Composite Structures 129 (2015) 36–46

Contents lists available at ScienceDirect

Composite Structures

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

Experimental characterization of a fiber metal laminate for underwater applications

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A R T I C L E I N F O

Article history:
Available online 20 March 2015

Keywords:
Ageing
Dynamic properties
Fiber metal laminate
Low-velocity impact
Water absorption

A B S T R A C T

The use of fiber reinforced plastics in underwater and environmental aggressive applications is limited due to their scarce resistance to moisture absorption. In this work, we characterize the mechanical properties of a fiber metal laminate, where an outermost steel layer is utilized as protection against contamination. In particular, we perform experiments on wearing resistance, static strength characterization, moisture absorption, low-velocity impact behavior, dynamic behavior, and dynamic thermal analysis. Experiments are conducted on specimens conditioned in hot water and findings are compared against results obtained with dry specimens that underwent the same thermal cycles, but without being in contact with water. Results show that the water absorption in unprotected specimens decreases all the mechanical properties of the laminate. Instead, the outer protective metal layer is found to be very effective against water absorption, whereby results on the conditioned protected specimens are in line with the ones obtained for the dry specimens. Further, the protective steel layer is found to remarkably increase the wearing resistance.

1. Introduction

Advanced composite materials development has accelerated during the past three decades, triggering the use of composite structures into a broad series of applications, spanning from aerospace to nautical engineering [1–3], in replacement of traditional materials.

An important class of composite materials is constituted by the Fiber Reinforced Plastics (FRP). Peculiarity of this class of composites is that they are immune to corrosion. Such property is extremely interesting for all those applications where the component is foreseen to be in contact with water. However, matrix can absorb humidity [4,5], with subsequent degradation of the fiber–matrix interface, that is detrimental for its mechanical properties [6–17]. As protection against water absorption, it is common to apply a layer of gel-coat [18] to the outer surface of the laminate. However, there exist some applications where friction contact is expected; some examples out of many are extendible periscopes and antennas. In such applications the use of a protective gel-coat is a short term solution, because it would wear out due to friction, leaving the composite surface exposed to the environment. A much more reliable outer protection for such applications is a dire need.

Fiber metal laminates (FML) is a category of composite materials developed for aeronautical applications [19–21]. As an example, Glare [22,23] is on the most successful FML. It is composed of alternated layers of Glass Fiber Reinforced Plastics (GFRP) and aluminum sheets, to form a hybrid material with improved mechanical properties [24]. Its primary advantage is the enhanced fatigue resistance with respect to the original comprising materials [25]. Other interesting aspect of typical FML materials is that metal sheets act a primary role against the diffusion of humidity inside the structure, increasing its hygrothermal resistance [26,13]. Botelho et al. [26] estimated the influence of hygrothermal effects on static and dynamic properties of GFRP laminates. They found that pure GFRP specimen show a strong decrease of tensile and compressive strength, whereby Glare strength was found to be unaffected from hygrothermal conditioning.

It is of special interest to investigate the impact response of FML. Impact damage of composite materials undergoing low-velocity impacts is usually driven by matrix cracks, which act as onset for delaminations [27–29]. Impact strength strictly relates to delamination resistance when low-velocity impacts are involved. The influence of water absorption on the laminate impact

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http://dx.doi.org/10.1016/j.compstruct.2015.03.046
0263-8223/

resistance has been studied by Imielińska and Guillaumat [30] and Dale et al. [31]. They performed impact tests on laminates exposed to moisture to evaluate eventual variations of the impact dynamic response and of the impact-induced damage. Both these works report negligible changes on the impact response. However, several other studies reported that when metal sheets are alternated to FRP laminae, such discontinuity can be a source for delamination [32–37].

In this work, we experimentally investigate the performance of a FML composed by a solid GFRP core, co-cured with protective outermost steel AISI 316L layers. Such configuration is expected to provide wear resistance and protection from moisture absorption, whereby not affecting the impact resistance of the laminate. In fact, differently than traditional FML, the layup proposed here does not introduce discontinuity between the layers [34]. The hardness of the steel allows for higher contact pressures, drastically increasing the wearing resistance. Nonetheless, the reduced thickness of the steel layer does not introduce any stress concentration at the steel-GFRP interface.

The results of an extended experimental campaign are here presented. The experimental campaign has been designed to elucidate the role of water absorption on a wide range of mechanical properties, quantifying the beneficial effects introduced by the proposed layering configuration. Particular attention is given to the effect of water absorption on the shear strength of the laminate, as this strictly rehearses for delamination resistance, which directly relates to the impact response.

The rest of the paper is organized as follows. In Section 2 the procedure used to produce the specimens is described, along with details on the conditioning procedure. In this section we also introduce the techniques used for the estimation of the mechanical properties, and the tribological and hygrothermal behavior. In Section 3 we present and discuss the results about the mechanical tests introduced in Section 2. Conclusions and final remarks are summarized in Section 4.

2. Materials and experimental procedure

In this work, we study the effect of utilizing an outermost steel layer on GFRP to serve as protection against moisture absorption. Objective is to characterize un-protected and protected GFRP on a broad range of mechanical properties. In particular, we focus on friction coefficient, wearing resistance, moisture absorption, flexural strength, low-velocity impact behavior, and dynamic mechanical behavior. In the following sections we detail the material utilized to produce the specimens, their manufacturing process, and the tests procedures.

2.1. Materials

Experiments are conducted on two groups of specimens. Pure GFRP specimens comprise the first, while GFRP specimens protected with outer 0.1 mm thick stainless steel layers (AISI 316L) comprise the second. We will here refer to the first group as GFRP, and to the second group as GFRP + steel for brevity.

Specimens were prepared in autoclave with 12 layers of E-Glass/Epoxy balanced woven prepreg with specific weight of 600 $\mathrm{g/m^2}$, nominal elasticity modulus $E = 72.4$ GPa, Poisson ratio $\nu = 0.2$, and shear modulus $G = 30.0$ GPa. The prepreg layers were positioned between two steel plates, which acted as mould, then packed into a vacuum bag, thus subjected to the pressure and temperature cycle needed to allow the polymerization of the epoxy resin. To ensure the process conditions to be identical for the whole set of specimens, the laminates were assembled simultaneously and synchronously cured in the autoclave. The final in-plane dimensions of the panels were approximately 450 by 500 mm, with a thickness of 5.7 ± 0.2 and 6 ± 0.2 mm for the GFRP and the GFRP + steel, respectively. Two panels of each kind were fabricated, from which all the specimens used in this study were extracted.

A total of 54 specimens have been produced out of the four laminates. Fig. 1 shows the skeleton of the specimens repartition for each of the experimental characterization. Size and amount of specimens, divided for mechanical characterization, conditioning, and layering sequence are listed in Table 1. The red arrows in Table 1 indicate that the dry specimens utilized for the dynamic tests have been later conditioned and further tested. One more specimen, not listed in Table 1, has been further utilized to perform the dynamic thermal analysis.

2.2. Hygrothermal conditioning

First, the specimens are cut out from the original laminates utilizing a diamond saw. Then, half of the specimens are subjected to hygrothermal absorption in 35 ppt salt water. In the following, we will refer to such specimens as “conditioned” for brevity. To prevent water uptake by the sides of the specimens and ensure a unidirectional diffusion phenomenon, the sides of all the specimens were sealed with a thin layer of high temperature resistant adhesive silicone. Specimens have been submerged in approximately 30 liters of salt water for a total of 880 h at a constant temperature of 80 °C, which is substantially lower than the nominal glass transition temperature of the matrix reported by the supplier. We further anticipate that such temperature is lower than the measured glass transition temperature of both dry and saturated matrix.

Please note that the specimens that were not subjected to hygrothermal conditioning underwent a similar thermal cycle, without being in contact with water. This way, we minimize possible discrepancies eventually introduced by the exposition of the resin to high temperature if only conditioned laminates had been subjected to such temperature cycle. We will here refer to these specimens as “dry”.

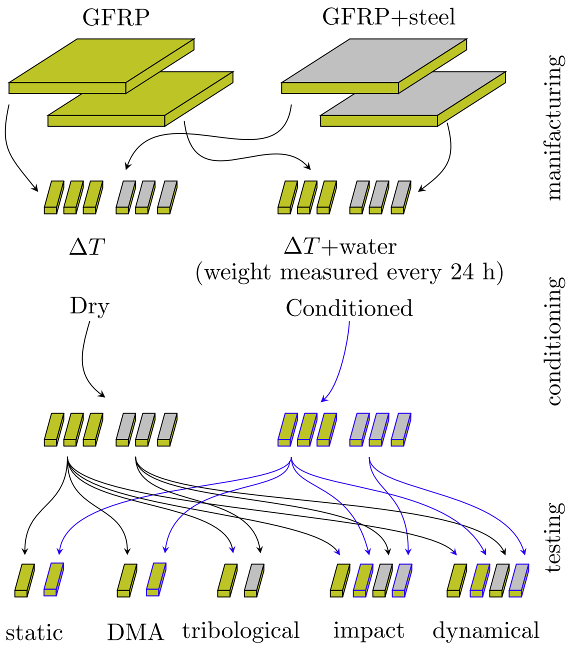

Fig. 1. Schematics of the subdivision of specimens, conditioning, and mechanical characterization utilized in this work.