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

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# NSERC Innovation: Hybrid Structural Wood Composites for Non-Residential Construction

by

Ciprian Pirvu, Ph.D.
Research Scientist
Building Systems Department

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| Ciprian Pirvu | Bill Deacon | Erol Karacabeyli |
|---|---|---|
| Project Leader | Reviewer | Manager |
| Wood Engineering | Wood Engineering | Building Systems |

# Summary

In recent years, significant attention has been paid to the engineering performance of wood structural systems, and a new generation of more reliable engineered wood components for building construction has evolved.

The latest trend is towards advanced products that combine wood and synthetics. This increases performance and structural reliability of engineered wood products, and leads to new markets and expanded opportunities. It is anticipated that cost of fibre reinforcement decreases over time and advances developed on reinforcing techniques and methods of evaluation would provide wood producers with more options to better position their products in the marketplace.

A new reinforcing technique has been developed and applied to manufacture a hybrid wood product for structural applications. The technique involves a layering analogy using layers of synthetic reinforcement sandwiched between layers of wood composite. The product manufactured in the laboratory used regular OSB laminations and alternating layers of E-glass fabrics and resin. Three- and four-ply billets were manufactured with various layouts and then tests were conducted to characterize mechanical properties of the hybrid products. Overall, the test specimens performed well relative to the controls. Shear failures were observed as a result of the limited performance of OSB in shear, and consequently the next tests will be conducted with plywood laminations instead of OSB.

Selected issues related to code acceptance of structural FRP-reinforced wood products are discussed in the appendix. Future work is suggested to completely characterize and understand the properties and behaviour of the FRP-reinforced wood products, including fire performance, long term durability, maintenance and cost, in order to establish an environment in which to work comfortably with such materials. Overcoming these issues is vital for product acceptance in building codes.

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# 1 Objectives

The long term goals of this project are (1) to determine how best to use synthetic fibres or fibre reinforced polymers (FRP) to increase the performance and structural reliability of engineered wood composites while maintaining competitive costs, and (2) to provide options for incrementally improving the performance of existing engineered wood products and new products so that they can compete in Canadian and offshore target markets against wood and non-wood products. The key objective is to develop techniques to produce high performance structural members from wood composites reinforced with synthetic fibres.

# 2 Background

An intensive literature survey carried out on utilization of reinforcements on wood and wood based products is the main reference for the report entitled "State-of-the-art Report on Fibre Reinforced Polymer (FRP) Utilization in Wood Products", Project Report 4198 at Forintek Canada Corp., completed in January 2004. The report presents an update on utilization of reinforcements on wood products, providing the motivation for reinforcing wood with synthetic fibres, and surveying 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. Besides the informative role for the present project, the state-of-the-art report is intended to be a useful reference tool for the Canadian wood products industry that can assist future developments in structural and non-structural applications of fibre-reinforced wood products.

FRP-reinforced wood composite materials offer engineering advantages over traditional materials for many applications, primarily 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. 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. 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 due to interferences that may occur.

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.

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 building construction has evolved. Early structural wood composites were manufactured from large wood elements, such as lumber and veneer. Examples of these composites include glued laminated lumber, or glulam, plywood and laminated veneer lumber (LVL). Recently, the trend has been toward using wood materials derived from small diameter and/or fast-growth plantation trees, for producing strand-based composites as both a lumber and a panel substitute. The strand-based composites have resulted in increased building efficiency because of their improved use characteristics and increased availability of size and configuration.

Code acceptance of FRP-reinforced wood products requires deep understanding of the properties and behaviour of these materials in structural applications. Future work is suggested in the area of fire performance, long-term durability, maintenance and cost, in order to establish an environment in which to work comfortably with FRP-reinforced wood products. Selected issues related to code acceptance of structural FRP-reinforced wood products are discussed in the appendix.

The development of new manufacturing techniques and advanced products combining wood and synthetics will likely boost consumer confidence in wood construction, and potentially lead to new markets or expand uses into the markets traditionally dominated by steel and concrete.

# 3 Materials

The most important aspect when developing new composites is establishing the mechanical, chemical and physical compatibility between the wood fibres and synthetic fibres, which influences the structural integrity and properties of the resulting product.

For the purpose of this study, oriented strand board (OSB) wood composites were chosen for their popularity as materials used in structural applications. OSB from three major manufacturers, identified as A, B, and C, was used. Today’s wood raw material comes from second or third growth, or from species that were not considered commercially important a few decades ago, because of a continuous process of decreasing quantity and quality of large solid timbers.

Simply choosing a synthetic fibre is a complicated and rather discouraging process due to a large number of options available on the market. For most composite structures, however, there only three fibre types to consider: glass, aramid and carbon. They all have advantages and drawbacks, therefore when selecting the fibre type the decision has to be based on the requirements of the (structural) application, surrounding environment, lifetime requirements (durability), and the exigencies of their fabrication process. The ideal reinforcement for many types of organic matrix composites is E-glass (“E” stands for electrical), which was selected for this study in chopped strand mat (CSM) form and biaxial woven fabric (cloth) form, in various specific weights. Newer advanced knitted fabrics incorporate layers of directional fabrics with a lightweight support of CSM. E-glass is the most common form of reinforcing fibre used in FRP composites. E-glass has good tensile and compressive strength, good electrical properties, but poor impact resistance, low stiffness and short fatigue life.

An orthophtalic polyester resin was selected as matrix for the synthetic fibres. The polyester resin is typically used in hand lay-up applications where water resistance and cosmetic surface appearance is desired. The resin is designed for room temperature cure using methyl ethyl ketone peroxide initiator.

# 4 Methods

Structural wood composite billets were manufactured by laminating together alternating layers of structural OSB, cut parallel to the strand orientation, and layers of E-glass synthetic fabrics. The billets were designed with three layers of 16 mm (5/8 inch) thick OSB (3-ply OSB) or four layers of 9.5 mm (3/8 inch) thick OSB (4-ply OSB). Various lay-ups were used for specimen manufacture (Table 1). For the 3-ply OSB billets, a layer of biaxial woven fabric (WR) of 620 g/m$^2$ (18 oz/yd$^2$) and a layer of CSM 34 g/m$^2$ (1 oz/yd$^2$) were used between the OSB layers (architecture Ia). Other 3-ply billets were manufactured with advanced knitted biaxial synthetic fabrics, which offer improved stiffness without adding weight or thickness to the assembly. Several specimens were fabricated with layers of planed OSB. Specimens fabricated with OSB that was not planed were marked with a star (*) in Table 1. The reason behind planing the OSB material was to obtain a smooth and freshly cut surface with enhanced chemical and mechanical compatibility with the resin. Planing of the OSB laminations was performed within 24 hours of bonding. A few 4-ply OSB billets were manufactured with layers of biaxial cloth alternating with layers of OSB (architecture III). Other 4-ply OSB specimens were manufactured with a layer of biaxial woven fabric and a layer of CSM between the outer OSB layers, and a CSM layer between the central OSB layers (architecture IIa).

Following resin application onto the laminations (wet lay-up), the assemblies were cold pressed at approximately 138 kPa (20.8 PSI) for 3 hours, and then conditioned for a week at 20°C and 65% relative humidity to allow the resin to fully cure to its ultimate durability and to reach an equilibrium moisture content. Some of the specimens manufactured with woven fabric and CSM were further reinforced with biaxial cloth (CLOTH) of 315 g/m$^2$ (9.7 oz/yd$^2$) on the critical tension side (architectures Ib and IIb). The billets were finally sawn to a nominal size of approximately 813 x 102 mm (32 x 4 inch).

**Table 1: Lay-up of hybrid structural wood composites**

| OSB Producer | Lay-up Architecture | Laminations | | | | | | | Tension Side Reinforcement |
|---|---|---|---|---|---|---|---|---|---|
| | | Top | | Center | | | Bottom | | |
| A, B | Ia | OSB (16 mm) | WR<br>CSM | OSB (16 mm) | | | WR<br>CSM | OSB (16 mm) | n/a |
| | Ia* | OSB (16 mm) | WR<br>CSM | OSB* (16 mm) | | | WR<br>CSM | OSB* (16 mm) | n/a |
| | Ib | OSB (16 mm) | WR<br>CSM | OSB (16 mm) | | | WR<br>CSM | OSB (16 mm) | CLOTH |
| C | IIa | OSB (9.5 mm) | WR<br>CSM | OSB (9.5 mm) | CSM | OSB (9.5 mm) | WR<br>CSM | OSB (9.5 mm) | n/a |
| | IIb | OSB (9.5 mm) | WR<br>CSM | OSB (9.5 mm) | CSM | OSB (9.5 mm) | WR<br>CSM | OSB (9.5 mm) | CLOTH |
| | III | OSB (9.5 mm) | CLOTH | OSB (9.5 mm) | CLOTH | OSB (9.5 mm) | CLOTH | OSB (9.5 mm) | n/a |

Legend: WR- biaxial woven roving; CSM- chopped strand mat; CLOTH- biaxial E-glass synthetic cloth

The specimens were loaded flat-wise and subjected to a centre-point bending test with a clear span of 762 mm (30 inch). Span to depth ratio ranged from 17 (for 3-ply billets) to 20 (for 4-ply billets). Load-displacement behaviour of specimens reinforced with synthetic fibres was compared to behaviour of non-reinforced specimens (controls). The controls were manufactured with the same number of OSB layers and same type of resin as the reinforced specimens, but without synthetic reinforcement.

# 5 Results and Discussion

Test results for the bending test are summarized in Table 2. Three-ply OSB billets manufactured with planed OSB and 4% (by volume) woven fabric and CSM had 25% increase in strength relative to the controls. An additional 32% was gained if extra 2% reinforcing (by volume) was placed on the tension side. Billets manufactured with OSB that was not planed performed surprisingly better than those manufactured with OSB that was planed. A reasonable explanation is that by shaving even a very thin stratum off the OSB, its internal structure is altered and mechanical properties greatly reduced. OSB has layers of strands aligned parallel to each other, but perpendicular to adjacent layers, like the cross-laminated veneers of plywood. Similar general trends were observed for the 4-ply billets, which had 4% synthetic fibres by volume, although they had higher energy dissipated during loading than the 3-ply billets. High-energy dissipation in structural members is a highly desired attribute in structures located in earthquake prone areas.

| OSB Producer | Lay-up Architecture | Max. Load | Max. Displ. | Stiffness | MOR | MOE |
|---|---|---|---|---|---|---|
| | | lb | in | lb/in | psi | msi |
| A | Ia* | 992.5 | 0.54 | 2169.1 | 3472.79 | 0.635 |
| A | control | 634.1 | 0.49 | 1458.0 | 2078.89 | 0.388 |
| A | Ia | 785.9 | 0.56 | 1701.0 | 2544.05 | 0.444 |
| A | Ib | 1087.1 | 0.86 | 1701.0 | 3349.16 | 0.412 |
| B | control | 670.7 | 0.50 | 1587.2 | 2380.35 | 0.469 |
| B | Ia | 847.1 | 0.58 | 2070.6 | 2938.57 | 0.595 |
| B | Ib | 1069.2 | 0.70 | 1987.5 | 3568.14 | 0.541 |
| C | control | 565.7 | 0.61 | 1054.7 | 3108.09 | 0.610 |
| C | IIa | 836.2 | 1.13 | 1354.7 | 4096.50 | 0.654 |
| C | IIb | 1130.5 | 1.11 | 1443.3 | 5423.09 | 0.678 |
| C | III | 638.3 | 0.69 | 1120.2 | 3320.74 | 0.592 |

**Table 2: Test results for three-point bending test**

Note: All values represent averages of three replications, except values for architectures Ib and IIb where one sample was tested.

All billets had remarkably good internal bond strength, with no visible failures at the interface between reinforcement (FRP layers) and OSB laminations. Typical failure modes for the controls and 3-ply specimens un-reinforced on tension side are shown in Figures 1, 2, and 3, while Figure 4 shows the failure mode of a 4-ply specimen un-reinforced on tension side. Generally, control specimens failed in tension; the failure started at the bottom lamination and progressed through the centre lamination(s) (Fig.1). For the 3-ply specimens un-reinforced on tension side, the failure started in tension at the bottom lamination up to the first layer of reinforcement, and then continued in shear at the centre lamination (Fig. 2). A buckling of the strands on the top lamination could be observed on many samples due to extreme compressive forces (Fig. 3).

**Figure 1: Typical failure mode of control specimens (Tension failure)**

**Figure 2: Typical failure mode for a 3-ply specimen (Shear failure through centre lamination)**

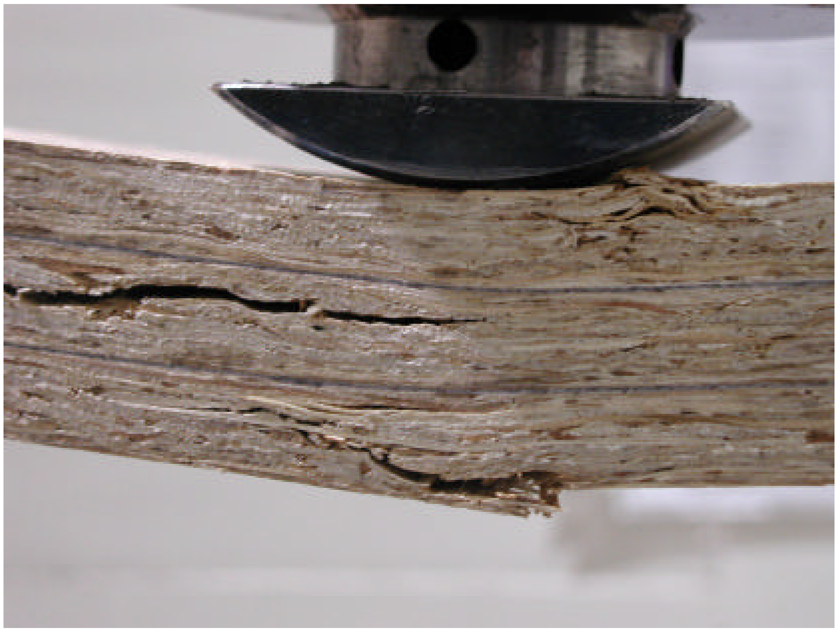

**Figure 3: Detail: Typical failure mode for a 3-ply specimen [Tension failure (bottom lamination), shear failure (centre lamination), localized compression (top lamination)]**

**Figure 4: Typical failure mode for a 4-ply specimen (Tension failure of bottom and centre laminations)**

Tension failure modes were typical to 4-ply specimens un-reinforced on the tension side (Fig. 4). These specimens failed predominately in tension due to the presence of the centre reinforcement layer along the neutral axis, as opposed to the 3-ply specimens where the centre OSB lamination was along the neutral axis. Poor performance of regular OSB materials in shear is the main cause of shear failures observed for the 3-ply specimens. Better results can be expected if plywood is used, or OSB panels with improved shear performance, such as the Advantek engineered OSB panel produced by Huber. Further tests will be conducted on billets using plywood laminations instead of OSB laminations, with no planing and with the layout unchanged.

Hybrid Structural Wood Composites (HSWC) may be used as tension/compression members to increase tensile/compressive capacity and reduce high sensitivity to growth defects of structural members. Localized reinforcement of the weak zones increases strength of the joint, leads to reduced member cross-section and provides material continuity. If used as flexural members, the reinforcement increases shear and torsional capacity, and improves fatigue and creep performance. Beams are commonly reinforced on the critical tension side to increase stiffness and resistance to bending forces.

# 6 Conclusion

A new reinforcing technique was successfully used to develop hybrid structural wood products with improved performance. Specimens with alternating layers of FRP and OSB had from 25% to 32% higher bending strength relative to the controls, however more mechanical and structural tests are necessary to fully characterize their properties.

The next steps include selection of connection methods compatible with the advanced materials developed. A commonly used connection system will be selected for easier comparison with other systems presently available on the market. Integrated in a commonly used structural system, hybrid structural wood composites would presumably have a smoother and uncomplicated arrival and acceptance on the market.

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# Appendix

## Code Acceptance of FRP-Reinforced Structural Wood Products

*Current Issues*

In contrast to the past when wood products were developed based on product standards and then marketed, current and future structural wood products will be tailored to meet specific market needs and 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 resulting in greater final product yield. However, conventional materials have a long tradition of proven performance, and many difficulties will have to be overcome before there is a wide recognition and utilization of FRP-reinforced wood products.

The initiation process for code acceptance of FRP-reinforced wood products includes gaining more knowledge and establishing a database on structural performance, durability, fire performance, serviceability and maintenance of these materials. Once these issues have been addressed, fibre-reinforced products will need to undergo the process of product acceptance by regulatory agencies. At present, reinforced glulam beams are being used commercially and glulam standards are now in process. ASTM Subcommittee D07.02.02 is working towards 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); however, similar comprehensive standards and engineering design procedures and specifications should be developed for wood reinforced with FRP. Recognition of these materials also depends on their wide acceptance by the engineering community and on their wide availability on the markets.

Some of the issues related to code acceptance of FRP-reinforced structural wood products are briefly presented below.

i) There is need for comprehensive research leading to a complete characterization and understanding of the properties and behaviour of FRP-reinforced wood products. The amount of data to fully characterize the long-term performance and durability of these wood products is scarce. There is no Canadian or US standard that specifies allowable percent delamination at the interface in wood-FRP composites. In-depth studies on failure mechanisms and development of advanced fabrication processes to prevent voids, fibre misalignments and non-uniform resin distribution areas within the product need to be pursued. Evaluation of FRP-reinforced wood products needs to be performed at the microscopic level, coupon (sample) level, component level and system level to fully and accurately characterize these materials. Tests and analysis should be carried out at various levels of temperature, relative humidity and UV exposure. Building a database on structural performance, durability, serviceability of FRP reinforced wood composites is mandatory to gain acceptance for these materials by regulatory organizations.

ii) A survey rated wood 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, wood 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. 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 specific applications need to be established.

iii) 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.

iv) Uniformity of properties of mass produced FRP-reinforced wood products is one issue of great importance for a wider acceptance of these materials. 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.

v) 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, some modern structural connectors can accommodate reinforced beams without the need to machine bolt holes through the reinforcement.

vi) 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.

vii) Another impediment to their wider use is lack of familiarity with these materials. 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.

*Outlook*

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. Engineers 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. FRP composites may also be applied for structural rehabilitation of historical structures, structures partially damaged by fire or vehicle impact, or for modified structures.

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.