Composites: Part A 69 (2015) 178–185

Contents lists available at ScienceDirect

Composites: Part A

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

Effects of thickness and fiber volume fraction variations on strain field inhomogeneity

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ARTICLE INFO

Article history:
Received 5 June 2014
Received in revised form 11 November 2014
Accepted 15 November 2014
Available online 20 November 2014

Keywords:
A. Polymer–matrix composites (PMCs)
B. Defects
C. Finite element analysis (FEA)
D. Optical microscopy

ABSTRACT

In this study, variations in thickness and fiber volume fraction are investigated as causes of elastic strain inhomogeneity in composite laminates under an applied transverse load. Standard carbon/epoxy tensile specimens were fabricated from unidirectional pre-impregnated material using two different manufacturing techniques that produced two different levels of surface roughness. Fiber volume fraction variation was computed by analyzing optical micrographs of the samples. During loading and unloading of the samples two-dimensional surface strain fields were measured on the specimen using digital image correlation. It was shown that in both cases the strain in the specimen is not uniform, as is generally assumed. Using finite element simulations the effects of fiber volume fraction variation and thickness variation were modeled individually and in combination. The simulations agree well with the experimental results and suggest that thickness variations are the dominant mechanisms involved in this elastic strain inhomogeneity.

1. Introduction

Fiber reinforced polymers (FRPs) have found widespread use in weight–critical structures across several industries including the aerospace, automotive, and wind energy industries [1–3]. Failure of these structures can have severe consequences, making accurate failure predictions for these materials of critical importance. Unfortunately, FRP properties can exhibit large levels of variability, particularly in long term behavior such as lifetime and creep strain-to-failure. In order for more efficient designs to be achieved by reducing safety factors associated with composite materials, the cause of mechanical property variability must be identified and understood so that improved failure predictions can be made.

Recently we observed significant elastic strain inhomogeneity both in static and creep tests of nominally flat unidirectional composite laminates [4]. Optical micrographs and visual inspection suggested two potential causes for the strain inhomogeneity: fiber volume fraction variation and laminate thickness variation. Several researchers have studied fiber volume fraction gradients in composite laminates [5–9]. However, the bulk of this research focuses on through-thickness fiber volume fraction gradients that may give rise to laminate curvature. The focus in this paper is on the fiber volume fraction variability in the plane of the laminate that may give rise to surface strain inhomogeneity under applied load. Recently, we have shown that fiber volume fraction is not necessarily uniform in the plane of the laminate and its variation is length scale dependent [10], but we did not evaluate the apparent surface strains that would arise. Other researchers have examined thickness variations in composite laminates, but these efforts have either focused on thickness variability with respect to angled laminates [11–13] or the influence of thickness variations on buckling [14,15]. None have examined the effect of thickness variations in a flat panel on the resultant strains under an applied external load.

Due to the small scales associated with microstructural variation, in order to clearly observe strain inhomogeneity a two-dimensional strain field measurement technique is required. Several of these have been developed including Moiré interferometry, electric speckle interferometry, and digital image correlation (DIC). Digital image correlation is appealing because the specimen preparation is relatively simple, requiring only a black and white speckle pattern on the surface, and the testing environment requirements are minimal [16]. Consequently, DIC has become widely used to view strain distributions on the surface of composite materials. Some studies have focused on stress concentrations and damage propagation [16]. Others have looked at the strain distributions caused by using a woven material [17]. Still others have looked at the effects of microstructural defects such as voids in glass mat thermoplastics [2]. All of these previous efforts focus

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http://dx.doi.org/10.1016/j.compositesa.2014.11.019
1359-835X/

on items with known strain inhomogeneity or large material property variation. To the authors' knowledge, no study has examined strain inhomogeneity induced by an applied load in pre-impregnated (prepreg) composites under typical cure conditions with no added defects. Lastly, although many researchers suggest the measurement of two dimensional strain fields allows for comparison to finite element analyses few extend this to actual model comparisons.

In this study a wind energy pre-impregnated carbon/epoxy material was cured under recommended conditions. Then nominally elastic load and unload tests were performed on the specimens. DIC measurements showed elastic strain inhomogeneity in these tests even though the specimens were nominally uniform and unidirectional with no prescribed stress concentration. To predict composite failure the strain is typically assumed to be uniform and the material is transversely isotropic. The measurements illustrate that this is an oversimplification and that significant strain variability exists that is not typically considered in most composite analyses. This variability could cause the strength of the material to be overestimated leading to static failure. More importantly, this variability has profound effects on damage evolution due to fatigue or creep [4], and could substantially impact reliability estimates [10]. Therefore, it is crucial that the mechanisms behind this variability be identified and understood.

The goal of this work was to investigate the effect of local in-plane fiber volume fraction variation (as averaged through the thickness) and specimen thickness variation on the measured surface strain fields of a unidirectional composite under an applied transverse load. Finite element models investigating these proposed mechanisms were studied and the results compared with the experimental measurements. Good correlation between the finite element results and the experimental measurements were achieved, illustrating that specimen thickness variation and local fiber volume fraction variation both affect strain homogeneity under these conditions, but the dominant mechanism is shown to be thickness variation. This study also illustrates that this behavior can be captured using finite element models, allowing for estimation of strain variability *a priori*.

2. Experimental methods

2.1. Composite fabrication

Two carbon/epoxy plates $[90]_4$ were fabricated from Panex 35 carbon fiber/M9.7 epoxy unidirectional pre-impregnated material (prepreg). The plates were cured at 120 °C for 30 min under a 0.4 MPa pressure applied after the plate reached the cure temperature. These conditions are within the recommended cures provided by the manufacturer [18]. The only difference between the processing of the two plates was how the pressure was transferred to the curing composite plate. In the first technique, termed the bag cure, pressure was applied to a bag, which conformed to the shape of the composite plate. In the second technique, referred to as the caul plate cure, pressure was applied to a flat aluminum plate, which then transferred the pressure to the composite plate. These techniques are illustrated in Fig. 1. The first technique produced a plate that showed thickness variation while the second technique produced a flat plate. Due to the large sizes and complex shape of wind turbines when pre-impregnated material is used it is typically cured under atmospheric pressure applied by a vacuum bag layup so the variation of the bag cure is likely more representative of actual material in use [3]. Tensile specimens were cut from each plate using an OMAX jet machining center. Fiberglass end tabs were bonded to each specimen. A speckle pattern of flat black and flat white spray paint was deposited on each specimen

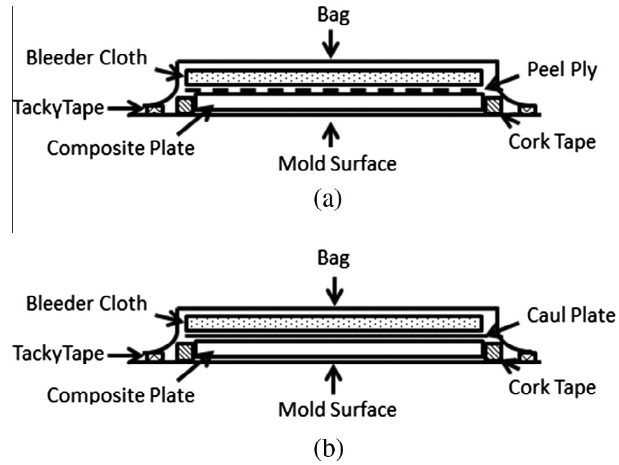

Fig. 1. Curing diagrams (a) bag cure and (b) caul plate cure.

to allow for two-dimensional strain field measurements via digital image correlation (DIC). A 25.4 mm length of the gage section was marked such that the area studied with DIC could be subjected to microstructural analysis.

2.2. Experimental setup

The composite specimens were loaded in tension using a MTS hydraulic testing machine. A load of 1.1 kN (250 lbfs) was applied with a crosshead rate of 1.27 mm/min (0.05 in/min). This load was then removed at the same rate. This load corresponds approximately to 50% of the nominal failure load. During testing the specimen was imaged with a JAI BM 500-GE monochrome 5 megapixel camera with an Edmund Optics bilateral telecentric lens with primary magnification of 0.28×. This magnification provided a field of view approximately 30.3 × 25.4 mm (1.19 × 1.00 in). The bilateral telecentric lens is critical for accurate displacement measurements because it provides a constant magnification over a moderate depth range, which ensured that slight motion of the specimen or the sensor in the depth of the lens would not produce a change of magnification [19]. The evolution of two-dimensional strain fields was then measured using digital image correlation as described in Appendix A.

2.3. Specimen quantification

The microstructures of the two specimens were imaged along the marked 25.4 mm section of the gage length with a Zeiss Axio A.1 optical microscope under epi-fluorescence and a Cannon EOS 60D camera. Images were taken at an optical magnification of 18.5, as calculated by a 1951 USAF glass slide resolution target. The edge of each specimen was polished with wet silicon carbide sand paper using up to a grit of 600 for adequate imaging. Due to the limited depth of field at this magnification several images of the specimen were taken in the same location with different areas in focus. These stacks of images were then merged using Photoshop CS6 [20]. The field of view required that approximately three areas, with a stack of images being taken at each area, be imaged to span the thickness of the specimen. These three areas were then merged so that an image slice of the specimen across the entire thickness could be created. This process is illustrated in Fig. 2. This method was repeated until the entire 25.4 mm section had been imaged. Once completed several stacks or slices could be merged to produce a combined image of a desired length of the gage section.