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Review

Mechanical characterization of composite materials by optical techniques: A review

Luigi Bruno

Department of Mechanical, Energy and Management Engineering, University of Calabria, Via Bucci 44C, 87036 Rende (CS), Italy

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ABSTRACT

The present review provides an overview of work published in recent years dealing with the mechanical characterization of composite materials performed by optical techniques. The paper emphasizes the strengths derived from the employment of full-field methods when the strain field of an anisotropic material must be evaluated. This is framed in contrast to the use of conventional measurement techniques, which provide single values of the measured quantities unable to offer thorough descriptions of deformation distribution. The review outlines the intensity and articulation of work in this research field to date and its ongoing importance not only in the academy, but also in industrial sectors where composite materials represent a strategic resource for development.

1. Introduction

Composite materials first appeared in human artifacts early in our history. Thousands of years ago, in fact, the first bricks made of straw and mud were used in construction projects by builders who quickly understood the mechanical property advantages of obtaining a material by joining two or more constituents with different physical and chemical characteristics, combined macroscopically [1]. Furthermore, according to this definition, we see several examples of composite materials occurring in nature itself, attained simply through the principle of natural selection. Wood and bone are two common examples of composite materials: the first is formed by cellulose fibers bound by a lignin matrix, whereas the second is formed by bone cells (osteocytes) surrounded by a complex fibrous matrix mainly formed by ossein. Other examples include leather or natural fibers, which are widely used in the textile industry. In all cases, these natural complex structures were developed over the course of millions of years with the goal of achieving the most highly evolved solution that would guarantee the survival of one species over another.

Aside from the first prehistoric examples reported by archeologists and present in museums and history books, the systematic design, production and use of composite materials for engineering applications can be considered quite recent [2]. Up to the Second World War, in fact, engineers largely employed metals in their designs, while occasionally using ceramics and polymers. The only composite material regularly used by engineers until that point was reinforced concrete, which had ushered in a civil engineering revolution from the end of the nineteenth century.

In the 1930s, the need to improve the mechanical properties of polymers launched the creation of the first Glass Fiber Reinforced Polymers (GFRP), which in a few years would lead to the fabrication of the first composite parts, such as radar domes, boat hulls, and car body sections. But it was the invention of innovative manufacturing methods in the 1950s, such as pultrusion or vacuum bag molding, and the patent of the first carbon fibers in the 1960s, that really boosted the composite material market. Today the variety of this kind of material offers a wide spectrum of choice to the designer, while this field of research continues to evolve [3].

Due to their nature, composites express a mechanical behavior significantly different from that of conventional materials, such as metals. For these, the hypothesis of homogeneous isotropic behavior is consistent in most cases. In addition, the linear-elastic hypothesis, which, provided that the elastic limit is not exceeded, allows one to assume the material stiffness (or compliance) matrix – the 6×6 tensor providing the relationship between the six stress and six strain components – in a simplified form depending on just two constants [4]: E, the Young's modulus and ν, the Poisson's ratio. In the case of composite materials, even when the elastic limit is not exceeded, the assumption of homogeneous-isotropic behavior is not possible, and more complex models have to be used based on a number of constants certainly higher than two [5].

The higher complexity of composite mechanical behavior requires more sophisticated experimental procedures for their characterization. The standards normally used for linear-elastic homogeneous isotropic materials [6–8] are inadequate for the complete identification of the required parameters. In fact, even in the simplified assumption of linear-elastic behavior – i.e. a set of constants is enough to describe the elastic behavior of a material that is able to recover the entire deformation – the anisotropy requires that the material be tested in more than one direction. The heterogeneity, in turn, implies a local

E-mail address: bruno@unical.it

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variation of the mechanical properties, which requires the averaging of deformations over areas sufficiently larger than the heterogeneity sizes.

For these reasons, the ASTM (American Society for Testing and Materials) has issued hundreds of standards attempting to define procedures and techniques in order to carry out proper tests on composite materials. Without giving a complete overview of these standards, which is beyond the scope of the present review article and this journal, it is worth mentioning at very least the most common standards applied in the mechanical characterization of composites. In some cases, the properties of the constituents can be measured separately [9,10]. This allows for the documentation of the overall material's heterogeneity aspects, but properties of the resulting composite are then deducted by way of a micromechanics (sometimes also defined as minimechanics [11], due to the millimetric dimensions of the constituents) tool, which unavoidably neglects some aspects and causes some inaccuracy, as a consequence. Therefore, other standards designed for directly evaluating the mechanical properties of composites are usually preferable, such as those in which tensile [12], compressive [13] and shear [14,15] tests are described in detail, providing the dimensions, environmental restrictions, operating test conditions, and accuracy requirements of specimens.

The determination of material properties always requires the measurement of displacement or strain, and for this purpose, the equipment suggested by the standards are usually extensometers or strain gauges [16]. These transducers are capable of single value measurements, which means that at every instant of the experiment they provide just a single value of displacement or strain – the mean value obtained over their gauge length. Hence, the amount of information regarding the deformation field is limited, while, in the case of the composites, due to the higher complexity of their mechanical behavior, it would be useful to have a larger amount of data than in the case of conventional materials.

In this scenario, optical techniques can provide powerful tools to overcome this limitation due to one of their most important features, which is the capability to carry out full-field measurements [17]. Among the numerous techniques available today, those applied in the mechanical characterization of composites and remarked upon in the present review include holographic interferometry (HI), digital speckle pattern interferometry (DSPI) [18], digital holographic interferometry (DHI) [19], moiré interferometry (MI) [20], geometric moiré (MG) [20], digital image correlation (of which 2D version – 2D-DIC –, 3D version – 3D-DIC – and volumetric version – DVC or VDIC – exist) [21] and grid methods (GM) [21].

Apart from the full-field capability common to all these techniques, they are all able to work not only on specimens, but also on both prototypes and real components without any surface treatments, with the exception of MI, MG and GM, which require the application of a grid on the surface under investigation. At times, a thin layer of paint is applied on the surface under investigation in order to improve the optical texture, which does not have any impact on the displacement fields occurring during the tests. Moreover, it is worth briefly mentioning some of the strengths and drawbacks implied in the use of the aforementioned techniques. In particular, interferometric techniques (HI, DSPI, DHI, MI) offer a high sensitivity given the use of laser sources, whose small wavelength (about 0.5 micrometer) combined with phase identification methods [22] allow for the measurement of the displacement field with an accuracy of a few nanometers. This feature is particularly useful in measuring linear-elastic displacements, which are commonly very small. On the other hand, the application of an interferometer often requires complex experimental apparatuses (which could be expensive and demand qualified operators). In addition, they are extremely sensitive to external disturbance (particular attention must be paid to vibration insulation during the tests). Alternatively, the non-interferometric techniques (MG, DIC, GM) offer a significant lower sensitivity if compared with interferometric options, because they depend on the spatial resolution of the observation system – i.e. camera sensors – that can be assumed within a few tenths of a micrometer. Consequently, there is one or even two orders of magnitude between the sensitivity of interferometric and non-interferometric techniques. Nevertheless, the latter require a less complex optical setup and have a significant lower sensitivity to disturbances.

The present review continues in the next section with a description of the mathematical tools usually adopted for modeling linear-elastic behavior of anisotropic materials, including the most important equations and coefficients used for the characterization studies. Subsequently, the three most popular approaches applied in mechanical characterization are considered separately, and in each case, contributions provided by the optical technique are discussed. The first approach discussed is that of a standard test – the kind of test proposed by standards or derived from them, according to which a simple stress/strain state is applied to a (usually geometrically simple) specimen. The consequent stress and strain parameters are evaluated by simple formulas and a small number are experimentally measured. The second approach is based on virtual field method, which, starting from the principle of virtual work, provides some simplified mathematical tools for directly calculating the stress and strain parameters in the presence of a loading configuration for which an analytical solution is not available. This allows for a decrease in the number of tests required for performing a mechanical characterization. The third and final approach considered in this review is based on finite element model updating, which is in turn based on experiment simulations carried out until the numerical and experimental solutions match within a specified tolerance. Theoretically, this approach allows the highest flexibility, and further reduces the number of required tests, thanks to the actual high reliability of the numerical simulations, especially in the case of linear-elastic mechanical behavior. Final remarks summarizing and comparing the discussed approaches are reported in the last section.

Other approaches (often based on the use of full-field methods) were successfully used for linear elastic characterization, such as the constitutive equation gap method [23], the equilibrium gap method [23,24], the reciprocity gap method [25], and the constitutive compatibility method [26]. All these approaches, reviewed in [27,28], were mostly used for isotropic materials, hence they will not discussed in detail in the present review.

It is worth pointing out that in 2004, Grédiac published a review on the mechanical characterization of composite materials using full-field methods [29]. In this work, the author gave an overview of the use of optical techniques for composite material and structure characterization. In particular, in the case of the identification of constitutive parameters, the virtual field method and finite element model updating approaches are thoroughly discussed as the current state-of-the-art in 2004. On the other hand, the present review offers an update on these approaches, through studies carried out in the following years. In addition, it includes work based on full-field methods applied to cases using the standard tests approach.

Finally, it is important to note that full-field techniques can be advantageously used not only for analyzing the linear-elastic mechanical behavior of the composite materials, which is the focus of the present review. In fact, the potential offered by this particular class of experimental techniques was and is also used in the field of non-destructive testing and evaluation (NDT&E) [30–34] and interfacial properties [35–39]. In the case of NDT&E, the use of interferometric techniques has been more popular due to the small and mainly out-of-plane nature of the displacement field occurring on composite structures that present flaws and cracks. On the other hand, the larger and mainly in-plane nature of displacement field implied by tests used for the interface characterization of composites has led researchers to use mostly non-interferometric techniques – i.e. DIC and GM.

2. Mathematical models

The present section reports a brief survey of the mathematical models that can be adopted to describe the mechanical behavior of a material, and how they can be adapted in the specific case of composites. In