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The Use of High-strength Composites in the Reinforcement of Timber

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Abstract The use of high-strength composites in the reinforcement of structural timber has been documented to enhance the strength and stiffness of wood structural members. Global reinforcement is applied over the entire surface of the reinforced member. Local reinforcement is a targeted strengthening of highly-stressed zones susceptible to failure. Both types of reinforcement enhance the capacity of the reinforced members and mitigate brittle failure modes. This paper presents an overview of the application of fiber-based composites in the reinforcement of beams, columns and connections of timber structures and discusses the state-of-the-art technologies in reinforcement. The applications are illustrated on the reinforcement of beams, arches, frames and beam-to-column connections.

Keywords: Wood, composite reinforcement, brittle failure, failure mitigation

Introduction

Historical structures are subjected to environmental loads throughout their lifespan. In many instances, partial damage may lead to a compromised structural integrity that can accelerate further deterioration, damage or collapse under moderate loads. Deterioration of ceilings, beams, columns, and other structural elements may be attributed to ageing, environmentally-induced degradation, poor initial design and/or construction and lack of maintenance. In addition to the partial damage due to mechanical impacts or decay, strengthening of structures is often required because of large deflection in existing ceilings due to creep or changes in the use of the building and the associated increase of life load et cetera.

Traditionally, the strengthening or repair of timber structures focused on replacement of deteriorated members or their parts by new wood material using adhesives or mechanical fasteners. This merely substitutes the deteriorated mass but almost always reduces the strength of the repaired member. Use of high-strength composite materials can be used to repair damaged components and enhance their capacity at the same time. While applying a composite fabric to a surface may be questionable especially where historical value is a concern, internal reinforcement offers an opportunity for hidden reinforcement that may compromise the historic and architectural authenticity to an acceptable level. The reinforcement consists of a fabric made of high-strength fibers that can be glass-, Kevlar-, or carbon-based. The fabric is adhered to the surface of the structural member via adhesive that is either epoxy-, polyester- or polyurethane-based. The internal reinforcement consists of composite rods or plates that are inserted and glued into pre-drilled holes or slots. In most cases, the use of glass-fiber fabric or rods provides sufficient capacity, while a significant increase in stiffness can be achieved only by applying high modulus carbon fibers. The issues that arise in conjunction with the composite applications are:

- Compatibility between reinforcing and reinforced materials
- Strength and durability of the adhesive interface
- Performance under temperature and moisture changes
- Long-term behavior of the composite system

Composite Applications in Reinforcing Wood: General Aspects

Composite reinforcement consists of technical-fiber and fabrics embedded in a resin matrix. The material properties of the fiber-reinforced plastic (FRP) depend on those of the fibers as well as the matrix, where the overall behavior is dominated by the fiber properties. FRP are highly organized composites and can be used in combination with wood to mitigate the random character of wood properties and low strength in tension perpendicular to fibers and shear. The parameters of some of the materials used and tested by the authors are listed in the *Table 1*; others were taken from the literature. The properties of wood are highly variable and depend on species, directions, and moisture contents. Even within the same species, the properties can have variability by as much as 30% or more (Kasal 2004).

Table 1: Properties of composite reinforcement material compared to wood (Kasal 2004) and steel

Parameter	*Tensile strength [*MPa*]*	*E-Modulus [*GPa*]*	*Failure strain [%]*	*Density [*g/cm^3*]*
E-glass	2400	73	3.0	2.6
Kevlar	2700-3100	80-130	2.1	1.45
Carbon	1400-5000	180-550	0.5 - 1	1.7 – 1.9
Epoxy cold curing	40 - 140	3 - 4.5	2 - 10	1.1 – 1.4
Polyester	35 - 90	1.5 - 2.0	2 - 4	1.1 – 1.5
Composite[a]	400	16	1.8	1.6
Composite[b]	220	12	-	1.6
Steel (S355)	550 - 600	210	25	7.8
Wood	45-140[c]/1.7-15.4[d]	7-16	0.5-0.9[c]/0.1-0.2[c]	0.25-0.9

[a]composite tube - - (E-glass/Kevlar/epoxy)(Kasal et al. 2004), [b]composite - (E-glass/epoxy) BD bidirectional woven fabric 0°/90° (200g/m^2),
properties highly variable depending on species, moisture contents, and direction, [c] parallel to fibers, [d] perpendicular to fibers

From *Table 1*, it follows that the properties of reinforcement may have to be tailored to match specific properties of reinforced wood. Important parameter is the strain at failure, which should be higher for reinforcing material. As shown, this requirement is easy to meet. The problem arises during the design of the wood-FRP composite, since the wood reaches the failure strain relatively early. If we now apply the first ply failure criteria, the member reaches its design load relatively fast, while less than half of the FRP strength is utilized. Another often underestimated problem concerns the design values of composites that are significantly lower than the materials properties given in the literature. Some characteristic values of various materials are given in *Table 2*.

Table 2: Characteristic material properties of composites compared to wood and steel

Parameter	*Tensile strength (para/perp) [*MPa*]*	*Shear strength [MPa]*	*E-Modulus (para/perp)[*GPa*]*	*Density [g/cm^3]*
Laminated Wood (spruce GL24h)[1]	16.5/0.5	2.5	11.6/0.39	0.38
Hardwood (beech D40)[1]	24/0.5	3.8	11/0.75	0.59
GFRP[2] - BD	270/270	14.6	14.5/14.5	1.8
CFPP[3] UD	1350	-	300	1.6
Steel (S355)	510	510	210	7.8

[1] characteristic values from design code for timber structures (DIN 1052 2008-12),
[2] values from EUROCOMP design code (Clarke 1996) bidirectional (BD) GFRP - fiber vol. 38%
[3] min. values undirectional (UD) CFRP – from Sika (Sika website 2004) CarboDur H- fiber vol. 68%

As shown, the strength of the GFRP composite is about 10-times the strength of wood, while the E-modulus barely reaches a factor of 2. In order to obtain design values the characteristic values have to be divided by the appropriate partial safety factors, which can be large for composite materials due to the moderate long-term behavior (Clarke 1996, Sika website 2004). For this reason, the benefit of reinforcement in parallel to grain of wood will be small. Depending on the duration of load, type of manufacturing, degree of post-curing etc., the partial safety factor can easily exceed a

value of 2. In composite structures, the stresses in each layer result from the distribution of stiffness. For this reason, only machine-made, high modulus CFRP composite lamellas (see *Table 2*) provide sufficient stiffness to enhance the structural performance of the wood member to some degree. It has to be noted that the parameters given in *Table 1* and *2* are values for pre-fabricated composites. Such semi-finished products have the advantage of reduced variation of material properties; while hand-laminated fabric contains the risk of incorrect application and workmanship. It is recommended that pre-fabricated products be used to reinforce members and/or connection zones with plane surfaces. Manually laminated fabric is highly efficient in reinforcing free-form surfaces because of the ease of application.

Due to the moderate modulus of elasticity, the application of glass-fiber-based composites is limited to local reinforcement of timber, where it can be efficiently applied to strengthen the wood in week the axis (perpendicular to grain direction). In most cases, the reinforcement is used to avoid brittle failures and to enhance the tensile strength perpendicular to grain, the shear strength and the dowel-bearing strength of wood (Haller 2007).

In order for the composite reinforcement to function, bond, durability and compatibility between the reinforcement and the reinforced materials must be considered. This includes:

- Bond behavior and failure modes
- Acceptable differential shrinkage and swelling
- Acceptable differential thermo expansion

The bond is necessary to transfer forces from wood into the FRP; hence bond failure modes must be considered. Bond failure implies a complete loss of composite action between wood and FRP reinforcement. In general, a failure will occur in wood section near the interface between wood and FRP due to the low wood strength in shear. Most critical areas are the anchorage zones, where the FRP may peel off as a result of shear fracture of wood. A surface reinforcement can protect wood against weathering, chemical and biological attack. This, however, requires a reliable and durable bond between wood and the laminate.

Shrinkage and swelling are highly variable for wood (as are all properties) and can be as high as 10% in transverse direction and less than 1% in longitudinal direction. Shrinkage or swelling of composite reinforcement is negligible compared to wood. This will create additional interfacial stresses since environmental conditions (relative water vapor pressure) may fluctuate or change between the time of installation and service. Limited studies are available to investigate if such changes significantly inhibit the composite applications. Depending on the orientation of the wood and the placement of the reinforcement, free edges will present a problem. Such configuration will result in large interlaminar shear stresses peeling off the FRP at the edge of the wood-FRP interface. Thus, an internal (glued-in) reinforcement is preferred and the reinforcement should not be wrapped around the entire section without a free edge. The wrapping of members with FRP has been reported and was found relatively effective in shear reinforcement of beams (Pizhong et al. 1998). The problem with wrapping is the entrapment of water underneath the FRP and the adjacent cross-section. Since the water cannot freely evaporate from the wood surface, there is high potential for decay. We do not recommend wrapping the members with impermeable material.

Global Reinforcement

Beams The load-carrying capacity of wood beams is limited due to natural defects, such as knots, and potential finger joints on the tension side of the beams. Longitudinal reinforcement of members (mostly loaded in bending) by a ribbon of FRP has been known for some time and applied to glulams and solid timber beams (Borri et al. 2005, Blass et al. 2003). In general, steel or composites are used for reinforcing tensile zones by gluing the reinforcement to the surface in order to enhance tensile capacity and stiffness. The key for the use of externally bonded FRP reinforcement in timber structures is the surface preparation that must be planed, smooth, clean, and dry.

Blass et al (Blass et al. 2003) investigated the performance of CFRP reinforced glulams. CFRP layers (Sika website 2004) were proved to enhance the strength of the investigated beams. The

disadvantage of this solution is the high cost of the CFRP layers and the fact that a face timber lamella is required to protect the FRP against fire and damage. Bending tests conducted by Blass showed that compared to standard glulams, reinforced beams had 1.4 to 1.7-times higher strength and 1.1 to 1.3 times higher stiffness.

However, the application of CFRP lamellas for the reconstruction of historical roof structures can be advantageous in practice, as shown in (Kempe 2007) for several historic structures. The CFRP lamellas are glued into vertical slits at the bottom of the beams instead of on the surface. The glued-in solution is characterized by a higher anchorage capacity, avoiding the peel-off problem. Glued-in solutions, such as composite rods and/or lamellas, are less invasive in historic structures compared to surface applications.

Columns To enhance the buckling load of timber columns a longitudinal reinforcement has been investigated by Tanaka et al (Tanaka et al. 2006). Steel plates or carbon fabric sheets were attached to the wood surface to increase stiffness and buckling strength of the so-called hybrid columns. Steel plates or carbon fabric sheets were attached using lag screws or glue. Since the buckling load is driven by stiffness, the efficiency of such reinforcement techniques is limited, as discussed above.

Local Reinforcement

Similarly to global reinforcement, local reinforcement is used to mitigate the anisotropic property of wood that results from low strength in tension perpendicular to fibers. In historic preservation, the reinforcement of structural members frequently has local character and is used to repair already compromised material. This is different from new construction where reinforcement is used to enhance the material and optimize the design.

Curved Beams Longitudinal cracks are always present in large wood cross- sections but do not necessarily result in compromised strength. Excessive cracks, however, can potentially propagate under-loads and cause full or partial collapse, especially under extreme loading such as seismic or snow loads. In the case of arches, tension stresses perpendicular to the grain develop due to the redirection of bending stresses. In the past, several instances of damage were observed with the result that the design codes now require reinforcement of the curved zone by appropriate reinforcement techniques.

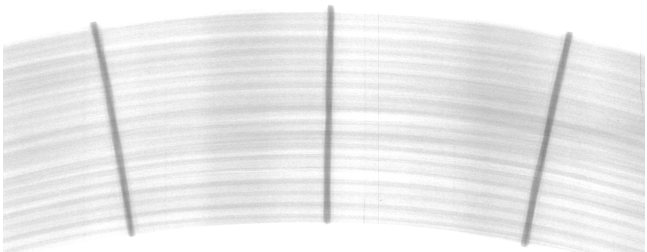

Figure 1: X-ray image of the transverse reinforcement of an arch (Blass et al. 2009)

It has been shown in laboratory experiments that glued-in GFRP rods (Tanaka et al. 2006)) embedded in a laminated arch significantly enhance the moment capacity of the beam. The advantage of using composite rods as opposed to steel (which has been commonly used) lies in the compatibility of wood and FRP, especially with regard to the thermal expansion, which reaches similar values. Steel rods have an advantage of a higher stiffness so they provide a better distribution of shear stresses along the glueline. Therefore, the application of glass fiber rods is limited to perpendicular to grain reinforcement. Rods glued in parallel to the grain should be made of steel or high modulus CFRP.

Connections Joints represent the only plastic links in timber structures while they are often the weak link at the same time. Typically, joints are either carpentry-type construction (such as mortise and tenon) or are using mechanical dowel-type metal fasteners such as spikes, nails or bolts. In

either case, joints represent weakening in the cross-section. Carpentry-type joints are accompanied by stress concentrations around the sharp corners and there is potential for cracking.
Well-designed connections using mechanical fasteners generally provide sufficient ductility to allow for distribution of loads. While connections with dowel-type fasteners have high ductility, they suffer from low stiffness and load-carrying capacity relative to the solid members. Even if designed according to the design recommendation for edge distance, end distance and spacing, a brittle-type failure may occur, especially when loaded by moments and shear forces. The reinforcement of connection can be divided into two categories:

Type 1. To prevent brittle-type failure and/or splitting and shear failure

Type 2. To enhance stiffness and load capacity through the increase in dowel bearing strength

Type 1: To prevent the wood from splitting and/or shear failure, composite fibers will be oriented in 90° and/or ±45° with respect to wood fibers, where only a relatively small amount of reinforcement is required. The limiting dowel spacing for composite-reinforced wood is currently unknown, but one can expect that the dowels can be placed closer due to the mitigation of brittle failure modes. A closer dowel placement permits the use of more dowels per joint area. This will improve the joint performance and allow material savings by reducing the cross sections without a reduction of safety. The authors (Kasal et al. 2002) studied the performance of moment-resisting connections with circular dowel placement. The beam-to-column connections were subjected to cyclical loads. The connection zones were reinforced by GFRP. Typical hystereses for the unreinforced and reinforced connections are shown in *Fig. 2*.

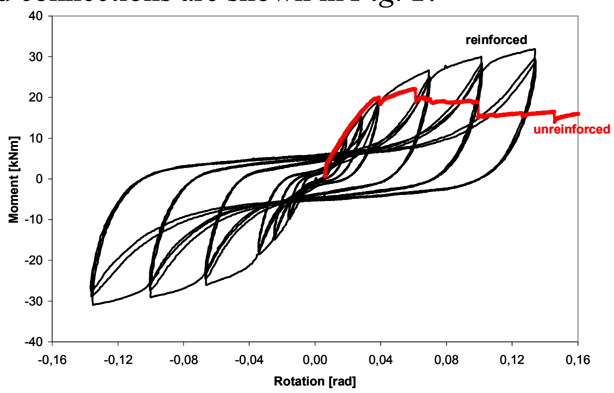

Figure 2: Moment-rotation relationships for (a) unreinforced and (b) reinforced joints (Kasal et al. 2002)

The hystereses reveal that the reinforced configuration is capable of undergoing large deformations compared to unreinforced control. The deformation at the ultimate capacity indicates that reinforced connections exhibited high ductility while having only a slight increased strength and stiffness.

Type 2: In order to obtain an appreciable increase in strength and stiffness of a connection, it is necessary to increase the embedding strength. To do so, relatively thick layers of reinforcement are required. For such applications, pre-fabricated FRP plates are recommended. Past research performed by Heiduschke et al (Heiduschke et al. 2008) showed that the performance of the monotonically loaded hinge-bolt connections (with a dowel diameter of 50mm) increased significantly by the use of plates made of (1) tailor made textiles, (2) pultruded profiles and/or (3) laminas with quasi-isotropic properties such as stacks of non-woven fabric layers. The plates had a thickness of 10-12 mm and were glued to the surface or into slots. The tests demonstrated that stiffness, strength and ductility of the connections were significantly enhanced by composite reinforcement. The load-carrying capacity of the reinforced connections was about six times that of the unreinforced reference.

Conclusions

Performance of synthetic composite materials used for wood reinforcement has been extensively studied for short-term load but we lack the knowledge of long-term performance, creep and mechano-sorptive creep, performance under elevated temperatures and randomly varying environment and loads. In addition, little is known about behavior of the interface between the reinforcement and reinforced materials. These questions must be answered in order to establish the durability of repair and retrofitting techniques. Although examples of applications of reinforcement of wood structural members exist (for both new and old structures), the applications are largely based on limited research focusing on short-term structural performance while long-term and environmental effects have been largely neglected. Main reasons for the limited use of FRP in structural engineering are the relatively high costs of material yielding an unfavorable price/performance ratio when compared to cold-formed steel.

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