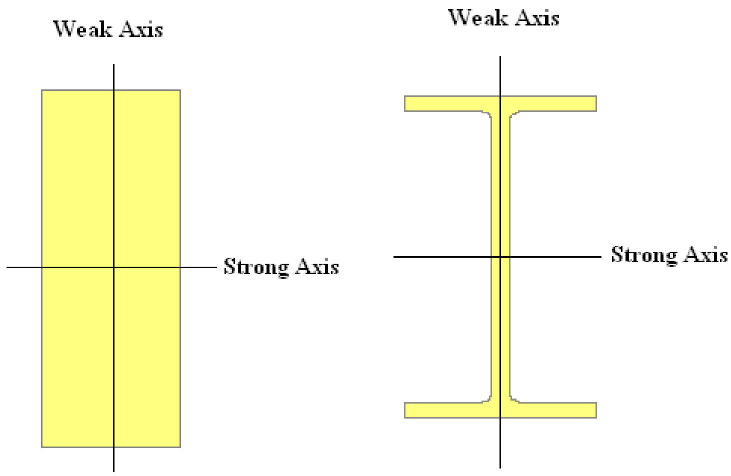


Figure 5-3 Geometric Strong and weak axes

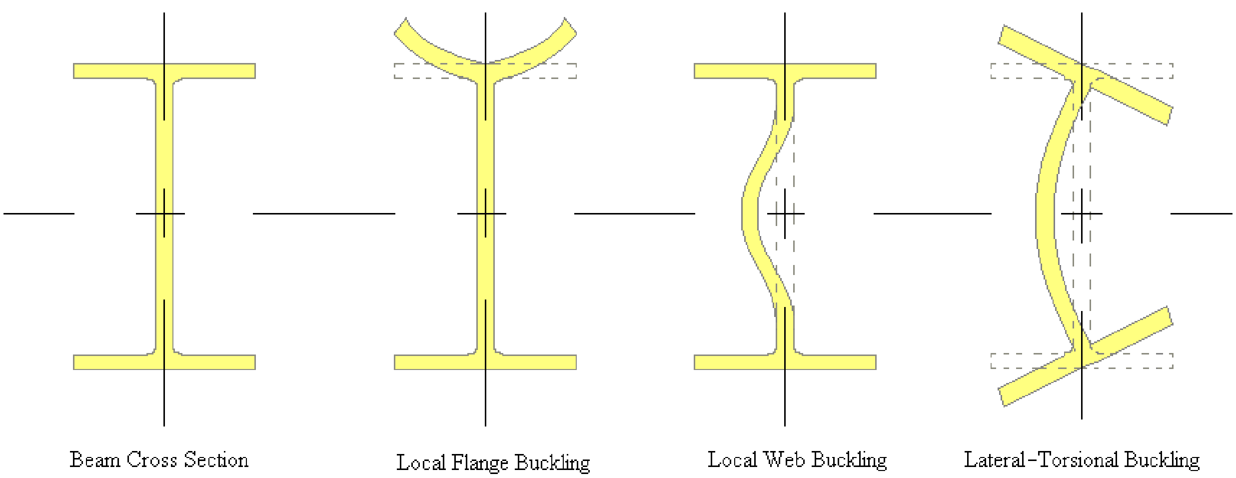


Figure 5-4 Buckling Examples

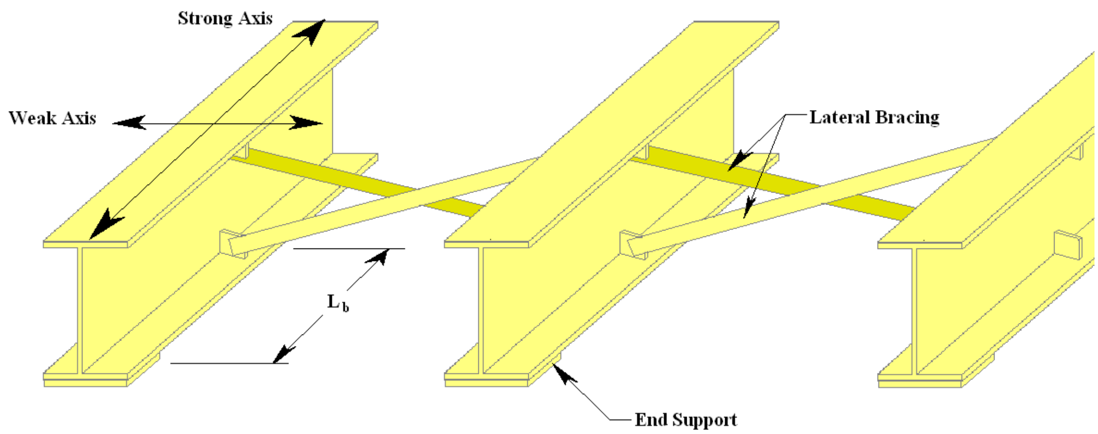


Figure 5-5 Strong and weak axes of bending

There are two types of buckling in design; local buckling and lateral-torsional buckling. (See **Figure** 5-4) Local buckling is when buckling occurs in a compression element within a cross section (i.e. the flange or web of a beam in flexure). The thickness and stiffness of plate elements within the cross section governs if local buckling will occur. This includes thicknesses of webs and flanges of a cross section. The local buckling limit state of flange buckling occurs when the compression due to flexure of a beam causes the flange to buckle. Flange thickness, width, stiffness, and span factor into the buckling resistance of a member. Web buckling resistance depends on web stiffness, thickness, and depth. Web buckling can occur from flexural stresses and shear stresses. Beam webs can be stiffened by altering the web stiffness or thickness with web stiffeners or web doubler plates. Web buckling resistance is typically required at the supports of a simply supported beam or at the point of concentrated loads. Lateral-torsional buckling occurs when a flexural member deflects perpendicular to the plane of bending while twisting. Lateral-torsional buckling is dependent on the bracing length and the limiting laterally unbraced length for yielding and inelastic lateral-torsional buckling.

As mentioned earlier, pultruded profiles have different moduli of elasticity for longitudinal and transverse axes. This means a member's longitudinal modulus of elasticity can resist forces but the transverse modulus of elasticity must resist buckling. After years of testing and analysis the AISC Steel Design Manual provides a table (Table B4.1, AISC 3rd Edition) that provides limiting width-to-thickness ratios for compact and slender elements. This table allows the engineer to specify an adequate profile without checking to see if local buckling will occur. Table 7-1 of the ASCE *Structural Plastics Design* Manual provides maximum width-thickness ratios to prevent local buckling for pultruded FRP profiles; however, the highly customizable nature of pultruded profiles requires that local buckling of the flanges and webs are checked.

Serviceability Limit States

Serviceability limit states are associated with excessive deformations or deflections that affect the appearance or use of the structure. Serviceability limit states also include excessive vibrations or local damage (i.e. buckling, delamination, cracking).

Deflections

Deflections cause movement of a structural member which can lead to cracking of masonry or stone facades or warping of surfaces. A structural member deflects as it resists a load. This deflection depends on the intensity of the load and the stiffness and configuration of the member and beam conditions. (See **Figure** 5-1) Pultruded FRP shapes have a relatively low modulus of elasticity, so deflection typically governs the design and specification of members. Deflection is designated as delta (Δ). Pultruded FRP members take into account deflection due to shear because the low shear modulus (modulus of rigidity) significantly contributes to the overall deflection especially in shorter span beams. The modulus of rigidity (G) is a ratio of the pressure applied transversely a material and measuring the lateral displacement, whereas, the modulus of elasticity (E) is a ratio of tensile pressure and longitudinal displacement. Steel is such a rigid material that the deflection due to shear is negligible so it is ignored in this calculation. Structural wood design tables include the effects of shear deflection in the modulus of elasticity values, therefore eliminating the need to calculate shear deflection for wood members. (American Forest & Paper Association & American Wood Council, 2005)

Connections

Arguably the most critical points of a structure are the connections. Connection design is important because an inadequate connection design could result in a catastrophic failure of the entire structure. Connections are designed to transfer loads between members so they must be stronger than the members. Pultruded FRPs pose interesting options for connections. Two categories of connections are mechanical and adhesive. A combination of the mechanical and adhesive connections is also common. These connections are responsible for keeping the structure intact and stable.

Mechanical Connections

Mechanical joints involve the joining of two or more laminates or plates with fasteners which transfer the load from one structural member to another. The number and spacing of fasteners affects the strength of the connection. FRP connection design is similar to other traditional materials' because limit states like bearing, tensile, shear, and fastener failure govern. Design parameters such as geometry of the connection, fastener diameter, plate thickness, and loading condition should be taken into account when designing a mechanical connection. In FRP connection design, the anisotropy of a plate plays a crucial role because the connection might have multiple scenarios with varying load direction. Each plate and web or flange of a beam must be designed to resist all foreseeable forces. FRP connections require fasteners to be either stainless steel or FRP because components in the resin matrix can cause corrosion to occur within the joint. Corrosion of the fasteners can jeopardize the structural integrity of a connection.

Mechanical connections are easier to construct because the tools needed are readily available and the connections can be prefabricated or created on the construction site. Much like wood pultruded FRP profiles can be sawn or drilled by using carbide tipped power tools. (Strongwell Corporation, 2008) A certain amount of quality control is necessary but does not require someone to be professionally licensed. Mechanical joints are easy to inspect and can be disassembled, however efficiently distributing the load can be difficult due to the anisotropy of the plate and member elements and attaching the connection can be rather time consuming.

Adhesive Connections

Adhesive connections, also known as bonded joints, join two adherends with the use of an epoxy adhesive where load transfer occurs. When applied correctly, adhesive joints provide far superior strength than mechanical joints because the surface area of the connection is larger. A larger connection, or lap length, results in a stronger connection. Other factors that affect the strength of a connection are adhesive thickness and fiber orientation of the adjoining adherends. Again, the anisotropic nature of FRPs plays a crucial role in the design so engineers must be fully aware of all loading scenarios. There are three failure modes for bonded joints: adhesive failure, cohesive failure of the adhesive, and cohesive failure of the adherend. Adhesive failure occurs when the adhesive bond fails and causes a separation between the adherend and adhesive. This is most likely due to inconsistent materials or inadequate surface preparation. Cohesive failure of the adhesive occurs when a load exceeding the adhesive strength causes it to fail. Cohesive failure of the adherend occurs when a load exceeding the adherend strength causes it to fail. (Structural Design of Polymer Composites: EUROCOMP Design Code and Handbook, 1996) Engineers design connections to exceed loads resisted by the members they support in order to dictate a governing limit state stay with the design of the beam (i.e. deflection or lateral-torsional buckling).

Quality control is very important with bonded joints. If the entire structure has been planned and finalized then having the connections prefabricated in a closed environment rather than on the construction site might be a feasible option. Surface preparation of an FRP plate involves chemical solvents and abrasive cleaning to expose the outermost fibers. Careful application of the adhesive requires precise dimensions and locations along with a steady hand all while the surface stays clean, which can be near impossible on a construction site. Adhesive thickness is crucial because any variation could cause a decrease in strength or misalignment. Curing of the adhesive could take some time so the connection might have to be temporarily braced or clamped. Also, curing may require excess heat or cause an exothermic reaction. There are many fine intricacies involved with the proper application of an adhesive connection.

Environmental Effects

Structural materials are often chosen because of environmental effects. Environmental effects pertain to the outdoor or indoor conditions that the member might come in contact. Such conditions can severely inhibit performance or durability. High heat, fire, moisture, chemical, UV ray degradation, rot and decay are all environmental effects that must be taken into consideration when designing any structure.

High Heat/Fire

Heat and fire are the great destroyers. Heat can attribute to deterioration and degradation of a material, almost anything becomes destroyed in a hot enough fire. Pultruded FRP shapes have a coefficient of thermal expansion of 7×10^{-6} in./in.°F (Strongwell Corporation, 2008), which is near steel's coefficient of thermal expansion of 6.5×10^{-6} in./in.°F (Simmons, 2001) so deflections due to temperature variances are similar to one another. The change of temperatures with the seasons causes materials to expand and contract, which can introduce stresses and deformations in a structure. Certain tolerances within critical areas of a structure ensure that no damage results from thermal deformations. Fire resistance, flammability, fire propagation, heat generation, smoke emission, and toxic and noxious fumes can factor into the effectiveness of a structural material's performance during a fire. More importantly, a structural material's strength retention while exposed to high heat or fire plays an important role in the safety rating and reliability of a structural material. When exposed to elevated temperatures of 100°F, 125°F, and 150°F pultruded FRPs retain 90%, 85%, and 80% of their strength for vinyl ester resin systems and 85%, 70%, and 50% for polyester resin systems, respectively. (Strongwell Corporation, 2008) This is a drastic drop in strength and one of the main reasons many engineers shy away from designing FRP structures. In wood design, a prolonged exposure to 150°F temperature merits a 0.7 or 0.9 reduction factors in strength. (American Forest & Paper Association & American Wood Council, 2005) Steel retains 100% of its strength in temperatures as high as 750°F and 50% of its strength at 1100°F (AISC, 2005). In addition to their destructive nature fires create smoke which may contain harmful compounds that the occupants might inhale as they exit the building. Fire resistance for pultruded FRPs may involve a surface coating or certain fillers and additives within the resin making them self extinguishable or smokeless when exposed to an open flame. Fire suppression or isolation of the overall design of the structure with the use of fire sprinklers and adequate fire ratings on partitions greatly reduces the danger of damage and failure due to fire.

Moisture/UV light

Moisture and UV light degradation affect the resin matrix. Moisture is important because it has the potential of reducing strength within the resin matrix or causing other issues such as mold or corrosion. Resin polymers are extremely susceptible to moisture degradation. This issue is amplified when a composite material is in question because the strength of one of the components is dependent on the other. Adequate moisture and UV protection is achieved with a resin matrix with no imperfections and shielded with a surface veil.

Corrosion/Chemical Attack

Some of the most hostile environmental effects involve corrosion or chemical attack. Corrosion can obliterate a steel structure to scrap with the right amount of moisture and time. Fortunately, FRPs are highly known to resist corrosion. The engineer or designer should be aware whether an FRP member will ever endure highly corrosive or chemical environment because it may influence the grade of fiberglass and resin matrix required.

Design Applications

A structure must be designed to resist loads it will experience in its life cycle. Whether these loads are due to the self weight of the structure (dead loads), the weight of the structure's occupants and equipment (live loads), environmental forces (rain, snow, soil), and lateral forces (wind, seismic) every engineer and designer must come up with a solution to successfully and safely resist the loads with the construction materials that are available. However, some structural materials may effectively resist loads experienced in the life of the structure, but they may not be the best choice due to the surrounding environment. Certain materials are very unfavorable in harsh environments. Marine applications deal with elevated levels of salt water, which is extremely corrosive to steel. Chemical and petroleum processing plants are almost immersed in harmful chemicals that can degrade most of the conventional structural materials. These design scenarios involve intensive maintenance to ensure no structural elements have been compromised.

Standards, Codes, and Testing

Codes and standards govern the design of structures. All structural materials have a governing code or standard that engineers and designers follow in order to design a safe and stable structure. These codes and standards are normally written by committees and agencies that specialize in and understand the structural material. Each country has its own governing bodies that regulate the codes and standards of structural materials. In the United States, for instance, the main four structural materials (wood, concrete, masonry, and steel) have their separate entities that publish codes and standards. The American Institute of Steel Construction Inc. (AISC) publishes the *Steel Construction Manual*, which assists engineers in the design of steel structures. For wood, the American Forestry & Paper Association (AFPA) publishes the National Design Specification (NDS) for Wood Construction. The NDS provides engineers and designers with standards and specifications that must be followed in order to design a structure that will maintain its structural integrity and provide for the safety of the occupants throughout the structure's life span. The American Concrete Institute (ACI) publishes many codes that are used by engineers for the design of concrete structures. Similar to the AFPA and other agencies associated with structural materials, the ACI is divided into committees and subdivisions that specialize in certain areas of the industry, such as materials and properties, design and construction, and special applications. Masonry design is governed by the Masonry Standards Joint Committee, which is comprised of the ACI, The Masonry Society (TMS), and American Society of Civil Engineers (ASCE). The ASCE publishes technical guidelines, codes, and standards that engineers follow to ensure safety and promote reliability and efficiency.

Although FRP pultruded shapes are relatively new in today's construction methods there are many agencies that are hard at work developing a better understanding of FRPs and how they can be used in structures. In industry, progress is a very slow process but eventually every engineer or designer will benefit from the work of these agencies and be able to safely design FRP structures. Past design manuals, such as the ASCE *Structural Plastics Design Manual* and the EUROCOMP *Structural Design of Polymer Composites* Design Code and Handbook have been the main resource in the design of pultruded FRP structures. The 2009 *International Building Code* by the International Code Council (ICC) provides standards for fire safety and load information for the design of fiberglass reinforced polymers, but offers no assistance with the design of the members.

The American Composites Manufacturers Association (ACMA) is an organization that represents manufacturers and suppliers in the composites industry. They act as a forum for the composites industry to address issues and share information to help and promote the use and design of composites. They have been commissioned by the American Society of Civil Engineers to lead the development of a national pre-standard for pultruded FRP members to be used by engineers.

The Pultrusion Industry Council (PIC) is a subgroup of the ACMA that focuses on the pultrusion industry. Their focus mainly involves manufacturers, suppliers, designers, and users of pultruded products.

ASCE LRFD Standard for Pultruded FRP Structures

The ASCE awarded a contract to the ACMA and PIC to develop a pre-standard for pultruded FRP structures. As of September 2010, the *Load Resistance Factor Design (LRFD) Standard for Pultruded Fiber Reinforced Polymer (FRP) Structures* is available through the

ASCE to testing committees; however, it is not available to all engineers until it is approved by the testing committees. (Busel, 2010) This standard closely follows the EUROCOMP *Structural Design of Polymer Composites* Design Code and Handbook and provides design equations similar to those found in it. With this standard, FRP structures can be more easily designed in the United States.

ASTM Testing

Testing is vital to understanding how a material behaves under loading conditions. The American Standard for Testing and Materials (ASTM) is responsible for conducting controlled tests and providing results that help engineers and designers better understand a material. The ASTM provides the standardization required for materials in a global marketplace so there is a tolerable consistency among materials from different manufacturers.

Manufacturers

Manufacturers play a vital role in the development of codes and standards for FRP materials. They are responsible for manufacturing a consistent product to a certain specification that will always yield the same results within tolerances deemed acceptable by the governing codes and standards. For wood construction, the American Wood Council (AWC) and the American Forest & Paper Association (AFPA) publish the *ASD/LRFD National Design Standard (NDS)* that provides certain criteria and specifications that must be met by all structural wood manufacturers. For steel, the American Institute of Steel Construction (AISC) publishes the *Steel Construction Manual* that provides the specifications for structural steel to be followed by all steel manufacturers.

Plastics manufacturers will eventually follow suit and be required to manufacture products that meet certain specifications. Strongwell Corporation and Bedford Reinforced Plastics Incorporated are two of the leading manufacturers setting the standard for FRP pultruded shapes. Both manufacturers publish design manuals for their own FRP pultruded shapes.

CHAPTER 6 - Beam Comparisons

When designing a structure, engineers make decisions based on their calculations and their best engineering judgment for that specific structure. There are many factors that affect the choices made by engineers so there may be more than one acceptable solution that can satisfy one structure. These factors may include how conservatively the engineer designed the structure, the level of occupant safety and importance, budgetary restrictions, the level of skilled labor available, and the projected lifespan of the structure. Engineers consider and accommodate for these and other factors that ultimately affect the design approach of the structure.

Steel, timber, and FRP structures have different advantages and disadvantages, but that does not mean they cannot be compared amongst each other. A great way to compare the three materials is to subject them to identical loading conditions and design them as three separate structures. This way, side-by-side comparisons of governing limit states and member size and weight is easily done, which gives unique insight into the performance of each structural material. For this report, uniformly loaded simple span beams were designed for steel, timber, and pultruded FRP beams.

Beams and Loading Conditions

The design conditions for the analysis of this report can be divided into two categories: beam configuration and loading conditions. Each of the two categories plays a significant role in the design of the member. Beam configuration involves the span, tributary width, and end conditions of the member. These affect the types of stresses the member must resist. Loading conditions involve the distribution and intensity of the load resisted by the member. Concentrated loads apply different stresses than uniformly distributed loads. The importance of subjecting beams to different conditions provides a wide spectrum of members for analysis and comparison.

Steel, timber, and FRP beams have different capabilities for achieving attainable spans. The availability of longer spans of steel members may not be the same for timber or FRP members. Therefore, typical spans were considered when selecting beam configurations. **Table** 6-1 shows each beam's span, tributary width and area, and braced length. These configurations are similar to those used in typical structural bays for floor and roof assemblies.

BEAM DIMENSIONS				
BEAM	SPAN (ft.)	TRIBUTARY WIDTH (ft.)	Tributary Area (ft.^{2})	BRACED LENGTH (ft.)
3010	30	10	300	Continuously Braced
2010	20	10	200	Continuously Braced
2005	20	5	100	Continuously Braced
1005	10	5	50	Continuously Braced
1002	10	2	20	Continuously Braced

Table 6-1 Beam Dimensions

In the design of structures, loads are categorized according to their source and duration. Two types of loads are gravity loads and lateral loads. Gravity loads are a result of weight applied to a structure while lateral loads result from wind or seismic forces. For simplicity, this paper will focus on beams resisting only gravity loads. Gravity loads come in all different forms. Dead loads are associated with self weight of a structure or permanent loads experienced throughout the life of the structure. Live loads are variable loads that are caused by the occupancy or use of the structure and do not include construction or environmental loads. Roof live loads are similar to live loads because they are both variable, however, roof live loads are associated with loads experienced during construction or maintenance by workers, equipment or materials and are not affected by occupancy. Snow loads result from the weight of snow on a structure. Snow loads are only experienced on the roof of a structure. **Table** 6-2 shows three loading conditions used in this report's analysis.

BEAM LOADING CONDITIONS					
LOADING CONDITION	DEAD LOAD (psf)	LIVE LOAD (psf)	ROOF LIVE LOAD (psf)	SNOW LOAD (psf)	TOTAL (psf)
High (H)	55	100	0	0	155
Medium (M)	55	0	0	45	100
Low (L)	55	0	20	0	75

Table 6-2 Beam Loading Conditions

Three loading conditions were used in order to obtain a wide variety of data as well as mimic loading conditions experienced by a typical structure. The high loading condition (H) resembles a loading scenario of a highly occupied structure, such as apartment buildings, office and theater lobbies, and other general assembly areas. The medium (M) and low (L) loading conditions resemble a roof structure with either a high snow load or a typical construction/maintenance load. These loading conditions matched with the various spans and tributary widths provided a variety of scenarios for different beams to be designed.

Beam Design

Although these beams were designed to resist the same loads, the design equations for steel, timber, and pultruded FRP beams differed from one another. Each material behaves differently under loading due to their inherent properties and characteristics, but they all experience the same ultimate and serviceability limit states. Two design philosophies were used in this analysis: Allowable Stress Design (ASD) and Load and Resistance Factor Design (LRFD). ASD compares the actual stresses due to forces experienced by the member to the allowed stresses from a member's mechanical properties and configuration. In order to ensure that the allowable stresses were never exceeded a safety factor (Ω) was applied. Wood design typically uses ASD due to the inconsistencies of wood members. Pultruded FRPs currently utilize ASD, but, as mentioned earlier, the ASCE in conjunction with the ACMA and PIC hope to publish the *Load Resistance Factor Design (LRFD) Standard for Pultruded Fiber Reinforced Polymer (FRP) Structures* to be available for all engineers. LRFD compares required strength due to the resisted forces of a member to the actual strength of a member. A resistance factor (Φ) is applied to the nominal strength of a member to ensure that the design strength capacity does not exceed the actual strength. Steel and concrete design commonly use LRFD because both materials provide consistent mechanical properties and known ultimate strengths.

Design manuals and handbooks published by specialized committees and organizations facilitate the design and construction of structures. As mentioned in the previous chapter, organizations such as the AISC and AFPA specialize in the design of steel and wood structures, and are responsible for the progress and advancement of the structural design of their respective materials. Pultruded FRPs currently lack a uniform code in the United States, but the ASCE *Structural Plastics Design Manual* has assisted engineers in the design of fiber reinforced plastics since 1984, and the EUROCOMP Design Code and Handbook, *Structural Design of Polymer Composites*, has provided design equations for pultruded FRP structures in Europe since 1996. Manufacturers have also published handbooks and design manuals for their pultruded profiles. For this report, these resources were used in the design of the steel, timber, and FRP beams.

Steel Beams

The AISC 360-05 in the *Steel Construction Manual* assisted in the design of the steel members for this analysis. It provides specifications for dimensions and properties of steel beams. The preferred type of steel used for wide-flange beams is A992 steel. A minimum yield stress (F_y) of 50,000 psi and an ultimate stress (F_u) of 60,000 psi were used in the design. To simplify the analysis only beams with compact webs and flanges were used in the design. This ensured that the limit state of flange or web buckling did not govern the design strengths of the beams. Table B4.1 of the AISC Specification provided limiting width-thickness ratios for compact webs and flanges.

Limiting Width-Thickness Ratios for Compression Elements (Table B4.1 AISC Specification)

Flanges

Equation 6 - 1: $\lambda = \frac{b_f}{2t_f} < \lambda_p$

Equation 6 - 2: $\lambda_p = 0.38\sqrt{\frac{E}{F_y}}$

Webs

Equation 6 - 3: $\lambda = \frac{h}{t_w} < \lambda_p$

Equation 6 - 4: $\lambda_p = 3.76\sqrt{\frac{E}{F_y}}$

LRFD was used in the design of steel members so the design values were multiplied by the corresponding Φ factor, and the applied gravity loads were factored according to the appropriate load combinations from the ASCE 7-05 Chapter 2, Section 2.3 listed below:

Equation 6-5

1.) 1.4D

2.) 1.2D + 1.6L + 0.5(L_r or S)

3.) 1.2D + 1.6(L_r or S) + L

4.) 1.2D + L + 0.5(L_r or S)

Design equations for compact steel beams were obtained from Chapters F and G of the AISC 360-05. The beams in this analysis were designed using the following design equations:

Steel Design Equations

Flexural Design: Chapter F, AISC Specification

Equation 6-6: $\Phi_b M_n \geq M_u,\ \Phi_b = 0.9$

Equation 6-7: $\mathrm{L_b} \leq \mathrm{L_p} : M_n = M_p = F_y Z_x$

Equation 6-8: $\mathrm{L_p} < \mathrm{L_b} \leq \mathrm{L_r} : M_n = C_b \left[M_p - (M_p - 0.7 F_y S_x) \left(\frac{L_b - L_p}{L_b - L_r} \right) \right] \leq M_p$

Shear Design: Chapter G, AISC Specification

Equation 6-9: $\Phi_v V_n \geq V_u, \Phi_v = 1.0$

Equation 6-10: $V_n = 0.6 F_y A_w C_v$

Equation 6-11: $C_v = 1.0 \text{ if } \frac{h}{t_w} \leq 2.24\sqrt{\frac{E}{F_y}}$

Normally, braced length would a critical role in the design of steel wide flange beams because lateral-torsional buckling typically governs for beams with compact webs and flanges; however, the compression flange of the beam was continuously braced by the roof or floor decking so lateral-torsional buckling did not govern. The serviceability limit state of deflection was the governing limit state for all steel beams. Allowable deflection limits were obtained from the *International Building Code (IBC) 2009*, Table 1604.3. Live load deflections were limited to the span/360 and total load deflections were limited to the span/240. Thus, beams were selected to satisfy the most stringent limit state, which typically was the deflection limit state.

Wood Beams

As mentioned earlier, the *National Design Specification (NDS) for Wood Construction* assisted in the design of the wood beams for this analysis. ASD was used in the design of wood members, so design stresses were factored and compared to the actual stresses. The NDS provided allowable nominal stresses (F_b, $F_{c\perp}$, F_v) to be multiplied by a variety of adjustment factors depending several design parameters (load duration and axis, moisture content, ambient temperature, beam dimensions and stability and repetition), which obtained the allowable design stresses (F'_b, $F'_{c\perp}$, F'_v) to be compared to the actual stresses (f_b, $f_{c\perp}$, f_v). For this analysis, sawn lumber members of the species Douglas-Fir Larch and glued laminated, or “glulam”, members with a combination symbol of 24F-V4 were used. Nominal allowable stresses can be found in the NDS. Below are the design equations for sawn lumber and glulam beams:

Wood Design Equations (National Design Standard for Wood Construction)
Sawn Lumber
Equation 6 - 12: $F_b' = F_b C_D C_M C_t C_L C_F C_{fu} C_i C_r$
Equation 6 - 13: $F_v' = F_v C_D C_M C_t C_i$
Equation 6 - 14: $F_{c\perp}' = F_{c\perp} C_M C_t C_i C_b$
GluLam
Equation 6 - 15: $F_b' = F_b C_D C_M C_t C_L C_V C_{fu} C_c$
Equation 6 - 16: $F_v' = F_v C_D C_M C_t$
Equation 6 - 17: $F_{c\perp}' = F_{c\perp} C_M C_t C_b$

Each adjustment factor serves the purpose of increasing or decreasing the design allowable stress according to the appropriate design parameter. C_D adjusts the design stress by accounting for the duration that the load is applied. Wood can resist substantially greater loads for shorter durations than for longer durations, so C_D accounts for the type of loads applied to a beam. Permanent loads, such as dead loads, provide a C_D of 0.9 that reduces the allowable design stress. Less permanent loads, such as snow or roof live loads, increase the allowable design stress by 1.15 and 1.25, respectively. The magnitude of these loads governs which C_D value is used. C_M adjusts the design stress by accounting for the moisture content of the member. Moisture content higher than 19% for sawn lumber beams and 16% for glulam beams reduces the design allowable stress. For this analysis, the moisture content of the members was designed to be less than the limit so C_M equaled 1.0. C_t adjusts the design stress according to ambient temperature. Prolonged exposure to temperatures exceeding 100°F can reduce the moisture content of wood and alter its mechanical properties so C_t accounts for these affects. For this analysis, the ambient temperature was assumed to be below 100°F so C_t equaled 1.0. Beam stability factor, C_L, adjusts the design allowable stress for the effect of lateral-torsional buckling and takes into account for braced length and slenderness of the bending member. Since all the beams were laterally braced from the deck, C_L equaled 1.0. The sizes of beam cross-sections can vary greatly. Nominal values (F_b, $F_{c\perp}$, F_v) for different sizes of profiles can be inconsistent in wood design so C_F and C_V adjust the design values to accommodate for these inconsistencies for sawn lumber and glulam members. C_{fu} adjusts the design values for loading on the wide face of the member. For this analysis, no loading occurred on the wide face of any member so C_{fu} equaled 1.0. Incising involves making slit-like holes parallel to the grain of the entire sawn lumber member to ensure more uniform and deeper penetration of preservatives. This, however, can have a detrimental effect on the strength of the wood so the incising factor, C_i, adjusts the design value for incising of the member. For this analysis, there was no incising done to the members so C_i equaled 1.0. Typically in wood framing, sawn lumber joists are spaced relatively closely in a floor or roof system. This redundancy often proves to be advantageous for the strength of the system. The repetitive member factor, C_r, increases the design values by 1.15 if three or more sawn lumber members are spaced within 24" on center of each other. For this analysis, C_r equaled 1.15 for the beams designated as "1002" and 1.0 for the others. C_b adjusted the design value for the bearing area at the supports of the beam. C_c accounted for any curvature in glulam beams. For this analysis, the glulam beams had no curvature so C_c equaled 1.0. The allowable design stresses were calculated using the appropriate adjustment factors and compared to the actual stresses. Similar to the steel design, the serviceability limit state of deflection governed for all members. The same deflection limits were used.

Pultruded FRP Beams

For this analysis, the EUROCOMP Design Code and Handbook, *Structural Design of Polymer Composites*, the ASCE *Structural Plastics Design Manual*, and manufacturers' design manuals and product specifications assisted in the design of the pultruded FRP beams. Safety factors played an important role in the design of pultruded FRP beams. Generally, manufacturers' design manuals take a much more conservative approach than typical design codes. All three of the manufacturers (Bedford Reinforced Plastics, Inc.; Creative Pultrusions, Inc.; Strongwell Corporation) researched for this analysis applied a safety factor of 2.5 to stresses associated with bending and 3.0 for stresses associated with shear. To simplify this analysis, the mechanical properties from Creative Pultrusions, Inc., *Pultrex*® **SuperStructural** Profiles were used for the design of all the pultruded FRP beams (see **Table** 4-3). Flange buckling, web buckling due to bending, web buckling due to shear, and lateral-torsional buckling would normally dictate the beam dimensions for the ultimate limit state, but since the compression flange was braced by the decking lateral-torsional buckling did not govern. Flexural, shear, and bearing stresses were also checked against the allowable stresses provided by the manufacturer. As with the steel and wood beams, the serviceability limit state of deflection governed for the pultruded FRP beams. In fact, deflection limits resulted in the somewhat overly conservative design of the beams due to the relatively low stiffness of pultruded FRPs. The longer spans of beams (3010, 2010, and 2005) were able to deflect well past the deflection limit before exceeding any of the ultimate limit states.

Maximum width-to-thickness ratios from Table 7-1 of the ASCE *Structural Plastics Design Manual* were used to prevent local buckling for FRPs and design equations for pultruded FRP beams were taken from the EUROCOMP Code:

Limiting Width-Thickness Ratios for Beam Elements (Table 7-1 ASCE Structural Plastics Design Manual)

Flanges

Equation 6 - 18: $\lambda = \frac{b_f}{t_f} < \lambda_p$

Equation 6 - 19: $\lambda_p = 0.6\sqrt{\frac{E}{F_b\left(1-v^2\right)}}$

Webs

Equation 6 - 20: $\lambda = \frac{h}{t_w} < \lambda_p$

Equation 6 - 21: $\lambda_p = 5.7\sqrt{\frac{E}{F_b\left(1-v^2\right)}}$ (Bending)

Equation 6 - 22: $\lambda_p = 2.7\sqrt{\frac{E}{F_v\left(1-v^2\right)}}$ (Shear)

v : Poisson's ratio $\left(\text{in.}/\text{in.}\right)$

E : Modulus of Elasticity (psi)

F_b, F_v : Nominal Bending and Shear Stress (psi)

b_f : Flange width (in.)

t_f : Flange thickness (in.)

h : Web depth (in.)

t_w : Web thickness (in.)

Equation 6 - 23

$$\sigma_{cr}^{\ flange} = \frac{\pi^2}{t_f\left(b_f/2\right)^2}\left(D_x\left(\frac{b_f/2}{a}\right)^2 + \frac{12D'_{xy}}{\pi^2}\right)$$

t_f : Thickness of flange (in.)

b_f : Width of flange (in.)

D_x, D_{xy} : Stiffness of elements (in.-lbs.)

a : Half wavelength of buckling element (in.)

Equation 6 - 24: $\sigma_{cr}{}^{web} = \frac{2\pi^2}{t_w b_{eff}{}^2}\left(\sqrt{D_x D_y} + H_o\right)$

Equation 6 - 25: $\tau_{cr}{}^{web} = \frac{32\left(D_x D_y{}^3\right)^{0.25}}{d_w{}^2 t_w}$

Equation 6 - 26: $H_o = \frac{1}{2}\left(v_{xy}D_y + v_{yx}D_x\right) + \frac{G_{xy}t_w{}^3}{6}$

d_w : Depth of web (in.)

t_w : Thickness of web (in.)

b_{eff} : Effective width of web (in.)

G_{xy} : Modulus of Rigidity (psi)

D_x, D_y : Stiffness of elements (in.-lbs.)

v_x, v_y : Poisson's ratios $\left(\text{in.}/\text{in.}\right)$

Equation 6 - 27: $\sigma_{cr}{}^{LTB} = \left[\frac{C_b\pi}{S_x\left(KL\right)}\sqrt{EI_yGJ + \frac{d^2\pi^2E^2I_y{}^2}{4\left(KL\right)^2}}\right]$

C_b: Moment Gradient Adjuster = 1.13 (no lateral support), 0.97 (full lateral support)

K : Effective Length Coefficient = 1.0 (no lateral support), 0.5 (full lateral support)

L : Braced Length (in.)

E : Modulus of Elasticity (psi)

I_y : Second Moment of Inertia (minor axis) (in.^{4})

G : Modulus of Rigidity (psi)

J : Rotational Moment of Inertia (in.^{4})

d : Depth of Member (in.)

Comparisons

A side-by-side comparison of all three beams provides interesting insight and a better understanding of each material's effectiveness in resisting load. Member dimensions, weight, and governing limit states are a few aspects that can be examined from a side-by-side comparison. **Table** 6-3 lists the dimensions and governing limit states of each beam. Primary limit states were associated with the serviceability limit state of deflection. Secondary limit states were associated with the governing ultimate limit state and shown in order to provide insight into the failure mode for each beam. The secondary limit states were obtained by ignoring the deflection limits and identifying the ultimate limit state that governed. These limit states included deflection (Δ), flexural strength (B), shear strength (V), web buckling (WB), and flange buckling (FB). This analysis resulted with pultruded FRP beams that reached the limit state for deflection much prior to exceeding any other ultimate limit state. The ultimate limit states that were prevalent in the FRP members selected were flange buckling for the longer spans of beams and web buckling for the shorter spans. Of course, the highly customizable nature of pultruded FRPs allows for a wide variety of element thicknesses that could resist local buckling. Deflection also governed the steel members selected, but the limiting web height-to-thickness ratio for shear yielding and bending stress governed for slightly smaller members. Deflection and stress due to bending were the governing limit states for wood members.

MEMBER SIZES						
BEAM	STEEL MEMBER	LIMIT STATE	WOOD MEMBER	LIMIT STATE	FRP MEMBER†	LIMIT STATE
3010H	W21X44	Δ, V	8-3/4 X 27*	B, Δ	10 x 30 x 1	Δ, FB
3010M	W18X35	Δ, V	8-3/4 X 22-1/2*	B, Δ	10 x 24 x 1	Δ, FB
3010L	W16X31	Δ, V	8-3/4 X 19-1/2*	B, Δ	10 x 21 x 1	Δ, FB
2010H	W14X22	Δ, V	5-1/8 X 22-1/2*	B, Δ	10 x 18 x 1	Δ, FB
2010M	W12X19	Δ, B	5-1/8 X 19-1/2*	B, Δ	10 x 15 x 1	Δ, FB
2010L	W12X19	Δ, B	5-1/8 X 16-1/2*	B, Δ	10 x 13 x 1	Δ, FB
2005H	W12X16	Δ, B	3-1/2 X 19-1/2*	B, Δ	10 x 13 x 1	Δ, WB
2005M	W12X16	Δ, B	3-1/2 X 16-1/2*	B, Δ	10 x 12 x 3/4	Δ, WB
2005L	W12X16	Δ	3-1/2 X 15*	B, Δ	8 x 12 x 3/4	Δ, FB
1005H	W8X13	Δ	6 X 12**	B, Δ	8 x 8 x 1/2	Δ, WB
1005M	W8X13	Δ	6 X 10**	B, Δ	4 x 8 x 1/2	Δ, WB
1005L	W8X13	Δ	6 X 8**	B, Δ	4 x 8 x 3/8	Δ, WB
1002H	W8X13	Δ	4 X 10**	B, Δ	4 x 8 x 3/8	Δ, WB
1002M	W8X13	Δ	4 X 8**	B, Δ	4 x 8 x 3/8	Δ, WB
1002L	W8X13	Δ	2 X 10**	B, Δ	4 x 8 x 3/8	Δ, WB
† Sizes designate (flange width) x (beam depth) x (flange & web thickness) in inches.						
* GluLam sizes.						
** Sawn Lumber nominal sizes.						
LIMIT STATES: Δ = Deflection, B = Flexural Strength, V = Shear Strength: shear yielding and shear buckling, WB = Web Buckling, FB = Flange Buckling						

Table 6-3 Steel, Wood, and Pultruded FRP Beam Sizes

A noticeable difference among the three types of members is the beam dimensions. The largest steel beam in this analysis measures 21 inches deep and 6-1/2 inches wide at the flange; a relatively small member compared to 8-3/4 inch wide by 27 inch deep wood member and 10 inch wide by 30 inch deep FRP member. This can be attributed to the high strength of steel as it does not require very much material to resist loads. As the loads and spans decrease the steel member gradually arrives at minimum size of 8 inches deep and 4 inches wide for workability and connection purposes, but a more ideal option could be the use of open web steel joists for the smaller spans. The use of open web steel joists provides a much lighter alternative than the minimum W8X13 shapes while sufficiently resisting the same loads. Web and flange thickness vary with pultruded FRP and steel members. The steel member for the “3010H” beam has a web thickness of 3/8 of an inch and a flange thickness of 7/16 of an inch while the FRP member had a web and flange thickness of 1 inch. Different web and flange thicknesses optimize a member’s ability to resist flexural loads. For the FRP design, the thicknesses for the flanges and web were the kept the same to narrow in on the sufficient width and depth dimensions. The maximum width-to-thickness ratios to prevent local buckling provided by the ASCE *Structural Plastics Design Manual* were considered but often resulted in beams slightly with thicker flanges and thinner webs than the ones selected, in which case the governing limit state (after deflection) was bearing stress of the webs at the beam supports. Further research and analysis would provide optimal beam dimensions; namely the web and flange thicknesses. The pultruded FRP and wood sizes show some similarities in the depth of the members. Glulam wood beams are essentially a composite material as they incorporate smaller wood laminates adhered together with an epoxy; however, they typically have a rectangular cross-section whereas the pultruded FRP members’ profiles resemble a wide-flanged beam similar to steel members. Again, a minimum depth of 8 inches was used for pultruded FRP beams for workability and connection purposes.

This analysis provided interesting results regarding the weight of the members designed. Member weight plays an important role in the decision of one structural material over another. The overall weight of the structure affects foundation sizes as well as the lateral force resisting system (LFRS) in the event of a seismic event. Moreover, the success of a structural material can be measured by its effectiveness in resisting loads including its self weight. Pultruded FRPs boast a high strength-to-weight ratio primarily due to the fiberglass content of the members; however, in the side-by-side comparison each pultruded FRP member weighed almost the exact same as both the steel and wood members.

MEMBER WEIGHTS (plf)			
BEAM	STEEL MEMBER	WOOD MEMBER	FRP MEMBER
3010H	44	49.2	40.3
3010M	35	41.0	35.3
3010L	31	35.5	32.8
2010H	22	24.0	30.2
2010M	19	20.8	27.7
2010L	19	17.6	26.0
2005H	16	14.2	26.0
2005M	16	12.0	19.2
2005L	16	10.9	16.7
1005H	13	13.2	9.7
1005M	13	10.9	6.3
1005L	13	8.6	4.8
1002H	13	6.7	4.8
1002M	13	5.3	4.8
1002L	13	3.4	4.8

Table 6-4 shows the weights of each beam in pounds per linear foot.

MEMBER WEIGHTS (plf)			
BEAM	STEEL MEMBER	WOOD MEMBER	FRP MEMBER
3010H	44	49.2	40.3
3010M	35	41.0	35.3
3010L	31	35.5	32.8
2010H	22	24.0	30.2
2010M	19	20.8	27.7
2010L	19	17.6	26.0
2005H	16	14.2	26.0
2005M	16	12.0	19.2
2005L	16	10.9	16.7
1005H	13	13.2	9.7
1005M	13	10.9	6.3
1005L	13	8.6	4.8
1002H	13	6.7	4.8
1002M	13	5.3	4.8
1002L	13	3.4	4.8

Table 6-4 Beam Weights

The self weights for the steel, wood, and FRP beams were almost identical for the longest span of 30 feet, but as the spans and load magnitude decreased the weights of the steel and wood members decreased steadily and quickly. The weight of the FRP members decreased at a much more gradual rate. The pultruded FRPs seem more effective and economical at the beams with the shortest span of 10 feet. One possible explanation may be that the serviceability limit state of deflection resulted in much larger profiles of FRPs to be used due to its relatively low stiffness.

If the deflection criteria been ignored then a much smaller FRP beam would suffice resulting in a lighter beam.

For this analysis, the limit state of deflection was the governing limit state for every beam of every structural material. All materials experienced deflections due to bending, but FRP members also experienced deflections due to shear because of the low modulus of rigidity in FRPs. Shear account for 8% to 14% of the overall deflection of the FRP beams, while only accounting for 2% to 4% of the overall deflection of the steel beams. The modulus of rigidity (G) of the steel members (11,500,000 psi) is significantly higher than that of pultruded FRP members (500,000 psi), which explains the different values of deflection due to shear. In fact, steel's modulus of rigidity is so high that it is often neglected in flexural design.

The limit state of deflection prevents deformations that may endanger the occupants or interfere with the proper use of the structure so its importance should not be overlooked, but it is also important to know the governing ultimate limit state in the absence of the deflection limit state. Steel's ability to yield and deform while taking on more load makes it an extremely effective structural material, so engineers design steel members to exhibit these warning signs of yielding to allow the occupants adequate time to evacuate. Abrupt failures such as shearing are avoided. For this analysis, only steel members with compact webs and flanges were selected to eliminate local buckling limit states, otherwise checking for web and flange buckling would necessary. The FRP members, however, were checked for local buckling because the maximum width-thickness ratios of the webs and flanges were exceeded for some cases. Also, the compression flange of all the beams was continually braced by the decking so lateral-torsional buckling did not govern. The governing ultimate limit states for pultruded FRPs were flange buckling for the 30-foot spans, flange and web buckling for the 20-foot spans, and web buckling for the 10-foot spans. Pultruded FRPs are extremely customizable so the stiffness and thickness of each element can be tailored for any application or loading scenario.

As mentioned at the beginning of this chapter, one project may have several adequate solutions. Just because one design satisfies the project does not mean that another one is wrong. Engineers may juggle several options until choosing one that they feel provides an efficient and economical solution.

CHAPTER 7 - Conclusion

As with every structural material pultruded fiber reinforced polymer profiles have advantages and disadvantages that either makes them an ideal or insufficient material choice. Steel, wood, and other traditional structural materials have withstood the test of time and proved worthy of constructing safe and lasting structures. The progress of pultruded FRP members relies heavily on the quality and optimization of the material as well as the performance and durability of the member.

Pultruded FRP's versatility seems to imply it has a niche in nearly every sector of construction; industrial, commercial, infrastructure, etc. Corrosion and chemical resistance, electromagnetic transparency, incombustibility, high strength-to-weight ratio, and insect and rot resistance make FRPs an impressive structural material suitable for applications that prove too harsh for traditional materials. However, some less than desirable characteristics of FRPs inhibit the construction material's growth in the United States. A relatively low modulus of elasticity results in large deflections that exceed the serviceability limits for most structures, which consequently requires deeper and thicker profiles eliminating the advantage of light weight. The anisotropic nature of pultruded FRPs requires special attention to transverse forces that may cause the member to buckle. Prolonged exposure to heat or moisture drastically reduces the strength and stiffness of pultruded FRPs, which may cause issues with fire safety but is no more of a concern than with wood structures. A lack of standards or specifications for the mechanical properties of pultruded FRPs leaves engineers to rely on all the manufacturers' specifications, which provide a range of properties. Also a lack of a unifying code to assist engineers is a major deterrent, but progress is slowly being made and eventually the ASCE will publish the *Load Resistance Factor Design (LRFD) Standard for Pultruded Fiber Reinforced Polymer (FRP) Structures*. Overall, pultruded FRPs mark the future of structural materials, but many issues and concerns must be resolved before they become more common in the construction industry.

FRPs exhibit unique characteristics and behaviors that may eventually be of interest to all engineers and designers. Until then FRPs must pass all the tests and erase all the doubts in order to become more popular and widely known. The constant improvement in performance and efficiency ensures a bright future for pultruded FRP profiles.

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