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Speckle Interferometry Analysis of Full-Bending Behavior of GFRP Pultruded Material

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Abstract

The use of Glass Fiber Reinforced Polymer materials (GFRP) has increased in the last years even among civil structural engineering due to their high specific strength, lightweight and excellent corrosion resistance. With application of the pultrusion method, the manufacture of large-scale profiles with various cross-section forms became potentially possible with relatively low costs. Usually two different technological approaches are available to realize the element: in the first one a mat-roving-mat sequence is adopted, in the second one only roving is present. Continuous filament mat (CFM, fibers distributed randomly in all directions) is often used to build up laminate thickness quickly, as well as to enhance transversal strength and stiffness. Besides, the intrinsic particular features of GFRP materials require the application of new techniques of mechanical analysis to define a correct material model. Many papers study the mechanical behavior of GFRP structural elements at a macroscopic scale even in particular environmental conditions. From the other hand full-field contactless techniques (e.g. digital image correlation, thermal stress analysis, speckle interferometry) are effective tools to correctly model complex mechanical behavior and to define the consequent parameters. Among these techniques, Electronic Speckle-Pattern Interferometry (ESPI) has been asserted as very effective due to the technological improvements of the laser sources. One of the significant advantages of ESPI is to produce real-time fringe patterns on objects with optically rough surfaces, with a displacement sensitivity of the order of the light wavelength. Aim of the paper is to apply ESPI handled by phase-stepping technique to the experimental study of GFRP materials in the case of mat-roving-mat sequence.

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Keywords: Speckle interferometry; GFRP materials; full-field analysis; displacement field maximum;

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The mechanical test adopted is the four-point bending test, which allows the evaluation of pure bending response of the material. Specimen with longitudinal axis aligned with the pultrusion direction is tested.
The main results are the following: 1) CFM represents a weakness zone for the material especially in bending in which the extreme edges are more stressed with respect to other zones; 2) the weakness due to CFM is more evident in tension than in compression; 3) the neutral axis position is not fixed and does not coincide with the geometrical axis of the section.

1. Introduction

Nowadays, fiber-reinforced polymer (FRP), are widely used in several engineering fields such as aeronautics, automotive, naval industries and civil applications. Thanks to their lightweight, stiffness, strength, and versatility, in the last decades they became always more frequently solution for many structural problems. Among FRP, those with Glass fibers (GFRP) are common due to their relatively low cost, although they exhibit much lower elastic modulus and ultimate strength than other fibers such as carbon ones. Nowadays, the manufacturing technology allows to create FRP structural elements of any constant shape by means of pultrusion process. One important drawback of GFRP pultruded elements is constituted by their transversal deformability, which is commonly limited by appropriately placing continuous filament mat (CFM) through the thickness of the element. Pultruded structural members reinforced with CFM and roving are widely used [1]. It is to be emphasized that the international standards (e.g. ASTM D638, D790, UNI EN ISO 14125, UNI EN ISO 527-4) do not make any difference between members created only by roving and those created with CFM and roving. Further, due to their intrinsic composite nature, these materials show a different mechanical behaviour in tension and in compression; such feature is fundamental especially when bending is present. The complexity of mechanical behaviour of composites materials and the opportunity of direct observation of the phenomena, make full-field experimental techniques ideal instruments for both the scientists and the engineers. In the last decades, due to technological improvements and evolution, a number of optical methods were developed to measure the displacement field on the outer surface of non-transparent bodies or inside transparent bodies [2]. Further, optical methods are independent from the samples geometry [3] and their non-contact nature makes them suitable for those applications in which the sensor/device stiffness may affect the result (i.e. foams [4] and thermoplastic polymers [5]). The improvements in laser science and reduced costs, 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 [6]. One ESPI advantage is its capability to produce real-time fringe patterns on objects with optically rough surfaces, with a displacement sensitivity of the order of the light wavelength. Among the different techniques for performing an ESPI analysis, “phase stepping speckle interferometry technique” offers high sensitivity together with a high contrast of the acquired fringes. In last years, ESPI has been applied also to fracture analysis [7] with very interesting results.

Aim of the paper is to investigate the effects of the CFM on the mechanical behavior of GFRP pultruded material. The sample is extracted from a H-shape member on sale, created with five different layers (three CFM and two roving). In order to avoid the shear influence the experimental test is a four-point bending one, ESPI (handled by phase-stepping technique) is applied to obtain the full field displacement field, the longitudinal strain is numerically obtained. The results show that CFM strongly influences the mechanical response especially in tension even at low loading levels.

2. Materials and methods

2.1. Material and experimental test

The pultruded composite (H-shaped section beam), belonging to Triglass® series, was furnished by TopGlass S.p.a. (Italy), with nominal thickness of 10 mm and 15 mm for the flanges and for the core, respectively (Figure 1 a, b). The prismatic specimen (mean dimensions, l x b x h, 200.23 mm x 14.96 mm x 14.79 mm) has been extracted from the core by a water-saw, being the longitudinal axis in the pultrusion direction (Figure 1c). The CFM thickness is not constant but, in the central zone of the specimen (zone of interest), the mean values are: 1.25 mm (upper CFM), 1.18 (lower CFM) and 1.0 mm for the middle one. In order to analyze the pure bending behavior of the material, a four-point bending test has been selected. In Fig. 2a the loading system, constituted by a moving steel head driven by NEMA 34 step-by-step motor and characterized by a maximum load of about 1.5 kN is sketched. A loading cell (AEP

3kN model TS) is placed between the moving head and the specimen. The support span is equal to 177.5 mm while the load span is 60 mm.

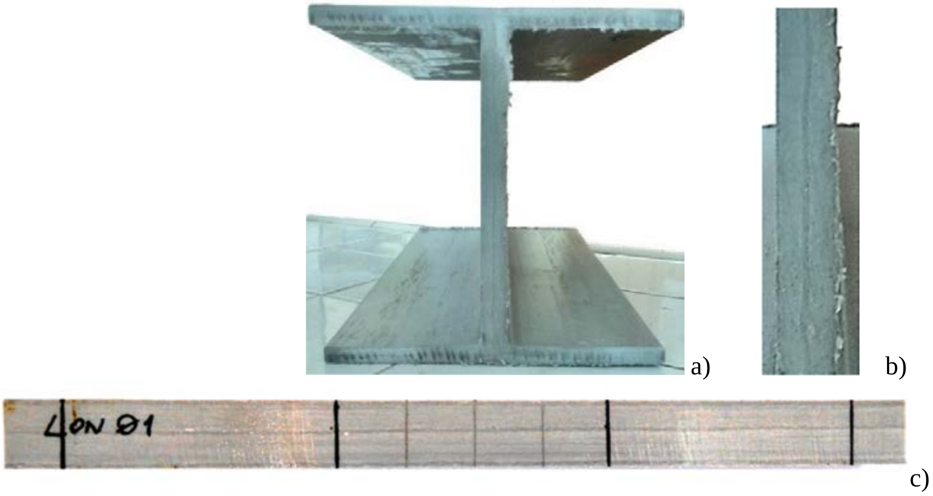


Figure 1: Images of the composite beam: a) overall view of the cross-section; b) particular of the core; c) overall view of the specimen.

2.2. Speckle interferometry

In this paper a “four phase stepping speckle interferometry technique” has been implemented. A set-up suitable for in-plane displacements measurement was used; it is characterized by the fact that the beam originating from the laser source is divided by the beam splitter in two beams which symmetrically impinge on the specimen surface with incidence angle α (Figure 2b). In the same figure, the optical hardware setup used in this work is reported. The in-plane displacement sensitivity of the set-up is within 0.3÷0.6 μm with no influence of out-of-plane displacement. The phase fringe pattern has been filtered by an iterative auto adaptive mean filter, producing a good S/N ratio improvement of the phase fringes. All the phases (setup configuration, image acquisition, post-processing) are handled by a custom software, developed in LabView® 2014 environment.

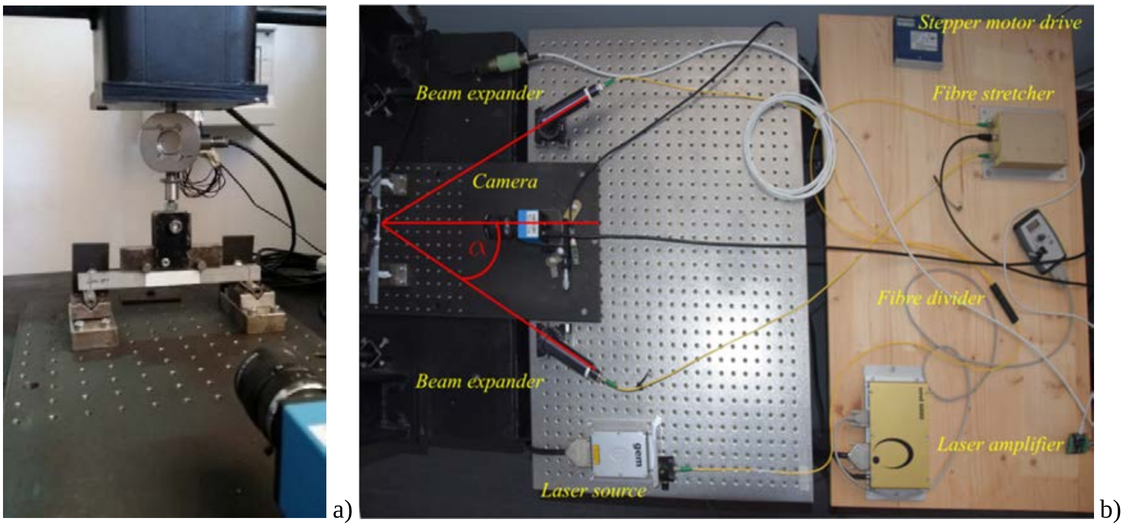


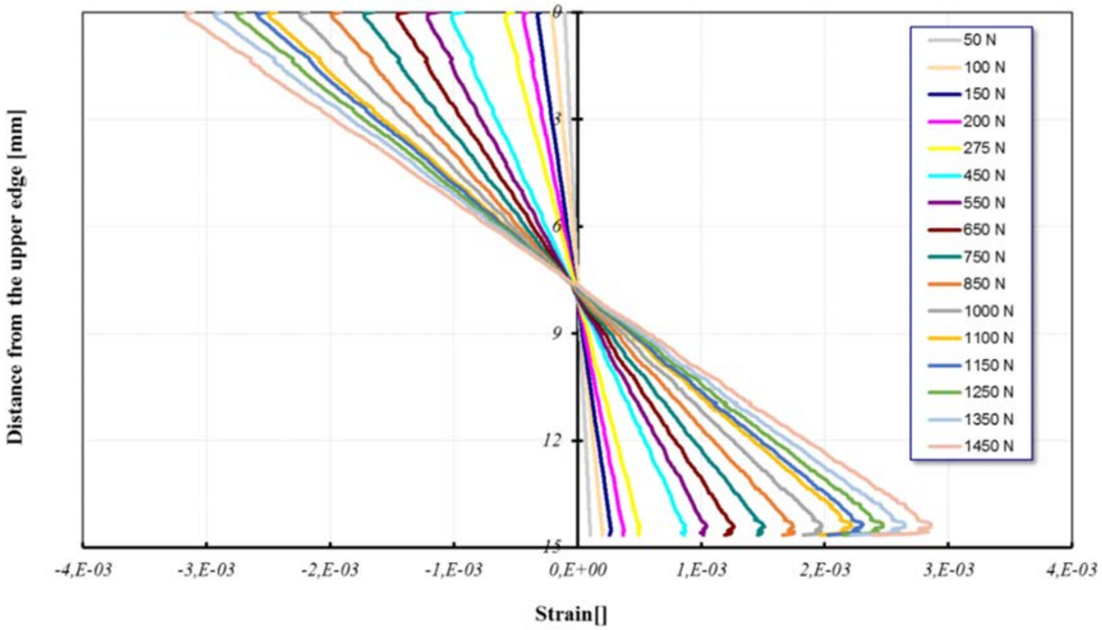
Figure 2: Experimental setup: a) particular of the loading system; b) overall view from above.

3. Results

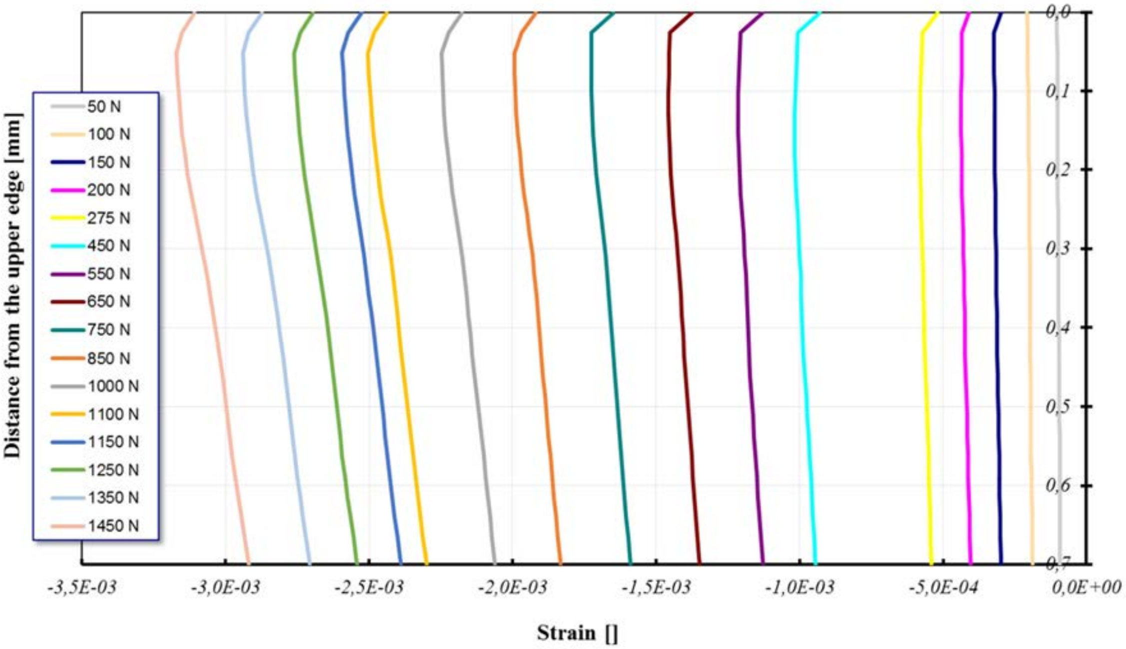
The four-point bending test has been performed in the range 0-1500 N of applied load. The experimental images have been acquired taking as reference image that for a preload of 50 N. An examination of all the acquired images, here not reported for sake of brevity, leads to the following remarks: 1) the neutral axis is aligned with the longitudinal axis but its position is neither coincident with the geometrical middle axis of the specimen nor fixed; 2) generally at a given y coordinate the longitudinal strain ε_x shows a behavior which can be regarded as approximately constant as in the case of homogenous material. The latter remark suggests that the main strain can be assumed as meaningful information about the overall bending behavior. Therefore, it has been calculated for all the loading steps, and the corresponding graphs are reported in Figure 3a. In order to study the material behavior and the role of the CFMs, in Fig. 3 b, c and d, a zoom of Fig. 3a in the lower, upper and middle zone of the specimen is respectively reported. The following remarks arise: a) in the lower zone of the specimen (traction), starting from the third loading step the CFM shows a nonlinear behavior with increasing irregularities clearly indicating damage growth; b) in the upper zone (compression) a CFM nonlinear behavior is found, related to fiber buckling but no damage is present; c) the parts of the specimen where roving is present show a linear behavior in all steps d) in the middle zone, besides a nonlinear behavior related to numerical problems, it can be affirmed that the neutral axis shows a moving position.

4. Conclusions

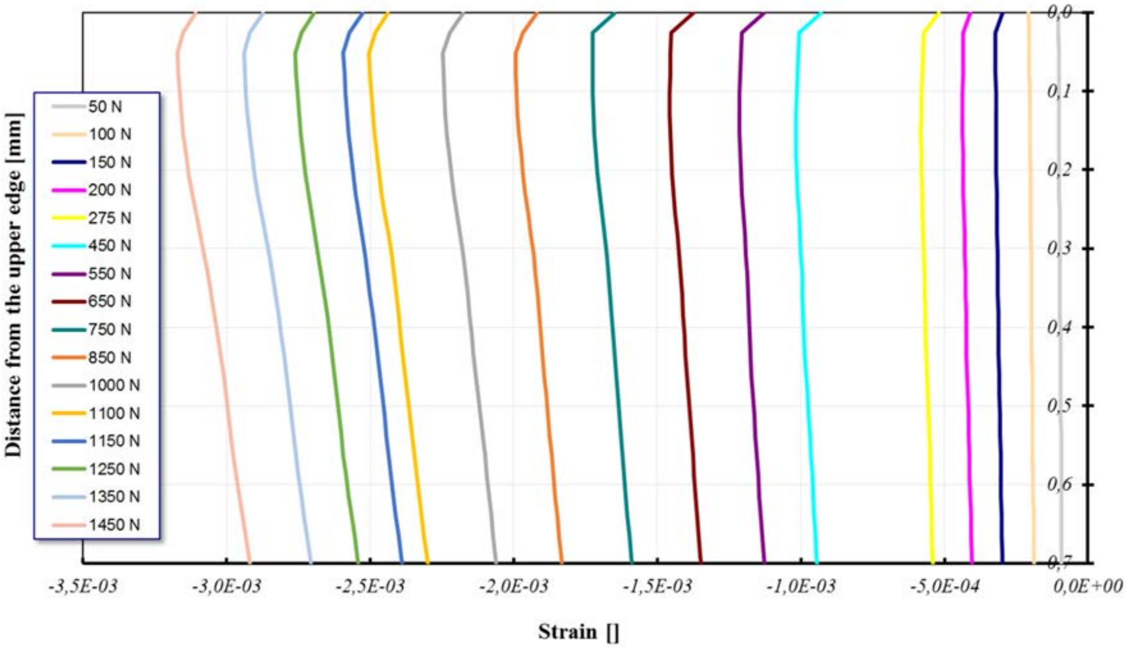
In the paper the effects of the continuous filament mat (CFM) on the pure bending behavior of GFRP pultruded material has been investigated. The research development is outlined as follows: a) the tested sample has been extracted from an H-shape member on sale with five different layers (three CFM and two roving); b) the experimental analysis makes use of full-field Electronic Speckle-Pattern Interferometry (ESPI) handled by phase-stepping technique; c) from the full field displacement field the main longitudinal strain is derived numerically. The main results are: 1) CFM represents a weakness zone; 2) this weakness is more evident in tension than in compression; 3) the neutral axis position is not constant not coinciding with the geometrical axis of the section; 4) CFM shows increasing damage in tension even for very low loading level.



a)


Distance from the upper edge [mm]
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
-3,5E-03
-3,0E-03
-2,5E-03
-2,0E-03
-1,5E-03
-1,0E-03
-5,0E-04
0,0E+00
Strain []
50 N
100 N
150 N
200 N
275 N
450 N
550 N
650 N
750 N
850 N
1000 N
1100 N
1150 N
1250 N
1350 N
1450 N

b)


Distance from the upper edge [mm]
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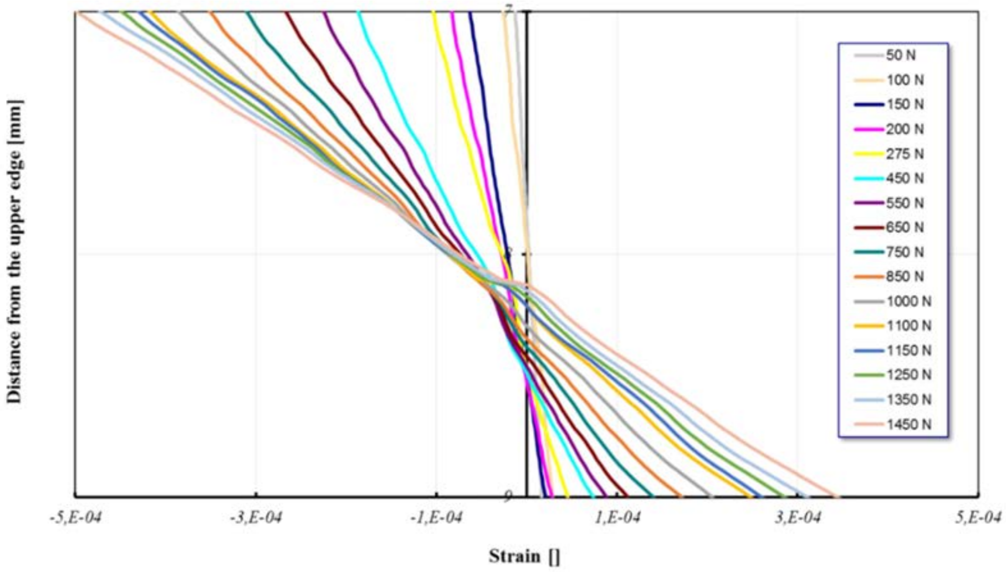
-3,5E-03
-3,0E-03
-2,5E-03
-2,0E-03
-1,5E-03
-1,0E-03
-5,0E-04
0,0E+00
Strain []
50 N
100 N
150 N
200 N
275 N
450 N
550 N
650 N
750 N
850 N
1000 N
1100 N
1150 N
1250 N
1350 N
1450 N

c)



d)

Figure 3: Mean strain for different applied load values: a) overall view; b) particular at lower mat; c) particular at upper mat; d) particular at the middle mat.

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