Prestudy of utility poles in fiber composite

Master of Science Thesis

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Preface

This master thesis is a prestudy of the usage of fiber composite as material in 220 kV utility poles. The thesis has been done on behalf of Svenska Kraftnät.

I would like to thank Lillemor Carlshem of Svenska Kraftnät, who offered the opportunity to make this thesis and her role as instructor. I also would like to thank the following persons at KTH, who have helped me in various questions throughout the thesis work: My examiner Malin Åkermo as well as teachers Per Wennhage and Stefan Hallström, all at the department of Aeronautical and Vehicle Engineering, Royal Institute of Technology (KTH).

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Abstract

The job requestor for the thesis work has been Svenska Kraftnät; the Swedish state utility which runs and administers the national electrical grid. Svenska Kraftnät is interested in finding suitable alternatives in terms of material for utility poles, which traditionally have been made of wood. Wooden utility poles are difficult to find for heights more than 20 meters. Poles of wood are also subject to wood peckers. Furthermore, a possible future ban of creosote may pose an obstacle to use wooden poles.

The aim of this thesis work has been to look at the possibilities of using fiber composite as material for 220 kV line utility poles. The thesis work has been done in form of a prestudy.

The work has been performed as literature studies based on books, articles and internet searches. Calculations have been carried out using Euler methods and classic beam theory to estimate the material thickness of a utility pole. The calculations have been based on load cases, loads and deflection boundaries provided by Svenska Kraftnät.

There are four utility pole manufactures in North America. Most of the fiber composite utility poles are present in North America. According to manufacturers, their poles will last 40 to 80 years and the poles are resistant to biological factors like fungus or woodpeckers.

The materials currently used for fiber composite utility poles are combinations of glass fibers and polymer based thermoset resins such as polyester, vinylester or polyurethane. The utility pole manufacturers have chosen different resins for their specific product but all of manufacturers have chosen glass fiber as reinforcement material.

The fibers in the composite determine the mechanical properties due to their strength and modulus. The values of the mechanical properties of the fibers are often one to two degrees higher than the corresponding values of the matrix. The material of choice for utility poles is glass fiber due to its combination of good general properties and cost efficiency. In order to choose a resin for the utility pole further work should be done, based on more specific requirement specifications.

As a result of the load case of beam bending, i.e. transverse and longitudinal loads, the pole should be braced in order to meet the requirements of maximum deflection. It is noteworthy that also a wooden pole would need to be braced in order to fulfill these requirements. When bracing the pole the maximum vertical load will be the dimensioning load for the material thickness.

As of today, there are no recycling industries present that can take care of fiber composite material. This is however an area currently subject to research. Of the methods being discussed in this report, the fluidised bed process is the only method being able to recover and recycle the fibers. The other methods are based upon milling or combustion of the material, the remains then being used as fillers or reinforcement in other materials.

Sammanfattning

Uppdragsgivaren till detta examensarbete har varit Svenska Kraftnät, ett statligt bolag vars uppgift är att driva och förvalta de nationella elkraftnätet. Svenska Kraftnät är intresserade av kraftledningsstolpar i alternativa material. Stolpar har hittills varit av trä. Materialförsörjningen av trästolpar högre än 20 meter är dock svår och hackspettar är dessutom ett problem vid användandet av trästolpar. Ett möjligt framtida förbud mot kreosot kan vara ett hinder för fortsatt användande av trästoplar.

Syftet med detta examensarbete har varit att undersöka möjligheterna att använda fiberkompositer som material för 220 kV kraftledningsstolpar.

Arbetet har utförts som en litteraturstudie, baserat på böcker, artiklar och sökningar på internet. Beräkningar har utförts genom Eulers knäckningsfall och klassisk balkteori, för att kunna uppskatta nödvändig materialtjocklek på en kraftledningsstolpe. Beräkningarna har varit baserade på indata från Svenska Kraftnät gällande lastfall, laster samt utböjningstoleranser.

Det finns i nuläget fyra tillverkare av kraftledningsstolpar av fiberkomposit i nordamerika, där även de flesta stolpar av fiberkomposit återfinns. Enligt tillverkarnas egna uppgifter kommer deras stolpar att hålla i 40 till 80 år. De påverkas dessutom inte av biologiska faktorer som röta eller hackspettar.

De material som i dagsläget används för kraftledningsstolpar av fiberkomposit är olika kombinationer av glasfiber och härdplaster, såsom polyester, vinylester eller polyuretan. Olika tillverkare har valt olika härdplaster som matris, men de har alla valt glasfiber som förstärkning.

De mekaniska egenskaperna i en komposit bestäms till största delen av fibermaterialet p.g.a. dess styrka och höga e-modul. Dessa värden är ofta en eller två storleksordningar större än motsvarande värden för matrismaterialet. Glasfiber är det föredragna fibermaterialet p.g.a. dess kombination av goda mekaniska egenskaper och kostnad. För att göra ett val av härdplast för matrisen så bör lämpligtvis ett mer detaljerat arbete göras, baserat på tydligare kravspecifikationer.

Beräkningarna för belastningsfallet böjning, d.v.s. transversell och longitudinell last, visar på att stolpen måste stagas för att klara kraven på maximal utböjning. Värt att notera är att detta gäller även för en stolpe i trä, för att klara kraven. Med stagning kommer maximal vertikal last att vara den dimensionerande lasten för stolpens godstjocklek samt diameter.

I dagsläget finns ännu inte någon etablerad industriell återvinning av fiberkompositer. Dock så utförs mycket forskning på området. Av de återvinningsmetoder som nämns i detta examensarbete så är det endast fluidised bed process som har möjlighet att ta tillvara och återanvända fibrerna. De övriga metoderna baseras på malning eller förbränning av kompositmaterialet, för att därefter använda resterna som fyllnadsmaterial eller förstärkning i andra material.

Table of content

1 Introduction

This chapter introduces the background, aim and method of the work. Fiber composite is a material relatively new for the purpose of utility poles, although fiber composites in general have been in use for a long time for different applications, such as aerospace, automotive and boats.

1.1 Background

The national electrical grid in Sweden is administered and run by Svenska Kraftnät which was established 1992. The grid consist of approximately 15.000 kilometers of 220 kV and 400 kV lines, divided in 4.400 km respectively 10.600 km lines plus additional installations and interconnections to neighboring countries and IT systems [9].

The system of transmission lines are supported by steel towers and wooden poles. The wooden poles are present in the 220 kV lines. The wooden poles are based on natural grown pine trees which are impregnated with creosote, which protects the wood from rot. The poles are divided in different dimension classes: L to S, where the S-class is the largest. S-class include poles that are up to 23 meters, though these are more seldom and not easy to find.

Finding a substitute to wooden poles is of interest mainly due to two facts;

- Difficult to find trees in lengths over 20 meters.
- Woodpecker attacks.

To confront these problems, Svenska Kraftnät is interested in finding alternative materials to be used in utility poles instead of wood.

In the future, it might also be possible that creosote is banned. Such a development will further strengthen the need for a substitute material for wood.

1.2 Aim of work

The purpose of this thesis work is to look at the possibilities to replace the traditional 220 kV line wooden utility pole with a pole using fiber composite as the material of choice. The influence from the environment is to be evaluated. This work has been done in form of a pre-study.

1.3 Limitations

This thesis work has been based on 20 weeks of work. The company Svenska Kraftnät has no previous experience of fiber composite applications. Therefore, emphasis has been put on describing different aspects on using fiber composite as material in utility poles. Also, the work tries to give a background to the different questions which will arise during a process of choosing material and supplier for a utility pole of fiber composite.

Due to the width and amount of the related subjects, this work does not give an in-depth precise answer for all questions that arise during a process of deciding and defining a new utility pole of fiber composite. However, the orderer will have a good background for discussions with e.g. suppliers and manufacturers, as well as for internal decision process.

The work is based on the agreement that Svenska Kraftnät is providing all loads on a given utility pole. The dimensioning is based upon Svenska Kraftnät's load information.

1.4 Method

The work has mainly consisted of literature studies and calculations. Literature studies have been based on books, articles and internet searches, including manufacturer's websites.

Calculations have been made in order to estimate the needed thickness of composite material for a utility pole. The calculations have been based on information and load cases provided by Svenska Kraftnät.

Typical materials for fibers and matrix have been reviewed and suggested, matching the specific application of utility poles. The work has also been focused to answer Svenska Kraftnät's questions regarding the use of fiber composites. This, and the reviews and suggestions are based on the literature studies.

2 Constituent materials of fiber composites

A common way to explain what a composite is in a general, yet simple way is to use the following definition for a composite: “A macroscopic combination of two or more distinct materials into one with the intent of suppressing undesirable properties of the constituent materials in favor of desirable properties”[5]. In this thesis the type of composite investigated is fiber composite. A simplified description of fiber composites is that it contains fibers as reinforcement and matrix material that keeps the fibers in place and protects the fiber from the surrounding environment.

Different constituent materials are investigated in order to define a fiber composite suitable to replace the wooden pole for a 220 kV line.

2.1 Fibers

As mentioned above, the fibers are the reinforcement in the fiber composite. The main function of the fibers is to carry the load that the composite is exposed to. The fibers also determine the mechanical properties of the composite, mainly due to their strength and modulus. The values of these properties are often one to two orders higher than the corresponding values of the matrix [1]. To achieve a desired strength of the composite material, the fibers can be placed in different orientations. The placement should be set depending on in which directions the loads are distributed within the material.

When designing a composite material, one must take into consideration the character of the fibers, i.e. whether the fibers are isotropic, anisotropic or orthotropic. This in turn affects the properties of the finished composite in different directions.

There are several different fibers that can be used as reinforcement in an application, e.g. carbon, Kevlar, spectra, glass, to mention a few. The properties of these different fibers differ; each type having specific characteristics.

Carbon fibers are a semi conducting material that offers the highest stiffness [1,4]. They have very low density and a relatively high strength. The price is relatively high. Carbon fibers are available in different groups:

- high strength (HS)
- intermediate modulus (IM)
- high modulus (HM)
- ultra high modulus (UHM).

Other properties that characterize carbon fibers are their high resistance to corrosion, creep and fatigue [4].

Aramid fibers can be recognized by its golden yellow color. Aramid fibers have high strength, although not as high as carbon fibers. The density of Aramid is lower than carbon. Typically for Aramid is the good resistance to impact. Aramid fibers can degrade when exposed to sunlight [4]. Its price is relatively high [28].

Glass fibers present good strength properties but lower stiffness than Aramid and Carbon fibers. Glass fibers are a good electrical insulator. The material has good corrosion resistivity and a major advantage is its low price compared with Aramid and Carbon fibers.

Property	**E-glass**	**Carbon (HT)**	**Aramid/Kevlar**
Tensile Strength [MPa]	2200 (Roving)	3500	2340
Young´s Modulus [GPa]	74	230	143
Density [kg/m^3]	2540	1760	1470
Thermal Expansion [x10^{-6}/K]	5,0	-0,5	-4,9
Thermal Insulation [W/mK]	1,0	10	0,041

Table 1 *Table of specific properties* [28]

Further focus is put on glass fibers due to the combination of good general properties and cost efficiency. Glass fibers are also a good choice due of its electrical insulation character and good chemical resistance in corrosive environments.

Glass fibers are produced by mixing quarry products, i.e. a composition of:

- Silica ($SiO2$)
- Alumina ($AL2O3$)
- Calcium Oxide (CaO^{+})
- Magnesium Oxide (MgO)
- Boron Oxide ($B2O3$)
- F2, Na2O + K2O
- Fe2O3
- Other substances in smaller amounts

The substances are elaborated in a furnace at very high temperatures, approximately 1550ºC [3]. The liquid from the furnace is extruded throughout a platinum alloy. The platinum alloy has several holes which gives the filaments an approximate diameter of 3 – 25 µm. The final size of the fiber diameter is determined by [1]:

- hole size of the platinum alloy
- temperature and viscosity of the melt
- cooling rate
- drawing speed

The fibers are quenched after leaving the platinum alloy. Before the fibers are gathered together they are sized in order to protect the fibers. The sizing can be designed for different matrix types. By varying the proportions of raw materials, different types of glass fibers can be produced, e.g. E, C, D, R, S, T or AR-glass.

E-glass (electrical) is the most common used fiber among composites [3]. E-glass has good tensile and compressive strength. The cost is relatively low compared to other glass fiber types. The impact resistance is however fairly poor.

C-glass (chemical) has the best resistance against chemical attacks of the different glass fiber types. Thus, C-glass is a good material that can be used in the outer layer of applications which are exposed to harsh environments.

D-Glass is characterized by excellent dielectric properties. It has low electrical losses and is consequently a good application for structures which needs to be permeable for electromagnetic waves. D-glass fibers are used for applications such as electromagnetic windows, radomes and high performance printed circuit boards [3].

R, S or T-glass are the manufacturer’s trade names for equivalent fibers. These fibers have a higher modulus, higher tensile strength and higher interlaminar shear strength than E-glass. However, these fibers come with a higher price.

AR-glass is a glass fiber that was especially developed for reinforcing cement. The high zirconium content gives good resistance to the alkaline compounds that is being generated during drying of the cement. A typical application is building components.

The mechanical properties of the above discussed glass fiber types are compared to each other in Table 2.

Mechanical properties:

Properties	**E-glass**	**D-glass**	**R-glass**	**AR-glass**	**C-glass**
Density	2.60 g/cm^3	2.14 g/cm^3	2.53 g/cm^3	2.68 g/cm^3	2.53 g/cm^3
Tensile strength	3400 MPa	2500 MPa	4400 MPa	3000 MPa	
Tensile modulus	73000 MPa	55000 MPa	86000 MPa	73000 MPa	
Elongation at break	4.5%	4.5%	5.2%	4.3%	

Table 2 *Mechanical properties* [3]

2.2 Matrix

The fibers of a fiber composite are combined with a matrix to form the composite material. The function of the matrix is to transfer loads to the reinforcement, i.e. the fibers. The matrix also holds the reinforcement in place and acts as a protection of the fibers from the surrounding environment, as fibers can be quite brittle.

Whereas polymers are the dominating matrix material in fiber composites, there are some other matrix that are used as well in composites, e.g. metals, carbon, ceramics and concrete. Concrete as matrix are used in building structures where the reinforcement is made of glass fiber and replaces steel. The concrete/glass combination gives a weight reducing effect on building structures. Carbon matrices are used in carbon-carbon composites and are applied in high-temperature applications, e.g. rocket engines. For the utility pole construction further focus is set on polymer matrices.

2.2.1 Thermosets and thermoplastics

There are two major groups of polymers; Thermosets and Thermoplastics. The two groups differ in their chemical structure. One of the most fundamental differences is the molecular structure, where thermoplastics consist of long molecules with only secondary bonding between them, e.g. van der Waals bondings. In contrary, thermosets form besides secondary bondings also covalent bonds between the original molecules. These covalent bonds are formed during the crosslinking process, when the thermoset resin cures.

The highly crosslinked bonds in thermosets result in a three-dimensional network. The structures of thermosets result in properties such as:

- excellent mechanical properties (high stiffness, hardness and strength)
- better resistance to solvents and heat.

However, thermosets matrices can be more brittle than thermoplastics.

Due to the differences in the molecule structure, thermoplastics can be melted; thermosets on the other hand cannot due to the covalent bonds. As a consequence, the possibilities to recycle fiber composites differ between thermosets and thermoplastics. See section 9.1.

When choosing a matrix for an application one must also consider the matrix processability. In section 3 the production methods are described. Thermosets have an advantage in processing due to their lower viscosity. Lower viscosity in the matrix improves the reinforcement impregnation. In Table 3 a comparison between thermoset matrices and thermoplastics matrices is presented. In Table 3 “+” represents an advantage.

Property	Thermosets	Thermoplastics
Cost	+	
Temperature tolerance	+	
Stiffness	+	
Strength	+	
Toughness		+
Fatigue life	+	
Creep	+	
Chemical resistance		+
Viscosity	+	
Recyclability		+

Table 3 *Comparison table Thermosets vs. Thermoplastics* [1]

Based on the result of Table 3 one can see that for a utility pole application, thermosets are preferred as matrix. Therefore, further focus presenting different matrix materials will be on thermosets.

The most common thermosets used in today fiber reinforced composites construction are:

- Unsaturated Polyester
- Vinylester
- Phenolics
- Epoxies

2.2.2 Unsaturated Polyester

Unsaturated Polyester resin (UP) is the most commonly used resin for the composite industry [6] and is sometimes referred as the workhorse of thermosets [1]. The UP comes in different types with different properties and is classified by its building blocks.

To construct an UP molecule, i.e. a basic building block, a special alcohol and a di-basic acid are put together which starts a reaction and creates the polyester and water as a byproduct [7]. By modifying the acids, alcohols and cross-linking monomers, and other additional products that are inserted in the polymer, different UP:s are produced.

The two most common UP:s that are used are orthophthalic polyester and isophthalic polyester. The differences between these two polyesters are that the orthophthalic polyester has lower cost but also has more modest mechanical properties than isophthalic polyester. Isophthalic polyester on the other hand has better environmental and water resistance properties than orthophthalic polyester [7].

Figure 1 shows an idealized chemical structure of a typical isophthalic polyester. In the figure, the reactive sites and the ester groups are indicated.

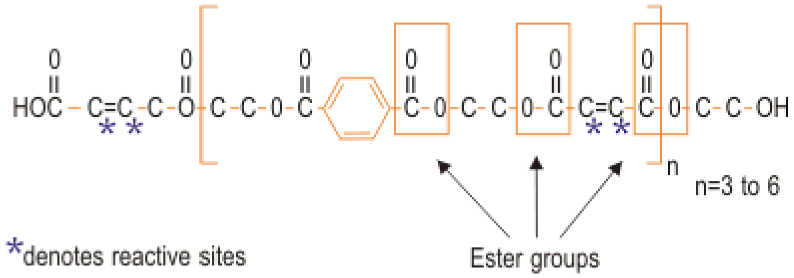


Figure 1 *Idealized chemical structure of a typical isophthalic polyester* [7].

2.2.3 Vinylester

Vinylester is a thermoset that is produced by making an epoxy react with an unsaturated acid [1]. The molecular chain of Vinylester is similar to unsaturated polyester. The main differences are that vinylester has reactive sites and ester groups at the end of the molecule chain.

Since the reactive sites are at the end of the chain, this will give vinylester with high molecule weight a lower modulus based on the lower crosslink density [1]. This is due to the fact that crosslinking takes place at reactive sites. The ester groups on vinylester are fewer than on UP, which gives vinylester better resistance to water due to the fact that ester groups are sensitive to water degradation by hydrolysis. Vinylester also gives a better resistance to chemicals than UP. The cross linking reaction is equal to the reaction of UP which gives vinylester the same advantages as the UP reaction, i.e. it can crosslink fairly rapid and in room temperature. Vinyl ester also gives a superior toughness compared to UP since the whole molecule chain can absorb shock loadings. Figure 2 shows an idealized chemical structure of a typical vinyl ester. In the figure the reactive sites and the ester groups are indicated. Note the position of the reactive sites and the position of the esters at the end of the molecule.

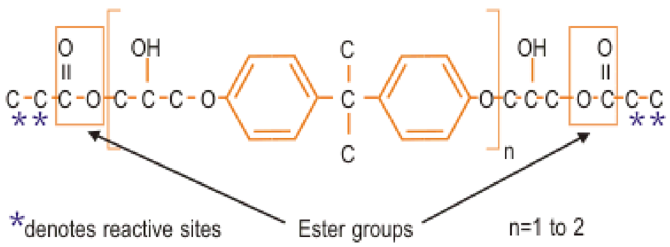


Figure 2 *Idealized chemical structure of a typical vinyl ester* [7].

2.2.4 Epoxy

Epoxy represents the highest performance matrix among the matrices that are presented above. The mechanical properties, resistance to environmental degradation and temperature tolerance are superior in comparison to both unsaturated polyester and vinyl ester. Epoxy is often used in high performance applications, e.g. aerospace, defense and sports applications.

Compared to unsaturated polyester and vinylester, epoxy does not have an ester group. The lack of the ester group gives good water resistance [7]. There are a wide range of modifications that can be made of the epoxy resin to suit a specific application; more than in unsaturated polyester. Further advantages of epoxy are a very low shrinkage level during processing. Epoxy also adheres very well to reinforcements which gives a good and durable product. Some drawbacks of epoxy are its price tag; it is rather expensive which results in a product that has a high material cost. Complex manufacturing processing of the composite also leads to an expensive product. A further drawback for epoxy is the health issue with allergy. Figure 3 shows an idealized chemical structure of a typical epoxy. The CH2-CH-O represents the epoxide group.

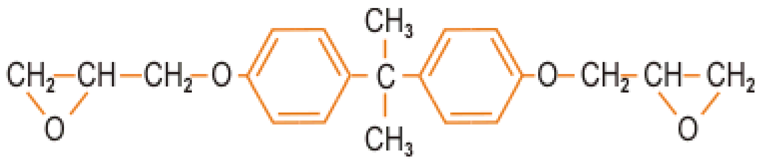


Figure 3 *Idealized chemical structure of a typical epoxy* [7].

Table 4 provides a summary of properties of the three different matrices above; unsaturated polyester, vinylester and epoxy.

Polyester	**Advantages**	**Disadvantages**
	Easy to use	Moderate mechanical properties
	Lowest cost of resins available	High styrene emission in open moulds
		High cure shrinkage
		Limited range of working times
Vinylester		
	High chemical/environmental resistance	Post cure generally required for high properties
	Higher mechanical properties than polyester	High styrene content
		Higher cost than polyester
		High cure shrinkage
Epoxy		
	High mechanical and thermal properties	More expensive than vinylester
	High water resistance	Critical mixing
	Long working times available	Corrosive handling
	Temperature resistance can be up to 220° C (dry)	

Table 4 *Advantages and disadvantages of Unsaturated Polyester, Vinylester and epoxy* [7].

2.3 Additives

Beside the matrix and the reinforcement, additives of different types are almost always present in fiber composite materials. They can be of various types, e.g. fillers to lower the cost of the matrix material and/or changing the mechanical properties. Additives may also have specific tasks, like adding UV-light resistance or fire tolerance to the material.

In this chapter, additives will mainly be presented in general since the type and quantity of chosen additives should be set when the exact material is chosen for a product and the desired properties thereof.

2.3.1 Additives in general:

There is a wide range of possibilities to change the properties of a matrix material by the use of additives. As a result of altered properties of the matrix, the properties of the composite will also change.

Examples of properties that can be altered:

- Processability
- Mechanical properties
- Electrical properties
- Shrinkage
- Environmental resistance
- Fire tolerance
- Color
- Cost

In thermosets specifically, additives in small amounts are also used in order to control the chemical crosslinking reaction during hardening of the resin, i.e. crosslinking agent, inhibitor, initiator, etc [1].

2.3.2 Additives – for a utility pole composite

Decisions about what additives to use in the matrix material could preferably be done in a late stage in the design phase, since several aspects influence the choice of including additives. Such aspects are:

- what composite material is to be used
- are there any mechanical properties that need to be altered
- is it desired to lower the cost of material by the use of inexpensive fillers, and if so, what will be impact be on mechanical properties

Nevertheless, some additives will most likely be considered:

UV-absorbers:
Also called Stabilizers. A UV-resistant additive. The impact of sunlight on most polymers may lead to discoloring and/or a more brittle material after exposure. A stabilizer can prevent such long-term effects by absorbing UV-light [1,29].

Colorants:
An alternative to have an outer paint layer is to include small amounts of colorant in the resin. Such a choice eliminates the need for costly painting. Most colorants are in the form of pigments [1,29].

3 Composite Manufacturing Techniques

There are a number of manufacturing techniques used for fiber composites. Depending of the product, some techniques are better suited for the product than other. Price, shape and material are some of the parameters that govern the choice of manufacturing technique. In this section, manufacturing techniques well suited for fiber composite utility poles are introduced.

3.1 Filament Winding

The filament winding process is commonly used for circular or oval products such as pressure vessels, drive shafts, tanks and pipes. The winding process is automated and the fibers are accurately placed onto a rotating mold, which is called a mandrel. Before the fibers are wound onto the mandrel they are impregnate in resin. The resin impregnation can be performed in different ways; this depends on the winding equipment. For example the reinforcement can be impregnated by a dip-through tank, by a pick up cylinder [1] or by a prepreg system [10].

After the fibers have been impregnated they are wound up on the mandrel in desirable orientations in order to achieve required strength in the direction that suits the product. The fibers in the 0° direction are restricted due to the nature of the equipment. Figure 4 shows a schematic illustration of reinforcement being impregnated in resin and then wound onto the mandrel.

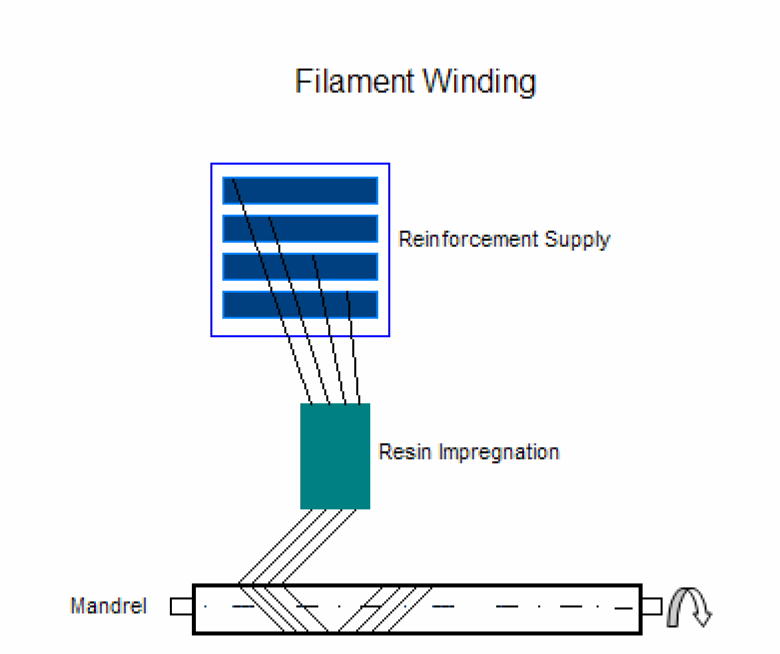


Figure 4 *Schematic illustration of filament winding process.*

After adequate layers have been applied to the mandrel, the processed part is left to cure. Depending on what matrix that is used the cure process can take place in either room temperature or if the matrix requires, in enhanced temperature using an oven. An autoclave may be used to assist the cure process when required.

The filament winding offers a fast and automated process which lowers the labor cost. A wide selection of thermoset matrices can be used in the process, e.g. epoxy, polyester, vinylester and phenolics [10]. As reinforcement material a wide selection of strand can be used e.g. glass fiber, carbon, Kevlar and etcetera.

Void fractions are relatively low with the filament winding process and the mechanical properties are good. The resin content can be controlled and the volume fraction of the reinforcement can be up to 70% [1]. The cost for large mandrels is however quite high and is therefore more suited for long product series. Another negative aspect is that the surface finish has an unattractive look.

3.2 Pultrusion

Pulltrusion is a process for producing full or hollow shapes. The method is continuous. The reinforcement is impregnated in resin. Fiber impregnation options:

- open resin bath
- RIM pultrusion

With an open resin bath the reinforcement is pulled by rods that are placed in the resin bath. The impregnation by the open resin bath method is accomplished by guiding the reinforcement into a bath through holes. The RIM method lets the reinforcement become impregnated by the resin in a cavity in which the reinforcement is pulled through.

After the impregnation, the material is pulled through a heated die to its final shape. In the pultrusion manufacturing process the fibers, from creels, are represented in the 0° direction, e.g. along the pultruded component. But also other fabrics may be used in the pultrusion process which can offer fiber directions other than at 0°.

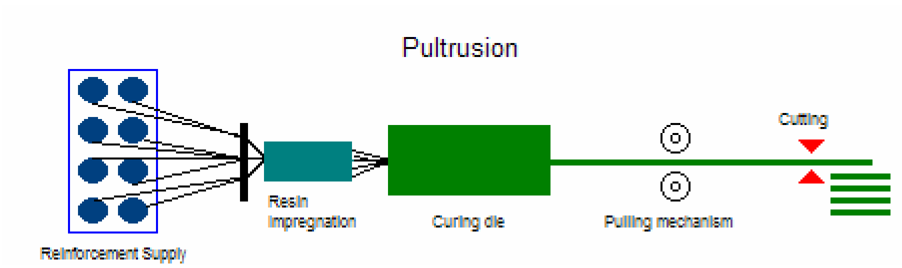


Figure 5 *Schematic illustration of pultrusion process*

The pultrusion process can offer products consisting of fiber materials and with a weight fraction from 30 to 70 percent, depending on shape, design and etcetera. Resins that can be used generally in the process include epoxy, polyester, vinylester and phenolics. Also some thermoplastics can be used.

The main advantage with pultrusion is that the method can be very fast and therefore economic. On the other hand, heat die costs can be high. The labor costs are low due to the automated process. The properties can be very good since the fibers can be accurately straight and high fiber content is possible. A disadvantage with pultrusion is the limitation to near constant cross sections, which leads to restricted possibility to process a conic shape. Another disadvantage with pultrusion is when it is processed with open resin bath due to the volatile emissions from the resin.

3.3 Centrifugal Casting

With the centrifugal casting method, the fabrics, mats or pre-impregnated components are placed into a hollow stationary mould. A catalyzed resin is sprayed onto the mat during slow rotation, which ensures that the resin is allocated over the mat. The mould is then rotated at a high speed during heating. The centrifugal force helps distribute the resin onto the reinforcement. When the process is finished the mould is stopped and the component is removed.

Common products that are manufactured using the centrifugal casting method are hollow products such as poles, pipes and tanks. Figure 6 shows a schematic illustration of the centrifugal casting process.

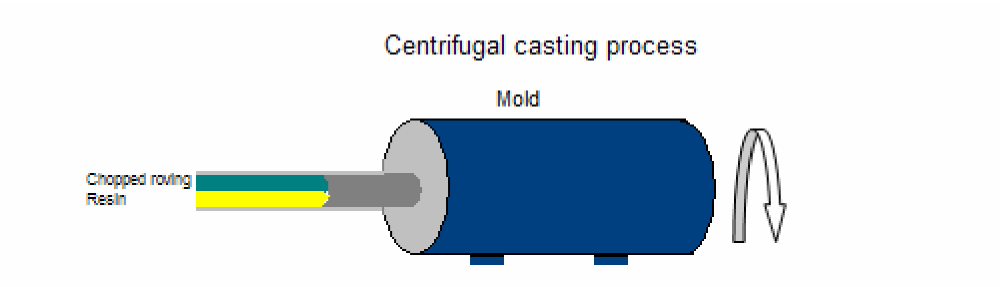


Figure 6 *Schematic illustration of centrifugal casting process*

An advantage with the centrifugal casting method is that it can provide good surface both on the inside and the outside. Further, the process is automated which leads to the possibility to high production rates.

Mechanical properties on products manufactured by this method are general lower than when using the filament winding process.

4 Attachments

No matter in what material the utility pole is designed for, the pole needs to have details attached to it such as:

- Climbing aids to make it possible for maintenance personnel to climb the pole
- Crossarms
- Stays, if they are not fastened in the crossarm
- Ground attachments

For structures made of wood or metal, there are widely established methods to join attachments to the structure. Joining attachments to a structure of fiber composite is not very different, but there are a few things to keep in mind, partly due to the material having non-homogenous properties.

The two most common techniques in joining different part are mechanical joining and adhesive joining. Both techniques can be used for composite parts and they both have advantages and disadvantages.

4.1 Adhesive joining

Adhesive joining requires an overlap area in which the two different parts adhere. This area must be sufficiently large in order to carry the transferred load. It is also important to analyze how the forces to carry are directed. Preferred mode of load transfer is shear [1].

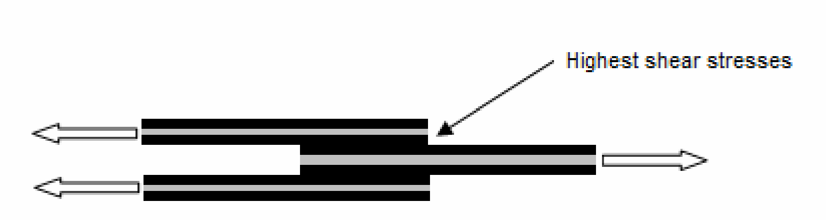


Figure 7 *Schematic illustration of shear stress*

As seen in Figure 7, the highest shear stresses occur at the ends of the joint. Therefore, a failure is likely to be initiated at the ends of the joint.

A very disadvantageous load case is when there is a load perpendicular to the joint, also known as ”peel force”. This type of loading may lead to delamination of the joint. The risk of delamination through peel forces can be reduced by carefully designing joints.

Figure 8 *Schematic illustration of delaminate lamina*

The most commonly used adhesives are based on epoxies. But also thermoplastics are used as adhesives for composites. Thermoplastics are hot melted and applied. When they cool, they re-harden. A disadvantage of epoxies is their weak peeling strength. Epoxies are therefore often modified with elastomers in order to improve fracture toughness and peel strength [14].

Before joining parts adhesively, proper surface preparations are important. The surfaces have to be cleaned accurately and all kind of contaminations have to be removed. The surfaces then are abraded in order to get a rough surface. This increases the active surface area as well as the surface energy in order to improve the bonding [14].

A disadvantage with adhesive joining compared with mechanical joining is that the part's surfaces must match each other quite well.

4.2 Mechanical joining

The basic method of mechanical joining is characterized by fixing together two materials with a mechanical fastener, e.g. a screw or bolt, through a cut-out hole, like a drilled hole. The components are held together by physical forces, like frictional forces between the components and shear and tensile forces in the fasteners.

An advantage with mechanical joining compared with adhesive bonding is the possibility to easily disassemble the joined components.

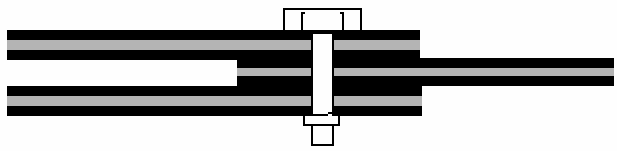


Figure 9 *Schematic illustration of mechanical joined components*

Although mechanical joining withstands peel forces much better than adhesive joining there are also negative aspects on choosing mechanical joining. It requires a hole to be drilled in the material where the load may act as a stress-concentrator [1].

Other disadvantages are the problems that may occur during the drilling of a hole, if not done properly. Possible problems include delamination, surface damage fiber re-orientation and pullout of cracked fibers. The effect may be a weakened composite material. In order to prevent such damages, proper tools and techniques are needed when processing holes and cut-outs. For example, a correct drill turning speed and feed rate reduces effects such as delamination and fiber pull-outs.

5 Composite Utility Pole Manufacturers

5.1 Existing manufacturers

The found suppliers of composite utility poles are mostly present in North America. Even though the global market for replacement and new poles is huge, the market break-through so far has mainly been taken place in North America.

Outside North America a new supplier in Brazil has emerged, Petrofisa. At the annual JEC Composites show in Paris, Apr 2007, the fiber glass manufacturer Owens-Corning highlighted their cooperation with Petrofisa, a local Brazilian fiber composite company which will produce composite utility poles for the Brazilian electrical power distribution sector [30]. This company will not be presented further in this text due to the lack of material in English.

In Europe, no manufactures presently producing utility poles in fiber composite material have been found.

5.1.1 Shakespeare

www.skp-cs.com

Shakespeare Composite Structures, based in South Carolina, U.S.A, has been filament winding composite utility poles since 1992 [31].

The matrix consists of a polyester thermoset. For UV-resistance, the resin contains UV-inhibitors. A polyurethane coating is present in order to further enhance the UV-protection.

Based upon experience and accelerated testing, Shakespeare claims a minimum life of 40 years, after which the product may show visual effects of ageing but retain a very high percentage of its strength. The company also claims composite poles will outlast wood, aluminum, steel and concrete pole under the same climatic conditions.

A variety of colors can be achieved by pigmentation of the resin during manufacturing. The polyurethane coating, containing UV-inhibitors, prevents fading over the years.

The company uses filament winding as manufacturing method. Axial strength may pose a challenge for filament winding due to the difficulties of positioning fibers axially. With technology advances, Shakespeare has however succeeded in winding fibers at low angles.

Utility poles are available up to 75ft (22,8m) height.

Figure 10 *A Shakespeare composite utility pole* [16]. *Photo by Shakespeare.*

5.1.2 Resin Systems Inc.

https://web.grouprsi.com/rsweb/

Resin Systems Inc, also known as "RS Technologies", is a relatively new Canadian company based in Calgary. In the year of 2003, the company transformed from being mainly a R&D company to having two commercialized composite product lines;

- Composite transmission & distribution poles
- Composite roller tubes

The poles are marketed under the name RStandard poles and are sectionalized and tapered in order to optimize weight.

The composite is made up of a Polyurethane matrix and glass fiber, using a filament winding process. Characteristic for RS Technologies is their resin system named Version, a multi-component polyurethane that is claimed offering better strength than polyester [31]. Furthermore, the company has been able to modify the filament winding process by their own fiber placement technology in order to enable layers with axially oriented fibers within the composite pole.

Composite poles are available up to a height of 41 m, and poles as high as 55 m are under development. The poles are manufactured in tapered modules, nested inside each other for easy transportation and storage. A module is never longer than 11m during transportation even though the full length is up to 41 m. Thus the poles are easy to transport to difficult locations.

In November 2005, an initial shipment of poles was shipped to a non-disclosed European energy producer for testing. The initial order was however not fulfilled and since March 2007, Resin Systems Inc. has chosen a strategy to focus on the North American domestic market for utility poles [17].

5.1.3 Powertrusion

www.powertrusion.com

Powertrusion is a company based in Tucson, Arizona, USA, which started production of composite utility poles in the late 90's.

The main product of the company is a composite pultruded power distribution pole. The design of the pultruded pole is non-tapered, with a fixed diameter throughout the pole's length. Even though the non-tapered design might offer a higher weight than tapered poles, Powertrusion nevertheless claims the weight of their composite pole is only about 40% compared with a standard wooden pole of the same class.

The material used today for the company's composite poles consists of glass fiber with a polyurethane resin from Reichhold [15], an American global resin supplier with production facilities present in Europe as well as other continents.

With the pultrusion manufacturing technique, the poles of Powertrusion contain glass fibers that are pre-stressed and placed longitudinal, as well as woven fibers for hoop strength. *[Hoop strength: The ability of a tube to withstand bending and crushing forces]*. The manufacturing technique delivers a standard deviation in strength of 1,9%.

Powertrusion poles are available up to 60 ft (17m). The poles can be pre-drilled with e.g. steps or other mounting hardware according to the requirements of a customer.

The UV-protection consists of three levels:

1. UV-inhibitors throughout the matrix resin
2. A UV-stable pigment additive in the matrix resin to provide color.
3. A resin-rich surface veil for giving additional protection. The surface veil is not a load-carrying part of the structure.

Powertrusion claims an expected service life of their utility poles up to 80 years, once installed. During a major firestorm in the year 2003 outside San Diego, California, a Powertrusion pole (which a local energy company was testing) withstood the fire, whereas approximately 3000 ordinary utility poles were consumed by the fires [31,32].

5.1.4 Strongwell

www.strongwell.com

Strongwell has been pultruding fiber reinforced polymers composite products since the year 1956. The company is active in many different markets, including utility poles. Its headquarters as well as the main manufacturing site is located in the State of Virginia, U.S.A.

The market name of Strongwell's composite utility pole is SE28; a tapered pole available in lengths up to 80ft (24m), weighing 612kg. Strongwell uses pultrusion as manufacturing technique. The composite contains glass fiber as reinforcement and a matrix made of vinylester resin [31].

In contrast to other composite utility pole producers, Strongwell's pole is not circular but shaped as a 12-sided polygon. Holes can be pre-drilled but the pole is also drillable in field. In terms of engineering, the poles are intended to be a direct replacement for wooden poles.

The UV-protection is based upon:

1. UV-inhibiting binders inside the matrix
2. Surface veils
3. Paint coating

According to Strongwell, the poles can last indefinitely. After 25-30 years of service, a re-application of the UV-inhibiting paint coating may be required as the only significant maintenance needed.

Company	**Shakespeare Composites**	**Resin Systems Inc**
Location	Newberry, South Carolina, U.S.A	Calgary, Canada
Website	www.skp-cs.com	www.grouprsi.com
Type of Fiber	Glass Fiber	Glass Fiber
Composite Matrix	Polyester thermoset	Polyurethane thermoset
Production method	Filament winding	Filament winding
Maximum height	21 m	41 m
Power Pole Experience	1993	2003
UV resistance	- UV-inhibitors in resin - Polyurethane coating	- "Built-in UV-protection" - Details not known

Table 5 *Composite pole manufacturers*

Company	**Powertrusion International**	**Strongwell**
Location	Tucson, Arizona, U.S.A	Bristol, Virginia, U.S.A
Website	www.powertrusion.com	www.strongwell.com
Type of Fiber	Glass Fiber	Glass Fiber
Composite Matrix	Polyurethane thermoset	Vinylester thermoset
Production method	Pultrusion	Pultrusion
Maximum height	17 m	24 m
Power Pole Experience	Since late 90's	
UV resistance	- UV-inhibitors in resin - UV-stable pigment - Resin-rich surface veil	- UV-inhibitors in resin - Surface veil - Paint coating

Table 6 *Composite pole manufacturers*

5.2 Future manufactures

Most of the found manufacturers of composite utility poles are present in North America. A manufacturer in Scandinavia could be preferable by some reasons, e.g. easier and/or cheaper shipping, as well as time to delivery aspects.

The focus has therefore been to look at companies that might be possible future candidates for the manufacturing of composite utility poles. Among those are the companies Exel Oy in Finland and Fiberline in Denmark.

5.2.1 Exel

http://www.exel.net

Contact: Jan Lord, Sales
Email: jan.lord@exel.net

Exel is a well established company which manufactures composite profiles. The company consists of the parent company Exel Oyj in Finland and ten subsidiaries. Their production plants are located in:

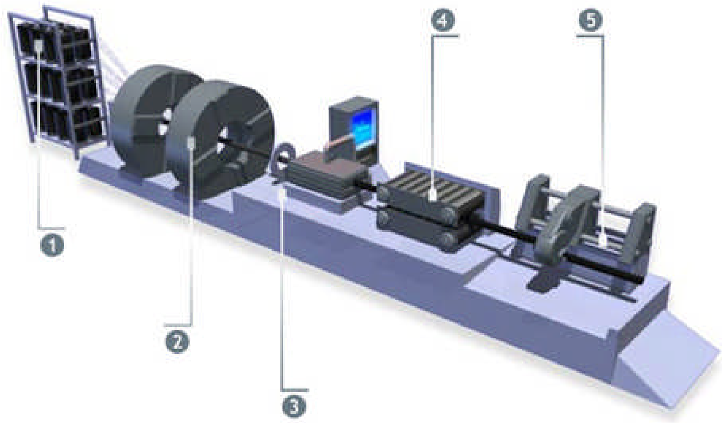
- Finland
- Germany
- Belgium
- Austria
- Australia
- UK
- China

Exel utilize production techniques such as:

- pultrusion
- pullwinding
- co-winding continuous lamination
- pre-preg manufacturing

The different techniques are used in many of Exel's products, ranging from sports applications in Exel Sports to tubes and antenna radomes in Exel Composite, Industry Division.

Two of the production techniques that Exel offers are pultrusion and pullwinding, see Figure 13. Both pultrusion and pullwinding are suitable methods for manufacturing utility poles. Pullwinding is a method that combines pultrusion and filament winding. The method can offer inclusion of longitudinal reinforcement with helically-wound layers. According to Exel, the crosswise reinforcement performed by the pullwinding offers better performance than reinforcements in mats and fabrics that offer the crosswise reinforcement.



1. Reinforcement
2. Winding unit
3. Pultrusion unit
4. Pulling unit
5. Sawing unit

Figure 11 *The Pullwinding of process of Exel* [24]. *Photo by Exel.*

For a utility pole Exel can provide different matrix systems, such as epoxy, vinylester and unsaturated polyester. Different fibers such as glass fiber, Kevlar and carbon fiber are optional. The company can offer both a tapered shaped pole and continuous cross section poles. Exel has given a positive response on the question if they would be able to manufacture utility poles.

5.2.2 Fiberline Composites

http://www.fiberline.dk

Fiberline Composites is an established producer of composite profiles. The company was founded in 1979. Fiberline Composites areas of applications are:

- Structural profiles
- Windows, door, and facade profiles
- Wind turbine profiles
- Industrial profiles

As an example of applications, Fiberline Composites has developed the first composite bridge – the Fiberline Bridge in Kolding, Denmark. It was officially opened in 1997. The company has several co-operations among universities in Europe.

The production method used by Fiberline is Pultrusion. Fiberline are able to perform testing of different properties of their composite material:

Electrical tests
In their own laboratory, Fiberline can test and verify composite profiles with regard to electrical properties. This is done by a dielectric tester, high-voltage facilities and surface tension meter. Electrical isolation/insulation properties can also be verified.

Fire tests
A number of fire-technical standard tests can be performed in Fiberline's own laboratory. The company also works with several fire-technical laboratories that can perform certified tests.

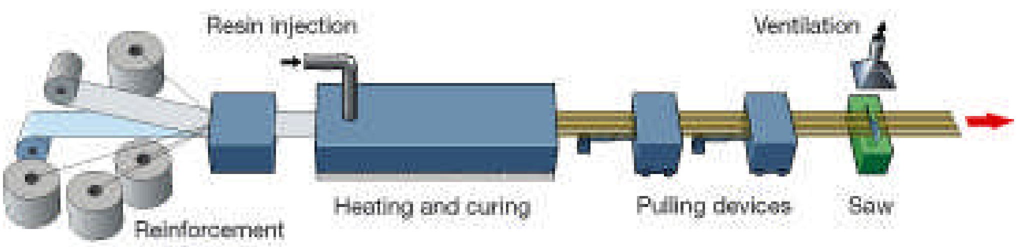


Figure 12 *The pultrusion process of Fiberline* [25]. *Copyright Fiberline.*

6 Maintenance and inspections techniques

6.1 Maintenance

Fiber composite utility poles in general require very little maintenance. Manufacturers claim their products are maintenance-free.

Due to the nature and properties of the constituent materials in a fiber composite utility pole; glass fibers and a thermoset polymer matrix; the product is practically immune to:

- Corrosion
- Biological attacks, e.g. fungus
- Animals and birds, e.g. woodpeckers or insects

Still, impacts of different kinds may damage a pole, e.g.

- Forest fires
- Vehicle impacts when pole positioned close to a road
- Falling ice from power lines during harsh weather

Damage may result in a fiber layer delamination which can affect the mechanical properties and the structural integrity of the composite pole, depending on the damage extent. Depending on the pole construction, a breach in the outer material layer should be repaired. This is true for poles that have an outer layer specially designed for UV-protection.

Composite poles that have a paint layer as a part of the UV-protection (e.g. Strongwell) might require a re-application of UV-inhibiting after 25-30 years.

No other treatment in general should be necessary during the entire life of a composite utility pole.

6.2 Inspection techniques

Destructive inspection techniques will for obvious reasons not be treated here. In order to diagnose damages in composite structures in general, there are several methods for non-destructive inspection (NDI).

Traditional methods might require the product to be taken out of service for inspection and are labor intensive. For a utility pole in an electrical power infrastructure, this is not an option since it would require the power line to be temporarily shut down and possibly the utility pole to be dismounted. Examples of traditional methods are X-ray inspections and ultrasonic inspections [1].

In case a composite utility pole needs to be inspected, e.g. due to a suspected damage, the inspection method should preferably be possible to conduct with the power line still in service – at least at damages in the lower part of the pole. Furthermore, any inspection equipment should preferably be reasonably practical to transport or carry to remote location deep into the nature. Two methods will be presented below which complements each other; a vibrational inspection commonly called the Tap Test and visual inspections [1].

6.2.1 Tap test

The Tap test is a vibrational inspection method which is widely used in many fiber composite applications, from boat building to aerospace applications. Sometimes the tap test is also referred to as the Coin Tap Technique.

By tapping on the material with a metal object, e.g. a coin, a sound is emitted. The pitch of the generated sound is normally of a certain frequency as the material vibrates due to the impact causing a mechanical excitation. In case of an anomaly in the material below the surface, the pitch of the sound will change. The person performing the test gets a clear notification. For example, a sub-surface local delamination of fiber layers may generate a low-pitch sound when tapping with a coin on that local area, in contrast to a high-pitch sound heard on the healthy areas.

In practice, the tapping needs to be done just on the faulty spot in order to discover it by the change in pitch of sound. This fact limits the method somewhat as it would be quite time-consuming to perform the tapping over a bigger area. Rather, the tap test is suitable whenever a local damage is suspected but not confirmed. For example, if the outer shell of the composite utility pole is damaged, the tap test can reveal whether or not the structural integrity is intact in the fiber layers below the surface.

6.2.2 Visual Inspections

Visual inspection is a frequently used inspection method for fiber composite structures. The method should not be underestimated as a method for inspecting components for defects and damages. For example, the method is used within the aerospace industry for checking airplanes.

Due to its nature, a visual inspection can only reveal damages that appear on the surface of the inspected structure. This can be seen as a drawback for the method.

For a utility pole, the visual inspection technique is a good method to identify damages on the surface of the structure, or the paint layer if there is such a layer present.

6.2.3 A combined inspection

Preferably, the visual inspection technique can be combined with the Tap test.
First, determine if any damage is present on a utility pole by inspecting it visually.
In case there are any visual damage to the paint layer or surface of the pole structure, proceed by performing a Tap Test on the damaged area. Compare the pitch of sound with non-damaged areas.

In case there is no difference in sound pitch, the structural integrity can be deemed intact and no repair other than some fresh paint might be necessary.

7 Design of Composite Utility poles

7.1 Pole dimensioning - Evaluated material thickness

In this section of the report, *Design of Composite Utility poles*, the material thickness of a utility pole is evaluated. These calculations can be seen as an example of one method for how to calculate a necessary material thickness for a composite utility pole. The prerequisites for these calculations are:

Fiber material is glass fiber. See section *2.1, Fibers*. This is the most realistic choice, and the composite pole manufacturers of today all use glass fiber.
Loads are given by Svenska Kraftnät.
Allowed deflections are given by Svenska Kraftnät.
The calculations are based on a 25 meter long pole with a uniform cross-section.

The estimated material thickness has been calculated by looking at the different loads (horizontal and vertical) separately only. This is the method used today in Sweden for wooden poles. The reason this method has been used is to facilitate a possible comparison between composite poles and wooden poles. However, within a development for composite poles for a power line, it is recommended that both horizontal and vertical loads in combination are being considered since this will represent the actual load case more accurately.

7.2 Determination of Elastic modulus

To predict and estimate the elastic modulus for a fiber composite the Rule of Mixtures (ROM) is used. Since the composite is a combination of both fibers and matrix the modulus of elasticity of the composite is a result of the contribution from both materials, i.e. the selected fiber and matrix. By multiplying Young's modulus with the volume fraction of the fibers and the quantity of the total e.g. fibers or matrix, see Eq. 1, that are placed in the principal direction the modulus is, here in 1-direction, estimated according to:

$$E_1 = \beta_f \cdot V_f \cdot E_f + \beta_m \cdot V_m \cdot E_m \qquad (1)$$

where

E_1	Material's elastic modulus in 1-direction (along the fibers)
β_f	Alignment amount of fiber content in the 1- direction.
V_f	Fiber volume fraction
E_f	Fibers' elastic modulus
β_m	Amount of matrix content in the 1-direction.
V_m	Matrix volume fraction
E_m	Matrix's elastic modulus

Equation 1 shows that depending on the following choices; what *constituent materials* that are chosen for the composite, the final *volume fraction* of those materials, and the *fiber directions*, the theoretical Young's modulus will have an approximately value of approximately 20 GPa to 35 GPa. The maximum value should however be seen as a high value where most fibers are presented in the 1-direction.

7.3 Classic Beam Theory

7.3.1 Euler buckling

The vertical load on the pole is presented in Table 8. To evaluate an approximate material thickness of the pole, as determined by the requirements due to the vertical load, Euler's buckling criteria is used.

Depending on how the pole is supported different Euler buckling modes can be used, i.e. Euler buckling mode 1-4. In order to calculate the material thickness in this work, focus has been put mainly on Euler's first buckling mode.

If the pole is not supported by a stay the poles end conditions for the pole is fixed-free, whereas the Euler buckling criteria fixed-free condition is used, see Equation 2.

Euler's fixed-free end condition:

$$P_k = \frac{\pi^2 \cdot E \cdot I}{4 \cdot L^2} \tag{2}$$

where

P_k	Vertical load
E	Material's elastic modulus in
L	Pole length
I	Moment of inertia

7.3.2 Beam bending

In order to estimate the needed material thickness for the horizontal forces see Table 8. The Equation for elementary case beam bending has been used.

Beam bending, elementary case:

$$\delta = \frac{P \cdot L^3}{3 \cdot E \cdot I} \tag{3}$$

where

δ	Deflection
P	Horizontal load
L	Pole length
E	Material's elastic modulus
I	Moment of inertia

Moment of inertia for a hollow, circular pipe is given by:

$$I = \frac{\pi}{64}\left(d_y^4 - d_i^4\right) \tag{4}$$

where

I	Moment of inertia for a circular cross section
d_y	Outer diameter
d_i	Inner diameter

7.4 Load and load cases

The loads and load cases in Table 7 are given from Svenska Kraftnät. T, V and L denotes transversal, vertical and longitudinal load and these loads are distributed on two poles. The load cases 1, 2a, 3 and 5a represent different load cases as follows:

- load case 1 represent high wind and no ice on the power lines
- load case 2a represent no wind and ice on the power lines
- load case 3 represent high wind and ice on the power lines
- load case 5a represent security loads

Load in kN	Load cases					
	1	2a	3	5a	5a	5a
T_1	3,66	0	7,05	0	0	0
V_1	9,42	21,96	20,82	21,96	21,96	21,96
L_1	0	0	0	22,29	0	0
T_2	3,66	0	7,05	0	0	0
V_2	9,42	21,96	20,82	21,96	21,96	21,96
L_2	0	0	0	0	22,29	0
T_3	3,66	0	7,05	0	0	0
V_3	9,42	21,96	20,82	21,96	21,96	21,96
L_3	0	0	0	0	0	0
T_4	1,45	0	4,84	0	0	0
V_4	2,29	10,44	9,19	10,44	10,44	10,44
L_4	0	0	0	0	0	30,38
T_5	1,45	0	4,84	0	0	0
V_5	3,29	10,44	9,19	10,44	10,44	10,44
L_5	0	0	0	0	0	0

Table 7 *Load cases given from Svenska Kraftnät*

The loads in Table 7 are distributed on two poles that support the power lines. This gives a load distribution on the two poles according to:

Pole number	**1**	**2**
Transverse load T:	$T_1+ T_4+ 0.5T_2$	$T_3+ T_5+ 0.5T_2$
Vertical load V:	$V_1+ V_4+ 0.5 V_2$	$V_3+ V_5+ 0.5 V_2$
Longitudinal load L:	$L_1+ L_4+ 0.5 L_2$	$L_3+ L_5+ 0.5 L_2$

The summarized values of the transverse, vertical and longitudinal loads on each pole are presented according to table 8:

	Pole 1			**Pole 2**		
Load cases	**T [kN]**	**V [kN]**	**L [kN]**	**T [kN]**	**V [kN]**	**L [kN]**
1	6,94	16,42	0	6,94	17,42	0
2a	0	43,38	0	0	43,38	0
3	15,415	40,42	0	15,415	40,42	0
5a	0	43,38	22,29	0	43,38	0
5a	0	43,38	11,145	0	43,38	11,145
5a	0	43,38	30,38	0	43,38	0

Table 8 *Distributed loads*

7.4.1 Vertical loads

Given that the pole shall withstand the given vertical loads of Table 8, the minimum material thickness will vary as a function of the final modulus of elasticity (Young's modulus).

To see what effect a different modulus of elasticity will have on the required material thickness, see Figure 13 and 14. These Figures are based on the Euler's fixed-free end condition, see Equation 2. The Euler's fixed-free end condition is used when the pole is not supported by any stays.

Figure 13 and 14 illustrate the variation of the material thickness that is required, based on the outer diameter. 5 1 is based on the vertical maximum in Table 8 (43,38 kN), see load case 2 and 5a and Figure 14 is based on the vertical minimum in Table 8 (16,42 kN), see load case 1.

By studying Figures 13 and 14, the needed material thickness is shown as a function of the outer diameter of the pole. The colored curves each represent a different elasticity modulus. Since the material is a fiber composite, the elasticity modulus is dependent on several factors, see section 7.2.

In order to estimate the material thickness based on the vertical forces, Equation 6 has been used. Equation 4 put in Equation 2 gives:

$$P_k = \frac{\pi^2 \cdot E \cdot I}{4 \cdot L^2} \Rightarrow \frac{\pi}{64}\left(d_y^4 - d_i^4\right) = \frac{4 \cdot P_k \cdot L^2}{\pi^2 \cdot E} \qquad (5)$$

Thus, the resulting pole thickness according to vertical load

$$\left(d_y^4 - d_i^4\right) = \frac{64 \cdot 4 \cdot P_k \cdot L^2}{\pi^3 \cdot E} \tag{6}$$

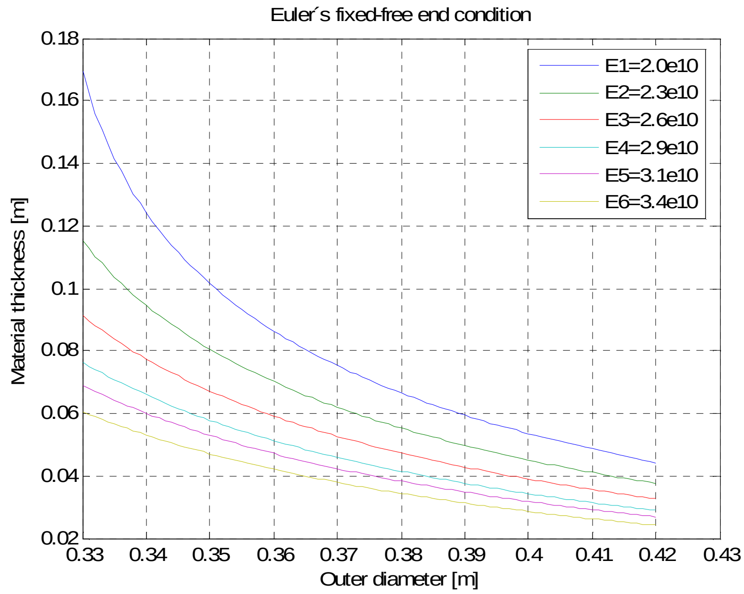


Figure 13 *Vertical maximum load 43380 N*

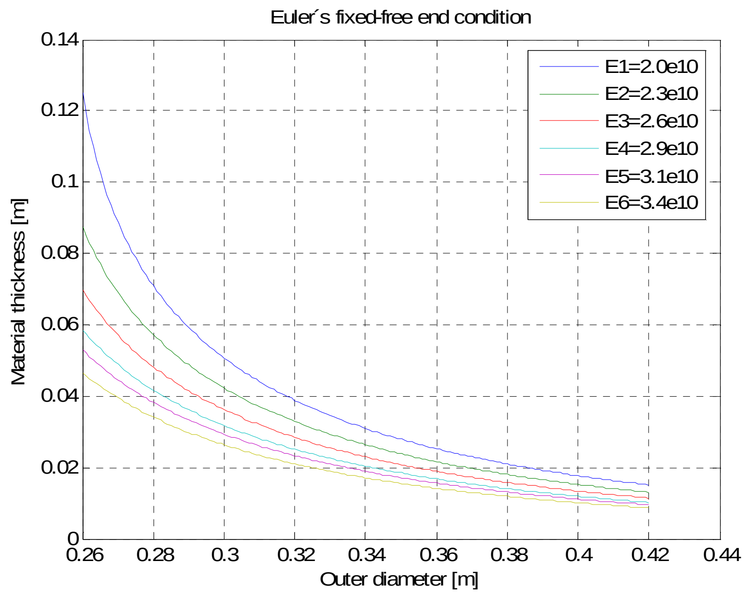


Figure 14 *Vertical minimum load 16420 N*

When dimensioning the structure, mainly three factors can be varied:

- Elasticity modulus of the material
- Outer diameter
- Material thickness

If the dimensioning is based upon the *maximum* load case, a high elasticity modulus should be chosen. If the dimensioning is based upon the *minimum* load case, a lower elasticity modulus can be chosen. However, the outer diameter should not be too narrow if a low elasticity modulus is chosen.

A comparison with a solid wooden pole, given the same loads and using the SIS value E_{wood} = 10 GPa [33], will result in the following diameter of the solid wooden pole:

Maximum load case: diameter = 0,39 m.
Minimum load case: diameter = 0,30 m.

7.4.2 Transverse and longitudinal loads

In order to estimate the material thickness based on the transversal and longitudinal forces, Equation 8 has been used. Equation 4 put in 3 gives

$$\delta = \frac{P \cdot L^3}{3 \cdot E \cdot I} \Rightarrow \frac{\pi}{64}\left(d_y^4 - d_i^4\right) = \frac{P \cdot L^3}{3 \cdot E \cdot \delta} \qquad (7)$$

Thus, the resulting pole thickness according to beam bending

$$\left(d_y^4 - d_i^4\right) = \frac{64 \cdot P \cdot L^3}{\pi \cdot 3 \cdot E \cdot \delta} \qquad (8)$$

where:

P_k	Transverse/Longitudinal load
E	Elastic modulus
L	Pole length
δ	Deflection

The approximation of the needed material thickness for the utility pole based on the transverse and longitudinal load is performed in two steps. The first calculation, according to Equation 8, is based on the maximum load, 15,425 kN, in the normal state load cases i.e. load cases 1-3, see Figure 15. The second step is done by estimating the material thickness based on the maximum load, 30,38 kN, in the security loads case 5a, Figure 16.

Figure 15 and 16 illustrate the variation of the required material thickness as a function of the outer diameter. These calculations have been performed as described in the above paragraph.

Similar to section 7.4.1 *Vertical loads*, Figures 13 and 14 shows the effects of different elasticity modulus of the composite material. The Figures have been constructed the same way as in section 7.4.1 in order to be easy to compare.

In Figure 15 maximum deflection is 0,10 m. The second Figure 16 has a slightly higher value, 0,20 m allowed deflection. The given allowed deflection values have been given by Svenska Kraftnät as input to this thesis work.

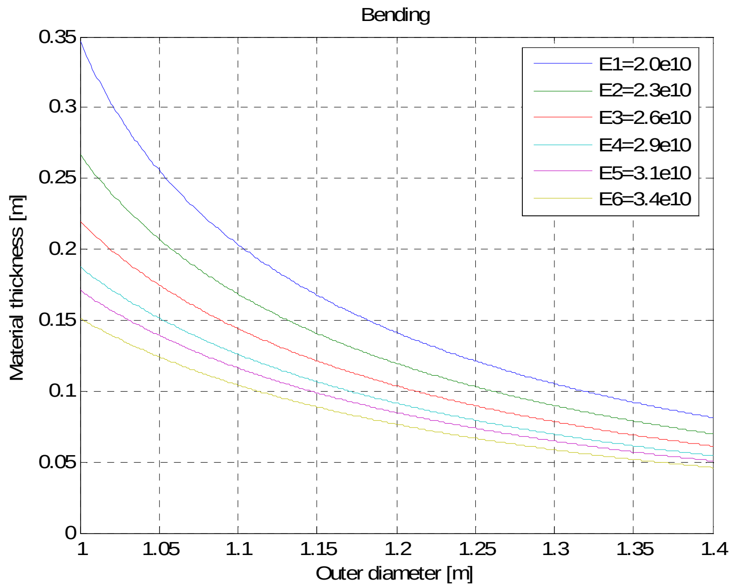


Figure 15 *Transverse load 15415 N, allowed delta =0,10m*

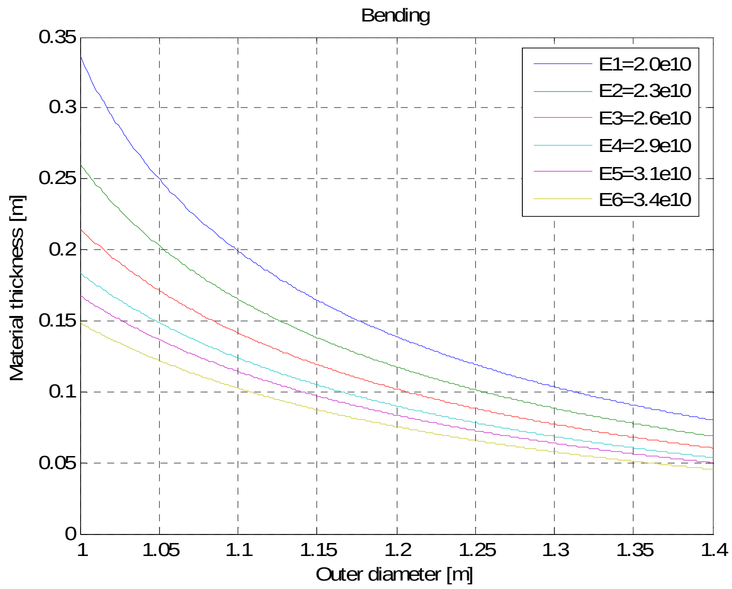


Figure 16 *Longitudinal load 30380 N security load, allowed delta =0,20m*

Both above cases, with different allowed deflections, show similar values. In order to handle the requirements on maximum deflection, a high diameter of the pole is required in combination with a large material thickness.

A comparison with a solid wooden pole, given the same loads and using the SIS value E_{wood} = 10 GPa [33], will result in the following diameter of the solid wooden pole:

Maximum load case: diameter = 1,13 m.
Minimum load case: diameter = 1,13 m.

In order to avoid the large required diameter and/or material thickness, the utility pole would need to be braced. If bracing the pole 5 meters from the top of the pole, a lower material thickness is required compared to a design without bracing. See Figure 17 and 18. It has been assumed that the pole does not deflect below the stays. Or with other words, it is assumed that the stays carry the entire deflecting load.

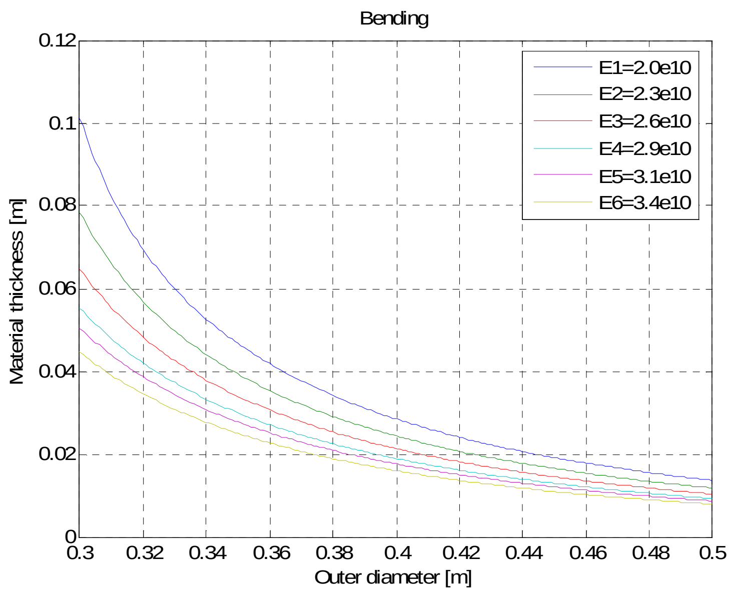


Figure 17 *Maximum transverse load 15415 N, load case 1-3, allowed delta =0,10m, based on a bracing 5m from the top.*

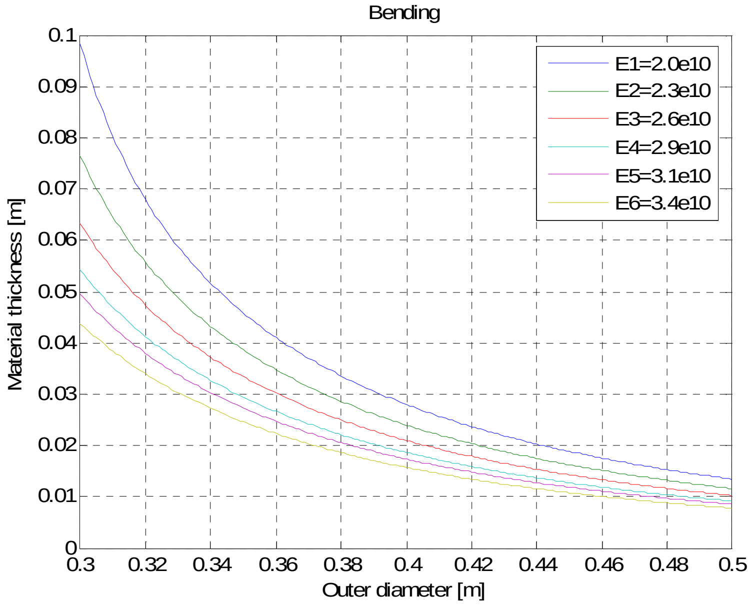


Figure 18 *Maximum longitudinal load 30380 N, load case 5a, allowed delta =0,20m, based on a bracing 5m from the top.*

Both cases where the pole is braced, with 0,10m and 0,20m allowed deflection respectively, show similar results. This is analogous with the cases with no bracing included. However, as already mentioned, with a braced pole a lower material thickness and/or the outer diameter is required.

A comparison with a solid wooden pole, given the same loads and using the SIS value E_{wood} = 10 GPa [33], will result in the following diameter of the solid wooden pole:

Maximum load case: diameter = 0,34 m.
Minimum load case: diameter = 0,34 m.

7.5 Stress calculations

In this section the compression stress in the 1-direction of the composite pole is calculated. The calculated value is compared to an experimentally determined maximum value of compression strength [1].

$$\sigma_{lc} = \frac{P}{A} \qquad (9)$$

where:

σ_{lc}	longitudinal compression strength
P	load
A	area

Based on the maximum vertical load of 43380 N and a pole with an outer diameter of 0,41 m and a material thickness of 0,03 m, the calculations gives a stress value of:

$\sigma_{lc} = 2{,}3MPa \leq \sigma_c^*$

Where σ_c^* is a glass fiber reinforced polyester (orthophtalic) with a compressive value of 294 MPa [1].

7.6 Conclusions design of utility pole

In the load case of beam bending, i.e. transverse and longitudinal loads, the pole should be braced in order to meet the requirements of maximum deflection, as given by Svenska kräftnät (0,10 m and 0,20 m maximum deflection). It is noteworthy that also a wooden pole needs to be braced in order to fulfill these requirements.

By bracing the pole 5 meters from top, the maximum vertical load will be the dimensioning load case for material thickness and diameter, see Figure 13.

An estimated material thickness, based upon the maximum vertical load graph in Figure 13, is approximately 0,03 m, with a pole diameter of 0,41 m. These values are based on a Young's modulus of 29 GPa. As seen in the graphs, variations can be made:

- A lower Young's modulus will require a higher material thickness.
- A smaller pole diameter will require a higher material thickness.
- A lower material thickness will require a larger pole diameter, or higher Young's modulus.

For a comparison between a wooden pole and a fiber composite pole, see table 9 and table 10. The density for wood is in the calculations set to 520 kg/m3 and the density for the fiber composite (glass fiber/unsaturated polyester) is set to 2000 kg/m3. The density of the material can vary, but these numbers can be considered typical values. As can be seen in the tables, a fiber composite power pole will be approximately 40% lighter than a corresponding wooden power pole, given the same dimensioning loads in this example.

Non-braced pole (vertical load)

Material	**Fiber composite**	**Wood**
E-modulus [GPa]	29	10
Outer diameter [m]	0,41	0,39
Material thickness [m]	0,03	Solid
Weight [kg]	972	1553
Dimensioning load [N]	43380	43380

Table 9 *Comparison chart, wooden pole vs. fiber composite pole. Non-braced pole.*

Braced pole (longitudinal load)

Material	**Fiber composite**	**Wood**
E-modulus [GPa]	29	10
Outer diameter [m]	0,41	0,34
Material thickness [m]	0,017	Solid
Weight [kg]	541	1180
Dimensioning load [N]	30380	30380

Table 10 *Comparison chart, wooden pole vs. fiber composite pole. Braced pole.*

8 Environmental effects

Fiber composite utility poles are generally well suited to withstand many environmental factors. The most common environmental factors for a fiber composite utility pole is sunlight, with its frequency spectrum including UV-light. Possible biological attacks to a utility pole include termite and woodpecker attacks. Other environmental factors are insects, fungus, corrosive environments and fires.

8.1 UV-light

Ultraviolet light, as part of the sunlight may impact on the fiber composite material. UV-light may cause long-term degradation of the unprotected material and color fading, sometimes referred to as yellowing. Color fading is a problem of aesthetic nature and does not significantly influence mechanical properties.

There are several methods to offer UV-protection to the fiber composite, by adding UV-absorbing additives into the matrix resin or by adding a protective outer shell of UV-paint. Some manufacturers combine these methods. See also Section 2.3 *Additives*.

8.2 Biological factors

The composite material composed of glass fiber and epoxy is not biodegradable. It is not subject to attacks by fungus or animals/insects, like woodpeckers.

8.3 Corrosion

Fiber composites are not affected by corrosion provided no metal components are used in e.g. attachments or other parts of the construction. This can be seen as a major advantage compared with pole construction made of steel.

8.4 Fires

Although the polymer matrix of the fiber composite is flammable by terms of being an organic material, utility poles of fiber composites perform quite well in terms of fire resistance.

The fiber composite utility pole manufacturer Pultrusion has done tests in order to prove the inherent flame resistance. The work was done together with University of Delaware and Reichhold, a company manufacturing unsaturated polyester resins. The tests showed the fiber composite poles being superior to both treated and untreated timber poles [15].

The flame resistance of composite utility poles in field was proven in 2003 during the fire storms in San Diego, California. A Powertrusion utility pole which was mounted for testing survived the fire, which consumed 3000 utility poles and 1440 km of power lines [15].

8.5 Length of life

The current manufacturers of fiber composite utility pole claim life lengths of about 40-80 years for utility poles based on fiber composites. Poles designed with an outer, protective paint layer might need to get a re-application of fresh paint after 25-30 years.

Due to the fact that fiber composite poles are relatively new, the life length has not been able to be verified.

9 Recycling

As of today, there are currently no industries or companies in Sweden performing recycling fiber composites. Due to new requirements for recycling in the future, combined with the increased use of fiber composites, it may however be likely that there will pop-up companies in the recycling business for fiber composites.

In this chapter, technologies for recycling of fiber-reinforced thermoset polymers are reviewed. For this type of a material, two main types of techniques are available; mechanical recycling and thermal recycling [20,21,22,23].

9.1 Problems in recycling

Polymer based fiber composites are a mixture of materials with quite different properties which does not make the recycling easier: Polymer, reinforcement in the form of chopped or continuous fibers, and sometimes fillers or additives.

The recycling of fiber-reinforced composites based on thermoplastics should in theory be less difficult than the recycling of material based on thermosets due to the fact that thermoplastics can be remelted and subsequently used again. A process including re-melting is however not possible for matrix material out of thermosets due to the physical structure of the material. During the curing of resin, the polymer molecules are crosslinked by covalent bonds and form an almost infinite molecule. Due to the crosslinking, thermosets cannot be remelted or remoulded.

Some thermosetting polymers, including Polyurethane, can however be converted relatively easily back to their original monomer. This might be an advantage of using polyurethane as matrix in utility poles made of fiber composites.

9.2 Mechanical recycling

This technique is based on reducing the size of the fiber components. In the process, the reductions in size starts by crush milling or slow speed cutting the material. Removal of possible other inserts, such as metal, is facilitated by this first coarse reduction.

The second step typically include ground or hammer milling the material. The final size may vary and can typically be from 10mm down to 50µm.

All of the constituents of the original composite are reduced in size and the resulting material is a mixture of fractions with different size and content. Typically, coarser fractions have slightly higher fiber content whereas the finer fractions have a higher content of polymer. The latter fractions may be present in form of a powder.

Applications

The finer fractions, i.e. the powder, can be suitable as fillers. For example, powders can be used as substitute for calcium carbonate filler in new SMC (Sheet Moulding Compounds) techniques.
Among different studies that have been made, rest products have also been tested for use as reinforcement in asphalt.

9.3 Thermal processing

Three methods have been found to be developed or tested; Combustion with energy recovery, Pyrolysis, and Fluidised bed processing.

9.3.1 Combustion with energy recovery

Thermosetting polymers, like other organic material, can be used as an energy source by burning it. Most resins have a calorific value of about 30.000 kJ/kg. This value is true for the fraction of polymer in the fiber composite. As glass fibers do not burn, one has to look at the weight fraction of polymer in the fiber composite to estimate the energy content of e.g. 1 kg composite material.

The non-combustible parts of the fiber composite can be used as cement fillers, although given some restrictions, for example regarding Boron content in glass fibers.

9.3.2 Pyrolysis

Pyrolysis is the chemical decomposition of organic materials by heating in the absence of oxygen. Pyrolysis degrades the polymer components of the fiber composite whereby oil and gas products are formed. There will be left overs in the form of fibers and char.

9.3.3 Fluidised bed processing

The fluidised bed processing technique enables the re-use of glass fibers in a fiber composite, as the fibers are recovered with this technique. The University of Nottingham, U.K., has performed a lot of research on the method during the past decade.

The fluidised bed is made up of a bed of silica sand, which is fluidised with a stream of hot air of a temperature of typically 450-550 ºC. The velocity of the air through the sand bed is typically 0,4-1,0 m/s.

The fiber composite to be recycled is put onto the fluidised bed where the polymer part of the composite will start to vaporize, which releases the fibers, and fillers if any present, into the hot gas stream. The fibers are separated in the cyclone for recovery whereas the gas stream continues to the afterburner chamber, where the polymer parts are oxidized. This stage may also provide energy to be recovered from the combustion products as the polymer oxidizes.

A glass fiber reinforced polyester composite can be processed at 450 ºC whereas composites containing epoxy resin require up to 550 ºC in order to get a quick vaporization.

The recycled fibers show reasonably good mechanical properties. The stiffness of the fibers remains compared to fresh, non-recycled fibers. The tensile strength however is reduced by approximately 50% with a processing temperature of 450 ºC. At higher temperatures, the mechanical strengths will however suffer significantly more; a processing temperature of 650 ºC reduces the strength of up to 90%.

The fluidised bed process yields quite clean products. The fibers are clean and have shown very little surface contamination. The mean length is in the region of 6-10 mm.

As a summary, there are as of today no recycling methods established suitable for glass fiber composites, at least not in Sweden. Several methods are however possible for recycling fiber composites.

If considering fiber composite utility pole compared with traditional wooden poles from a recycling perspective, it should be noted that the composite material does not include toxic substances, like creosote which the wooden poles are treated with and might pose a headache from a recycling perspective.

10 Conclusions

It has been shown that utility poles made of fiber composites are already in use, mostly in North America where also today's manufacturers are present. Potential future manufacturers do also exist in Scandinavia.

Utility poles of fiber composite may very well be a suitable alternative to the wooden poles of today. When using wood as material, properties are limited to the natural properties of wood. A composite material can be tailored in order to achieve the desired properties, e.g. strength, environmental resistance and price to mention a few.

Some of the advantages a composite utility pole has to offer compared with a wooden pole are lesser weight and the resistance against environmental attacks, like fire, fungus and woodpeckers, the latter being a problem of today according to Svenska Kraftnät. A composite pole may also be manufactured in several smaller sections and assembled on site, which can facilitate the transportation of poles. E.g. Resin Systems offer this modular concept.

Regarding an estimated life expectancy, no real data is available since composite utility poles are relatively new. But according to manufacturers, a length of life of 40-80 years can be expected. Since the material is not subject to any environmental attacks like rust or fungus, no reason is found against this statement.

The preferential choice of fiber is glass fiber, which also is the choice in today's present composite utility poles. All existent manufacturers use glass fiber, which has good mechanical properties to a reasonable price. As matrix, several thermoset polymers can be used. The manufacturers have different chosen solutions for the matrix. In order to make a choice of matrix, it is recommended that a thorough requirement specification is made and different choices are being discussed. This would include suitable additives.

Recycling of a composite utility pole is possible, with some limitations. By using a fluidised bed process, the fibers can be recycled for usage. All other processes will give a material usable only as filler or reinforcement is other materials. It is however noteworthy that new processes may be developed in the future, as there is not yet any major demand for composite recycling, the volumes still being relatively low.

11 Further work

In order to implement a new, or existent solution for a composite utility pole, a detailed requirement specification should be formulated where Svenska Kraftnät defines what desired properties that should be fulfilled by the material and pole.

The choice of material can be influenced by desired properties, such as electrical properties, long-term loads, e.t.c. Further work could include defining the requirements on these properties and loads.

As there are power utility companies that use composite poles, contacts could be taken in order to get experience feed-back from the users of today.

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