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Research paper

Effect of mesoscopic out-of-plane defect on the fatigue behavior of a GFRP

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ABSTRACT

This paper deals with the influence of buckles, a mesoscopic out-of-plane defect, on the fatigue behavior of a GFRP. Three cases were investigated: samples with no defect and two kinds of samples with buckle defects generated in the longitudinal or the transverse direction. Firstly, static tests were used to measure the differences in the mechanical properties of the two defect orientations and determine where the areas of maximum local strain were located. Secondly, fatigue tests were performed in the three configurations. The results revealed that both defect orientations have a significant effect on the fatigue behavior. The configuration with defects in the transverse direction was the most crippling condition but the longitudinal configuration was also strongly affected by the presence of mesoscopic defects. It was concluded that this mesoscopic out-of-plane defect has a major negative influence on the fatigue life of such a composite.

1. Introduction

Composite materials are widely used in industry thanks to their very good mechanical properties for a lower mass than metal alloys. However, the processes developed in order to create the parts are complex and can induce defects, especially during textile forming, which will then impact the mechanical behavior.

These defects can be divided in two groups: macroscopic and mesoscopic (Fig. 1). Macroscopic defects appear at the fabric scale. The most common and widely studied macroscopic defect is wrinkles. They are highly dependent on the fabric behavior and the boundary conditions. Initial studies limited the relationship between the limits of mechanical behavior reached during the process and wrinkles to the link between the in-plane shear behavior and the defect. Studies focusing on the shear angle reached during the process compared to the locking angle described this relationship (Wang et al., 1999; Potluri et al., 2001; Prodromou and Chen, 1997; Sharma et al., 2003). Recent numerical studies (Hamila and Boisse, 2008; Allaoui et al., 2011; Ten Thije et al., 2007) showed however that, as it is an out-of-plane phenomenon, the bending behavior of the membrane should be taken into account in order to correctly describe the shape and size of the wrinkles. A coupling between shear and tension has been highlighted in several papers (Boisse et al., 2011; Wilems et al., 2008; Allaoui et al., 2014) and wrinkles can therefore be avoided or delayed by applying tension along the yarn's network. Besides, wrinkles are the consequence of all the strains and rigidities of the fabric and of the boundary conditions (Allaoui et al., 2014). Wrinkle defects generate an over-thickness that impacts the geometrical tolerance and the aesthetics of the final part. Furthermore, studies have shown that this defect leads to a significant decrease in the composite performance, with up to 40% loss of failure strength (Bloom et al., 2013; Hallander et al., 2013; Potter et al., 2008).

The second kind of defect, mesoscopic defects, appears at the yarn level. Examples are fiber and/or yarn breakage, “buckles”, “weave pattern heterogeneity”, “yarn waviness”, etc. Some of them were only recently identified since, except for some work on the phenomena involved during the appearance of defects such as “yarn waviness”, “buckles” and “weave pattern heterogeneity”, few studies have dealt with mesoscopic defects (Allaoui et al., 2014; Lightfoot et al., 2013; Härtel and Middendorf, 2013; Gatouillat et al., 2013). To the best of our knowledge, apart from a few studies on the effect of fiber waviness on UD composites (Hsiao and Daniel, 1996; Piggott, 1995; Wang et al., 2012), the literature on the effect of mesoscopic defects is sparse (Allaoui et al., 2015b). However, it has been shown that they occur more often during the shaping of complex preforms (Allaoui et al., 2011; Ten Thije et al., 2007; Boisse et al., 2011; Wilems et al., 2008; Allaoui et al., 2014). In addition, inter-ply sliding significantly increases the amount and size of these defects when multi-layered composite shaping is concerned (Allaoui et al., 2015a), hence the need to understand the phenomena involved and their criticality on the obtained composite.

Most of the literature on the impact of defects on mechanical behavior focuses on static tests. However, since the late 2000 s, their influence on the fatigue behavior has begun to be investigated. It was observed for example that a ply drop increased the likelihood of the

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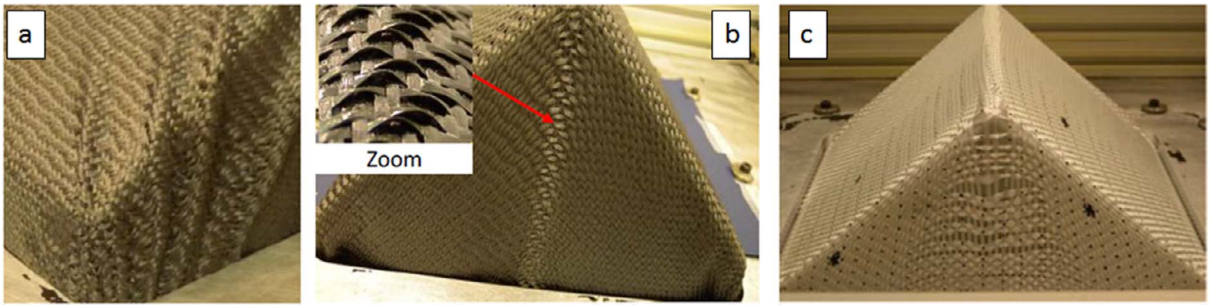

Fig. 1. Defects observed on a double curved shape: (a) macroscopic (wrinkles), (b) mesoscopic ("buckles") and (c) mesoscopic ("weave pattern heterogeneity") – from Allaoui et al. (2015b).

appearance of delamination (Helmy and Hoa, 2014; Thawre et al., 2016). Moreover, (Reis et al., 2009; Colombo and Vergani, 2014) pointed out that the presence of a defect inducing delamination was difficult to detect in static tests despite dramatically decreasing the fatigue life.

The present study aims to assess the effect of the "buckle" defect on the mechanical properties of a composite and specifically its fatigue behavior. To this end, "buckles" were generated on a dry fabric layer taking care to reproduce the amplitudes observed on a complex composite part (Fig. 1). Composite plates, stacked in layers with the same orientation, were then fabricated by injecting epoxy resin using a resin transfer molding device. Plates without defects were also fabricated to be used as a reference. Uniaxial tensile tests and fatigue tests instrumented with digital image correlation devices were then performed. The results of these different configurations were compared in order to evaluate the effect of "buckles" on the fatigue behavior of the composite.

2. Material and specimen preparation

2.1. Material

The material used in this study is a glass fiber reinforced polymer. The Resin Transfer Molding process was used to produce composite plates, with and without defects. The fabric used is a glass plain weave produced by Chomarat. It is denoted G-WEAVE 600P and has the following properties: a real weight of 600 g / m2 ± 5%, thickness of 0.55 mm, warp and weft yarns count of 600 Tex. Thermoset epoxy resin LY564 ARALDITE with a suitable hardener 3487 ARADUR was used to inject the stacks performed according to the protocol described below. The fabric is balanced which was confirmed following DMA measurements performed on the GFRP which showed that the mechanical characteristics were similar along the warp and weft orientations.

2.2. Sample preparation

In order to produce plates without defects, the reinforcement was cut into square samples of 250 × 250 mm^2. These dimensions were selected to fit the size of the mold. For plates with buckle defects, the reinforcement was cut into square samples of 500 × 500 mm^2. Then, the sample was placed on a machine equipped with four automated portal axes which can be commanded separately or simultaneously. Buckle defects were generated by applying a defined driving mode in the machine program. The sample was clamped on the machine upon its three sides (*X, X*' and *Y*, Fig. 2), then, a displacement at a constant velocity was applied on the *Y* side (*y* axis) while the opposite side (*Y*') remained free. Simultaneously, the other two sides, *X* and *X*', were piloted according to a force control order. As a result, the two sides move towards the center of the sample. Thanks to this type of control order, the reinforcement sample stretches in the *Y* direction and shrinks in the *X* and *X*' directions. After reaching the required amplitude of defects, the sample is kept fixed and a fixing agent is sprayed on the surface of the sample. When the sprayed layer has dried, the calibrated sample can be removed and then cut into a square of 250 × 250 mm^2, as shown in Fig. 2.

Several plies with calibrated defects were produced according to this protocol, and a stack of 7 plies oriented in the same direction was placed in the RTM mold. Then, the epoxy matrix was injected and the mold transferred into an oven preheated at 100 °C. After 3 h, the mold was removed and allowed to cool at ambient temperature for 6 h. The final thickness of the composite plates was about 2.5 mm. Lastly, these

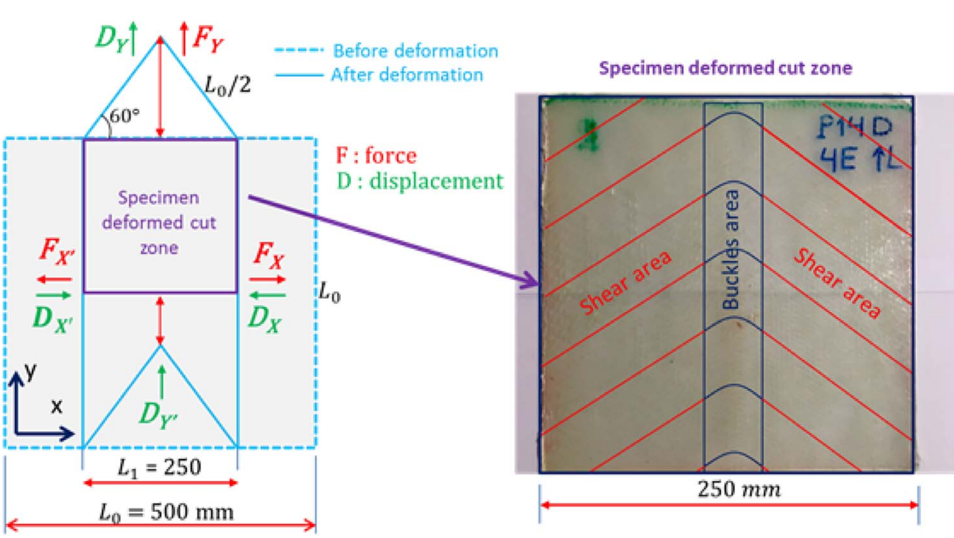

Fig. 2. Example for buckle defects generation.