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Structural evaluation and design procedure for wood beams repaired and retrofitted with FRP laminates and honeycomb sandwich panels

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ABSTRACT

As compared to other structural applications of polymeric composites, limited information is available on structural behavior of wood members strengthened with polymer composites. The focus of this paper is to evaluate the structural performance and practical use of wooden beams repaired and retrofitted with fiber-reinforced-polymeric (FRP) composites. The paper presents a summary results of an experimental study on the behavior of both Douglas Fir and Glulam wood beams repaired and retrofitted with different composite strengthening systems. In addition, the paper presents a simplified design procedure to predict the capacity of timber beams strengthened with FRP composites. Two types of composites; wet layup laminates and sandwich panels, and two lamination schedules; unidirectional and bidirectional, and two lamination geometries; U-laminate and flat laminates were evaluated. For "flexure/shear" wood beams repaired and retrofitted with bidirectional, carbon/epoxy U-shaped wet layup laminates, a total of eight Douglas Fir (Dug Fir) Larch # 1 wood beams were tested to failure. For "flexure-only" wood beams retrofitted with flat unidirectional laminates, both wet layup and precured sandwich honeycomb composites were evaluated. Experimental results indicated that the use of composites as external repair and rehabilitation elements resulted in an appreciable increase of both strength and stiffness. A practical case study is also presented that provides a step-by-step procedure for analyzing and designing a polymeric composite system for repair of partially damaged wood girders by fire.

1. Introduction

For the past decade or so, polymer composites were introduced to the construction industry as a valuable alternative structural system for repair and rehabilitation of reinforced concrete [7,16–18], steel [14], and masonry [15] structures. These applications were extended for be utilized for potential use as repair and capacity upgrade of wood structural members. One of the first applications was initiated in mid-1990, where E-glass/epoxy laminates were used to restore damaged wooden utility poles. This application was further studied by Ref. [23] and by Ref. [26]. Similar application of strengthening wood piles with composites was also investigated (*e.g.* Ref. [11]. A hybrid glued-laminated wood products were also developed by introducing thin laminates of E-glass/epoxy composites between the wood layers [2]. Gilfillan et al.[6] studied structural behavior of several Irish-grown Sitka timber beams strengthened with both composites and steel. These beams were evaluated under both short- and long-term mechanical loading. Experimental results indicated that an appreciable strength gain was been achieved for beams strengthened with FRP composites. Buell and Saadatmanesh [3] evaluated the behavior of timber bridge beams strengthened with carbon/epoxy composites. The results of their study indicated that the use of carbon/epoxy composite laminates for strengthen timber bridge beams has resulted if a significant increase in both bending and shear strength with a nominal upgrade of beam stiffness. Lyons and Ahmed [12] discussed different factors affecting the bondline strength of wood members including adhesive properties, wood surface conditions and moisture content, as well as the effect of service environment. The results of the study indicated that the roughening wood member surface has a positive impact on bondline strength and that the use of hydroxyl methanol resorcinol (HMR) improves the bond strength in wet conditions. The temperature-dependent creep of different adhesives for wood members and the influence of fillers on temperature stability of epoxy adhesives used for wood-composites application were investigated by Richter and Steiger [25]. Li et al. [10] conducted analytical and experimental investigation on the flexural performance of beams fabricated from two wood species, namely; Tsuga Chinensis and Cunninghamia

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Lanceolata that were retrofitted by carbon/epoxy composite. Similar conclusions were drawn confirming the increase of both the strength and stiffness of the retrofitted beams. The effect of the surrounding environment on the performance of FRP/wood adhesively bonded epoxy joints was evaluated by Ref. [27]. The authors observed that the first twenty months of environmental exposure have a significant effect on bondline failure due to tensile shear strength reduction. Modeling of wood beams strengthened with different CFRP composite laminates was reported by Ref. [8]. The used of FRP near-surface mounting (NSM) strengthening system was evaluated by Ref. [5]. In the study, flexural performance of fir and pine wooden beams strengthened with NSM carbon-fiber-reinforced polymer (CFRP) composite plates and rods were experimentally evaluated. Their experimental results verified the efficiency of both NSM systems in improving both flexural strength and stiffness of the strengthened wood beams.

2. Motivation & objective

Composites have a high potential as an alternative sustainable reinforcing repair system to existing under-deigned, historical and structurally deteriorated constructed facilities to increase the flexural strength and to enhance the ductility of existing and new wood structures (refer to Fig. 1). Increasing the structural capacity of wood members to carry heavier loads allows the structural engineer to reduce the cross-sectional area of the wood member for the same load resulting in a major reduction of wood consumption that lead in saving millions of trees worldwide. Kukule and Rocens [9] confirmed this fact through a study that indicated that the use of prestressed CFRP composite laminates for strengthening wood members can reduce the wood consumption by about 31%. Although, this potential have been verified by several pilot studies, however, its application is relatively limited due to several reasons including lack of design standards, and most important, the limited information on both the short- and long-term structural behavior of wood members externally reinforced with polymer composites. In order to successfully introduce this application to the construction industry, more analytical and experimental verification studies are essential. In addition, there is need for developing reliable simplified design procedures for this potential application. In this study, a total of eight large-scale tests were conducted to assess the flexural behavior of wooden members repaired and retrofitted with external composite laminates and to identify the predominated failure mode of such hybrid structural members. One of the major objectives of this study is to highlight the importance and advantages of adopting the proposed "flexure/shear" strengthening protocol for wood flexural members. As known, wood is an orthotropic material with mechanical properties dependent on grains orientation of the flexure member. Wood members subjected to flexural stresses with grains parallel to the member's longitudinal axis have limited interlaminar shear strength, and hence, the amount of additional external flexural reinforcement (*e.g. using E-glass/, carbon/or Aramid/epoxy laminates*) must be proportional and limited to such strength, otherwise, interlaminar shear failure is unavoidable (refer to Fig. 2). For this reason, and in order to take full advantages of the composite laminates placed at the tension side of the strengthened wood member, it is important to adopt what is referred to in this paper as "flexure/shear" strengthening scheme. In this scheme, a bidirectional [0°/90°] U-shaped composite laminate is proposed. The fiber volume fraction in each orthogonal direction is controlled by the target flexural strength enhancement capacity. Once this capacity is identified, the "parallel-to-grain" fiber volume fraction (0°-direction) can be calculated. Consequently, the resulting interlaminar shear stresses are determined that are used in calculating the "perpendicular-to-grain" fibers volume fraction (90°-direction). The use of this protocol will eliminate or minimize the potential premature interlaminar shear failure prior to reaching the full-capacity of the composite laminate placed at the tension side of the flexural wood member leading an optimum use of composites (see Fig. 2). In

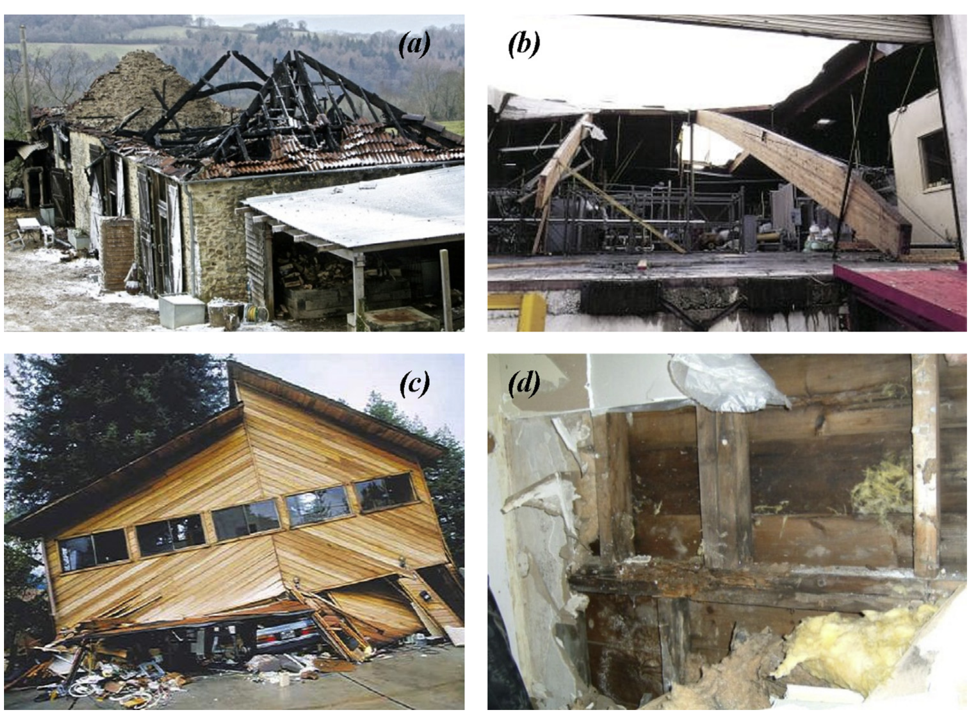

Fig. 1. Examples of Potential Damages of Wood Structures: *(a) Fire Damage, (b) Inaccurate Connection Details and Design Faults, (c) Seismic Capacity Deficiency, (d) Environmental Deterioration.*