Construction and Building Materials 102 (2016) 1070–1083

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Multi-scale characterization of moisture and thermal cycle effects on composite-to-timber strengthening

Maria Rosa Valluzzi [a,*], Fabiola Nardon [b], Enrico Garbin [b], Matteo Panizza [b]

[a] DBC – University of Padova, Piazza Capitaniato 7, 35139 Padova, Italy
[b] DICEA – University of Padova, Via Marzolo 9, 35131 Padova, Italy

HIGHLIGHTS

- Use of vinyl glue for the application of natural (flax) textiles on timber elements.
- Multi-scale experimental study on flax applied to timber.
- Extensive study of flax-to-timber bond (pull-off, shear, microstructural analyses).
- Proposal of procedures for the study of durability of composites applied to timber.
- Comparison of flax and carbon fibers performance for timber strengthening.

ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form 10 June 2015
Accepted 5 July 2015
Available online 20 July 2015

Keywords:
Timber
Composite
Bonding
Flax
Carbon
Pull-off test
Single-lap shear test
Bending test
Optical microscopy
IR spectrometry

ABSTRACT

The paper examines the influence of moisture and temperature cycles on timber elements reinforced with a wet lay-up system composed of various fibrous materials (carbon, flax) and matrices (epoxy resin, vinyl glue). A multi-scale experimental approach was adopted, including: (i) mechanical characterization of the composite reinforcement systems; (ii) investigation of behavior at the composite-to-timber interface by mechanical bond tests and microstructural analyses; (iii) four-point bending tests on strengthened timber beams. The results highlighted the good performance of natural-fiber composites compared with synthetic ones, and the marked influence of wood moisture content and temperature on bonding.

1. Introduction

Composite materials, mainly synthetic FRPs (Fiber Reinforced Polymers) applied with a wet lay-up system, are currently employed to strengthen and retrofit existing structures [6,24,23,14,41]. The main composites, also used on timber, are made of carbon, glass or aramid synthetic fibers, applied with epoxy resins. They can significantly enhance the mechanical performance of structural elements, thanks to several common advantages of FRPs, e.g.: high strength/weight ratio, resistance to corrosion, high versatility and ease of application [29,18,3,39,30,17]. However, FRPs may be sensitive to changes in environmental conditions, and their application to porous materials problematic (low permeability, poor adhesion on damp substrates, etc.) [20,8,2].

Recently, natural plant-based fibers (e.g., cotton, hemp, flax, jute, sisal, bamboo) have been introduced as resistant materials to obtain natural fiber composites (NFRPs) [28,19]. They have several advantages over synthetic ones: natural fibers are biodegradable, renewable and recyclable, not toxic or pollutant, and their production and disposal require less energy and lower costs [25,22]. These aspects also make NFRPs attractive in terms of compatibility and sustainability in the choice of suitable interventions on existing structures. Nevertheless, critical aspects concerning the use of natural composites applied to wood should not disregarded,

* Corresponding author.
E-mail address: mariarosa.valluzzi@unipd.it (M.R. Valluzzi).

http://dx.doi.org/10.1016/j.conbuildmat.2015.07.008

e.g.: high moisture absorption, low resistance to heat, and sensitivity to biological attack [42,31,13].

The influence of environmental agents on the mechanical performance of composite materials used to strengthen timber structural elements has not yet been fully investigated. The few works available mainly concern the influence of moisture content on bond for rods [7] or textiles [43] and dry-wet cycles [11] or environmental conditions [30,16]. Particularly for NFRPs, studies have mainly focused on experimental evaluation of mechanical performance of beams or rafters strengthened with NFRPs (comparison of bamboo, flax and hemp, also applied in multi-layers, with basalt FRPs in [4,5], between bamboo and carbon FRP (CFRP) in [10] or application of sisal fibers in [21]). In all these studies, natural fibers are applied with epoxy resin; results show the lower but significant structural enhancement given by NFRPs with respect to synthetic FRPs and the contribution of fibers in preventing brittle ruptures in critical tension areas of beams. A recent study on durability [2] characterized bamboo FRP and steel reinforced grout (SRG) in accelerated aging and water absorption tests; a decrease of about 20% of the axial tensile strength of the bamboo fibers was detected.

Extensive experimental research was carried out at the University of Padova (Italy) to clarify the effectiveness, compatibility and durability of low-performance natural composite materials, also applied in multi-layer reinforcing systems, compared with most common high-strength synthetic FRPs. Flax and carbon fibers were selected as reinforcing materials, respectively. For the matrix, an epoxy resin, normally used for FRPs, was adopted for both flax (FFRP) and carbon FRP; a vinyl glue, commonly used with wood, was also selected to apply flax fibers, thus providing a new combination for composite materials, here called FFRP(V). Although vinyl glue is traditionally and widely used in the timber industry (as carpenter's glue) for its high compatibility with wood, it has not yet been considered for application to composite materials. It is a non-biodegradable matrix but, in terms of sustainability, it has many advantages: it is water-based, non-toxic, and does not contain solvents, tools can be cleaned with water, and it is readily available and cheaper than epoxy resin.

A multi-scale laboratory experimental campaign was carried out. Several test methods were adopted for: (i) material characterization (tensile tests of basic materials and composite strips); (ii) composite-to-timber bond study (pull-off and single-lap shear tests, microstructural analyses with optical microscopy and IR spectrometry); (iii) estimation of the mechanical effectiveness of the strengthening technique on structural elements (bending tests on reinforced beams). Significant procedures to evaluate the influence of various types of environmental exposure on the adhesion between composites and wood were identified. As the main critical aspects which may affect bonding between composite materials and timber elements, moisture content in wood, high temperature, and hydro-thermal cycles were selected. In this context, as standard procedures to qualify or quantify durability are lacking, experimental validation is needed. In the following, the preliminary assumptions (selection of variables, identification of procedures) and results obtained at the various levels of study, comparing NFRPs and CFRP performance, are discussed.

2. Experimental program

The influence of environmental conditions on composite-to-timber strengthening was studied, and several types of exposure and experimental procedures were applied. As no standards or recommendations are available in the literature to identify conditioning procedures (except for UNI EN 302-3 [34]), assumptions were made for setting significant environmental conditions. They refer to changes in humidity and temperature, also in combination with respect to reference laboratory conditions. The following aspects were examined: (i) moisture content of wood before application of composites to timber, and then on reinforced specimens: (ii) cycles of combined relative humidity and temperature, (iii) high temperature, (iv) prolonged exposure to humidity. The work was organized in five phases, as described below.

2.1. Conditioning

The chosen environmental parameters of temperature and humidity refer to five phases, the parameters of which were modified with respect to the reference laboratory condition.

2.1.1. Phase 0: reference conditions (Ph.0)

The pilot conditions considered here were: moisture content (MC) 10% (dry wood, according to [33]), temperature (T) 20 °C, and air relative humidity (RH) 65%. Phases 1, 3, 4 and 5 refer to these values for parameters which were not modified. These reference values also constituted the conditions in which the reinforced specimens tested in Phases 2, 3, 4, 5 were prepared, and cured after conditioning and before testing.

2.1.2. Phase 1: influence of high wood moisture content before application of FRPs (Ph.1)

This phase aimed at identifying how initial water content in wood can affect application of the composite material and consequent bonding. Specimens were soaked in water, and composites were applied at three values of moisture content: MC = 20%, 30% and 40%. Measurements were based on UNI EN 13183-1 [32].

2.1.3. Phase 2: influence of humidity and temperature cycles after application of FRPs (Ph.2)

This phase aimed at studying the combined effect of temperature and relative humidity. UNI EN 302-3 [34] was considered as basic reference. Four cycles, each composed of three steps (Table 1), were applied.

2.1.4. Phase 3: influence of high temperature after application of FRPs (Ph.3)

The specimens were exposed to high temperature for 24 h in a convection oven, to verify the influence of wood swelling on bonding and possible damage to the matrix due to heating. Six temperature levels were used: 50, 60, 80, 100, 120 and 140 °C. As most of the selected levels may have exceeded the glass transition temperature of both matrices, all samples were allowed to cool slowly inside the oven, to avoid thermal shocks.

2.1.5. Phases 4 and 5: influence of humidity over time after application of FRPs (Ph.4 and Ph.5)

These phases aimed at studying the effects of prolonged exposure to humidity, i.e., 30 days for Ph.4 and 60 days for Ph.5. The same MC levels of Ph.1 were assumed: MC = 20%, 30% and 40% but, in this case, the composites had already been applied to the timber elements. The reinforced specimens were kept in sealed bags for 30 or 60 days (according to Ph.4 or Ph.5), i.e., in high atmospheric humidity.

2.2. Testing procedures and selection of variables

After conditioning, the specimens were observed and subjected to laboratory testing. An extensive multi-scale experimental campaign was carried out, aimed in particular at characterizing the mechanical behavior of flax fibers applied with both epoxy resin and vinyl glue in various temperature and moisture conditions and their combination. The experimental approach included: (a) characterization of constituent materials (wood, fibers, matrices), (b) qualification of composites (tensile tests), (c) study of composite-to-timber bond (pull-off and shear tests, microstructural analyses), (d) characterization of mechanical behavior of reinforced structural elements (bending tests on beams). In addition, due to the substantial differences between carbon and flax fibers, application of flax textiles as a multi-layer system (1, 3 or 5 overlapping strips) was compared with a single-layer application of carbon strips.

The huge number of variables involved in this study required careful selection of the above aspects applied to mechanical testing. As bond is the most critical aspect demonstrating the effectiveness of the intervention, the whole set of conditioning phases was applied to the simplest experimental procedure (pull-off test). The results indicated some significant conditions, which were then assumed for the other tests. In particular, multi-layer NFRPs were tested at reference conditions

Table 1
Phase 2: combined temperature and humidity cycles.

Step	Time (h)	Temperature (°C)	RH (%)
1	24	50 ± 2	87.5 ± 2.5
2	8	20 ± 5[a]	87.5 ± 2.5
3	16	50 ± 2	⩽20

[a] Parameter modified with respect to UNI EN 302-3 [34] due to laboratory conditions.