Forintek Canada Corp.
Western Division
2665 East Mall
Vancouver, BC
V6T 1W5

Project No. 4198

State-of-the-art Report on Fibre Reinforced Polymer (FRP) Utilization in Wood Products

by

Ciprian Pirvu, Ph.D.
Research Scientist
Wood Engineering Department

January 2004

Forintek Canada Corp. would like to thank its industry members, Natural Resources Canada, and the Provinces of British Columbia, Alberta, New Brunswick, Newfoundland and Labrador, Nova Scotia, Quebec and Saskatchewan for their guidance and financial support for this research

Ciprian Pirvu, Ph.D. Project Leader Wood Engineering Dept.	Bob Knudson, Ph.D. Reviewer Wood Composites	Erol Karacabeyli Manager Wood Engineering Dept.

Notice

Abstract

Fibre-reinforced wood systems are light, strong, stiff composites that can efficiently replace larger wood members and can be relied on to provide consistent mechanical properties.

This report is an introduction to fibre-reinforced wood systems for members of the Canadian wood products industry. It provides the motivation for reinforcing wood with synthetic fibres, and surveys the choice of materials and their uses. Numerous examples of current applications are discussed to demonstrate the strong and weak points of various approaches and examine the durability and management of fibre-reinforced wood products, as well as to indicate opportunities that exist for the Canadian wood products industry.

This report is intended to be a useful reference for the Canadian wood products industry, and assist future developments in structural and non-structural applications of fibre-reinforced wood products.

Key words: Fibre, Wood, Composite, Polymer, FRP, GFRP, CFRP, Glass, Aramid, Carbon, Reinforcement, Durability, Structure, and Laminate.

Acknowledgements

This study is part of a project jointly supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Forintek Canada Corp.

Appreciation is expressed to all those who have reviewed and made contributions to this report. I am particularly grateful to the following colleagues at Forintek Canada Corp.: to Mr. Bill Deacon for the comprehensive editorial review and suggestions, and to Dr. Bob Knudson and Mr. Martin Feng for the technical review. I am also indebted to Mr. Erol Karacabeyli for his assistance and guidance in developing this work. In addition, I would like to thank our librarians, Mrs. Barbara Holder and Mrs. Phyllis Fraser, for their valuable contribution with the extensive literature search.

Table of Contents

List of Tables

List of Figures

1 Objective

Fibre reinforced polymer (FRP) composites have immense potential for use in combination with wood for strengthening existing structures and building new ones. The marriage of these materials yields a composite that handles like wood but performs like synthetics, extending the performance of wood, especially in demanding load applications.

With the increasing pace of development of these materials and their applications, it is time to bring together and organise the knowledge in this area. This report presents an overview of FRP utilization in wood products, provides examples of field implementation of FRP composites, and discusses the potential of these materials within the Canadian wood products industry.

The intention is to assist industry in improving existing building materials and developing a new generation of materials for residential and non-residential construction; materials that will play an important role in the emerging family of engineered wood products. With the support of appropriate research data, these composites will be the logical choice for engineers, architects, designers and builders in many non-residential projects.

2 Introduction

Fibre Reinforced Polymers or Fibre Reinforced Plastics (FRP) have been successfully used in the last 50 years in the aerospace, automobile, and sport equipment industries because they provide many design advantages, primarily cost reduction, ease of fabrication, simplified installation, weight reduction, increased strength-to-weight ratio, wear and corrosion resistance, and aesthetic appeal.

The same outstanding properties of FRPs have resulted in applications that enhance the performance of conventional wood composite materials such as glulam beams, structural composite lumber, I-joists, and panel products. Generally, FRP reinforced wood products are less variable in stiffness and strength, and have improved creep characteristics, thus can be considered more reliable than conventional engineered wood products. In addition, FRP reinforced wood products use less wood and wood of lower grades, leading to improved utilization of the wood resource and lower material costs.

FRP reinforced wood materials are increasingly accepted by the engineering community. The major drive for the adoption of these materials is the need to meet improved performance demands. These advanced materials combine new and traditional materials with attractive properties: durability, competitive cost, and reduced environmental impact. Also, with addition of synthetic materials to wood, improved resistance to moisture and biodegradation is generally achieved for exterior applications exposed to high moisture environments, such as laminated lumber for bridge applications or waterfront piers.

2.1 Definitions

A *fibre reinforced polymer (FRP)* is a composite system consisting of synthetic fibres embedded in a polymer matrix, as long as there is sufficient aspect ratio (length to thickness) to provide reinforcing in one or more directions. The fibres, primarily glass, aramid, and carbon in the form of continuous roving, woven fabrics, or chopped strand mats, are responsible for the strength and stiffness properties characteristic to FRP composites. The matrix, a thermosetting or a thermoplastic polymer, interconnects the fibres to take over the loads in unison and protects against environmental factors. Designed for compatibility with wood using conventional adhesives, the resulting thin FRP reinforcing system provides good mechanical, adhesive and toughness properties, and good resistance to environmental degradation.

Thermosetting polymers are resins that harden upon application of heat in the presence of a catalyst and cannot be remoulded once cured to the solid state. Typical thermosetting matrices used most frequently in FRP include polyesters, vinyl esters, epoxies and phenolics. *Thermoplastic polymers* are the reverse of thermosettings, and are materials that can be transformed into liquids by heat and solidified by cooling. They include polyethylene, PVC and polypropylene (Detrick, 1982). In wood-FRP composites the resin is used both as matrix and adhesive between the reinforcement and the wood.

Pultruded composites are materials such as rods, tubes and other structural shapes having constant cross section. The pultrusion process is continuous and consists of passing a fibre reinforcing material through a resin impregnation bay, then drawing it through a shaping die where the resin is cured before the laminate leaves the die.

Prepregs are ready-to-mould synthetic fibres pre-impregnated with resin and cured to a tack-free state to be stored for later use. Various ingredients can be added to obtain specific end-use properties and improve processing, storage and handling characteristics.

2.2 Why reinforce wood?

Today, synthetic fibre reinforced wood products present several advantages over the conventional construction materials: wood, steel and concrete.

Many wood composite materials currently in use have been developed as direct substitutes for solid lumber products because of the declining quantity and quality of large solid timbers. The old-growth trees that dominated our forests no longer exist for commercial purposes. Today's lumber comes from second or third growth, or from species that were not considered commercially important a few decades ago. The change in the wood resource is the cause for the increase in cost of high-grade wood fibre, which contributes to the success of engineered wood products.

Contemporary engineered wood materials can be manufactured in various shapes and sizes, with the defects and weak points typical of solid wood randomly homogenized into the body of the resulting composite. The engineering process therefore has the effect of increasing the reliability of wood, and enhancing its competitive position relative to building materials such as steel and concrete.

Once the concept of processing wood to form engineered wood products was developed, understood and implemented, it was a small step to extend the idea to combining wood with non-wood materials to create composites with improved mechanical or physical properties suitable for more demanding applications. The development of methods allowing use of conventional adhesives to bond wood to other materials also contributed to the progress of reinforced materials.

Traditional materials, primarily wood, steel and concrete, have been used for decades in construction for design, technical and financial reasons. Of these materials, steel and concrete dominate non-residential construction, due to a well-documented presence in building codes, design convenience, and cost-effective solutions in high load applications.

Wood has a high strength to weight ratio, a good resistance to corrosive environments, and is easily crafted. Moreover, wood structures deliver superior performance when subjected to earthquakes and high winds. None the less, wood construction is often perceived as traditional or non-engineered, and designers, engineers and architects work with wood in only about 17% of non-residential construction. This is partly due to excessively restrictive fire codes, lack of skilled labour and the relative difficulty of designing with wood (O'Connor, 2003).

While concrete and steel beams are now preferred for heavily loaded structures because of the potential for sudden failure on the tension side of wood beams, if the tension side of a wood structural element is adequately reinforced, it can bear greater loads and exhibit ductile behaviour. By reinforcing the tension side of decks or glulam girders with unidirectional FRP, the failure is moved from the tension side of the member to the compression side, generating a slow failure preceded by considerable deformation. The change in failure mode is responsible for an increase in flexural strength, stiffness and other properties formerly unattained with wood elements.

Wood has always been an environmentally friendly material. With regard to global warming, wood has caught the attention of numerous international groups for its capability to store carbon dioxide. According to the IPCC (1995), the burning of fossil fuel released about 5.5 billion tonnes of carbon dioxide per year between 1980 and 1990, which represents 77% of global carbon dioxide production. Of this, trees absorb about 0.5 billion tonnes per year of carbon dioxide. Moreover, carbon dioxide released from drying the wood needed for residential constructions was only about one fifth the carbon dioxide exhausted for the production of steel houses. Ogawa (2000) reports that carbon dioxide exhausted from materials used for construction of a steel reinforced concrete house was 23% higher than that released for a house constructed of wood. Development of improved wood products with longer cycle life, such as fibre-reinforced products, is of particular interest in replacing steel and concrete where appropriate, and thereby reducing emissions of carbon dioxide and the consequential effects to the environment.

Although many types of wood have natural durability, in adverse environments wood is susceptible to biological deterioration if not effectively protected. This is one more factor that limits end uses of wood, which is all the same suitable for many construction applications. In fact, with addition of synthetic materials to wood, improved resistance to moisture and biodegradation is generally achieved for exterior applications exposed to high moisture environments, such as laminated lumber for bridge applications or waterfront piers.

2.3 Importance to industry

In recent years, significant attention has been paid to the engineering performance of wood structural systems, and a new generation of more reliable and highly engineered wood components for structural purposes has evolved. The engineering community has welcomed the latest trends towards advanced products that combine wood and synthetics to meet improved performance demands. These materials continue to gain worldwide acceptance in the structural products market place.

When the first studies on reinforcing wood with fibreglass were published over five decades ago, the idea was not further developed because of the high cost. However, with the reduction in price of fibreglass and improvement in quality of the resins, today choosing a fibre reinforced wood product can be less expensive than choosing a conventional material. FRP reinforced wood products offer a wide range of new opportunities to meet consumer needs with wood.

With the support of appropriate research data and effective marketing, the Canadian wood products industry has the opportunity to dramatically increase the use of advanced wood composite materials, boosting consumer confidence in wood construction and creating new markets or expanding into markets traditionally dominated by steel and concrete.

Further research with an emphasis on hybrid composite technologies will have an enduring effect on the value-added sector. Gromala (1997) observes in New Directions in Wood Engineering, “We will see increasing combination of wood with other materials in structural products… Our success in managing this trend will largely determine our success or failure as a major player in the structural materials industry.”

3 Wood - FRP Laminates

3.1 Properties

Due to the complex nature of resins and fibres, as well as the multitude of systems available and possible combinations among the systems, there is a wide range in the properties of FRP composites. Generally, the following factors dictate the features of a fibre-resin system: the properties of the fibre, the properties of the resin, the ratio of fibre to resin, and the geometry and orientation of the fibres in the composite. (Please see Appendix A for a discussion of the properties of fibres and resins.)

The ratio of fibre to resin in a composite is known as the fibre volume fraction (FVF). Theoretically, higher FVF implies higher mechanical properties of the resultant composite. In practice, FVF varies from about 30 per cent for a hand lay-up process used in boat building to about 65 per cent for an advanced process used in the aerospace industry. FVF for a fibre-reinforced wood composite will typically range from 30 to 50 per cent. Above the upper FVF limit, mechanical properties of the composite will drop because of insufficient resin in the system to hold the fibres together.

The geometry and orientation of fibres in an FRP composite are also important determinants of the overall properties of the material. Actually, fibre selection is one of the first steps in any composite design project, and the task can be achieved by comparing the project requirements to the properties of fibres, since each family of fibres has general, well-defined properties. Another important consideration at the design stage is that fibres have the highest mechanical properties along their lengths, and should be strategically placed into the composite based on the magnitude and direction of the applied loads.

Unlike traditional construction materials, an FRP composite is synthetic, and as such is only as successful as its design. The properties of steel are well defined by the manufacturer; the properties of timber are labelled by grade and species, whereas in a composite material the person creating the system has a critical role in determining the performance of the resultant structure.

Based on the factors mentioned above, FRP composites occupy a large spectrum in terms of mechanical properties. The approximate range of tensile strength, tensile modulus and density of the most common FRP composites (glass, aramid and carbon) are presented in comparison with those of conventional materials in Figs. 1, 2 and 3 respectively. The high end of the range corresponds to advanced manufacturing processes and materials, while the low end relates to basic manufacturing processes and materials. A quick look at the graphs indicates high strengths and stiffness combined with low densities for FRP composites as compared with other structural materials such as solid wood, aluminum alloys, titanium and steel.

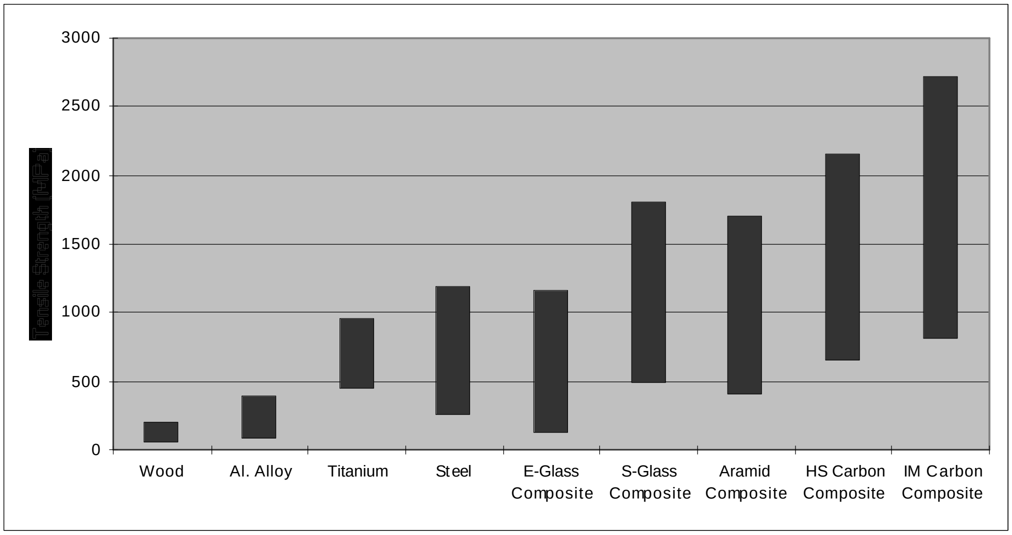

Figure 1. Tensile strength of common structural materials (SP Systems)

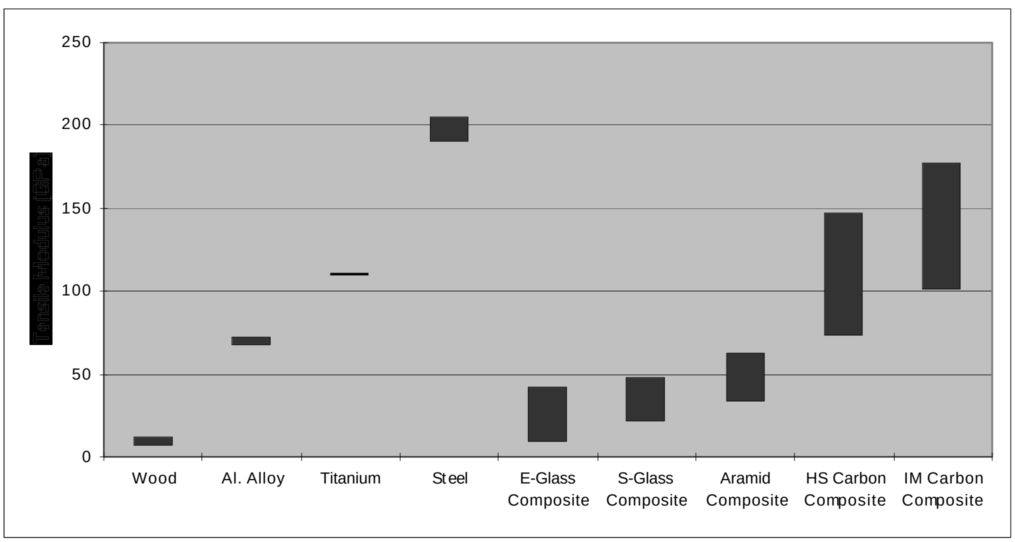

Figure 2. Tensile modulus of common structural materials (SP Systems)

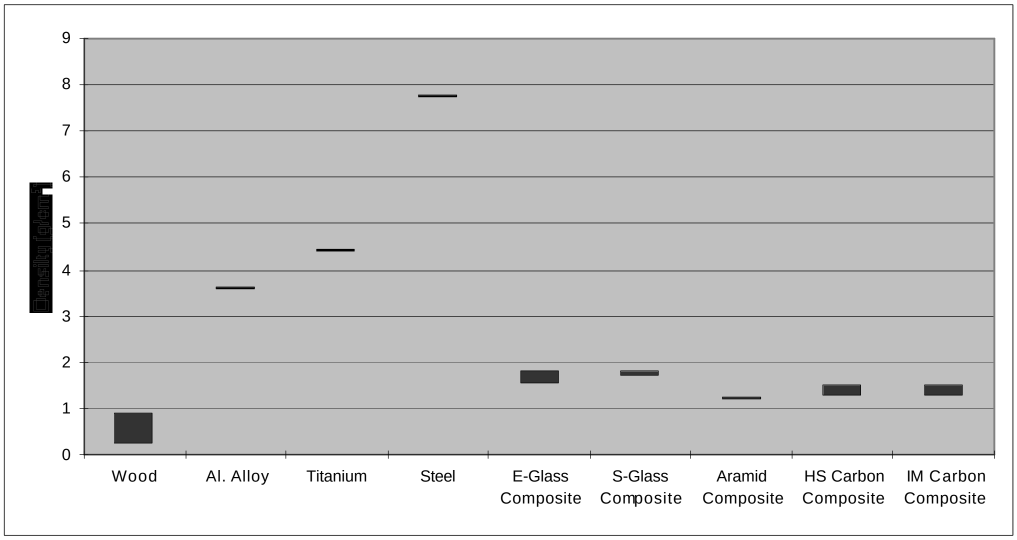

Figure 3. Density of common structural materials (SP Systems)

3.2 Advantages of wood - FRP composites

FRP-reinforced wood composite materials offer engineering, economic and environmental advantages over traditional materials for many applications, and so will continue to gain acceptance worldwide. (Laverty, 2002) Among engineering advantages of FRPs are improved specific strength and stiffness (strength/stiffness-to-density ratio), ease of moulding complex shapes, improved ductility and creep properties, reduced variability in mechanical properties, reduced volume effects, and enhanced resistance to fatigue, all coupled with low densities. From a design point of view, improved design capacity of a reinforced structural member generally allows longer spans and greater loads.

Many conventional materials with isotropic properties, such as steel and concrete are used in construction whether or not there is a need for identical properties in all directions. In many situations this is inefficient and uneconomic. Properties of FRP composites may be customized to specific applications so as to perform in the specific direction(s) required. Moreover, they may be efficiently combined with wood, an anisotropic material, resulting in a better utilization of its properties. Particularly advantageous for axial and bending load carrying structural members is unidirectional reinforcement with synthetic fibres that enhances their longitudinal strength and stiffness. Wood and reinforcement have very good compatibility, since they both have matching range of Poisson’s ratio; specifically, structural wood ranges from 0.033 to 0.47 and FRP from 0.12 to 0.36.

The economic advantages of wood-FRP composites include improved structural efficiency, reduced structural member cross section and weight, improved serviceability, reduced transportation cost, and in some applications reduced cost of chemical treatment. Also, large members of FRP composites may be fabricated offsite or in specialized plants and then transported to the construction site for installation, reducing costs and increasing the system reliability and overall safety. Moreover, this can lead to faster, year-round field installation, as compared to a rather seasonal construction if using conventional materials in many regions.

Environmentally, utilization of low-grade wood with FRP results in increased efficiency in utilisation of the wood resource, and copes with the present changes in the wood supply. In addition, FRP composites have non-magnetic properties making them suitable for use in areas where other materials like steel cannot be used, such as hospital operating rooms or radar sites, due to interferences that may occur.

Finally, the international trend toward adoption of performance-based codes increases the chances of introducing new materials such as FRP wood products in residential or non-residential construction.

3.3 Challenges in the adoption of wood - FRP Composites

The advantages presented above promote wood-FRP composite materials as more durable and lightweight than conventional construction materials like steel, concrete and wood. However, conventional materials have a long tradition of proven performance, and many obstacles will have to be overcome before there is a wide recognition and utilization of wood-FRP composites.

Careful consideration must be paid to shear performance between the layers of reinforcement and wood, as well as between the reinforcement layers themselves. Shear performance is directly linked to bondability between wood and synthetic layers. Another issue that requires consideration is the relative dimensional stability of the constituents of reinforced composites, since many applications are used in wet service design conditions. Wood and synthetics behave differently under wet conditions. As they shrink and expand in different ways due to absorption and desorption of moisture, stresses may develop at the interface of wood and FRP causing delamination, even without an applied load. Delamination is separation of adjoining layers of the laminate structure and can significantly influence the strength, stiffness and stability of the composite. Consequently, cyclic delamination tests are important for determining the bondability and dimensional changes of the constituents of reinforced composites (Tingley, 1994b, 1996a).

High strength FRP materials can be difficult to machine in some situations with certain fibres, and this may lead to problems especially for thicker layers of reinforcement. Past experience with machining FRP materials has shown that carbide-tipped tools have fewer wear problems than high-speed steel tools. In practice, however, this usually does not become an issue if the reinforcement is applied only in the central part of the beam. Besides, modern structural connectors can accommodate reinforced beams without the need to machine bolt holes through the reinforcement (Tingley and Leichti, 1993, 1994a)

Other important obstacles to the wider use of wood-FRP composites are cost, lack of familiarity with materials on the part of specifiers, lack of knowledge of design of composite structures, need for comprehensive standards and design guidelines, lack of knowledge about connections, and uncertain durability of the materials (Lopez-Anido and Naik, 1998). The synthetic fibres industry and plastics industry know little about the wood industry and vice versa. Some of these issues can be overcome by training, or adapting existing standards and design and analysis methods used for other materials to FRP composites. Important as well is the interaction with professionals in the adjacent fields of technical fibres, polymer chemistry and composites manufacturing. The other issues can only be met by in-depth research leading to a complete characterization and understanding of the properties and behaviour of FRP composites.

Although worldwide production of synthetic fibres and polymer resins has increased and the price has decreased significantly over the last 50 years, the cost for the basic materials in FRP composites is still higher than the cost of conventional materials. Since FRP composites weigh less than conventional materials, Lopez-Anido and Naik (1998) suggest that cost analysis of FRP composites with respect to conventional materials should be based on a per unit performance, with proper consideration to weight reduction. Thus, looking through the prism of their performance, it would be easier to fairly assess the actual cost of FRP composites.

There are environmental drawbacks of FRP composites as well. These include recycling, disposal of the product at the end of its service life, and high energy costs in the manufacture of reinforcements and resins. Increasing environmental concern has driven the use of materials from sustainable resources. Finding ways to recycle wood products reinforced with synthetic fibre would contribute to a wider acceptance of these hybrid materials.

FRPs are fairly new materials that have not been yet standardized like other conventional construction materials. Comprehensive research data are required characterizing the constituent materials and the interplay between them, as well as studies of failure mechanisms and development of advanced fabrication processes to preclude voids, fibre misalignments and non-uniform resin distribution areas within the composite.

4 Examples of Wood - FRP Reinforced Systems

The concept of reinforcing wood systems is not new. In the last 50 years, various materials have been evaluated as reinforcement materials for wood, such as steel or aluminum (van Rensburg, 1984; Kollmann, 1982; Lantos 1970; Mark 1961, 1962), cement (Aoki, 1990) and plastics (either thermosetting or thermoplastic polymers). Only a few of these materials proved to be truly compatible from an engineering point of view and economically feasible as reinforcement for wood; even fewer found their way to mass production.

Although most FRP reinforcements involve adding cost to the engineered wood products, this may not always be the case. A relevant example of cost savings is the world's first FRP reinforced timber pier, experimentally constructed in Maine, United States in 1995. Constructing this 124-foot-long bridge of native low-grade timbers reinforced with FRP was 25 percent less expensive than construction with steel (Dagher et al., 1995).

4.1 GFRP reinforced wood systems

There are three main groups of reinforced wood products: those reinforced with glass fibres (GFRP), aramid fibres (AFRP), and carbon fibres (CFRP).

Engineered wood products used for structural purposes are generally glulam beams reinforced on the outer sides with a pultruded high-strength fibre-reinforced plastic lamina. This reinforcement is produced in various thicknesses, widths and lengths, and marketed in the United States under the trade name FiRP™ Panel. The FiRP is inserted in the glulam beams in a similar way as the wood laminates, allowing the glulam manufacturer to continue using the current manufacturing process with few changes. Tingley (1996a, 1996b) has reported a number of patent claims on FiRP™ Panel manufacturing techniques, noting that FiRP technology is cost effective due to reductions in lumber volume and grade, and cost of transportation and treatment (1994). The technology has also been applied to various structural wood products such as laminated veneer lumber, I-joists and parallel strand lumber.

In the last decade many pedestrian and vehicular bridges using FRP technology have been constructed in North America, Japan and Europe. Some of the bridges use horizontally laminated glulam girders reinforced on the tension side with GFRP, others use a patented vertically laminated glulam deck panel reinforced on the tension side with a composite material made of phenolic resin and synthetic fibres. This unique composite material is only 1 percent of the panel's thickness and has twice the strength of steel.

Rowlands et al. (1986) doubled the strength of Douglas fir and increased its stiffness by 40 per cent by reinforcing it with glass fibre. Later, Kuilen (1991) raised the stiffness of GFRP-laminated Japanese larch beams by 17 per cent with 4 per cent reinforcement and by 55 per cent with 16 per cent reinforcement. Larsen et al. (1992) doubled the strength and changed the failure mode of curved and cambered glulam beams by reinforcing them with glass fibre. Dahlbom (1993) performed additional testing on end-notched beams and single bolt connectors, tripling their strength.

The tensile strength perpendicular to the grain determines the load-carrying capacity of timber joints and structural elements such as curved beams with or without camber. By reinforcing each side of the curved beams with a randomly orientated mat of glass fibres, Enquist et al. (1991) prevented failure perpendicular to the grain and increased the ultimate load by 85 per cent with a reinforcement of 225 g/m^2, and by 110 per cent with a reinforcement of 450 g/m^2. Deflection at failure for reinforced beams was 40-80 mm as compared to 10 mm for unreinforced beams.

Southern pine plywood showed a major increase in strength and stiffness when overlaid on both sides with two layers of polyester-impregnated woven glass (Biblis, 1999). The reinforced 3-ply plywood showed 27 per cent increase in stiffness and 57 per cent increase in strength, while the reinforced 5-ply plywood showed 22 per cent increase in stiffness and 34 per cent increase in strength when loaded in the direction parallel to face veneer grain. If loaded in the direction perpendicular to face veneer grain, improvement in stiffness was 718 per cent for 3-ply plywood and 94 per cent for 5-ply plywood, while improvement in strength was 310 per cent for 3-ply plywood and 264 per cent for 5-ply plywood. Such significant improvements in mechanical properties for reinforced plywood indicates its suitability for truck trailer bodies, containers, highway signs, and other industrial applications where strength, durability and weatherability are needed.

Bulleit (1985) analyzed and modeled the behaviour of glass-reinforced particleboard in plate and beam flexure. The stiffness and ultimate moment capacity of the reinforced beams was 3.4 and 2.8 times that of the unreinforced beam, respectively. The author modeled the elastic behaviour of reinforced particleboard plates using the theory of laminated composites, and the reinforced particleboard beams by an elementary classical solution using a transformed cross section.

Early research performed by Smulski and Ifju (1987) revealed significant improvement in strength and stiffness of dry-process hardboard reinforced with continuous glass fibre mat. The hardboard panels had 1, 2 or 3 plies of woven fabric at 0.01-inch intervals below the surface, and bonded with powdered phenol-formaldehyde resin. The authors cited in their paper previous unsuccessful attempts to reinforce wet-process hardboard with chopped glass fibres dispersed in the furnish (Calvin and Back, 1968; Nishikawa et al., 1974, 1975). The hardboards manufactured by Smulski and Ifju failed due to tensile fracture of the fibres on the tension side. However, they obtained a good interfacial adhesion between wood fibres and glass fibre mat.

A few researchers proposed the use of composite fabric wraps to improve the bending strength of glulam beams. Sonti et al. (1996) reported an 8-13 per cent increase in stiffness, with 13-20 per cent improvement in strength and enhanced ductility over the non-wrapped beams, even with a modest amount of reinforcement, such as one layer of 1.27 mm of unidirectional E-glass fabric wrap. For a better adhesion of the wrap, the authors used low viscosity resorcinol formaldehyde adhesive as a primer and a higher viscosity epoxy resin as the matrix. The wrap changed the failure mode of the glulam beams from a brittle, “catastrophic” mode to a ductile, “progressive plastic” mode. It was found that composite beams made of wood and one or two fibreglass layers glued with phenol-resorcinol resin could sustain large displacements after rupture of the outer lamella without any decrease of the supported load (Moulin et al. 1990). In the same study, an increased rigidity and loading capacity was reported for reinforced beams made of low-grade wood species, specifically poplar.

Finger joints are used for jointing lamellas in glulam manufacturing. The tensile strength of glulam lamellas usually dictates the bending strength of the beam, given that the outer laminates are in almost pure tension. Increasing the tensile strength of finger joints will enhance the strength of the glulam beam. Bui et al. (1996) used glass mat reinforcement with epoxy resin to enhance the tension strength of finger joints in each lamella. It was found that for one layer of reinforcement of 400 g/m^2 or 800 g/m^2 tensile strength of laminates increased from 40 per cent to 60 per cent, respectively.

A few researchers have attempted to reinforce glulam beams with reduced cross sectional areas due to large holes and cut-outs, which sometimes becomes critical in dimensioning. These holes are often required for ventilation ducts. Blom and Backlund (1980) used glass or aramid fibres to reinforce glulam beams with circular holes, and reported a total elimination of the detrimental effect of the holes on the beams. Later, Hallstrom (1996) obtained great improvements in strength when glass fibres were used to reinforce beams with circular and rectangular holes. The reinforced beams with rectangular holes showed an increase in load bearing capacity between 140 and 190 per cent, as well as a change in the failure mode. He also demonstrated that is possible to repair a cracked structural element on-site without replacing it, by clamping it together and reinforcing it with glass fibres and polyester resin. The repaired beams showed a 100 per cent improvement of the load bearing capacity, at a total cost less than if repaired with plywood and bolts. In another study, Hallstrom and Grenestedt (1997) presented a qualitative failure analysis of glass-reinforced beams with holes of different shape. Their results show that reinforcement inhibits further crack progression in wood and decreases the stress intensity at cracks. Failure occurs when the load has reached the strength of the reinforcement.

The fire resistance of timber structural elements in bearing depends on the cross section of the material beneath the char-line that is undamaged by the fire. Improving fire resistance of structural elements implies either increasing their cross section or reducing the charring depth of the timber elements. Since increasing cross sections is not a feasible option for existing structures, Piazza and Cont (1996) attempted to reduce the charring depth by improving the adhesion of protective coating products to the wood surface. The authors applied a glass fibre net on the wood surface facilitating the adherence of the flame retardant coating on wood, in an attempt to avoid premature peeling of the coating before it transforms into a layer of protective carbon foam. By using a glass fibre net the authors could always obtain improvements in fire resistance greater than those obtained through the use of only the protective coatings.

Most of the studies have examined the short-term effects on the addition of fibre reinforcement to wood and only little work has been done on the long-term effects of FRP composites. Plevis and Triantafillou (1995) performed a 10-month test on solid-sawn fir beams reinforced with FRP and tried to develop a predictive creep model. However, they did not consider mechano-sorptive effects nor calibrate the model to the experimental results. Their work was continued by Davids et al. (1999) who experimentally demonstrated that, although GFRP-reinforced glulam beams can bear significantly larger loads, they do not show increased relative creep. They also proposed a viscoelastic model that allows for mechano-sorptive effects and strain-dependent shrinkage and swelling phenomena, and the model was successfully used to predict the experimentally observed creep deformations of the reinforced Douglas-fir beams.

4.2 Aramid fibre reinforced polymer (AFRP) wood systems

Zeno et al. (2000) analyzed the effect of reinforcing truck wood flooring (decking) with AFRP on the tension side. The results indicated a significant increase in stiffness of 40-70 per cent and an increase in ultimate load by 85-140 per cent, for laminated White Oak flooring reinforced with glass-aramid fibres and aramid fibres.

Impact resistance of epoxy based woven fabric E-glass / aramid composites was evaluated by Eijk and Peijs (1995). The results revealed excellent impact resistance for all-GFRP as compared with all-AFRP. However, penetration resistance of all-AFRP composites may be substantially improved by addition of random glass fibres. The resulting glass / aramid composite had enhanced elastic energy storage capacity, and thus during the impact less energy was absorbed by the composite and available for damage.

The Taylor Lake Bridge, near The Dalles, Oregon is the first commercial structure in service using the FiRP technology (Leichti et al., 1993). The bridge uses glulam beams with strategically positioned E-rated laminates reinforced with AFRP. Cost savings of using the FiRP technology as opposed to conventional glulam were 32 per cent. In another example, by reinforcing the tension sides of the interior and exterior girders of the Lighthouse Bridge in Clallam Bay, Washington with CFRP/AFRP and AFRP respectively, the bridge used only 67 per cent of the wood that would have been required by a conventional glulam design. In the case of the Zongas Bridge constructed in Puyallup, Washington, three layers of 1.8 mm thick AFRP placed on the tension side of the interior and exterior girders reduced the cross section of girders and used only 73 per cent of the wood fibre required by the conventional glulam design. Besides conventional and reinforced glulam, Tingley et al. (1996d) evaluated steel and precast concrete versions of the Zongas Bridge for cost comparison purposes. The steel version would have been 11 per cent higher in cost and approximately equivalent in weight to the reinforced glulam bridge. The precast concrete version would have needed a modified construction design with three times the weight of the reinforced glulam bridge and would have been much more expensive than the reinforced version.

Deflection at failure of glulam beams with 0.3 percent aramid reinforcement by cross section may be increased by 100 per cent, reaching a ductility ratio of 2 or greater even with low-grade laminations (Tingley and Gai, 1997). The same study included repeated cyclic loading on glass, aramid and carbon FRP laminates. While the aramid and carbon laminates showed excellent fatigue results failing only at 80 per cent stress level, fibreglass laminates were very sensitive to failure. Therefore the authors recommended the use of fibreglass FRP laminates under conditions other than repeated cyclic loading.

In his studies, Tingley (1988, 1989) presents a simple cost calculation for materials and manufacture of 16-foot beams reinforced with aramid fibres. The cost of three layers AFRP including manufacture was $30 for a full-length specimen, while the cost of the unreinforced wood beam was $150, resulting a 20 per cent increase in cost for reinforcement. However, if the reinforcement is shortened by two feet at each end on two of the three layers of FRP, no apparent reduction in strength was observed, and the cost of the beam increased only 15 per cent, as opposed to 20 per cent.

4.3 CFRP reinforced wood systems

Carbon fibres, characterized by high specific strength (strength-to-density ratio or the specific stress at the point of failure) and specific stiffness (stiffness-to-density ratio), have great potential as reinforcing materials in wood composites. Wood and carbon fibres match each other in properties such as acoustic transmissivity, electrical conductivity, strength and dimensional stability, resulting in low density, high strength, fire and termite resistant composite boards.

A method of reinforcing glulam beams with carbon fibres was developed by a team of specialists in Japan in 1999. The team developed a novel technique to produce a new composite made of unidirectional carbon fibre sheet impregnated with phenolic type resin, called prepreg, which was then sandwiched between layers of paper impregnated with phenolic, called Pic, and cured (Ogawa, 2000). The resulting composite may be wound continuously on a spool of large diameter, and then applied on glulam by cold pressing in a continuous process. The team claimed a number of advantages over the conventional reinforcement with carbon fibres, such as simplicity and reduced cost.

Triantafillou et al. (1992) developed a promising technique for rehabilitating old wood structures or for reinforcing new structures by external epoxy bonding of pretensioned CFRP sheets on the tension side of beams. Pretensioning may be justified when cost of FRP reinforcement becomes an issue, such as when CFRPs are used, because thinner pretensioned laminates are as efficient as thicker unstressed laminates. The researchers found that structural components with excellent strength, stiffness and durability properties may be constructed for specific combinations of prestress levels and area fractions of the composite laminates.

Gilfillan et al. (2000, 2001) studied performance of home-grown timber glulam beams using carbon fibre reinforcement. The authors reinforced beams of various sizes with CFRP, and obtained a considerable increase in bending stiffness and ultimate load capacity even for modest reinforced beams. By reinforcing the tension side of a 6 m span beam with 0.4 per cent CFRP the ultimate load was increased with 48 per cent. Compression reinforcement prevented compression failure of the timber.

Dimakis (2000) confirmed that a level of reinforcement of 0.25-1 per cent by volume is sufficient to produce western hemlock glulam beams with compatible performance to benchmark products available on the market. The author also found out that, (1) FRP technology is not a cost-effective option for stiffness-driven construction applications; (2) GFRP is cost-effective at the current price for the most common type of glass fibre for structural reinforcements, E-glass ($0.75/lb.); and (3) CFRP becomes cost-effective if the price of carbon fibre drops below $5/lb. or its stiffness increases to 50 Msi (10^6 psi) and above.

Pulido et al. (1996) tested the strength and fire resistance of CFRP overlaid particleboard made of sugi (*Cryptomeria japonica*). The core material was either particleboard from sugi chips or particleboard from sugi bark. Interestingly, the fire resistance increased for cores of sugi bark. CFRP overlays increased the fire resistance of boards by 10-20 min for chip core and by 40 min. for bark core, whereas time to burn through gypsum bonded bark board was 40 min.

The effect of fibre length and orientation on the elasticity of plywood was studied by Xu et al. (1998). The specimens were composed of three plies of parallel veneers and two carbon fibre reinforcement layers bonded with phenol-resorcinol-formaldehyde resin. The effect of length was studied on 3, 6 and 14 mm long carbon fibres, arranged parallel to the wood grain direction, perpendicular to the wood grain direction and randomly. They found insignificant effect on elasticity for fibre lengths of 3 mm and 6 mm, and surprisingly, lower Young's modulus for 14 mm long carbon fibres. Based on their findings, the 6 mm long fibres were most suitable for reinforcement. As expected, different elastic values were obtained for different fibre orientations. The best results were obtained for the random fibre orientation.

There are other technologies employed in the composites industry: spray or hand wet lay-up, vacuum bagging, filament winding, resin transfer moulding (RTM) and other infusion processes (SCRIMP, RIFT and VARTM). Apart from the wet lay-up process, these methods are used for high-end plastic composites, and are not applicable to wood products.

5 Durability and Management of FRP Reinforced Wood Products

The factors affecting the durability of FRP composites are environmental factors such as moisture absorption, UV exposure, weathering; mechanical stresses like creep, fatigue; size and thermal effects, and fire. Often the combined effect of these factors affects the composites most.

Davalos et al (2000a, 2000b) studied the durability of untreated wood-FRP composites through cyclic delamination, shear strength and fracture tests, and found out that a modified version of ASTM D2559 is appropriate to determine the effect of bonding parameters. The authors used a modified version of ASTM D905 to obtain the average shear strength under dry and wet conditions. Lopez-Anido et al. (2000) also used a modified ASTM D905 as well as a modified ASTM D1101 to evaluate the effect of hydroxy-methylated resorcinol (HMR) coupling agent on interface durability between eastern hemlock glulam and E-glass/vinyl composites. It was found that the use of HMR coupling agent highly improved bond durability.

The University of Maine (USA) is well known for the state-of-the-art research on advanced wood-FRP composites. It was recently revealed that synthetic fibres could facilitate moisture movement and spread of microorganisms within the composite. FRP wood composites are not immune to fungal and bacterial growth, which can induce localized weak links and significantly affect their physical and mechanical performance. Recent studies on the effects of common wood preservative treatments on the durability of wood and FRP interfaces conducted by Tascioglu et al. (2003a) revealed that pre-treatment of wood laminations with various preservatives increase delamination between wood and E-glass/phenolic FRP. However, post-treatment of similar wood-FRP composites had more limited effects on bond delamination. The researchers brought to light the sensitivity of FRP reinforcement to fungal penetration by common wood decay fungi (Tascioglu et al., 2003b). The hypothesis supporting this conclusion was that fibres facilitate the movement of moisture within the composite, by acting as capillaries, and moisture ease microorganisms infiltration and spread at the wood-FRP interface, weakening the material. More research is necessary for a complete understanding of the behaviour of FRP composite materials subjected to biological attack. Further tests are needed to investigate the effect of various preservatives and pre-post- treatment processes on the durability of the wood-FRP interface.

GangaRao (1997) evaluated accelerated aging response of sawn and laminated wood beams wrapped with woven glass FRP fabric and bonded with various polymeric resins such as epoxy, resorcinol formaldehyde (RF), phenol resorcinol formaldehyde (PRF), polyurethane (PU), isopolyester, and RF/epoxy. Epoxy resin performed well under dry conditions, while RF/epoxy showed the highest resistance after the accelerated aging treatment. Aged samples bonded with isopolyester performed poorly due to over absorption of the adhesive into the wood. Generally, low viscosity primers or adhesives are first applied on the adherends to fill up the pores and chemically prepare the bonding surface for more viscous adhesives. This way a better adhesion between the two adherends may be obtained.

Management of FRP structures implies repair techniques and recommendations for regular inspection and maintenance of these structures. FRPs have excellent performance in various environments, but as any other construction material they can be damaged in service. Therefore, FRP structures require routine inspection and maintenance to attain their long-term performance. BRE Construction Division (Halliwell, 2003) recommends routine inspections every year for FRP structures and structures containing FRP components, and detailed inspections every six years for bridges and at least every ten years for buildings and other structures. Inspection of FRP structural components may be performed by suitable non-destructive testing methods or a simple tapping test. Based on the extent and accessibility of the damage, the availability of suitable repair materials and repair costs, structural components are replaced or repaired. If opting for repair, the goal is to restore as much as possible of the original properties, performance and appearance of the FRP component or structure. Pending on the degree of damage, there are various repair techniques, starting from simple re-coating of the damaged area with resin, to more advanced methods such as the vacuum bag procedure, which implies applying a prepreg or composite lay-up and sealing it with a flexible bag over the damaged area of the composite, then applying a vacuum to evacuate all the air from the bag, and heating it to cure. Bonded repairs are usually applied to thin FRP laminates while thick laminates are generally repaired with bolts. However, the most suitable repairing method depends on the particular application and the performance required.

6 Other Applications of FRP Reinforced Wood Products

6.1 Early applications of synthetic reinforcements

Commercially, fibre-reinforced wood qualities have been exploited over the past 50 years in applications such as FRP-reinforced wood transmission poles, finger joints reinforced with fibreglass impregnated with phenol-resorcinol formaldehyde, and reinforced laminated wood beams and glulam beams. Other examples of field implementation mostly for aramid and glass fibres include kayaks, canoes, and sailboat components, primarily rudders, masts and hulls. Trailer sides, cargo shipping containers and railroad cars made of glass-reinforced plywood have been gaining popularity in the transportation industry due to low maintenance, reparability, and increased volume for payloads.

These examples represent only a few applications of composites, which have resulted in increased efficiency because of their improved use characteristics and high strength-to-weight ratios. There are many other opportunities for use of reinforcements in the area of non-structural wood products.

6.2 Local reinforcement of weak points

Besides the common applications of strengthening axial and flexural members, fibre reinforcement can be used in zones of stress concentrations, for strengthening bolted, finger and butt joints. Many failure modes in wood associated with the tension zone in bending involve a combination of shear and tension, of splitting along the grain and rupture in pure tension. Local grain deviations around knots on the tension side of a beam are considered weak points because a tension load perpendicular-to-grain will initiate crack propagation that may lead to total failure. Local reinforcement of a weak zone prevents crack formation or crack growth, changing the failure mode from brittle to ductile and greatly improving the reliability of the structural member. Madsen (1997) explains the partial failures of pitched cambered beams in 1960 that caused the industry to stop production of this type of beam. The beams split parallel to laminations in the central part of the curvature because of tension perpendicular-to-grain developing in the curved area due to the change in cross section. The beams did not entirely fail but had to be reinforced or replaced. The author remarked that reinforcing pitched cambered beams with synthetic fibres may revive this market for the glulam industry. Johns and Lacroix (2000) recommended extension of the fibre reinforcement layer right out to each of the support faces, to eliminate combined shear and tension failures, as well as bending failures associated with random defects.

Lawrence et al. (1997) also tried to prevent bolted connections from failure under the bolt due to tension perpendicular-to-grain caused when the bolt wedges its way through the wood. He reported a 3 to 13 percent increase in shear strength and a 30 to 60 percent increase in tension perpendicular-to-grain strength, when adding one layer of bi-directional fibreglass fabric applied with an epoxy resin. If reinforcing the bolted joint with two or three layers of fabric, the failure mode for parallel loading changed from a brittle mode to a ductile mode. There was no change in failure mode for the perpendicular-to-grain loading. Other types of connectors for timber structures that may be reinforced with FRP are gusset plates. The tests pursued by Miyatake and Fujii (1995) showed increased strength for longer gusset plates.

Lopez-Anido et al. (2003) developed a technique to repair wood piles in the field by using a prefabricated FRP composite jacket. Generally, wood piles deteriorate in the portion above mud line by marine borers, fungi and other sources, losing the capacity to sustain design loads. The conventional repair technique involves dismantling the pier, replacing the damaged piles, and rebuilding the pier. Since the portion of the pile below the mud line is normally intact, pile repairs without pier dismantling are usually possible. The authors designed an FRP composite jacket to fit around damaged piles in the field. To test structural resistance of the repaired piles, wood piles were pre-damaged in the laboratory by reducing their cross section by approximately 60 per cent, decreasing this way their bending capacity to one-sixth of the value when intact. It was found that piles repaired with FRP composite jacket and cement-based grout exceeded the bending capacity of an intact reference wood pile.

An increasing number of marine and construction applications use fibre optic strain sensors for monitoring of field performance. Lopez-Anido et al. (2003) investigated the feasibility of using Extrisic Fabry-Perot Interferometric (EFPI) fibre optic sensors to monitor FRP composite materials. It was found that the embedded sensors did not affect the longitudinal and transverse elastic modulus and strength of the FRP composites, while strain readings with the sensors agreed well with gage readings applied on test specimens.

In-situ retrofitting of structural members with FRP is in many cases a practical and cost effective option to replacement. A special retrofitting technique was used by Kent et al. (2002) to enhance bending strength and stiffness of wood beams and decking. Three LVL planks and ten layers of carbon-aramid reinforced plastic were adhesively and mechanically connected to the underneath of the wood beams and decking to supplement the deficit bending strength and stiffness.

6.3 Miscellaneous applications

Other examples of present and future applications of wood products that incorporate FRP materials are: long span glulam beams, railroad crossties, underwater piles subject to marine borer attack, electrical transmission poles and highway sound barriers. Studies revealed performance and longevity improvement of wood railroad crossties if using glass fibre roving and epoxy resin reinforcement applied to critical areas of crossties (Davalos et al., 1999). Wood crossties were primed with phenol-formaldehyde and then wrapped with glass reinforcement applied by the filament winding process. The results indicated improved stiffness (21 per cent for dry and 25 per cent for wet conditions) and strength (28 per cent for dry and 70 per cent for wet conditions) for a relatively thin layer of reinforcement (1.78 mm).

7 Recommendations for Future Utilization of Reinforcements

Youngquist and Hamilton (1999) call for more efficient and responsible use of wood fibres by combining them with other materials. This way, resulting products with enhanced properties may compete more effectively with other materials, and be used where they best fit economically and environmentally.

In contrast to the past when wood products were first developed and then marketed, current and future structural wood products will be tailored to meet specific market needs based on performance standards. In the last few years, structural fibre-reinforced wood products have become more widely available, due to their enhanced mechanical properties, more predictable performance, and higher timber conversion efficiency that result in greater final product yield. However, more knowledge is needed about the dimensional stability, durability and fire performance of these materials. Once these issues have been addressed, fibre-reinforced products will need to undergo the process of product acceptance by regulatory agencies. Presently, reinforced glulam beams are being used commercially and glulam standards are now in process. ASTM Subcommittee D07.02.02 is developing a standard for fibre-reinforced glulam, which will be vital for its wide acceptance. Canada has already established structural design specifications for the use of FRP for concrete reinforcement (CSA 1996, 2002), and similar engineering design procedures and specifications should be developed for wood reinforced with FRP. The amount of data to fully characterize the long-term performance and durability of FRP composites is scarce. Presently there is no Canadian or US standard that specifies allowable percent delamination at the interface in wood-FRP composites. Building a database on structural performance and durability of FRP composites is required to gain acceptance of these materials.

Repeatability of properties of mass produced FRP composites is one issue of great importance for a wider acceptance of these materials. Again, development of specifications and quality control methods are essential to expedite the use of FRP composites in the wood products industry. Their recognition will be further widened by developing techniques for continued monitoring of their in-service performance. Moreover, research activities must be correlated among regulatory agencies, research institutes and academia at the international level to avoid duplication of effort (Bank 1997).

From a design standpoint, some of the most important properties of FRP composites are their high specific strength and stiffness. The combination of these two properties makes possible improved design capacities at lower weights and thicknesses, allowing for greater spans and loads, which would not be possible with conventional materials. However, some specific characteristics like non-homogeneity, anisotropy, modes of failure and corrosion resistance have to be properly addressed when designing with FRP composites.

Although wood is rated lower in overall material performance as compared with other infrastructure materials (Smith et al., 2000), highway infrastructure represents a potential niche market for FRP wood products. They may successfully compete with other materials such as steel, reinforced concrete, prestressed concrete, aluminium, and plastic for various end-uses, such as bridges, guardrails, barriers, signs and signposts. Durability, maintenance and cost are the most important decision factors in the material selection, because they primarily affect the ability to efficiently accomplish material's required task. In a survey conducted by Smith et al. (2000), wood was rated low in initial cost, high in corrosion resistance, high in ease of construction, high in ease of repair, and high in ease of field modification. However, it was also rated high for maintenance and life cycle cost and low in durability attributes, which include fatigue, mechanical wear, fire, weathering and biological decay resistance. Although FRP wood composites perform better than wood in these areas, in order to compete more effectively with the other infrastructure materials the high cost of FRP wood products needs to be reduced, their durability has to be improved, and FRP wood product designs for highway applications need to be established.

In a similar survey, Kozak and Cohen (1999) attempted to determine how architects and structural engineers specify structural materials, to understand the lack of wood usage in the construction of non-residential buildings and to find how to increase its market share in this sector. According to the survey, as building size and height increase, wood use decreases and is substituted by steel, concrete and masonry. Designers see wood as combustible, not durable and subject to deterioration, while steel, concrete and masonry are seen as long lasting, durable, safe and fire resistant. With the appropriate design, these are qualities that can be added to wood through combination with FRPs, creating a product that is suitable for offices, schools, industrial and public buildings, representing vast growth opportunities for engineered building components.

Potential for using FRP wood composites for structural rehabilitation of timber bridges exists in Canada. Johns and Lacroix (2000) acknowledged that current timber bridges in many Canadian provinces carry heavier traffic loads under today's conditions than called for in the original design calculations. Structures retrofitted with FRP composites have performed well in the past (Lopez-Anido and Naik, 1998). FRP composites may also be applied for structural rehabilitation of historical structures, structures partially damaged by fire or vehicle impact, or for modified structures.

Further evaluation of FRP composites needs to be performed at the microscopic level, coupon (sample) level, component level and system level to accurately characterize these materials. These tests and analysis should be carried out at various levels of temperature, relative humidity and UV exposure.

The outlook for FRP utilization in the wood industry is bright. Professionals will gradually gain more understanding of these materials, and ultimately FRP composites will be introduced in codes and standards, based on their performance and cost-competitiveness with conventional materials. The main opportunity for an increase in the use of FRP reinforced engineered wood products lies in the structural non-residential area, but there are possibilities in residential construction as well.

Nelson (2000) observes that "the future growth of engineered wood products is limited only by the creativity of engineers, customers, and the commitment of company management to make these products successful."

8 Selected References

Alexander, J.P., Shaler, S.M. and Gardner, D.J. 2000. Evaluating wood/FRP adhesive bond durability through chemical kinetics. Proceedings of Wood Adhesives. Lake Tahoe, NV. 58-60.

Aoki, Y. 1990. The manufacture of heat hardening cement particleboard. Proceedings of the 2nd International Inorganic Bonded Wood and Fibre Composite Materials Conference, Idaho. 35-44.

American Standard for Testing and Materials (ASTM). Standard Specification for Glass Fibre Strands. ASTM D578. Annual Book of ASTM Standards. ASTM, West Conshohocken, PA.

American Standard for Testing and Materials (ASTM). Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading. ASTM D905. Annual Book of ASTM Standards. ASTM, West Conshohocken, PA.

American Standard for Testing and Materials (ASTM). Standard Test Methods for Integrity of Adhesive Joints in Structural Laminated Wood Products for Exterior Use. ASTM D1101. Annual Book of ASTM Standards. ASTM, West Conshohocken, PA.

American Standard for Testing and Materials (ASTM). Standard Specification for Adhesives for Structural Laminated Wood Products for Use Under Exterior (Wet Use) Exposure Conditions. ASTM D2559. Annual Book of ASTM Standards. ASTM, West Conshohocken, PA.

Bank, L.C. 1997. Project Technical Report on the US Delegation to the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (Sapporo, Japan). National Science Foundation, Arlington, VA.

Barbu, M.C. 1999. Wood Composite Materials. Lux Libris. Brasov, Romania.

Berenberg, B. 1998. Fibre Selection. Composites/Plastics

Biblis, E.J. and Carino, H.F. 2000. Flexural properties of southern pine plywood overlaid with reinforced-reinforced plastic. Forest Products Society. 50(4):34-36

Blom, A. and Backlund, J. 1980. Composite material reinforcement of cutouts in laminated timber beams. Department of Mechanical Engineering, Linkoping Institute of Technology, Sweden.

Brunner, M. and Schnuriger M. 2002. Towards a future with ductile timber beams. The 7th World Conference on Timber Engineering, Shah Alam, Malaysia. 270-276.

Bui, Q.D., Milner, H.R. and Williams, J.M. 1996. Fibre reinforced finger joints. International Wood Engineering Conference. New Orleans, USA. (1):427-432.

Bulleit, W.M. 1985. Elastic analysis of surface reinforced particleboard. Forest Products Journal. 35(5):61-68.

Calvin, S. and Back, E. 1968. The effect of sheet density and glass fibre addition on the dimensional stability of fibre building boards. Svensk Papperstidning. 71(24):883-889.

Callister, W.D. 2002. Materials Science and Engineering: An Introduction. 6th Edition Wiley Publishers. ISBN 0-471-13576-3.

Canadian Standards Association (CSA). 1996. Canadian Highways Bridge Design Code, Section 16, Fibre Reinforced Structures (CHBDC), Toronto, Canada.

Canadian Standards Association (CSA). 2002. Design and Construction of Building Components with Fibre-Reinforced Polymers. CSA-S806-02. Canada

Canadian Wood Council. 1995. Wood Reference Handbook. A guide to the architectural use of wood in building construction. Ottawa, Ontario, Canada.

Canadian Wood Council. 1997. Introduction to Wood Building Technology. Wood Text Series vol. 4. Ottawa, Ontario, Canada.4, Ottawa, Ontario.

Composites for Infrastructure: A Guide for Civil Engineers. 1998. Ray Publishing, Inc.

Dagher, H.J., Kimball, T., Abdel-Magid, B. and Shaler, S. 1995. Behaviour of FRP-reinforced glulam beams. Report to the United States Dept. of Agriculture and the National Science Foundation, University of Maine, Orono, ME.

Dahlbom, O., Enquist, B., Gustafsson, P.J., Knudsen, R., Larsen, H.J., Omarsson, S. and Traberg, S. 1993. Advanced materials based on strew and wood. Fibre reinforcement of glulam. Rep. 1-7. Department of Structural Engineering, Technical University of Denmark and Division of Structural Mechanics, Lund Institute of Technology, Sweden.

Davalos, J.F., Zipfel, M.G. and Qiao, P. 1999. Feasibility study of prototype GFRP-reinforced wood railroad crosstie. Journal of Composites for Construction. 3(2):92-99.

Davalos J.F., Qiao, P.Z. and Trimble, B.S. 2000a. Reinforced-reinforced composite and wood bonded interface, part 1. Durability and shear strength. Journal of Composites Technology and Research. ASTM 22(4): 224-231.

Davalos J.F., Qiao, P.Z. and Trimble, B.S. 2000b. Reinforced-reinforced composite and wood bonded interface, part 2. Fracture. Journal of Composites Technology and Research. ASTM 22(4): 232-240.

Davids, W.G., Dagher, H.J. and Breton, J.M. 1999. Modeling the creep deformations of FRP-reinforced glulam beams. Wood and Fibre Science. 32(4): 426-441.

Detrick, J.H. 1982. Fire and chemical resistant fibreglass structures. Proceedings of a session sponsored by the Structural Plastics Research Council of the Technical Council on Research of the American Society of Civil Engineers, ASCE National Convention, Las Vegas, Nevada. 64-74.

Dimakis, A.G. 2000. Engineered Lumber Reinforcement: Engineering vs. Economics. Proceedings of the 34th International Particleboard/Composite Materials Symposium, Washington State University, Pullman, Washington. 35-41.

Enquist, B., Gustafsson, R.J. and Larsen, H.J. 1991. Proceedings of the International Timber Engineering Conference. London. UK. 3:242-250.

Forest Products Society. 1999. Wood Handbook: Wood as an engineering material. Reprint Forest Products Laboratory. General Tech. Rep. FPL-GTR-113, Madison, Wisconsin.

Gardner, D.J. 2003. Lecture: Wood Polymer Hybrid Systems: Polymer Matrices for FRP Composites. Course: WSC 550 Wood-Polymer Hybrid Composite Processing. (www.umaine.edu/adhesion/gardner.htm)

Gardner, D.J., Davalos, J.F. and Munipalle, U.M. 1994. Adhesive bonding of pultruded reinforced-reinforced plastic to wood. Forest Products Journal. 44(5):62-66.

GangaRao, H.V.S. 1997. Sawn and laminated wood beams wrapped with fibre reinforced plastic composites. Wood Design Focus. 8(3):13-18.

Gilfillan, J.R., Gilbert, S.G. and Russell D.R. 2000. Development of a structural composite using Irish-grown timer and fibre reinforcement. Proceedings of the World Conference on Timber Engineering, Whistler, British Columbia, Canada.

Gilfillan, J.R., Gilbert, S.G. and Patrick, G. 2001. The improved performance of home-grown timber glulam beams using fibre reinforcement. Journal of Institute of Wood Science. 15(6): 307-317.

Gromala, D.S. 1997. New directions in wood engineering. Proceedings of the Workshop on Wood Engineering in the 21st Century: Research Needs and Goals. Portland, Oregon. 134-143.

Halliwell, S. and Suttie, E. 2003. Repair and maintenance of FRP structures. Good Repair Guide No. GRG34. BRE Construction Division.

Hallstrom, S. 1996. Glass fibre reinforced holes in laminated timber beams. Wood Science and Technology. 30: 323-337.

Hallstrom, S. and Grenestedt, J.L. 1997. Failure analysis of laminated timber beams reinforced with glass fibre composites. Wood Science and Technology. 31:17-34.

Hughes, M., Mott, L., Hague, J. and Hill, C.A.S. 1999. The toughness of vegetable reinforced-reinforced unsaturated polyester composites. The Fifth International Conference on Woodfiber-Plastic Composites. 175-184.

Johns, K.C. and Lacroix, S. 2000. Composite reinforcement of timber in bending. Canadian Journal of civil Engineering. 27:899-906.

Kent, S.M., Leichti, P.E. and Stith, J. 2002. In-situ repair of glulam beams and roof decking using FRP and LVL composites. Wood Design Focus. 12(1):3-7

Ko, F.K., Kawabata, S., Inoue, M., Niwa, M., Fossey, S. and Song, J.W. 2001. Engineering properties of spider silk. (www.fmrc.coe.drexel.edu/publications)

Kollmann, F. 1982. Technologie des Holzes und der Holzwerkstoffe. Zweite Auflage. Springer Verlag, Berlin.

Kozak, R.A. and Cohen, D.H. 1999. Architects and structural engineers: An examination of wood design and use in non-residential construction. Forest Products Journal 49(4):37-46.

Kumar, R.N., Wei, L.M., Rozman, H.D and Abusamah, A. 1996. Sheet moulding composites from hybrid reinforcements of bio-fibres and glass fibre. Pacific Rim Bio-based Composites Symposium. Kyoto, Japan. 301-309.

Lantos, G. 1970. The flexural behaviour of steel reinforced laminated timber beams. Wood Science and Technology. 2(3):136-143.

Larsen, H.J., Gustafsson, P.J. and Enquist, B. 1992. Tests with glass-fibre reinforcement of wood perpendicular to the grain. Rep. TVSM-7067. Division of Structural Mechanics, Lund Institute of Technology, Sweden.

Laufenberg, T.L., Rowlands, R.E. and Krueger, G.P. 1984. Economic feasibility of synthetic fibre reinforced laminated veneer lumber (LVL). Forest Products Journal. 34(4):15-22.

Laverty, R. 2002. Advanced Engineered Wood Composites – Innovative Technologies for Maine's Forest Products Industry. Forest Products Journal. 52(11/12):18-26.

Lawrence, A.S., Ross, R.J and Windorski, D.F. 1997. Effect of fibreglass reinforcement on the behaviour of bolted wood connections. Wood Focus Design. 8(3):19-24.

Lee, A.W.C., Bai, X. and Bangi, A.P. 1997. Flexural properties of bamboo-reinforced southern pine OSB beams. Forest Products Journal. 47(4):74-78.

Leichti, R.J., Gilham, P.C. and Tingley, D.A. 1993 The Taylor Lake Bridge: A reinforced-glulam structure. Wood Design Focus. 4(2).

LeVan, L.S. 1997. Benefits from wood engineering research. Proceedings of the Workshop on Wood Engineering in the 21st Century: Research Needs and Goals. Portland, Oregon. 1-24.

Lopez-Anido, R. and Naik, T.R. 1998. Emerging materials for civil infrastructure. ASCE, Reston, VA. ISBN 0-7844-0538-7.

Lopez-Anido, R., Gardner, D.J. and Hensley, J.L. 2000. Adhesive bonding of eastern hemlock glulam panels with E-glass/vinyl ester reinforcement. Forest Products Journal 50(11/12): 43-47.

Lopez-Anido, R., Michael, A.P. and Sandford, T.C. 2003. Experimental characterization of FRP composite-wood pile structural response by bending tests. Marine Structures 16(4):257-274.

Lopez-Anido, R. and Fifield, S. 2003. Experimental methodology for embedding fibre optic strain sensors in fibre reinforced composites fabricated by the VARTM/SCRIMP process. Proceedings of the 4th International Workshop on Structural Health Monitoring. Ed. F-K Chang, Stanford University, CA. DEStech Publications, Lancaster, PA. 247-254.

Madsen, B. 1997. Reinforcing Timber Structures to Satisfy our Needs. Wood Design Focus. 8(3):4-12.

Mark, R. 1961. Wood-Aluminum beams within and beyond the elastic range. Part I. Forest Products Journal. 11(10):477-484.

Mark, R. 1962. Wood-Aluminum beams within and beyond the elastic range. Part II. Forest Products Journal. 12(11):516-518.

Miyatake, A. and Fujii, T. 1995. Strength properties of epoxy-bonded joints for timber structures. Materials and Structures. 28(176):106-107.

Moulin, J.M., Pluvinage, G. and Jodin, P. 1990. FGRG: Fibreglass reinforced gluelam – A new composite. Wood Science and Technology. 24: 289-294.

Nelson, S.A. 2000. Engineered Composite Lumber: Past, Present and Future. Proceedings of the 34th International Particleboard/Composite Materials Symposium, Washington State University, Pullman, Washington. 3-6.

Nishikawa, K.A., Matsumoto, A. and Niiro, O. 1974. Studies on the manufacture of fiberboards mixed with mineral fibers – The effect of mixing ratio of glass chopped strand and kinds of phenolic resin. Journal of Hokkaido Forest Products Research Institute. 10:11-15.

Nishikawa, K.A., Matsumoto, A. and Niiro, O. 1975. Studies on the manufacture of fiberboards mixed with mineral fibers – The effects of kinds of glass and other mineral fibres. Journal of Hokkaido Forest Products Research Institute. 1:8-12.

Piazza, M. and Cont, S. 1996. Timber fire resistance by fibreglass supported intumescent coatings. International Wood Engineering Conference. New Orleans, USA. (2):398-405.

Plevis, N. and Triantafillou, T. 1992. FRP-reinforced wood as structural material. Journal of Materials in Civil Engineering. 4(3):300-317.

Pulido, O.R. and Ma, L.F. 1996. Hybrid composites from wood and carbon fibers. Pacific Rim Bio-based Composites Symposium. Kyoto, Japan. 310-318.

Riccio, F.A. and Orchard, L.P. 1999. Nonwood fibre resources: availability, infrastructure and feasibility. The Fifth International Conference on Woodfiber-Plastic Composites. 211-215.

Rowlands, R.E., van Deweghe, R.P., Laufenberg, T.L. and Krueger, G.P. 1986. Reinforced-reinforced wood composites. Wood and Fibre Science. 18(1):39-57.

SP Systems. Guide to Composites Booklet. http://www.spsystems.com

Sonti, S.S., Hota, V.S., GangaRao, D.R., Talakanti, D.R. and Gray, G. 1996. Improving bending strength of glulam beams using composite fabrics. International Wood Engineering Conference. New Orleans, USA. (1): 420-426.

Smulski, S.J. and Ifju, G. 1987. Flexural behaviour of glass fibre reinforced hardboard. Wood Fibre and Science. 19(3):313-327.

Tascioglu, C., Goodell, B. and Lopez-Anido, R. 2003. Bond durability characterization of preservative treated wood and E-glass/phenolic composite interfaces. Composites Science and Technology 63(2003): 979-991.

Tascioglu, C., Goodell, B., Lopez-Anido, R., Peterson, M., Halteman, W. and Jellison, J. 2003. Monitoring fungal degradation of E-glass/phenolic fibre reinforced polymer (FRP) composites used in wood reinforcement. International Biodeterioration & Biodegradation 51(2003): 157-165.

Tingley, D.A. 1988. Reinforced glued-laminated wood beams. Wood Science and Technology Institute, Inc. Fredericton, N.B., Canada.

Tingley, D.A. 1989. Predicting strength criteria for Kevlar and fibreglass reinforced plastic (KRP & FRP) glued laminated beams. Pacific Timber Engineering Conference, New Zeeland.

Tingley, D.A. and Leichti, R.J. 1993. Reinforced glulam: improved wood utilization and product performance. The Globalization of Wood: Supply, Processes, Products and Markets. Proceedings No. 7319, Forest Products Society, Oregon.

Tingley, D.A. and Leichti, R.J. 1994a. Applications of high strength fibre reinforced plastic in building components of low-rise wood structures. The 2nd International Workshop on Full Scale Behaviour of Low Rise Buildings. James Cook University of North Queensland, Townsville, Australia.

Tingley, D.A. and Leichti, R.J. 1994b. Glues-laminated beams having a high-strength fibre reinforcement: The bimaterial interface. Pacific Timber Engineering Conference, Gold Coast, Australia.

Tingley, D.A. and Cegelka, S. 1996a. High-strength fibre reinforced plastic reinforced wood. International Wood Engineering Conference. New Orleans, USA. (1): 403-410.

Tingley, D.A. 1996b. Over a decade of research results in new, improved glulam. Canadian Consulting Engineer. 3/4:24-28.

Tingley, D.A. and Cegelka, S. 1996c. Shear stress distributions and maximums in reinforced glulam beams. International Wood Engineering Conference. New Orleans, USA. (3): 57-66.

Tingley, D.A., Leichti, R.J. and Gilham, P.C. 1996d. High-strength fibre reinforced plastic reinforced glulam highway bridges. International Wood Engineering Conference. New Orleans, USA. (2):353-359.

Tingley, D.A. and Gai, C.D. 1997. The effect of reinforced-reinforced plastic on glulam ductility and tension-tension fatigue resistance. Forest Products Society Annual Meeting. Vancouver, B.C. 18-22.

Triantafillou, T.C. and Deskovic, N. 1992. Prestressed FRP sheets as external reinforcement of wood members. Journal of Structural Engineering 118(5):1270-1284.

van de Kuilen, J.W.G. 1991. Theoretical and experimental research on glass fibre reinforced laminated timber beams. Proceedings of the International Timber Engineering Conference. London. UK. 3:226-233.

van Rensburg, B.W.J., Cillie C. du T. and Ebersohn W. 1984. Steel reinforced timber structural elements. Proceedings of the Pacific Timber Engineering Conference. Paper 208. Auckland, New Zeeland.

Wood Handbook – Wood as an Engineering Material. 1999. United States Department of Agriculture. Forest Products Laboratory. General Technical Report FPL-GTL-113.

Wolcott, M.P. 1997. Materials and wood-based composites. Proceedings of the Workshop on Wood Engineering in the 21st Century: Research Needs and Goals. Portland, Oregon. 50-55.

Youngquest, J.A. and Hamilton, T.E. 1999. Wood Products Utilization – A call for reflection and innovation. Forest Products Journal. 49(11/12):18-27.

Xian, X.J., Yipp, M.W. and Shin, F.G. 1995. Hybridized bamboo fibre reinforced composite materials. Proceedings of ICCM-10. Whistler, B.C., Canada. (V)259-266.

Xu, H., Nakao, T., Tanaka, C., Yoshinobu, M. and Katayama, H. 1998. Effects of fibre length and orientation on elasticity of reinforced-reinforced plywood. Journal of Wood Science. 44(3

Zeno, M.A., Stith, J.K. and Tingley, D.A. 2000. Strength and stiffness performance of FRP reinforced White Oak. Proceedings of the World Conference on Timber Engineering. Whistler, British Columbia, Canada.

Appendix A

Materials for Reinforcement

By combining wood with other materials, new composites with better properties and benefits are obtained. The new composite materials are generally available on the market at lower cost than traditional materials; they have enhanced performance for a specific targeted end use. A selective analysis of the literature reveals a variety of lignin-cellulose composite materials made of wood in various shapes (such as strands, fibres, veneers, and flour), as well as non-wood materials (such as biomass, steel, plastic, synthetic fibres, and FRP) with wide areas of application.

Synthetic composites such as FRP materials consist of two basic systems, a polymer-based resin as the matrix, and a variety of synthetic fibres as the reinforcement. Either one of the resin or the fibre systems are seldom used for structural purposes on their own due to their limited mechanical properties or physical appearance if compared to other structural materials. When combined under specific conditions with advanced manufacturing procedures, FRP composites can offer a strong, durable and lightweight alternative to traditional materials.

A.1 Fibres

Current natural and synthetic fibres used as reinforcements for wood products are further presented in detail.

A.1.1 Natural fibres – A source of reinforcement fibres

Development of new materials by combining wood and other natural fibres has been the objective of numerous research projects along the years. The most important aspect when developing such new composites is the mechanical, chemical and physical compatibility between the wood fibres and the other natural fibres, which influences the structural unity and pre-established properties of the resulting product. While this report focuses on wood – synthetic composites, combination of wood with other natural fibres represents a field of interest for wood composites industry and therefore is briefly presented further.

Wood – A natural composite material

Wood is one of the oldest natural composite materials used by the mankind. Having a natural macromolecular structure, wood is a composite by itself with a complex chemical structure and specific physical and mechanical properties. Wood formation in a tree is the result of the activity of generating tissues, which produce elongated cells such as fibres, tracheids or longitudinal parenchyma cells, oriented parallel to the tree axis, and smaller size cells customarily called rays, oriented horizontally in the direction from pith toward bark. Wood cells are the structural elements of wood tissue (Wood, 1999). Since the elongated cells oriented parallel to the tree axis dominate in number and size the cells oriented perpendicular to the tree axis (up to more than 90 per cent for coniferous), physical, mechanical and technological properties of wood in the longitudinal direction greatly differ from its properties in the transversal direction. Wood-based materials are produced from a large array of elements obtained from wood through modern technologies that permit exploitation of all parts of the tree (trunk, branches, and bark). Wood cells characteristics affect such properties as strength, shrinkage and grain pattern of the elements produced.

If compared with other materials currently employed in construction, such as aluminium alloys, steel, concrete, FRP composites, wood has remarkable physical, mechanical and technological properties, as follows: various and reduced density, high fatigue strength, excellent workability, good insulator, non-corrosive, worm feeling and aesthetic beauty. As any other material, wood has its own weaknesses, primarily dimensional instability, high flammability and combustibility, as well as degradability under harsh environmental factors.

Examples of natural fibres used as raw materials or reinforcements

Combination of wood with other natural fibres rich in lignin-cellulose content represents a logical blend toward developing new cost effective products from an underutilized raw material, knowing also the downside of being susceptible to bio-photo-chemical attack.

Several natural fibres possess excellent mechanical properties that make them suitable as raw materials for the composites industry, or reinforcements for wood products. Riccio and Orchard (1999) classified non-wood fibres into dedicated fibre crops, agricultural residue and natural strands. Fibre crops can be further divided into seed hair fibres, bast fibres and leaf fibres. Seed hair fibres include cotton (*Gossypium*), coir (*Cocos nucifera*) and kapok (*Ceiba pentandra*). Cotton is highly used as a cellulose fibre in the higher value-added textile markets, and the resulted processing residues are consumed by the paper industry; therefore its availability as a raw material for the composites industry is limited. Coir and kapok have limited value and the infrastructure for processing and delivery of these fibres is restricted. Flax (*Linum usitatissimum*), true hemp (*Cannabis sativa*), jute (*Corchorus capsularis*), kenaf (*Hibiscus cannabinus*) and ramie (*Boehmeria nivea*) are examples of major commercial bast fibres. Similar to cotton, flax is grown for its fibres widely used in the textile industry, and has a good infrastructure, thus there may be great potential for residual materials to be used in the composites industry. Although hemp, jute, kenaf and ramie are notable textile fibres in terms of specific tensile strength, stiffness and toughness, their use as raw materials for composites or wood reinforcements is low due to their limited production and underdeveloped infrastructure. Among leaf fibres, the most important are abaca (*Musa textilis*) and sisal (*Agave sisalana*), which have been used in coarse textile, cordage and specialty papermaking applications. However, they have limited production to specific climatic regions of the world and weak infrastructure.

Equally valuable but with more potential as a fibre source in composites industry are agricultural residues from crops such as rice (*Oryza sativa*), sugarcane (*Saccharum officinarum*), corn (*Zea mays*) and sorghum (*Sorghum bicolor*). As Riccio and Orchard (1999) observed, these residual materials abundant in North America could be utilized in the plastic composite industry. Natural strands obtained from giant reed (*Arundo donax*), bamboo (*Bambusa*) and esparto (*Stipa tenacissima*) have industrial potential for many applications, but often considered more accessible than they really are. Particularly, bamboo fibres are considered a promising raw material due to their high tensile strength and bamboo's rapid growth rate. Although non-wood fibres are produced annually in vast amounts, their use as raw materials in the industry will require actual availability and development of feasible industrial infrastructures.

Performance of wood – based systems reinforced with natural fibres

It has been reported that laminated Moso bamboo flanges can significantly improve the flexural strength of southern pine OSB. Greater improvements were obtained for the MOR than for the MOE of the composite members (Lee, 1997). Tests performed on bamboo-jute, bamboo-coir, bamboo-bagasse, bamboo-nylon and bamboo-glass fibre composites with epoxy, polyester and urea formaldehyde matrices revealed increased compressive strength by 31 per cent and enhanced fracture toughness by 10 per cent for bamboo-bagasse/epoxy composites, and 17 per cent higher impact strength for bamboo-jute/epoxy composites (Xian et al., 1995). The authors also reported superior mechanical performance for bamboo fibres used as reinforcement in composite materials than for coir and bagasse fibres. Overall, glass and nylon fibres conferred the best enhancement in properties, followed by bamboo and jute fibres.

Wood composites reinforced with hemp fibres had shown improved strength, stiffness and toughness properties over unreinforced composites, but were inferior to those reinforced with glass reinforcement (Hughes et al., 1999).

Researchers developed sheet moulding compounds (SMC) from bio-fibres in combination with synthetic fibres (Kumar et al., 1996). The compound paste comprising filler, internal release agent, resin, catalyst and thickening agent was applied on the combination of bio-fibres such as coir, bamboo, rattan and veneer wastes. Chopped strand glass fibres were randomly and uniformly spread within the entire composite, which was then moulded onto a shape. End use areas for SMC include transportation, appliances, construction, electrical and chemical industries. It was found that introduction of bio-fibres into SMC as facings improved the mechanical properties of the composites.

A.1.2 Synthetic fibres

Simply choosing a fibre seems to be a complicated and rather discouraging process due to the large number of options available on the market. However, for most composite structures, there are basically only three fibre types to consider: glass, aramid and carbon. Other fibres such as boron, quartz, and ceramics are available especially for aerospace applications and specialized sporting equipment, and their use is not widespread. They all have advantages and disadvantages, therefore when selecting a fibre system the decision should be based on the details and requirements of the (structural) application, surrounding environment, lifetime requirements (durability), and the exigencies of their fabrication process.

Characteristics of Glass fibres (GFRP)

Liquid glass is formed by blending quarry products such as sand, kaolin, limestone or colemanite at 1,600ºC. Then, glass monofilaments of 5-24µm in diameter are obtained by passing liquid glass through micro-fine orifices that contains platinum bushings and cooling the liquid glass. At the end of the process, glass filaments are coated for adhesion and protection purposes. The most common type of glass fibre for structural reinforcements is E-glass (electrical), and ideal reinforcement for many types of organic matrix composites. Several other types of glass, such as E-glass (electrical), C-glass (chemical), R, S or T-glass were developed for aerospace and defence industries. It is available in strand form, yarns and rovings, and is the most common form of reinforcing fibre used in FRP composites. Glass fibres are generally not resistant to moisture, alkaline solutions and stress corrosion cracking.

E-glass has good tensile and compressive strength, good electrical properties, but poor impact resistance, low stiffness and short fatigue life. Glass fibres have stiffness modulus similar to aluminums alloys, which is a third that of steel. As a mixture of oxides, glass fibres do not burn in air or oxygen, however they can soften, melt and fuse at high temperatures (850-900°C). With lower specific strength and modulus, glass composites with glass will be significantly heavier than aramid or carbon composites. Glass fibres will almost always win where cost is the primary concern. E-glass is the cheapest synthetic fibre with a price range of about 0.75-$6 $/lb. and is assumed to remain stable over the next years (Composites, 1998 and Dimakis, 2000).

Characteristics of Aramid fibres (AFRP)

Aramid fibres are produced by spinning a solid fibre from a liquid aromatic polyamide blend. Aramids have roughly the same strength as E-glass and the same specific strength as S-glass, with a much lower density and a much higher modulus. On the other hand, compressive strength is only similar to that of E-glass. Typically the price for the high modulus type ranges from 12-30 $/lb. (Composites, 1998). Although it is more expensive than even S-glass, it can be used instead of glass or even carbon where weight is a concern. Aramid fibres are prone to water absorption and to significant creep. Moreover, they tend to fail nonlinear due to localized buckling after fibrillation.

Characteristics of Carbon fibres (CFRP)

Carbon or graphite fibres are produced by controlled stabilization, carbonization and graphitisation of carbon-rich organic precursors. The most common precursor is polyacrylonitrile (PAN), but fibres can also be made from pitch (commonly polyvinyl chloride (PVC), petroleum asphalt, and coal tar) or cellulose (rayon). PAN-based carbon fibres were developed by Dr. Shindo in Japan in early 1960s. Similar to the other two types of fibres, once formed carbon fibres are sized to improve adhesion compatibility with the matrix and add protection during handling. The filament diameter of most types is about 5-7µm. Carbon fibres are grouped according to their modulus in: high modulus (also known as 'high strength' (HS)), with E modulus below 40 Msi; intermediate modulus (IM), with stiffness values between 40-50 Msi; high modulus (HM), with stiffness between 50-60 Msi; and, ultra high modulus (UHM), with stiffness above 60 Msi. Carbon fibres usually produce the lightest structure but at the highest cost. Low-end carbon fibres have strengths as good as aramid or S-glass fibres. Carbon fibres are chemically suited to safely resist under severe environmental exposure, due to their inert chemical structure. They have good acoustical properties, electro-interference shielding and flame resistance.

In the late sixties the price for the high strength grade carbon fibres was about 240 $/lb (SP Systems). By the middle of nineties the annual worldwide production capacity had increased to about 7,000 tonnes and the price for the equivalent (high strength) grade was 20-32 $/lb. During the last ten years the cost of carbon fibres decreased even further to about 15-115 $/lb. (Callister, 2002), although it is used primarily for specialty applications. With a current annual production capacity about 35-40 million lb., Dimakis (2000) presented the current and projected price of carbon fibres at 8 $/lb. and 5 $/lb. respectively.

Fibre comparison

Although carbon, aramid, and S-glass fibres have roughly the same specific strength, aramid fibres perform poorly in compression, so carbon or S-glass would be a better choice for compressive loads. Material composition of E-glass and S-glass is not very different, but S-glass is more expensive than E-glass due to the tough quality control and specifications required for the aerospace industry where this material is frequently used. The cost of S-glass can be lowered if materials specifications such as ASTM D578-90 are not obligatory. Glass fibres are larger in diameter than carbon, so they may be competitive to carbon in compression. Glass fibres have a low coefficient of thermal expansion, thus often used to add dimensional stability to composites. The elongation to failure of aramid fibres is about half of that of S-glass but still large compared to carbon fibres. Glass fibre has very low tension - tension fatigue properties relative to aramid and carbon fibres (Tingey, 1996). The basic properties of glass, aramid and carbon fibres are presented in Table1.

Carbon has over ten times the thermal conductivity of E-glass. Since thermal conductivity of epoxy resin is about five times lower than that of E-glass, it is the fibres that have a decisive influence on the thermal properties of the composite containing epoxy resin.

Glass fibres do not absorb water in their bulk, but are susceptible to strength reduction in corrosive and alkaline environments. Aramid fibres absorb moisture, are degraded by UV exposure, and can't be used at moderately high temperatures. Coating is required to protect them from UV and moisture degradation. They are chemically stable but can be attacked by strong acids and bases.

Table 1. Main properties of typical reinforcing fibres (Lopez-Anido and Naik, 1998; SP Systems)

Material Type	Designation	Density	Tensile Modulus	Tensile Strength	Strain to Failure	Country of Manufacture
		g/cm^3	GPa	MPa	%	
Glass	E-Glass	2.55	72.4	3450	4.8	-
	S-Glass	2.49	86.9	4800	5.2	-
Pan Carbon	***Standard Modulus (<40 Msi)***					
	T-300[a,b]	1.76	230	3530	1.5	France/Japan
	AS4[c]	1.80	221	3930	1.7	USA
	Intermediate Modulus (40-50 Msi)					
	IM6/IM7[c]	1.74	275	5240/5300	1.7	USA
	High Modulus (50-60 Msi)					
	HMA	-	358	3000	-	Japan
	Ultra High Modulus (>60 Msi)					
	UHM[c]	1.85	441	3445	0.8	USA
Pitch Carbon	P-55	2.00	380	1900	0.5	France/Japan
	P-100	2.15	758	2410	0.3	France/Japan
Aramid	Kevlar 49[d]	1.45	131	3620	2.8	USA
	Technora[g]	1.39	74	3500	4.6	Japan
Aluminum	7020	2.70	1069	400	-	-
Titanium	-	4.50	110	950	-	-
Mild Steel	55 Grade	7.80	205	450	-	-
Stainless Steel	A5-80	7.8	196	800	-	-
HS Steel	17/4 H900	7.8	196	1241	-	-

[a]BP/Amoco, [b]Toray, [c]Hexcel, [d]DuPont, [g]Tejin

Because carbon is so brittle, it does not hold up well to impact. Both glass and aramid are better, though aramid should be used on the tensile side of potential impact sites if possible. Aramid works better for tension reinforcement while carbon is better for compression reinforcement. Glass and aramid are also fairly tough in abrasion, and carbon is a good conductor, both of heat and electricity (Berenberg, 1998). Unlike glass fibres, carbon fibres have very good fatigue strength. They are anisotropic materials, with strength and stiffness in the fibre direction 10 to 100 times higher than in the transverse direction.

New materials consisting of combinations of glass, aramid and/or carbon fibres are now available on markets. FRP composites of glass and aramid fibres have superior stiffness and strength per unit weight than all-glass composites. Table 2 shows a ranking of glass, aramid and carbon fibres along with a few desirable properties. In the table, properties are ranked 'A', 'B' and 'C' according to performance of fibres related to a desired property; 'A' stands for high performance, while 'C' accounts for lower performance. The wide range of properties represents an advantage for FRP composites by making them suitable for various end uses. A comparative cost of fibres with potential for the wood composites industry is shown in Fig. 4. The typical average cost for continuous fabric systems was compiled from various sources and is presented for comparative purposes only (Composites, 1998; Callister, 2002).

Table 2. Comparison of fibres (SP Systems)

Property	Glass	Aramid	Carbon
High Tensile Strength	B	B	A
High Tensile Modulus	C	B	A
High Compressive Strength	B	C	A
High Compressive Modulus	C	B	A
High Flexural Strength	B	C	A
High Flexural Modulus	C	B	A
High Impact Strength	B	A	C
High Interlaminar Shear Strength	A	B	A
High In-plane Shear Strength	A	B	A
Low Density	C	A	B
High Fatigue Resistance	C	B	A
High Fire Resistance	A	A	C
High Thermal Insulation	B	A	C
High Electric Insulation	A	B	C
Low Thermal Expansion	A	A	A
Low Cost	A	C	C

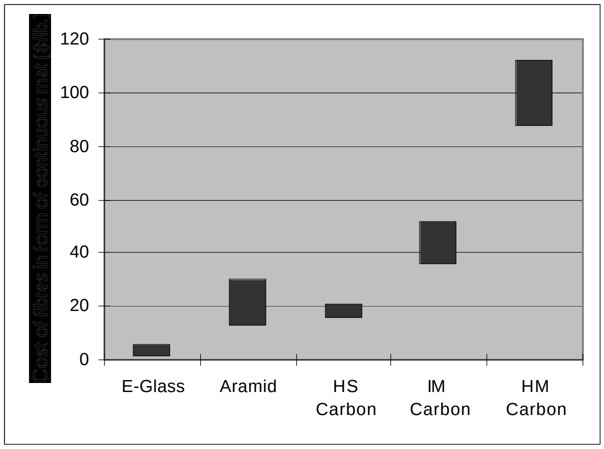

Figure 4. Comparative cost of fibres

In spite of the recent progress made by the polymeric fibre science, the search for a truly strong and tough fibre continues. Up to now, the fibre with the most outstanding properties is only found in the world of natural fibres. With toughness more than three times that of synthetic fibres (!), spider silk has strength close to 2 GPa, stiffness of 30 GPa, elongation at break over 30 per cent, and extreme fineness, from 0.01-4µm. These properties of spider “fibre” together with its environmental durability, serves as a natural model for the next generation of specialty fibres. (Ko, 2001)

A.2 Resin systems

This chapter briefly presents the most important resin types used as matrices in FRP composites for wood products, and a comparison of their mechanical properties.

A.2.1 Resin types

The most commonly used resins in the composites industry and for wood reinforcements are thermosetting resins, namely polyester, vinyl ester, epoxy and phenolics. Besides these four main types of resins, there are some other types of specialized resins that are used where their unique properties are needed. These resins are used in the aerospace industry (e.g. cyanate esters), for missiles (e.g. silicones), aircraft engine inlets (e.g. bismaleimides), and for aero-engine components (e.g. polyimides).

In many cases, thermosetting resins used for FRP composites require the addition of a catalyst or a hardener shortly before use to initiate the polymerization reaction. The speed of resin cure is controlled by the amount of catalyst in a polyester and vinyl ester resin and by varying the type, not the quantity, of hardener in an epoxy resin. Other additives are: thixotropic agents, pigments, fillers, and chemical/fire resistant compounds.

Polyester resins

There are two types of standard laminating polyester resins; orthophthalic polyester resin, which is the standard economic resin used in the composite industry; and isophthalic polyester resin, which the preferred material in applications where superior water resistance is desirable.

Vinyl ester resins

Vinyl ester resins have better resistance to water and chemicals than polyester resins, and are frequently found in applications such as pipelines and chemical storage tanks.

Epoxy resins

Epoxy resins form the largest family of structural adhesives currently available. These resins generally perform better than most other resins in terms of mechanical properties and resistance to environmental degradation.

Phenolic resins

Phenolics are the first commercially successful synthetic resins used in structural applications. They were found to produce durable bonds between solid wood laminations and FRP pultruded sheets attributable to performance qualities including high temperature resistance, creep resistance, excellent thermal insulation and sound damping properties, corrosion resistance and excellent fire/smoke/smoke toxicity properties.

A.2.2 Resin comparison

Among the four systems described above, phenolic resins have been used with success in structural applications for many years. However, despite their excellent durability, phenolic resins require high temperatures and pressures to cure. Common formulations of the other three resin systems, polyesters, vinyl esters and epoxies generally do not require high pressures to cure. Polyester resins have lower mechanical and adhesion properties than vinyl esters and epoxies. Polyester has a tensile strength of about 6.5 MPa if cured for 5 hours at 80ºC, as compared to 7.5-8 MPa for vinyl ester and epoxy. Stiffness ranges from 2.75 MPa for polyester and vinyl ester to 3.25 MPa for epoxy resin for the same curing conditions. At ambient temperature, the curing process requires longer time and mechanical properties are generally lower.

Experiments performed by Rowlands et al. (1986) revealed superior strengths for pre-impregnated (prepreg) reinforcements hot-pressed between adherends, than for reinforcements bonded with common structural adhesives such as, resorcinol-formaldehyde, phenol-formaldehyde, or isocyanate. Generally, phenol-formaldehyde prepreg exposed to a vacuum-pressure-water-soaking cycle (or accelerated-aging) degraded less than the control, suggesting that the adherend (maple) was more prone to degradation than the adhesive. Phenol-formaldehyde glass prepreg had an aged interface shear strength (2,716 lb/in^2) above that of dry Douglas-fir (1,500 lb/in^2). The author reported excellent performance under dry conditions for epoxy matrices with glass, aramid and carbon reinforcements, good suitability for resorcinol-formaldehyde and phenol-formaldehyde with glass and carbon fibres, but poor compatibility with aramid.

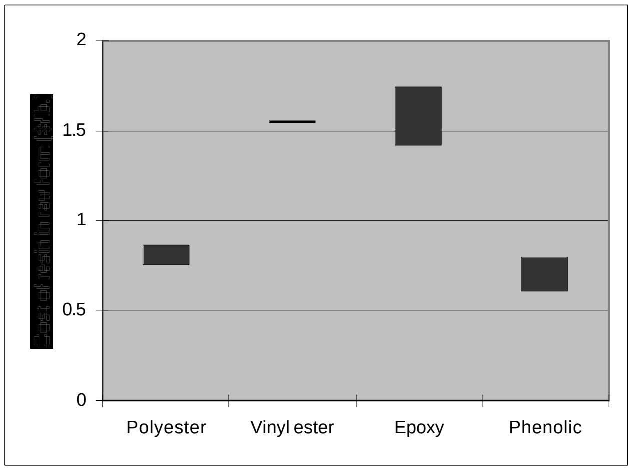

Figure 5. Typical cost of resin in raw form (Gardner, 2003)

An FRP-reinforced wood composite has to provide adequate bond integrity and shear strength between the wood adherend and the synthetic counterpart. Gardner et al. (1994) examined bond performance under dry and wet conditions between wood and polyester/vinyl ester pultruded FRP sheets bonded with resorcinol-formaldehyde (RF), epoxy and emulsion polymer isocyanate (EPI) adhesives. The EPI adhesives are two-component systems consisting of a mixture of water based emulsion polymers and a crosslinking agent (hardener) containing a polymeric isocyanate. The adhesive formulations are suitable for bonding various wood products to core materials (such as styrene and urethane foam, paperand aluminum honeycomb), and for bonding overlays (such as painted metal and FRP) to wood products. The EPI adhesive forms water-resistant bonds and is intended for structural use. The results for the wet conditions indicated that the RF adhesive produced significantly higher shear strengths and wood failure percent than the epoxy and EPI adhesive. However, the epoxy adhesive produced the highest shear strengths and wood failure percent (>90 per cent) under dry conditions. The authors obtained similar strengths for polyester FRP wood composite and vinyl ester FRP wood composite for under dry conditions, but the wet strengths were considerably higher for the polyester FRP wood composite than the vinyl ester FRP wood composite. They concluded that both adhesives RF and epoxy are suitable for interior applications, while RF is the most promising adhesive for bonding polyester and vinyl ester FRP composites to wood for exterior applications.

During the curing process volatile by-products are evaporated, and induce built-in stresses and ultimately shrinkage that can weaken the material. Polyesters and vinyl esters can show shrinkage up to 8 per cent, but the epoxies need very little molecular rearrangement to reach their cured state and have typical shrinkage of about 2 per cent. Phenolic resins also show low shrinkage upon polymerization. An equally important property of a laminating resin is its ability to resist to moisture degradation. All resins are prone to moisture absorption leading to a gradual and long-term loss in mechanical properties. Both polyester and vinyl ester resins can be expected to retain about 65 per cent of their laminar shear strength after immersion in water for a period of one year, whereas an epoxy laminate immersed for the same period will retain about 90 per cent. (SP Systems)

The cost of resin formulations for composites is shown in Fig. 5 (Gardner, 2003). Typically, vinyl esters and epoxies are priced two times higher than polyesters and phenolics.

Appendix B

List of Wood – FRP Composite Identification

A useful list of current and future potential applications for FRP reinforcements for wood products, together with the desired characteristics of reinforcements and various end use examples was originally presented by Laufenberg et al. in 1984 and is shown again in Table 3 with a few modifications.

Table 3. List of wood-FRP composite identification (Laufenberg, 1984)

Application	Purpose of reinforcement	Desired characteristics	Specific end-use
Tension members	- Reduce member's high sensitivity to growth defects; increase effective area, tensile capacity, and the reliability of the member. - Localized reinforcement at connectors leads to smaller cross-section.	- High, predictable tensile strength. - Ease of placement parallel to tensile stress direction. - High modulus. - Versatility of physical properties.	- Diagonal bracing - Chord members of trusses - Tension webs in trusses - Perimeter members in dome structures.
Compression members	- Increase compression capacity and stiffness. - Increase buckling load about either axis.	- High strength and modulus. - Placement of reinforcement uniformly around the perimeter of member.	- Truss components - Interior columns in buildings, frames - Compression members in plates and shells structures. - Box columns - Beam to column seat connections ad fixtures.
Flexural members	- Use reinforcement to increase beam stiffness and decrease deflection. - Reduce variability, hence allowable stress values will be increased or ultimate strength may be used. - Increase shear and torsional capacity. - Improve fatigue and creep performance.	- High strength and stiffness - Predictable fracture stress at ultimate load - Placement of reinforcement at or near both tensile and compressive faces of beam for deflection control - Reinforcement on vertical side faces for shear and torsion	- Continuous span beam - Floor joists - Headers - Rigid frame members - Bridge stringers - Electrical or street pole cross-arms - Crane runway girders - Box beams

Application	Purpose of reinforcement	Desired characteristics	Specific end-use
		purposes - Localized reinforcement for impact purposes	- Ladders - Scaffolding - Wood piles, poles, barriers, signs and signposts
Joints	- Reinforcement of zones of stress concentration ("weak zones") increases the strength of the joint and provides material continuity. - Increase bearing strength and stiffness as with columns and flexural members. - Reinforcement would prevent crack formation and/or growing, and inhibit stresses perpendicular to grain.	- High strength - Resistance to environmental effects - Improved reliability	- May be applied to any member with internal joints and splices or local grain deviations around the knots. - Finger and butt joints - Bolted and gusset plate connections. - Nailed or stapled components - Continuous tension members - Pitched cambered beams.
Beam-columns (flexure plus axial tension or compression)	- Reinforcement increases resistance to axial and bending forces. - Generally increase strength and stiffness with as columns and flexural members.	- High strength and stiffness. - For axial load purposes, place reinforcement uniformly around member's perimeter. - Large bending moments require concentration of reinforcement at face or largest compressive or tensile force.	- Bracket-loaded columns - Columns of frames where moments of girders are partly resisted by abutting columns - Transversely loaded columns (utility poles) - Inclined rigid frame members - Arch ribs
Other assemblies	- Increase bending, tension, pressure and impact capacities where forces are applied in quick, repeatable succession - Provide light weight-to-strength ratio, with increased tensile capacity - Increase nail-holding system - Increase strength at stress	- High strength and modulus - Relatively low specific gravity - Resistance to environmental effects - Resistance to	- Windmill blades - Ski construction - Containment silos - Wood pallets - Chemical plant structural members - Railroad crossties

Application	Purpose of reinforcement	Desired characteristics	Specific end-use
	concentration (corners)	chemical attack - Dimensional stability	- Trailer bodies, cargo shipping containers - Kayaks, canoes, sailboat components