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A micromechanical approach for predicting effective mechanical properties of Fiber-reinforced polymer (FRP) composites fabricated with 3D printers

Soufiane Belhouideg [1*], Morade OUHSTI [2], Benachir EL HADDADI [2]

[1] Department of physics, Polydisciplinary Faculty, Sultan Moulay Slimane University, Beni Mellal, Morocco

[2] Laboratory of Sustainable Development, Department of physics, Faculty of Science and Technology, Sultan Moulay Slimane University, Beni Mellal, Morocco

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* Corresponding author.
E-mail address: soufianebelhouideg@gmail.com

ABSTRACT

Additive Manufacturing or Three dimensional (3D) printing is a new technology widely used to produce three-dimensional parts. 3D polymer-based printers have become easily accessible to the public. Recently, a new kind of 3D printer has been developed to manufacture printed polymer composites reinforced with continuous or short fibers. Usually, the technology used by these 3D printers is Fused Deposition Modelling (FDM). The aim of this study is to predict the mechanical properties of printed materials in Fiber-reinforced polymer (FRP) composites using a micromechanical approach. Indeed, the main idea of this approach is to characterize the effective mechanical properties from a microstructural description of the heterogeneous materials and the knowledge of the local behavior of constituents using the homogenization process. The predictions of the effective mechanical properties were confronted with experimental data obtained from the literature. The difference between the predicted and experimental values does not exceed 28.6%. The micromechanical approach is a good tool for designers to estimate the mechanical properties of fiber-reinforced 3D printed polymer composites which require specific mechanical properties.

1. Introduction

Due to its design flexibility, low cost and other excellent properties, Fiber-reinforced polymer (FRP) composites are widely used in several fields such as aerospace, civil engineering, transportation and sports equipment [1]. Recently, the 3D printing has been developed to manufacture FRP composites by different 3D printing processes [2]. Indeed, the additive manufacturing (AM) or 3D printing is a new technology used to produce three-dimensional pieces. The new object was created adding the material layer by layer. This technology has a major impact on innovation, design and manufacturing practices in companies. It is allow to fabricate functional pieces having complex geometrical shape in reasonable time period, without incurring any further costs due of absence of tooling [3]. The addition of fibers (such as carbon or glass) and particles of different shapes to polymer matrix improve significantly the mechanical properties of the composite [4, 5]. A review of Fused Filament Fabrication of Fiber-Reinforced Polymers was carried out by Brenken et al. [6]. The authors have been presented a summary of mechanical properties of printed parts for different composite materials. In a another study, Parandoush et al. [7] have been presented a review on Additive Manufacturing of Polymer-Fiber Composites. Also, Hao et al. [8] prepared and characterized continuous carbon fiber reinforced 3D printed thermosetting composites using a 3D printing platform based on Fused Deposition Modeling (FDM). An epoxy resin was used as the thermosetting matrix material, and a carbon fiber was used as the reinforcement. It is found that the mechanical properties of the 3D printed thermosetting composites were significantly improved. Goh et al. [9] was evaluated the mechanical properties of continuous carbon fiber and glass fiber reinforced thermoplastics fabricated by Fused Filament Fabrication (FFF). The thermos-mechanical properties of 3D printed polymers for fiber reinforced polymers was investigated by Türk et al. [10]. Melenka et al. [11] have been evaluated the elastic properties of the fiber reinforced 3D printed composites. Also, they used the Average Stiffness (VAS) method to predict elastic properties of studied material. Dickson et al. [12] was evaluated the mechanical performance of continuous carbon, Kevlar and glass fiber reinforced nylon composites fabricated by FDM technique. The thermomechanical properties of short carbon fiber reinforced polyamide-6 composites prepared using FDM printer was determined by Karsli and Aytac [13]. In another study conducted by Tekinalp et al. [14], the mechanical properties of short carbon fiber reinforced polymers have been investigated.

However, the heterogeneity and anisotropy of fiber-reinforced polymer (FRP) composites fabricated with 3D printers present major challenges for the design and prediction of mechanical properties. In order to meet these challenges, the modern trend is multiscale modeling or micromechanical approach [15]. It allows to predict the effective properties of heterogeneous materials from their micro-structure. Also, it even gives the possibility to design new materials with desired or optimized properties. Among the multiscale methods, we distinguish those that are based on direct calculations of Representative Elementary Volume (RVE), such as the finite element method. These direct methods can be very precise, but are very expensive in terms of computation time and user time to obtain a good mesh. On the other hand, the mean-field homogenization (MFH) method is a (semi-) analytical method that can predict the mechanical properties of composite materials with acceptable accuracy, while having a cost calculation very much lower than that of direct methods.

In this study, the micromechanical approach is used to predict the effective mechanical properties of Fiber-reinforced polymer (FRP) composites fabricated by a 3D Printers. This method allows to evaluate the influence of microstructure properties on macro behavior of FRP composites materials.

The present study is organized as follows. Fused Deposition Manufacturing 3-D printing technique used to manufacture FRP composites is presented in section 2. The basic principles of micromechanical approach applied on fiber reinforced 3D printed polymer composites are presented in section 3. The goal is to establish a tool for designers to predict the effective mechanical properties of fiber reinforced 3D printed composites. In section 4, these predictions are confronted with experimental data obtained from the literature. Finally, the major conclusions of the paper are summarized in Section 5.

2. Fused Deposition Manufacturing (FDM)

Fused Deposition Manufacturing (FDM) 3-D printing is a process of manufacturing a three-dimensional object by laying down and fusing materials together in layers [16]. Currently, FDM is the most technique used to fabricate Fiber-reinforced polymer (FRP) composites. FDM technology is the most flexible, low cost, and a popular method of 3D printing today. Also, FDM allows to build 3D pieces of complex geometry. This technology uses heated thermoplastic filaments which are extruded from the tip of nozzle in a prescribed manner in a semi molten state and solidify at chamber temperature. A thermoplastic filament is wound on a reel which is unwound to supply material to an extrusion nozzle head. The nozzle head heats the material and turns the flow on and off. Typically stepper motors are used to move the extrusion head and adjust the flow. The head is moved in both horizontal x-axis and y-axis, while the build platform moves up and down (z-axis). The control of this mechanism is carried out using a computer-aided manufacturing (CAM) software tool which runs a microcontroller (Figure 1). A heated nozzle deposits molten polymer onto a supportive structure layer by layer. Various polymers are used, including acrylonitrile butadiene styrene (ABS), polycarbonate (PC), poly-lactic acid (PLA) and nylon. Also, various fibers can be used such as Carbon Fiber (CF), Glass Fiber (GF) and Aramid Fiber (AF).

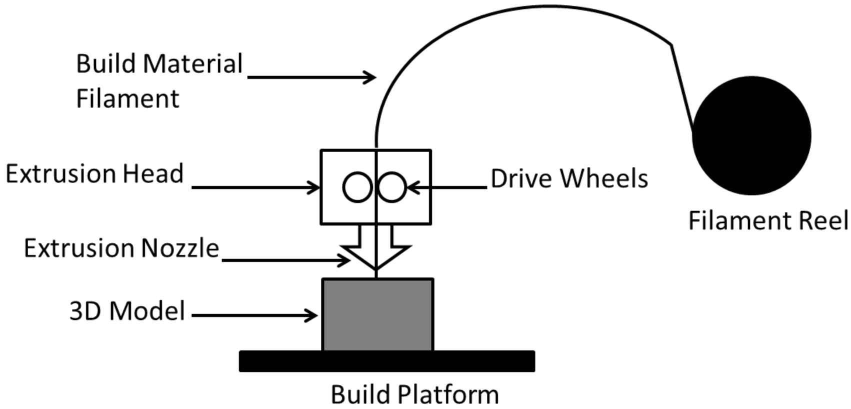

Figure 1. Illustration of the working principle of FDM-based 3D printing

3. Micromechanical approach

The aim of micromechanical approach is to establish a relationship between the macroscopic behavior of composite materials and their microstructure. Homogenization methods, called mean-field approach, require three steps: representation, localization and homogenization [15, 17]. The localization step, which links microscopic and macroscopic mechanical quantities, is particularly essential for the formulation of homogenization methods. Mean-field homogenization methods require the consideration of a Representative Elementary Volume (RVE) Ω of heterogeneous material. The size of the heterogeneities d must be sufficiently small compared to that of the RVE (l): $d \ll l$. This condition allows to characterize the behavior of RVE by a homogeneous law. The size of RVE must also be very small compared to that of structure (L) at the macroscopic level: $l \ll L$. This condition allows to study the structure as a continuous medium. The conditions $d \ll l \ll L$ are called scale separation conditions and are well verified in the context of this study.

Since these scale separation conditions are satisfied, the representation step must be specified by the description of the mechanical and geometrical properties of the constituents (phases) of the heterogeneous medium: mechanical characteristics, shapes, spatial distributions, orientations and volume fractions of constituents. For the Localization step, it is possible to adopt homogeneous traction boundary condition or homogeneous displacement boundary condition imposed on the boundary $\partial\Omega$ of the RVE. The principle of homogeneous displacement boundary condition will be presented. Readers interested in a more complete presentation may refer to [17, 18].

The displacement boundary condition $\underline{u}(\underline{x}) = E.\underline{x}$ is applied on $\partial\Omega$, with E is the macroscopic strain and $\underline{u}(\underline{x})$ is the displacement field at the microscopic scale. The macroscopic strains E, applied on the boundary of RVE are equal to the spatial average of the local strains ε in the RVE:

$$\langle \varepsilon \rangle = \frac{1}{|\Omega|}\int_{\Omega} \varepsilon(\underline{x}) d\Omega = E \qquad (1)$$

All the phases of the heterogeneous material are considered linear elastic. So, a strain concentration tensor A was introduced, such that:

$$\varepsilon(\underline{x}) = A : E \qquad (2)$$

A is a symmetric tensor that checks: $\langle A \rangle = I$. With I is the fourth-order identity tensor. In addition, A possesses the minor symmetries ($A_{ijkl} = A_{jikl} = A_{ijlk} = A_{jilk}$) but A does not possesses major symmetries ($A_{ijkl} \neq A_{klij}$). By combining the localization relation (2), the local behavior law of the constituents and taking the spatial average, we lead to the classical result:

$$\Sigma = C^{hom} : E \qquad (3)$$

With:

$$C^{hom} = \langle C : A \rangle \qquad (4)$$

Σ : The macroscopic stresses; C: Elasticity tensor of the constituents of heterogeneous material.
C^{hom} is the homogenized elasticity tensor defining the macroscopic elastic constitutive law of the heterogeneous material. If the material consists of N phases, it is sufficient to know A on each phase r, the homogenized elasticity tensor C^{hom} of RVE is rewritten as:

$$C^{hom} = \sum_{r=1}^{r=N} \phi_r C_r : A_r \qquad (5)$$

C_r : elasticity tensor of the phase r, A_r : concentration tensor of the phase r, ϕ_r : volume fraction of the phase r.
The expression of A_r can be reached using the famous Eshelby solution [19]. It is an efficient tool to construct different schemes for estimating the homogenized elasticity tensor. In this study, the Mori-Tanaka scheme have been used [20].

4. Comparison with experimental data

The estimation of effective mechanical properties of fiber reinforced 3D printed polymers composites can be achieved using the micromechanical approach. The mechanical properties of the fiber reinforcement and polymer filament are taken into account by this approach. The results obtained by Mori-Tanaka scheme presented above have been confronted with experimental elastic modulus data from literature. The composite materials used for comparison are a printed polymer composites reinforced with continuous fibers. The printed composites are a transversely isotropic material [11]. For a transverse isotropic material, only five independent elastic constants are needed to describe the elastic behavior. If the axis of isotropy is the axis 3, the independent elastic parameters are: two Young's modulus (E_1 and E_3), two Poisson's coefficients ν_{12} and ν_{13}) and shear modulus (G_{13}). The compliance matrix can be written as follows (formula (6) (Voigt's notation) :

$$S=\begin{pmatrix} \frac{1}{E_1} & \frac{-\nu_{12}}{E_1} & \frac{-\nu_{13}}{E_1} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_1} & \frac{1}{E_1} & \frac{-\nu_{13}}{E_1} & 0 & 0 & 0 \\ \frac{-\nu_{13}}{E_1} & \frac{-\nu_{13}}{E_1} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2(1+\nu_{12})}{E_1} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{13}} \end{pmatrix} \quad (6)$$

The elastic modulus was measured experimentally in the direction 1 by Matsuzaki et al.[21], Van der Klift et al. [22],Tian et al.[23] and Dickson et al. [11]. So, the elastic modulus is estimated in the same direction. In order to predict the mechanical properties of the fiber reinforced 3D printed polymers composites, the mechanical properties of polymer matrix and fibers are summarized in table 1 and table 3. It is noticed that this values were taken by the authors according to the supplier's specifications of fibers and matrix.

Table 2 and table 4 summarize the obtained results for different types of Fiber-reinforced 3D printed polymer composites. It is shown that experimental results are very close to those predicted by the micromechanical approach (Mori-Tanaka scheme). The difference between experimental measurements and predictions using Mori-Tanaka scheme does not exceed 28.6%. This difference can be explained by the waviness and the misalignment of the fibers during the 3D printing process. The micromechanical approach assumes that the fibers are straight and no waviness in the fibers exists. Also, another reason for the difference between the predicted and measured values could be due to poor bonding between the fibers and the matrix. The micromechanical approach assumes that fibers and matrix are perfectly bonded.

Comparison with Matsuzaki et al.[21], Van der Klift et al. [22] and Tian et al.[23]

The mechanical properties of matrix and fibers used by Matsuzaki et al.[21], Van der Klift et al. [22] and Tian et al.[23] for this comparison are given in table 1.

Table 1. Mechanical properties of fiber (CF and Nylon) and matrix (PLA) **[21]**

	Elastic Modulus [GPa]	Poisson's ratio [-]
PolyLactic Acid (PLA)	3.5	0.36
Nylon	0.94	0.35
Carbon Fiber (CF)	230	0.3

Table 2. Experimental measurements and predictions of Elastic Modulus. V_f : Fiber Volume Fraction [%]. E_{exp} : Elastic Modulus Experimental [GPa]. E_{pred} : Elastic Modulus Predicted [GPa]. D: Difference between experimental measurements and predictions [%].

Source	Material	V_f	E_{exp}	E_{pred}	D
Matsuzaki et al.[21]	PLA/CF	6.6	19.5	18.4	5.6
van der Klift et al. [22]	Nylon/CF	6	14	14.6	4.3
van der Klift et al. [22]	Nylon/CF	18	35.7	42.1	17.9
Tian et al.[23]	PLA/CF	10	20.6	26.1	26.7

Comparison with Dickson et al. [12]

The mechanical properties of matrix and fibers used by Dickson et al. [12] for this comparison are given in table 3.

Table 3. Mechanical properties of fiber (CF, GF and AF) and matrix (Nylon) **[12]**

	Elastic Modulus [GPa]	Poisson's
Nylon	0.94	0.35
Carbon Fiber (CF)	54	0.3
Glass Fiber (GF)	21	0.25
Aramid Fiber (AF)	27	0.4

Table 4. Experimental measurements and predictions of Elastic Modulus. V_f : Fiber Volume Fraction [%]. E_{exp} : Elastic Modulus Experimental [GPa]. E_{pred} : Elastic Modulus Predicted [GPa]. D: Difference between experimental measurements and predictions [%].

Source	Material	V_f	E_{exp}	E_{pred}	D
Dickson et al. [12]	Nylon/CF	11	8.46	6.77	20
Dickson et al. [12]	Nylon/AF	8	4.23	3.02	28.6
Dickson et al. [12]	Nylon/GF	8	3.29	2.54	22.8
Dickson et al. [12]	Nylon/AF	10	4.76	3.54	25.6

5. Conclusion

The micromechanical approach presented in this article, proposes a tool for the estimation of the effective mechanical properties of Fiber-reinforced polymer (FRP) composites fabricated with 3D printers. The results obtained with the proposed approach were confronted with experimental mechanical properties data from the literature. A good agreement was observed.

Also, this approach can be used by the designers to easily predict the mechanical properties of fiber reinforced 3D printed components for functional applications which require specific mechanical properties.

It is noticed that the 3D printing is a new process used the fabricate FRP composite materials based on Fused Deposition Modelling technology. Thus, some points have to be improved such as the waviness and the misalignment of the fibers during the 3D printing process and bonding between the fibers and the matrix. The difference between the experimental and predictive model results could be due to these fabrication defaults. So, further research is required to fully characterize the mechanical behavior of composite materials fabricated by 3D printing.

6. References

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