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Effect of moisture on the mechanical properties of CFRP–wood composite: An experimental and atomistic investigation

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ABSTRACT

Adhesive bonding of fiber-reinforced polymers (FRP) to wood has been proven as a general way to achieve reinforcement and rehabilitation for wood structures. Although a significant mechanical enhancement can be acquired by using such approach, there exists a big concern about the long-term performance of the FRP–wood composite, especially under the effect of moisture. In this paper, both experimental and atomistic approaches are adopted for investigating the moisture effect on the entire FRP–wood composite system. Macroscopic mechanical tests show that its mechanical properties and its fracture behaviors notably change at different levels of ambient humidity. From an atomistic perspective, molecular dynamics (MD) simulations reveal that water molecules significantly reduce the adhesion energy between wood and epoxy. Results from experimental and numerical studies imply that the strength of the FRP–wood interface critically determines the mechanical performance of the entire system. The water molecules absorbed at the interface are crucial to the durability of multi-layer systems and a general mechanism governing the failure modes of such systems is found.

1. Introduction

Wood originates from trees and is a product from a complex biological synthesis. Growing trees gradually stretch and stiffen their stems in response to external mechanical loading, and eventually form wood bodies that exhibit good mechanical properties [1]. These naturally renewable resources are raw materials for manufacturing strong, durable, and useful wood products [2]. Great environmental benefits, relatively low costs coupled with good mechanical properties make wood a desirable engineering material nowadays as the concept of green building becomes the mainstream [3]. However, a relatively low load-carrying capacity of wood laminate compared to concrete and steel may restrain the utilization of wood as the structural material [4]. In addition, wood materials would become less stable over time due to the deterioration induced by the detrimental environmental conditions [5]. Improvements on the strength and durability are therefore essential considerations in order to make the most of wood resources. In terms of the reinforcing approach, there is an increasing awareness that the external bonding of fiber-reinforced polymers (FRP) to wood through epoxy is an efficient and practical way to enhance the mechanical performances of wood significantly [6,7].

FRP are composite materials made of strong and stiff fibers embedded within a polymer matrix [8]. FRP exhibit extremely high tensile strength and are expected to improve the flexural capacity when bonded onto the wood laminate. The bonding of wood and FRP is typically achieved by epoxy adhesive, as it can provide satisfactory adhesion [9]. There are a number of studies on the FRP–wood bonding technique, which cover feasibility [10], economic viability [11], mechanical enhancement [12–15], failure mode [16], selection of glue [17,18], selection of FRP [19–21], bond quality [22], effects from moisture content [23], effects from environmental conditions [24], etc. From all these studies, a general agreement is that the adhesive bonding of FRP to wood is indeed an efficient approach to strengthen the wood material. Meanwhile, an important concern is raised upon the durability issue, with a focus on whether or not the environmental conditions weaken the long-term performance of the reinforced composite system. The moisture affected interfacial degradation is a determining factor for the durability of both the FRP-concrete and FRP-steel systems, such findings indicate that the interface integrity under moisture effect is a major concern in the FRP-bonded composite system [25,26]. As a similar bilayer structure, FRP–wood system may also be critically affected by ambient moisture in terms of the long-term performance. Previous studies on the durability of FRP–wood

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bonding have shown that water can diminish the bond strength and reduce the effectiveness of strengthening approach by FRP composite [27,28]. Given that the mechanical experiments in this research field provide few insights related to the deterioration mechanism, computational simulation constitutes as a useful alternative, which can provide detailed microscopic information. From the nano-scale perspective, molecular dynamics (MD) simulation is a fundamental and powerful technique that enables one to study how this composite material interacts with the ambient environment. Recently, MD simulation has been successfully used for investigating the moisture affected adhesion in bilayer interfaces such as silica–epoxy [29,30], silica–peptide [31], graphene oxide inter-sheet [32] and chitin-protein [33,34]. The effect of water molecules may be beneficial or detrimental towards the bilayer material. For example, between adjacent graphene oxide inter-sheet layers, certain amount of water molecules can refine the hydrogen bonding network and contribute to the inter-layer adhesion [32]. In contrast, at the silica–epoxy interface [29,30], which is the representative of concrete surface, the water molecules may interfere into the bilayer connections and reduce the adhesion strength. Regarding the FRP–wood system, most of the recent studies have reported the degraded durability of epoxy-glued FRP–wood system, whereas the molecular details in epoxy–wood interface are rarely elucidated. Existing atomic experimental programs are very expensive and are mostly applied to investigating advanced nanomaterials, but few experimental studies are on the molecular details of conventional construction materials such as wood. Also, few molecular dynamics studies focus on the wood–FRP interface. Hence, there is a need to combine the macroscopic experiments together with the atomistic investigations so as to illustrate a complete picture and quantify the mechanical response of FRP–wood system under different moisture conditions at different length scales.

The present work aims to investigate the effect of moisture condition on the mechanical behavior of FRP-bonded wood system and further examine how water molecules affect the epoxy–wood interface at the atomistic scale. We firstly characterize the material properties of wood, FRP and epoxy adhesive. Then, by performing the mechanical tests, we obtain the mechanical responses and failure modes of FRP–wood composite under different moisture conditions. Furthermore, we build an atomistic model representing the epoxy–wood interface to provide the microscopic details of the moisture effect. In reference to this model, the effect of water molecules towards the adhesion strength of epoxy–wood interface is determined by calculating the adhesion energy under dry and wet scenarios, and it is further demonstrated by examining the molecular interactions of water molecules and the epoxy–wood interface during the simulation. Based on the experimental and computational results, we finally relate the molecular mechanisms of water molecules on the interface to the mechanical behavior of FRP–wood composites and discuss the relationship between the failure mode and the interfacial strength.

2. Materials and methods

Basic mechanical properties of the constituent materials, *i.e.* wood, epoxy and carbon fiber reinforced polymers (CFRP), are characterized in this paper. To understand the properties variation of CFRP-bonded wood system after moisture conditioning, the CFRP-bonded wood specimens are used. The details of the constituent materials, the CFRP-bonded wood specimens and the experimental program are given as follows.

2.1. Materials

The wood species selected in this program is the Canadian pine, which is widely used in construction industry. All wood samples were harvested from one single tree and flat sawn so as to minimize the extraneous variability. The wood samples were kiln-dried and then conditioned in the environmental chamber at 20 °C and 10% relative humidity [35]. After conditioning, a moisture content of 13% was achieved and a density of 514 kg/m^3 (Standard deviation: 40.1 kg/m^3) was recorded in accordance with the American Society for Testing and Materials (ASTM) D-4442 standard. Tensile and compressive tests were carried out to determine mechanical properties of wood along the parallel-to-grain direction. The cuboid samples with dimensions of 10 mm × 5 mm × 450 mm and 25 mm × 25 mm × 100 mm (height × width × length) were used in tensile and compressive tests separately. Both tests were performed using SANS mechanics testing machine under crosshead displacement control at a rate of 1.0 mm/min (in tensile test) and 0.3 mm/min (in compressive test) as suggested in the ASTM D143 standard. It should be noted that four identical samples were prepared for both tensile and compressive tests.

Table 1
The specifications of the epoxy after 7 days curing (from manufacturer).

Items	Values	Testing standard
Tensile strength (MPa)	55	ASTM D-638
Tensile modulus (GPa)	1.72	ASTM D-638
Flexural strength (MPa)	79	ASTM D-790
Flexural modulus (GPa)	3.45	ASTM D-790

The external reinforcement used in this investigation is a unidirectional CFRP. The thickness of the CFRP is 0.167 mm. The tensile test of CFRP along the longitudinal direction was conducted to acquire the tensile properties of CFRP. Three CFRP samples were tested following the ASTM D3039 standard.

A commercial epoxy is adopted to bond CFRP to the bottom surface of wood beams, which is subject to tension stress during the four-point bending test. When the wood beam is under bending load, the compression stress is developed at the top side of the beam and tension stress is developed at the bottom side of the beam [36]. The epoxy used here is composed of two parts, *i.e.* epoxy resin and hardener, which are provided by the Sika Company. The epoxy is solvent-free and possesses high strength, high modulus and high temperature resistance and it offers perfect adhesion that can transfer the stress between materials. The properties of the epoxy from the manufacturer are shown in Table 1.

2.2. CFRP bonded wood samples and conditioning

The wood beams are reinforced by the CFRP sheet in the tension face. Pre-treatment of the surface is necessary to safeguard the quality and durability of the bonding [24]. The knife planing is a preferable surface preparation method and is used to remove the impurities from the wood surfaces. After this treatment, the cellular structure in wood can be fully exposed and a high-quality bonding can be achieved. The epoxy adhesive is smeared onto the planed surface immediately after the knife planing in case of oxidation of fresh wood surface [18,22,37]. The surface of CFRP is cleaned by a methylated spirit wetted cloth for grease removal. After cleaning the surfaces of wood and CFRP, the gluing process can be carried out. The CFRP sheet is placed to wood beams following the alignment that the fiber directions of two materials are parallel. Then, a steel bar is used to sweep through the CFRP sheet for removing air gaps and squeezing out excessive epoxy. The extrusion of excessive epoxy indicates that sufficient epoxy adhesive is spread on the interface. After the bonding process, a second layer of epoxy is brushed on the CFRP sheet and a layer of plastic wrap is put on the CFRP. A uniform pressure of 0.7 N/mm^2 is applied onto CFRP for 24 hours to ensure that the wood and CFRP are well