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Original Research Article

Evaluation of continuous filament mat influence on the bending behaviour of GFRP pultruded material via Electronic Speckle Pattern Interferometry

Salvatore Benfratello^{*}, Vincenzo Fiore¹, Luigi Palizzolo¹, Tommaso Scalici¹

Department of “Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali”, DICAM, University of Palermo, 90128 Palermo, Italy

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ABSTRACT

Pultrusion is a process allowing the production of unidirectional (roving) fibre-reinforced polymer (FRP) structural elements with constant cross section. Recently, also civil engineers focused their attention on pultruded composite materials as alternative to traditional ones (e.g., concrete, steel). Furthermore, to improve the transverse strength and stiffness with respect to the fibres direction, continuous filament mat (CFM) is often placed within the stacking sequence. The CFM influence on the global mechanical behaviour is not considered by appropriate actual international standards. In this paper, the influence of the CFM layers on the mechanical behaviour of glass fibres pultruded composite material is investigated. In particular, the bending behaviour is analyzed by performing a four-point bending test on specimens extracted from an H-shape member. The experimental analysis was carried out via Electronic Speckle-Pattern Interferometry (ESPI) (handled by phase-stepping technique) to obtain a full-field displacement map and to numerically achieve the longitudinal strains. By imposing the equilibrium conditions and assuming the compression and tensile roving Young's moduli as constant, the CFM Young's moduli are determined. Finally, the mean stress acting on the material is obtained showing that CFM layers have to be considered to correctly evaluate the maximum stress and to optimize the design phase.

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1. Introduction

Nowadays, fibre-reinforced polymer (FRP) materials are widely used in several engineering fields such as aeronautics, automotive, naval and civil ones. Thanks to their lightweight, good mechanical properties and versatility in addition to their

good structural behaviour with respect to dynamic actions, in the last decades they were considered more and more often as solution for many structural problems. Pultruded FRPs generally consist of long continuous unidirectional fibres (e.g., glass, carbon or aramid) in a polymeric thermoset matrix (e.g., polyester, vinylester and epoxy resin). Glass fibres reinforced polymers (GFRP) are, therefore, a class of FRP

^{*} Corresponding author. Fax: +39 091 427121.

E-mail addresses: salvatore.benfratello@unipa.it (S. Benfratello), vincenzo.fiore@unipa.it (V. Fiore), luigi.palizzolo@unipa.it (L. Palizzolo), tommaso.scalici01@unipa.it (T. Scalici).

¹ Fax: +39 091 427121.

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materials with glass fibres as reinforcement. The combination of glass fibres and polyester resins are widely used due to their low cost, although glass fibres and polyester resins exhibit lower mechanical properties and chemical stability, than carbon fibres and epoxy resins, respectively.

Even if pultrusion is a fast and continuous process to produce FRP structural elements with constant section, the use of long unidirectional fibres adversely affects their transversal stiffness, which can be enhanced by properly controlling the pultrusion process. Moreover, pultrusion process allows to combine different kind of layers (i.e. roving, woven fabric, continuous filament mat (CFM)) and to obtain long, thick and constant-section modules with the desired properties [1]. This process consists in a series of steps in which the reinforcement is impregnated and, after the curing of the matrix (i.e. resin) in a hot die, the component is cut to the required length [2]. CFM layers are generally placed within the stacking sequence of the composite beam or plate to enhance the transverse strength and stiffness with respect to the fibres direction. Pultruded structural members reinforced with CFM and roving are widely used [3].

Due to the above reasons, civil engineers begin to use pultruded composite members as alternative of those made with traditional materials such as concrete or steel. On the other hand, since the mechanical behaviour of composite material is complex, certification authorities, in order to ensure the structural safety, require stricter parameters than the ones referred to traditional materials.

Moreover, the international standards (e.g., ASTM D638, ASTM D790, UNI EN ISO 14125, UNI EN ISO 527-4) for the composite material characterization do not consider any difference between all roving elements and those having some CFM layers in the stacking sequence. Furthermore, due to their intrinsic nature these materials show different mechanical properties in tension and in compression. This feature has to be properly considered in the evaluation of the structure behaviour especially under bending loads to ensure the structural safety.

To extensively understand the mechanical behaviour of composite materials in order to correctly design structural members, the direct observation of the phenomena through non-contact full-field techniques represents an useful tool for both scientists and engineers.

In the last decades, due to the technological improvements, several optic methods were developed with the aim to measure the displacement field on the outer surface of non-transparent bodies or inside transparent bodies [4]. This kind of methods allows to quantify the full displacement field in a region of interest by non-contact analysis, thus leading to obtain a dense 2D or 3D cloud of information instead of the average strain between two marks or point values (i.e. video extensometer and local strain gauge respectively). In addition to this, optical methods are independent from the samples geometry [5] and their non-contact nature makes them suitable for those applications in which the sensor/device stiffness may affect the results (i.e. foams [6], thermoplastic polymers [7,8] and biomaterials [9]).

The improvements in laser science and cheaper costs if compared to the past years ones, lead to an extensive use of the Electronic Speckle Pattern Interferometry (ESPI) as an

effective technique to obtain highly accurate measurement of the near-to-real-time strain full-field during a mechanical test [10], even for orthotropic material such as wood [11–13].

The ESPI method is based on the use of a coherent, intense, collimated and narrow beam of light coupled with video correlation. Electronic Speckle-Pattern Interferometry has a capability to produce near-to-real-time fringe patterns on objects with optically rough surfaces, with a displacement sensitivity of the order of the wavelength of the light. Several different techniques are available to perform an ESPI analysis. Among these techniques, the “phase stepping speckle interferometry technique” offers high sensitivity in addition to high contrast of the acquired fringes, which is a fundamental feature for the use of accurate automatic processing techniques. This ESPI technique is used to obtain displacement fields from fringe patterns representing contour maps of the phase difference induced by the specimen deformation.

Depending on the set-up, ESPI allows to obtain 1D, 2D or 3D displacement fields and, as result, a complete description of the strain fields which represent a key parameter for the design, manufacturing and performances of the structure during the service life [14]. Some papers concerning the use of this non-destructive technique on fibre-reinforced composite materials can be found in the literature. Richoz and Schajer [15] achieved multi-component measurements using a single colour camera and multiple monochromatic light sources with different wavelengths showing how this setup may improve the stability of the method. Richardson et al. [16] showed how intensity fringes and phase maps from phase stepped ESPI may be used to evaluate delaminations, cracks and other defects in glass-fibre reinforced polyester pultruded panels in which the damage is originated by falling weight impact tests. In particular, the damaged areas were calculated and compared with those derived from conventional ultrasonic C-scan and sectioning techniques, showing promising correlation. It was also demonstrated that there is a consistent correlation between impact event parameters and the extent of the revealed damage.

In the paper of Ambu et al. [17], thin laminates impacted with different energy levels were analyzed by a holographic procedure and by ESPI technique. The obtained results were compared with those acquired by a pulse-echo full-volume ultrasonic technique, showing that both optical methods are able to identify the presence of impact damage, with an efficiency dependent on the through-thickness location of the delaminations produced by impact. Moreover, it was found that the ESPI technique allowed significant reduction in the inspection times, even if quantitative estimates of impact damage were drastically impaired due to the high level of speckle noise, typical of the technique. Kim et al. [18] compared the detection performance of three non-destructive techniques as ESPI, digital shearography and ultrasonic C-scan for low-velocity impact damage in unidirectional and cross-ply fibre glass composite laminates inspected from front surface (i.e. impact side). The experimental results showed that ESPI and digital shearography techniques are able to identify the barely visible low-velocity impact damage. However, some limitations for detection depth were found in ESPI and digital shearography due to the difficulties in the detection of the impact damage on reverse side. Corigliano

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