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Effects of fiber bundle size and weave density on stiffness degradation and final failure of fabric laminates

Mehdi Saeed Kiasat *, Mohammad Rezai Sangtabi

Department of Marine Technology, Amirkabir University of Technology, Tehran, Iran

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ABSTRACT

The mechanical behavior of twill-weave carbon fabric laminates under tensile loading is experimentally studied in this work. The focus is on the effect of the fiber bundle size and weave density of the fabric. The twill-weave carbon fabrics are woven from two different fiber bundles, 3 K and 12 K, with three different weave densities. The carbon fabrics are thus of three types having areal densities between 200 and 600 g/m^2, and crimp ratios from 0.049 to 0.12. The laminates are manufactured through vacuum infusion process to minimize the effect of voids and poor resin regions. Tensile tests show serious differences in the behavior of the low and high areal density fabrics although the crimp ratio is about the same in some of the laminates. The low density fabric laminates show a linear stress–strain curve up to a sudden rupture of the laminate. The higher density fabric laminates present a stiffness degradation observed in their stress–strain curve which occurs after a plateau region or just a knee behavior. These high density fabric laminates encounter a severe delamination before the final failure. Digital image correlations (DIC) performed in this work show novel changes of the strain distribution before and after the stiffness degradation in the laminates.

1. Introduction

Woven carbon fabrics are nowadays widely used in producing advanced lightweight composite structures such as car body panels and special long yacht hulls. For these applications, in order to decrease the number of fabric layers required to reach the desired thickness, there is an increasing demand for carbon fabrics woven from large fiber bundles up to 50 K filaments with high weave densities. The fiber bundle size and the weave density directly increase the thickness and the areal density of the fabric. A good knowledge of the mechanical behavior of the carbon fabrics woven from different fiber bundles is vital for design purposes.

The past and recent developments in predicting the mechanical behavior of textile composites using theoretical as well as numerical methods were reviewed in some papers [1,2] where the experimental works were not considered. Many researchers have applied tensile tests to investigate the mechanical behavior of woven carbon and glass reinforced composites. In some research [3–5], woven carbon/epoxy composites have shown linear behavior in the stress–strain curve up to the final failure. On the other hand, a decrease of slope of the stress–strain curve has been reported in several studies [6–10]. Stiffness degradation due to initial failure mechanisms in the composites has been addressed as the reason for the decrease of slope of the stress–strain diagram. This phenomenon has been referred to as *knee behavior* and the point corresponding this change as *knee point*. Ishikawa and Chou [11,12] were the pioneer researchers in using analytical methods to model the knee behavior and comparing it with the experimental results on 8-harness satin weave glass/polyimide and carbon/epoxy composites.

Only in a few of experimental works [8–10], the knee behavior observed in the stress–strain diagram has reasonably been discussed. Chou et al. [6] conducted some tensile tests on the woven carbon/epoxy laminates made up of 6 K fiber bundles and they observed the change of slope of the stress–strain diagram. Dauda et al. [7] examined plain weave E-glass/epoxy laminates with three weave densities, 2.4, 2 and 1.4 picks/cm. The average fabric thicknesses were 0.46, 0.44 and 0.41 mm, respectively. They observed the knee behavior in the stress–strain curve but did not explain this phenomenon. Takeda et al. [8] investigated the tensile behavior of plain weave glass/epoxy composites at three different temperatures. The knee behavior due to damage accumulation was observed only at a very low temperature of −269 °C.

Nicoletto and Riva [9] examined 3 K fiber twill weave carbon/epoxy laminates under tensile test. They tried to describe the failure

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* Corresponding author. Tel.: +98 21 64543115.
E-mail address: kiasat@aut.ac.ir (M.S. Kiasat).

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mechanism of the fabric laminates. Their laminates showed a linear stress–strain curve up to the failure, which they attributed that to the small value of the crimp ratio, i.e. less than 0.1. They also showed that in the finite element modeling the knee behavior has occurred due to the increase of the crimp ratio. Osada et al. [10] performed uniaxial tensile tests on single-layer as well as 10-layer plain and satin weave glass/vinylester laminates. Weave density was approximately equal for both plain and satin weave patterns. Knee behavior was observed in the test results and it was shown that this phenomenon does not depend on the number of the layers as well as the weave pattern.

Various types of optical methods are used for full-field measurement of displacement and strain in a specimen during tensile test such as moiré interferometry, speckle photography, and digital image correlation [13,14]. Among all of these techniques, digital image correlation (DIC) as a reliable method has previously been applied to woven composite laminates [15–18]. A non-uniform distribution of strain on the surface of carbon fabric composites was reported previously [18,19]. This important behavior of woven fabrics was however not correlated with the stress–strain curve and the failure mechanism of the material during the tensile test.

In the present work, the mechanical behavior of twill-weave carbon fabric laminates is experimentally studied under tensile loading. The tensile tests are equipped with the necessary cameras in order to obtain strain distribution via digital image correlation (DIC). The twill-weave carbon fabrics made up of different fiber bundles with different weave densities are used in the laminates. The effects of the fiber bundle size and the weave density on the stiffness degradation and the failure of the laminates are to be studied in the present work.

Table 1
Carbon fabrics used for making laminates.

Fabric code	Weave pattern	Fiber bundle size (K)	Weave density, d_w (picks/cm)	Fabric areal density (g/m^2)	Fabric thickness ~ (mm)	Fabric density (kg/m^3)
P2	Plain	3	5	200	0.23	1.76
P6	Plain	12	3.7	600	0.60	1.80
T2	Twill	3	5	200	0.23	1.76
T4	Twill	12	2.5	400	0.45	1.76
T6	Twill	12	3.7	600	0.60	1.80

2. Materials and experimental setup

2.1. Materials

Five different TORAY woven carbon fabrics are used to make laminates in the present work listed in Table 1. As shown in Fig. 1, not only twill weave but also plain weave carbon fabrics are used here. These fabrics are woven from two fiber bundle sizes 3 K and 12 K (number of filaments in one bundle), with three different weave densities of 5, 2.5 and 3.7 picks/cm (number of bundles per centimeter). The fiber bundle size and the weave density are the same for the warp and weft bundles in all of the fabrics. The carbon fabrics are of three areal densities of 200, 400 and 600 g/m^2. An epoxy resin from HUNTSMAN is appropriately selected for vacuum infusion process of laminates, see Table 2.

Nine laminates are manufactured as different combinations of 3–13 fabric layers all in the same lay-up direction. The specifications of the laminates are presented in Table 3. A2 and A6 laminates are not used in this work due to their low quality. The impregnation of the fabric layers is carried out using vacuum infusion process in order to minimize the effect of voids and poor resin regions, and also to minimize the excess resin, see Fig. 1. The fiber volume fraction in the laminates is therefore relatively high between 45% and 57% presented in Table 3. The fiber volume fractions are calculated by using the measured fiber mass fractions and the volumetric densities of the fabrics and the resin shown in Tables 1 and 2.

The crimp ratio, cr, as a measure of the fiber bundle undulation [10] depends on the fiber bundle width a, thickness b, and spacing g. In this work, the crimp ratio for the fabric laminates is calculated by using the weave density d_w, the laminate thickness t, and the number of the fabric layers n, as in Eq. (1), see Fig. 2. The crimp ratio for the laminates is from 0.049 to 0.12, see Table 3.

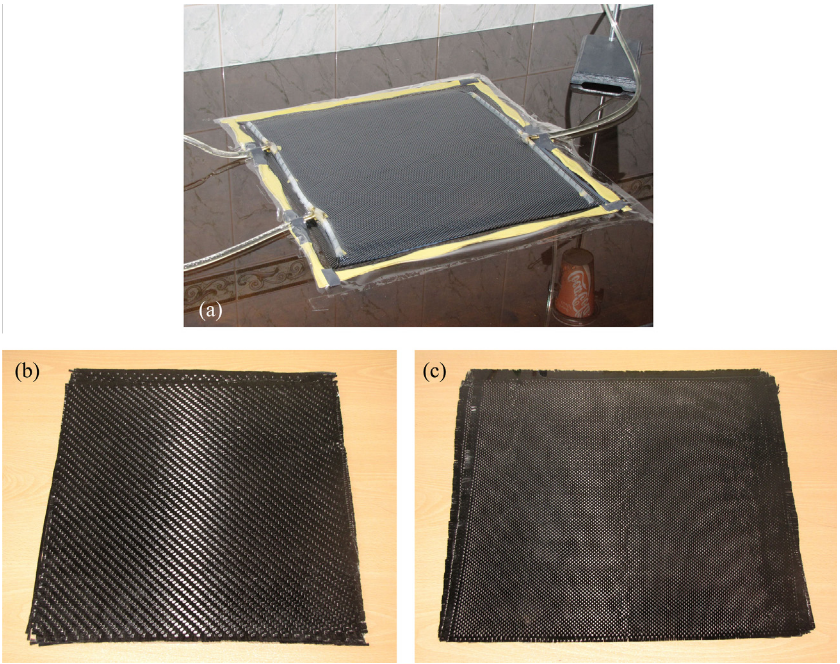

Fig. 1. Photographs of (a) vacuum infusion processing of a laminate, (b) 12 K twill weave laminate, (c) 3 K plain weave laminate.