Hybrid materials in construction – requirements and fundamental research questions

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1. Introduction

Wood is a traditional construction material with known qualities such as a high strength-to-mass ratio and high ductility of mechanical fasteners. Its drawbacks are equally known and include low tensile and compressive strength in the direction perpendicular to fibers, high variability of properties andhygroscopicity, among others. A number of strategies has been employed to mitigate these negative properties. One of the strategies to increase strength and decrease brittle tensile failure is reinforcement of wood with fiber-reinforced plastics (FRP) or wood-concrete hybrid systems. A combination of wood and steel (steel reinforcement) has been reported in literature but is relatively rare. The combinations of wood with other usually qualitatively superior materials (at least with respect to a specific property) have been conceptually proved and a number of examples exists. The application of concrete or FRP in construction shows the confidence in hybrid systems, at least in specific cases. While classical structural experiments such as short- or even long-term loading experiments (static or dynamic) are necessary to prove the functionality of the systems, they do not give insight into the fundamental questions such as interface behavior, material compatibility, aggressive environment effects and chemical stability of interfaces between dissimilar materials. In this paper the author will attempt to point to some gaps in fundamental research specifically related to hybrid wood-other material systems. To demonstrate the point, he will focus on a wood-FRP hybrid system but the same questions are, in his view, equally applicable to, for example, concrete-wood or steel-wood systems. It is the author´s observation that most of the research in timber structures focuses on behavioral aspects of the issues (what) and avoids the fundamental research question (why), which in his view favors short-term benefits compared to the long-term critical fundamentals.

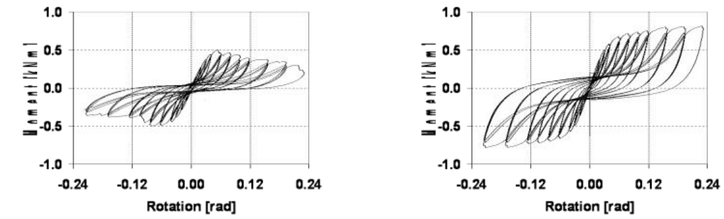
1.1. What is a hybrid system?

The definition of a hybrid system is fairly loose and includes a combination of at least two materials in a structural member (such as beam or column) or in the structure itself (such as a frame with steel columns and timber beams). A composite material is not seen here as a hybrid system because it can be represented by composite properties (using a law of mixtures, for example) and is therefore represented by a set of material parameters unique to that system. Transformation of a cross-section using a parallel-axis theorem is not applicable to a composite material but can be used for some hybrid systems (such as FRP reinforced beam). Both composite materials and hybrid systems, however, contain interfaces between two or even more dissimilar materials and the behavior of these interfaces is critical and must be understood at the fundamental (physical and chemical) levels.

2. Some resolved and unresolved issues in a hybrid FRP-wood system

Composite materials based on glass-, carbon- or Kevlar fibers are used in the reinforcement of wood structural members to enhance their stiffness and strength or to mitigate the brittle-type of failure associated with tension perpendicular to the fibers. Steel is also used as reinforcement but caution must be exercised due to incompatibility and difficulties in providing a reliable bond between steel and wood. The composites are applied either as a fabric to the surface of laminated beams or in the form of reinforcing rods embedded in a laminated member. The global effect of such reinforcement on the structural properties of laminated wood members, connections and structures is well documented. Thus, the potential for the application of laminated composite fiber reinforced wood to frames of eight or more stories high is clearly demonstrated. What is missing and necessary for structural applications is to understand the behavior of the reinforced system, consisting of wood-synthetic resin-composite material interfaces under various environmental and loading conditions. While the functionality and practicability of reinforcing was demonstrated in laboratory conditions, the fundamental interfacial properties and response of the natural-synthetic system to mechanical and environmental loads is not understood. This is critical if such systems are to be used in structural applications where safety, reliability and life-cycle performance are directly affected by composite reinforcement and its interaction with the natural material.

Fundamental research questions are not necessarily unpractical or esoteric. In fact, they are necessary for our general understanding of any phenomenon and have decisive influence over the future development of any product, process or system. As mentioned in the Introduction, FRP-wood systems have been around for some time and their conceptual function has been demonstrated and documented. Proof of concept, even if demonstrated in practice, however, does not constitute a high level of understanding of a system beyond perhaps the level of a hypothesis. It also fails to investigate the reasons for the demonstrated result. In addition, proofs of concept are specific to an investigated object and other conditions employed, and a generalization of findings and thus transfer to other sets of circumstances is largely impossible.
In the following, some of the fundamental questions related to the interfacial properties of hybrid systems will be underlined. Dynamic performance of moment connections has been experimentally studied and demonstrated excellent performance under static-cyclic and dynamic loads (Kasal 2008a, b) – see Figure 1. Such experiments prove short-term performance but no statement can be made about the long-term function of the reinforcement, the effect of the surrounding environment on the composite-adhesive-wood interfaces, the effect of elevated or low temperatures and load history, for example. Such questions must be answered at the fundamental molecular or even atomic structural levels, which require a fundamental understanding of bonding mechanisms, interface properties and the interaction of different chemical components under various environmental conditions.



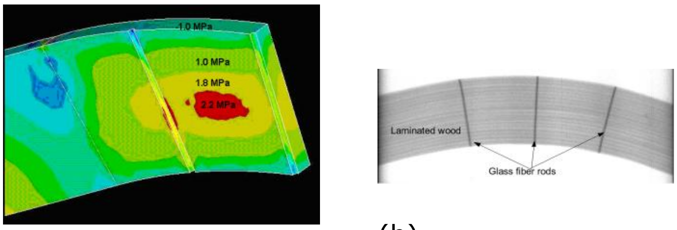
(a) (b)

Figure 1. Effect of local reinforcement (unwoven GF epoxy fabric) on failure mode of moment connections under cyclic loads: (a) typical unreinforced connection and (b) reinforced connection (Kasal 2008a).

The following literature review represents selected papers considered fundamental in defining the research needs discussed below and reflects the current state-of-the-art in the area of fiber reinforced wood structures and connections.

Tingley and Gai (1998) studied a time-dependent deformation of in-situ laminated bridge girders reinforced with carbon/aramid plastic (reinforcement ratio of 0.86 - 1.04 %). Over a period of three years, no significant deflection increase was found. However, it is not clear from the paper how the bridge was instrumented and what the environmental factors were during the experiment. No theoretical evaluation was offered.

Dagher and Breton (1998) performed a limited creep study on laminated beams reinforced on the tension side by an E-glass fiber reinforced plastic (FRP). They did not find a significant difference between the creep of the reinforced and unreinforced beams loaded 25% above their design stress (reinforced beams carried twice the load of the unreinforced ones). Although the tests were performed in a controlled environment, they indicated that the reinforcement would not significantly affect the beam's creep behavior. This finding, however, has to be confirmed for cyclic and arbitrary temperature/relative humidity (wood moisture content) variations to include the mechanosorptive creep effect.



(a) (b)

Figure 2: Stress distribution (radial tension) in a reinforced, curved beam at a crack initiation load (a), and (b) radiographic image of the internal reinforcement (Kasal 2008a).

Several researchers have studied the application of FRP in wooden bridge girders. In external applications, the environmental effects such as cyclic changes in moisture and temperature conditions, and their effect on the bond between FRP and the wood substrate is a concern. Currently, no standard method is available to evaluate the durability of the FRP-wood interface (Dagher and Lindberg 2000). Battles et al. (2000) studied the effect of environmental factors on two E-glass fiber wood-compatible composites (with phenolic resin matrix). The composite was subjected to a series of tests to determine durability. Test results indicated that the surface properties of the reinforcing composite may significantly affect durability. Kasal et al. (2002) used a glass fiber non-woven fabric for radial reinforcement of densified wood. In order to facilitate an efficient bond between the fabric and wood material, an epoxy resin was used. Phenol, phenol-resorcinol and melamine-based adhesives could not be used due to a poor bond between the fabric and wood substrate. Using radially-oriented composite tubes or rods is effective in the arrest of cracks that develop in timber arches and moment connections – see Figure 2. Again, this proves the functionality of the hybrid system but no statements about interface properties or environment-hybrid system interaction can be made.

Haller et al. (1996) introduced an interesting concept of using densified wood combined with glass fiber reinforcement at the joints of wood trusses. The connector embedment strength increased linearly with the degree of densification, up to 3 times that of undensified wood, and was further enhanced by using glass-fiber fabric attached to the surface. Haller (1998) discussed various approaches to model nonlinear behavior of timber joints, along with possible ways to mitigate undesirable behavior such as brittleness. A recently published series of articles dedicated to tall timber buildings summarizes the state-of-the-art and clearly demonstrates the possibilities of the material (Smith and Frangi 2008).

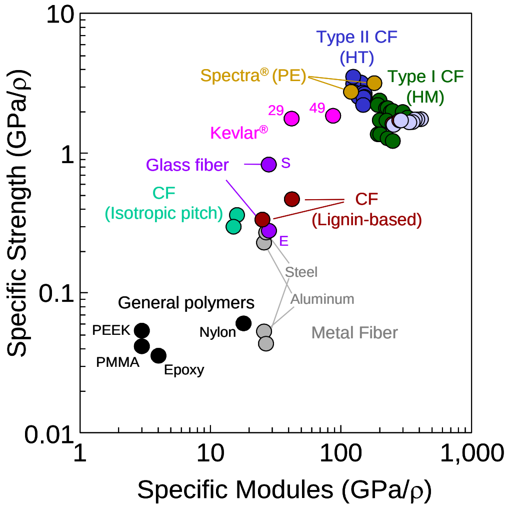


Figure 3: Specific Strength and modulus of typical fibers used in composite reinforcement – from Kadla (2008).

Properties of the wood-FRP interface have been studied using tapered double cantilever beams (TDCB) and fracture mechanics theory (Davalos et al. 1997, 1998). Theory corresponded well with the experimental results. A recent study investigated interfacial adhesion properties of wood cell lumen and UF adhesive (urea formaldehyde) by means of nanoindentation (Obersriebnig et al. 2012). The authors observed that reduced hydrophilicity of the wood adherents resulted in lower interfacial bonding on the micro scale, which agrees with reduced adhesion strengths on the macro-scale.

The properties of various types of composites may also change due to mechanosorptivecreep. Scott et al. gave a comprehensive review on this subject (Scott et al. 1995). Composites, especially polymer-based composites, experience physical aging and creep. The former is basically a process of approaching thermodynamic equilibrium that leads to a reduction in volume and increase in stiffness, though it is recoverable up on heating (Hastie and Morris, 1993). The latter is a viscoelastic deformation that results in permanent deformation due to molecular movement under stress (Scott et al. 1995). Creep of composites can be attributed mainly to creep of the matrix, when the composites are tested at an off-fiber axis angle, and to fiber creep, when the composites are tested at an on-fiber axis angle. There are mainly four theoretical approaches proposed for the prediction of creep deformation of composites, namely Findley's power law (Findley et al. 1976), the Boltzman superposition principle (Leaderman 1943, Findley et al. 1976), the Schapery single integral procedure (Schapery 1969, Lou and Schapery 1971), and the lamination theory (Lilhot 1988, Dillard et al. 1989). These approaches have had different degrees of success in predicting the creep behavior of various types of composites. Creep of composites is greatly affected by heat and moisture. Elevated temperature usually greatly increases creep strain rate such that one may use the time-temperature superposition principle to predict long term creep deformation of composites at a lower temperature (Gramoll 1990). Moisture acts as a plasticizer, affecting polymer properties. Wang et al. found that moisture sorption greatly increased creep strain of fibers containing hydrogen bonding, such as Kevlar and cellulosic fibers, while it did not influence the creep behavior of fibers without hydrogen bonds (Wang et al. 1993). They believe that the moisture was disrupting the hydrogen bonds between molecules. It has been proven by Nissan that moisture absorption reduces the modulus of hygroscopic polymers due to the interruption of hydrogen bonds by water molecules (Nissan et al. 1976). Mohan and Adams investigated the effect of moisture on creep behavior of graphite/epoxy and glass/epoxy composites, and found that some of the nonlinearizing parameters in the Schapery equation were greatly altered (Mohan and Adams 1985).
Of the various composite types, the potential for reinforcement efficiency is greatest for those that are fiber reinforced. In such composites, the applied load is transmitted and distributed among the fibers via the matrix. Significant reinforcement is possible provided the matrix-fiber bond is strong. Since reinforcement discontinues at the fiber extremities, reinforcement efficiency depends on fiber length – the critical length depending on the fiber-matrix combination with both long- and short fibers producing a composite with unique properties. Fiber arrangement is also crucial relative to composite characteristics. The mechanical properties of aligned fiber composites are highly anisotropic – maximum in the alignment direction, whereas those of randomly oriented fibers are isotropic. In designing fiber-reinforced composite materials, the selection of the fiber and matrix is dependent on the properties being sought. Of the various fiber-reinforced composites, polymer-matrix is the most common, typically reinforced with glass, carbon and aramid fibers. Preference for these fibers is due to their high specific strength and specific modulus – see Figure 3.

From the above literature review it follows that:

1. Experimental data is available describing the behavior of some fiber reinforced wood structural members (beams and axially loaded members). The data pertains mostly to large structural members and no fundamental properties of the new material have been systematically studied.
2. Some experimental results are available studying the time-dependent behavior of wood-textile reinforced systems. Again, a global approach (large members) has been preferred.
3. Experimental data is available describing the global behavior of fiber-reinforced joints. The data show excellent performance under dynamic loads. Questions remain as to how the joints will perform under long-term loading and to a cyclically or arbitrarily changing environment.
4. Little attention has been paid to the wood-adhesive-synthetic fiber interface.

2.1. Research Needs and Opportunities

To further increase the understanding of wood-synthetic/natural fiber composite hybrid systems, the following needs are identified:

1. A basic understanding of physical and chemical surface characteristics of adherents needs to be intensified at a microscopic level, such as for the surface structure of wood and synthetic fibers.
2. Interfacial compatibility between bonding material and composite components as well as compatibility of wood and reinforcing fibers in a mechanical manner are essential to achieve manufacturability and desirable performance of the resulting composite.
3. The effect of environmental factors on the behavior of wood-adhesive-synthetic fiber systems must be fully understood, including time, time-temperature, moisture, time-moisture and time-temperature-moisture effects. Atmospheric oxidation, the effects of urban pollutants (SO_x and NO_{xx}) and aggressive environmental effects, such as salt water applications, are important as well.

2.2. Acknowledgment

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