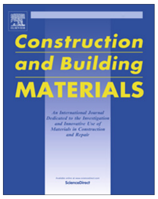
Construction and Building Materials 171 (2018) 140–151

Contents lists available at ScienceDirect

Construction and Building Materials

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



Comparison between different tensile test set-ups for the mechanical characterization of inorganic-matrix composites

T. D'Antino [a,b,*], Catherine (Corina) Papanicolaou [b]

[a] *Politecnico di Milano, Department of Architecture, Built Environment, and Construction Engineering, IT-20133 Milan, Italy*
[b] *University of Patras, Department of Civil Engineering, GR-26500 Patras, Greece*

HIGHLIGHTS

- Tensile tests of TRM rectangular prism and dumbbell specimens are performed.
- Rectangular prism and dumbbell specimens provide completely different results.
- DIC is employed to study out-of-plane and in-plane rotations of dumbbell specimens.
- Two mechanics-based criteria are proposed to identify reliable test results.

ARTICLE INFO

Article history:
Received 29 November 2017
Received in revised form 8 February 2018
Accepted 5 March 2018

Keywords:
Inorganic-matrix composites
FRCM
TRM
Digital image correlation
Tensile tests

ABSTRACT

Inorganic-matrix composite materials can be effectively employed to strengthen and retrofit existing reinforced concrete and masonry structures. These composite materials comprise high-strength fiber textiles embedded within inorganic matrices. Different textile layouts and types of matrix and fibers can be employed resulting in a multitude of different composite materials and mechanical behavior thereof. As in most composite materials, the mechanical characterization of the single constituents (matrix and fiber) does not provide indications on the behavior of the composite material. Therefore, the mechanical characterization of the entire composite material is of fundamental importance to understand the interaction (i.e. composite action) between the fiber textile and the embedding matrix. Although different tensile test set-ups were proposed in the literature, a shared standard testing method for the mechanical characterization of inorganic-matrix composites is not yet available.

In this paper, the mechanical properties of four different inorganic-matrix composites comprising carbon, glass, basalt, and steel fibers embedded within cement- and lime-based matrices are investigated using two different tensile test set-ups. Analog LVDTs and digital image correlation (DIC) measurements are employed to study the specimen longitudinal strain behavior. Two criteria to assess the reliability of results of tensile tests are proposed. Comparison between results described in this paper shows the strong influence of the test set-up on the tensile behavior of inorganic-matrix composites and helps to shed light on the reliability of the mechanical parameters obtained.

1. Introduction

Strengthening and retrofitting of existing structures have become a growing need due to deterioration with age, change of applied loads, deficient design or construction, and seismic vulnerability. Composite materials, which are relatively easy to install and have a high strength-to-weight ratio, represent an efficient solution to strengthen reinforced concrete (RC), masonry, and wood structures. Between them, fiber reinforced polymer (FRP) composites attracted a large interest from the civil engineering community and are widely employed. However, the use of organic matrices as bonding agents is responsible for some issues associated with the application of FRP composites, such as the degradation at temperatures close to or above the matrix glass transition temperature [1] and in presence of moisture [2] and the poor compatibility with concrete and masonry substrates [3]. A valid alternative to FRP composites that promisingly overcomes these issues is represented by inorganic-matrix composites. Inorganic-matrix composites consist of high-strength open mesh textiles embedded within an inorganic matrix responsible for the stress-transfer between the fibers and the substrate. Although different names have been used to indicate inorganic-matrix composites,

---

* Corresponding author at: Politecnico di Milano, Department of Architecture, Built Environment, and Construction Engineering, IT-20133 Milan, Italy.

E-mail address: tommaso.dantino@polimi.it (T. D'Antino).

https://doi.org/10.1016/j.conbuildmat.2018.03.041
0950-0618/

they are usually referred to as fiber reinforced cementitious matrix (FRCM) or textile reinforced mortar (TRM) composites. In this paper, the acronym TRM has been adopted to indicate that inorganic-matrix composites comprising both cement- and lime-based matrices were used.

Although TRM composites can be employed for flexural [4–7], shear [8–14], and torsional [15,16] strengthening and for confinement of axially loaded elements [17–20], the research is still limited and the only design guideline available to date is ACI 549 [21]. Experimental evidences showed that TRM composites externally bonded to existing structural elements may fail due to debonding at the matrix-fiber or at the composite-substrate interface (with or without damage of the substrate) [22,23], although interlaminar failure (delamination) of the matrix [24] and rupture of the reinforcing textile has also been observed [25]. Therefore, the study of the stress-transfer mechanism between the matrix and fibers and between the composite strip and substrate is of critical importance to understand the behavior of TRM-strengthened elements. Since the mechanical characterization of the single constituents (matrix and fiber) does not provide indications on the behavior of the composite material [26], mechanical tests of the entire composite are needed. Direct-shear tests are employed to study the bond behavior of inorganic-matrix composites applied to different substrates [25,27–29]. Bending tests were also used to obtain mechanical parameters for design purposes [30] and recently a new test set-up that employs rectangular prism specimens was proposed to study the bond behavior of inorganic-matrix composites that fail due to matrix-fiber debonding [31]. In addition to direct-shear tests, tensile tests are used to classify/compare different matrix-fiber combinations and to obtain mechanical parameters that can potentially be used for design applications [32]. Different tensile test set-ups are proposed in the literature and each provides different results [33]. Although rectangular prism specimens are largely used due to the low cost and ease of fabrication of the molds, dumbbell specimens are also employed [34]. The tensile load can be applied to rectangular prism specimens by direct clamping with the machine wedges (clamping-grip method [21] with absence of specimens' rotational capacity) or using metallic plates bonded to the specimen ends and connected to the machine through a transversal pin (clevis-grip method [28,35,36]). Tensile tests on TRM rectangular prism specimens using the clevis-grip method are required by ACI 549 [21]. A different clamping-grip method is recommended by Rilem TC 232-TDT [32] to determine the load bearing behavior of textile reinforced concrete (TRC) rectangular prism specimens under uniaxial tensile loading. According to this recommendation [32], clamping of the specimens should be realized through controllable mechanical, hydraulic, or pneumatic clamps and specimens should be furnished with at least an in-plane rotational capacity. Finally, dumbbell specimens can be loaded in tension using curved steel flanges matching the specimen shape (curved-flange method [37]) or using transversal pins passing through the specimen ends [26].

When the clamping-grip or the Rilem TC 232-TDT [32] method is adopted, the pressure exerted by the clamping wedges on the specimen ends should prevent slippage of the textile within the embedding matrix and failure should occur due to fiber rupture. However, the wedges' pressure affects the matrix-fiber stress-transfer mechanism and may not correctly reproduce the behavior of non-anchored TRM composites in real applications. Furthermore, testing methods recommended for TRC [32] may not provide reliable results when applied to TRM composites. In fact, TRC generally comprises high-strength concrete matrix [26] that allows for increasing the clamping pressure without damaging the specimen and preventing slippage of the embedded fibers with respect to the matrix. With TRM composites, increasing the clamping pressure may result in damage of the matrix, which compromises the results [38]. When the clevis-grip method is employed, failure generally occurs due to debonding at the matrix-fiber interface. However, different results can be obtained depending on the specimen length, end plates' bonded area, and location of matrix cracks [39]. Similarly, failure of curved-flange dumbbell specimens may occur due to slippage of the textile within the embedding matrix or textile rupture. Furthermore, the curved flanges induce compressive stresses in the specimen ends that may affect the result obtained [33].

In this paper, the results of tensile tests on four different TRM composites are presented and discussed. All TRM composites were tested using two tensile test set-ups, namely the clamping-grip method applied to rectangular prism specimens and the curved-flange method applied to dumbbell specimens. Longitudinal strain along the specimens was measured with analog LVDTs and was compared, in the case of dumbbell specimens, with the strain measured with the digital image correlation (DIC) method. The results showed that the two test set-ups provided completely different behaviors for the same composite material. Comparison between analog and DIC measurements allowed for studying possible specimen out-of-plane rotation. Furthermore, DIC was used to investigate specimen in-plane rotation and longitudinal strain distribution across the matrix width. Finally, a criteria to assess the results' reliability was proposed.

2. Materials

Four different TRM composites were studied in this work. Two standard modulus carbon fiber bidirectional (balanced) textiles with the same dry area weight, namely 170 g/m^2, and the same spacing between bundles (i.e. 20 mm on center), one with and one without fiber coating (named C170C and C170, respectively), were embedded within the same cement-based matrix, named matrix C. The same cement-based matrix was used to embed a unidirectional galvanized steel cord textile with an area weight of 80 g/m^2 and cord spacing of 7.5 mm on center, named S80. Finally, a coated AR glass fiber bidirectional (balanced) textile with a dry area weight of 250 g/m^2 and bundles spaced at 25 mm on center, named G250C, was embedded within a lime-based matrix named matrix L. In this paper, the term "coated" indicates full impregnation of fiber bundles according to the current literature and market practice.

Warp and weft bundles of textiles C170C and G250C had different shapes; the warp bundles comprised two twisted sub-bundles whereas the weft bundles consisted of a single bundle. Therefore, single warp bundles (yarns) and cords with cross-sectional area A_f were extracted from each of the non-metallic textiles and the steel mesh, respectively, and they were tested in tension to obtain the mean tensile strength σ_f, the corresponding mean rupture strain ε_f, and the mean elastic modulus E_f. The mean values obtained by averaging the results of at least 3 specimens for each textile studied are reported in Table 1 together with the corresponding coefficient of variation (CoV). The tensile strength obtained from tensile tests of carbon and glass warp bundles was lower than the tensile strength provided by the manufacturers, equal to 4800 MPa (textile C170C and C170) and 2000 MPa (textile G250C), respectively. However, values provided by the manufacturers refer to a single fiber filament and are often only theoretical because of the difficulties associated with testing a filament with a diameter that can be lower than 10 μm. When fiber bundles or textile strips are tested, individual bundles and single fiber filaments within each bundle are not evenly loaded and progressive rupture of the most stressed filaments occur, leading to a tensile strength lower than that of a single fiber filament.