Composites Part B 90 (2016) 76–85

Contents lists available at ScienceDirect

Composites Part B

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

# On the reinforcement of cement mortars through 3D printed polymeric and metallic fibers

I. Farina [a], F. Fabbrocino [a], G. Carpentieri [b, c], M. Modano [c], A. Amendola [b], R. Goodall [d], L. Feo [b], F. Fraternali [b, *]

[a] Department of Engineering, Pegaso Telematic University 80132 Naples, Italy
[b] Department of Civil Engineering, University of Salerno, Via Giovanni Paolo II 132, 84084 Fisciano, Italy
[c] Department of Structural Engineering, University of Naples Federico II, 80132 Naples, Italy
[d] Department of Materials Science and Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK

ARTICLE INFO

*Article history:*
Received 30 October 2015
Accepted 20 December 2015
Available online 30 December 2015

*Keywords:*
A. Fibres
B. Fibre/matrix bond
B. Fracture toughness
C. Surface analysis
Additive manufacturing

ABSTRACT

We employ additive manufacturing technologies for the design and fabrication of novel reinforcing elements of cement mortars. Three-point bending tests and optical microscope analyses are performed on a cement mortar reinforced with 3D printed fibers made of polymeric and metallic materials, which exhibit different surface morphology and roughness. Experimental and analytical results highlight that the shear capacity, flexural strength and fracture toughness of the examined materials greatly depend on the design and the material of the reinforcing fibers. Specimens reinforced with high surface roughness fibers exhibit shear failure and high interfacial bond strength, while unreinforced specimens and specimens reinforced with smooth fibers exhibit flexural failure and limited interfacial bond strength. We observe that mortar specimens reinforced with titanium alloy Ti6Al4V fibers exhibit load carrying capacity more than twice as high as specimens reinforced with photopolymeric fibers.

## 1. Introduction

The nascent field of structural “metamaterials”, i.e. artificial materials showing unconventional properties mainly derived by their geometric design is growing rapidly and attracting increasing attention from many research areas (refer, e.g., to [1] and references therein). In recent years, additive manufacturing (AM) has become the most common technique for fabricating materials that exhibit unusual behaviors, which are not found in natural materials. Some popular AM methods are: polyjet 3D printing technologies; electron beam melting; x-ray lithography; deep ultraviolet lithography; soft lithography; two-photon polymerization; atomic layer deposition; and projection micro-stereolithography, among other available methods (refer to [2–6] and references therein). However, the potential of rapid prototyping in the design of novel mechanical metamaterials is not completely understood at present, and there is an urgent need for research exploring the suitability of such techniques for the manufacture of real life engineering materials.

Most natural shapes exhibit hierarchical organization of matter and fractal geometries, which provide increased surface area for the same volume of material. Recent studies have shown that hierarchical composites showing multiscale fibers coated with carbon nanotubes feature enhanced interlaminar shear strength (ILSS), a key property of composite materials, which can be weak in the presence of smooth matrix-fiber interfaces [7,8]. In such materials, the development of rough fracture surfaces near to the surface of the reinforcing elements, along with crack deflection mechanisms, enhances matrix toughness. The increase in the surface roughness of the reinforcing elements, as compared to smooth interfaces, delays the matrix failure and improves surface energy dissipation [7]. In addition, the pull-out of fine-scale features of the reinforcements bridges the matrix, significantly contributing to the enhancement of composite strength and toughness [8].

The present study investigates the use of additively manufactured reinforcing elements with multiscale geometry for the reinforcement of cementitious mortars. Fibers with structural hierarchy originating from their geometric design are manufactured from computer-aided design (CAD) data, employing additive

---

* Corresponding author.

*E-mail addresses:* ilenia.farina@unipegaso.it (I. Farina), francesco.fabbrocino@unipegaso.it (F. Fabbrocino), gcarpentieri@unisa.it (G. Carpentieri), modano@unina.it (M. Modano), adaamendola1@unisa.it (A. Amendola), r.goodall@sheffield.ac.uk (R. Goodall), l.feo@unisa.it (L. Feo), f.fraternali@unisa.it (F. Fraternali).

http://dx.doi.org/10.1016/j.compositesb.2015.12.006
1359-8368/

manufacturing techniques based on polymeric and metallic materials. A first source of hierarchical architecture arises from using fibers covered by lattices on a smaller scale [9]. A second strategy employs meshes with fractal geometry (Fig. 1) [10]. Reinforcements with hierarchical structure are combined with a cement mortar, in order to obtain advanced composites with enhanced ILSS, and enhanced first-crack strength and fracture toughness.

We begin in Sect. 2 by describing the preparation of the mortar and fibers analyzed in the present study. Next, we analyze the first-crack strength and toughness of fiber-reinforced mortar specimens through three point bending tests (Sect. 3). We continue by analyzing the morphology of the fibers' surface in the virgin state and after their pull-out from the matrix (Sect. 4). We end in Sect. 5 with concluding remarks and an outline of future work to be carried out to deepen the potential of AM for the optimal design of novel composite materials.

## 2. Cement mortar reinforcement with 3D printed fibers

Let us examine the fiber reinforcement of a pre-mixed cement-based mortar matrix of class M5 [11] with mechanical properties shown in Table 1. We employ reinforcing fibers fabricated through two different AM technologies: PolyJet 3D printing of liquid photopolymers through the Objet500 Connex commercial printer by Stratasys®, and electron beam melting (EBM) of high-strength metallic materials through the Arcam EBM S12 facility available at the Department of Materials Science and Engineering of the University of Sheffield.

We printed six polymeric fibers in the photopolymer transparent resin Fullcure 720 (see Table 1 for mechanical properties), with 7.5 mm diameter and 100 mm length, Three of these fibers show smooth lateral surface (hereafter denoted as “Pol_S” fibers, see Fig. 2a), while another three are coated on the lateral surface with a fractal lattice based on the Koch snowflake (“Pol_R” fibers, see Figs. 1a and 2b).

Metallic fibers were also produced, employing EBM to manufacture four cylindrical fibers in the titanium alloy Ti6Al4V [6], with 7.5 mm diameter, 160 mm length, and smooth lateral surface (“Ti_S” fibers, see Fig. 3a,c and Table 1). We also employed EBM to produce four 7.0 mm diameter Ti6Al4V fibers, coated with a 0.75 mm × 0.75 mm grid of cylindrical embossments. These cylinders exhibit 0.20 mm diameter and 0.50 mm length (“Ti_R” fibers, see Fig. 3b,d and Fig. 4).

A microscope characterization of the surface morphology of the examined fibers is given in Sect. 4. Such fibers were employed to reinforce prismatic specimens of a cement mortar with square cross-section, 40 mm width and 160 mm length. Mortar specimens were manufactured by adding 180 cc of water for each kg of the premixed cement mortar, according to manufacturer's recommendations. We set the mortar cover of Pol_S and Pol_2 fibers equal to 20 mm (effective depth equal to 200 mm: fibers placed at mid-height), and that of Ti_S and Ti_R fibers equal to 7 mm (effective depth equal to 33 mm). The above fiber placements were aimed at reproducing pure crack-bridging reinforcement in the case of the low modulus Pol_S and Pol_R fibers, and combined shear-flexure reinforcement in the case of the high modulus Ti_S and Ti_R fibers (see Table 1). All the specimens were cured at room temperature for 28 days before testing. We use the nomenclature Pol_R, Pol_S, Ti_R, and Ti_S to denote the mortar specimens reinforced with the corresponding 3D printed fibers, and unreinforced mortar specimens by the symbol UNR. We manufactured three Pol_R, Pol_S, Ti_R and Ti_S specimens each, and four UNR specimens.

**Table 1**
Mechanical properties of mortar and fibers.

| **Class M5 mortar** | |
|---|---|
| Mass density [kg/m$^3$] | 1515 |
| Compressive strength [MPa] | 5 |
| Flexural strength [MPa] | 1 |
| **Fullcure 720 Stratasys® photopolymer** | |
| Mass density [kg/m$^3$] | 1.18–1.19 |
| Tensile strength [MPa] | 50–65 |
| Modulus of elasticity [MPa] | 2000–3000 |
| **Fully dense Ti6Al4V titanium alloy** | |
| Mass density [kg/m$^3$] | 4420 |
| Tensile strength [MPa] | 910 |
| Modulus of elasticity [GPa] | 120 |

## 3. Three point bending tests

We studied the mechanical response of the examined fiber-reinforced mortars by carrying out three-point bending (TPB) tests in displacements control, with 0.25 mm/min loading rate. For each examined specimen, we first determined the applied load versus mid-span deflection curve, and next we computed the first crack strength, shear capacity and material toughness according to the methods specified in the international standards for construction materials. The load-deflection curves obtained for Pol_S and Pol_R specimens are illustrated in Figs. 5 and 6, respectively, while the analogous curves competing to Ti_S and Ti_R specimens are given in Figs. 7 and 8, respectively. Figs. 9–11 illustrate the synchronization of frames taken from in-situ videos of the TPB tests and the load-deflection curve of some Pol_R, Ti_S and Ti_S specimens [12]. Finally, Fig. 12 provides pictures of the configurations after TPB testing of selected specimens.

The results in Figs. 5 and 6 highlight that the maximum load carried by UNR specimens is approximatively equal to 0.6 kN, and is reached just before crack onset. Such specimens exhibit brittle failure, and fast snapping to a collapsed configuration with zero residual strength after crack onset (see Fig. 12a). In contrast to this, Pol_S specimens exhibit residual load carrying

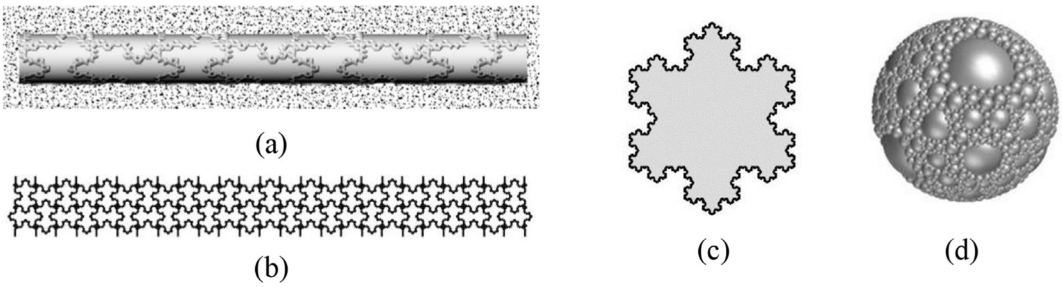

**Fig. 1.** Lattices with fractal geometry used to form reinforcements of composite materials: (a) fiber coating; (b) fabric; (c) fiber cross-section; (d) junction element/fiber embossment (Apollonian sphere packing) [10].