COVER SHEET

Title: ***Proper tensile testing of unidirectional composites***

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ABSTRACT

Tensile tests are a basic characterization method for composite materials, but the specimens often do not fail properly. Obtaining reliable results in tensile testing requires avoiding stress concentrations near the grips. The material near the tabbed section is under longitudinal, transverse and shear stress concentrations, which leads to underestimated results and conservative design. This study therefore examines different geometries to find the best testing method that yields the maximum failure strain. The experimental results show that the novel arrow shape end tabs and continuous tab specimens allow reaching the highest failure strain value.

Introduction

The standard test methods for tensile testing of unidirectional composites, such as ASTM and ISO, likely lead to failure at the edge of the end tabs rather than in the gauge section. The ASTM and ISO standards propose strategies for reducing the stress concentrations at the end tab edges. The most important parameters that can affect the stress concentrations are tab material, tab geometry, adhesive properties and thickness, specimen geometry and wedge grip position. In the following, these parameters are discussed in more detail.

- Tab materials: glass fiber reinforced composites are recommended for tab materials [1–3] due to their low stiffness, decent shear strength and broad availability. Glass fiber reinforced composites significantly alleviate the transverse and tangential stress concentrations compared to carbon fiber reinforced composites and aluminum end tabs.
- Tab length: a larger end tab length leads to lower clamping pressure and hence smaller stress concentrations. However, the length of the end tabs is limited by the wedge grip length. Kulakov et al. [3] performed a parametric study of specimen geometry and concluded the length of the end tab has an insignificant effect on stress concentrations. They recommended applying tabs with at least 60 mm in length.
- Tab thickness: reducing the tab thickness reduces the geometric discontinuity and reduces transverse stress concentration [3]. On the other side, the tabs should be thick enough to protect the specimen from surface damage. UD composites have high strength and consequently require higher grip pressure to avoid sliding during loading. This increases the penetration of the serrated surface of the wedge grip. A tab thickness of 1-2 mm is recommended [2].

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- Tab geometry: the ASTM and ISO standards proposed two types of end tab geometries, straight and bevelled end tabs. The bevelled end tab is recommended for UD tensile test to smooth out the geometric discontinuity. A smoother transition (lower θ angle) reduces transverse stress concentrations. However, the lack of clamping pressure along with tangential and transverse stresses can lead to tab delamination over the bevelled part. Hojo et al. [4] performed round-robin tests on both end tab geometries and reported an insignificant difference between them. Continuous tab is another tab geometry that removes the stress concentrations on the specimen and hence yield higher failure strain. Czél et al. [5] utilized a 2D FE model and demonstrated that the continuous tab protects the specimen from stress concentrations and also surface damage caused by the wedge grip surface. Recently, Kumar et al. [6] showed that rectangular specimen with continuous tabs may not lead to the highest failure strain, although it protects the specimen from the stress concentrations and surface damage.
- Adhesive properties and thickness: lower adhesive modulus could decrease the stress levels to a safe level. However, the adhesive bond and thickness do not affect the stress concentrations. The thick adhesive layer reduces the stress concentrations in rectangular end tabs. A preliminary test is recommended to optimize these parameters.
- Specimen geometry: the ASTM and ISO standards recommend a rectangular specimen for the tensile test of UD composites. However, using rectangular specimen with rectangular end tabs leads to premature failure due to the geometric discontinuity. To remove the stress concentration from the gauge section, butterfly or dogbone shape specimen were introduced [7,8]. Although the dogbone shape specimen promises to remove the stress concentrations from the gauge section, a longitudinal split at the curvature part of the specimen could result in premature failure. Kumar et al. [6] reported that the combination of continuous tab and dogbone shape specimen could significantly increase the failure strain. However, more detailed studies are required to confirm this result.
- Wedge grip positions: the position of the wedge grip play an important role in the level of transverse stress and consequently end tab-specimen delamination. There are three different wedge grip positions: completely inside, partly outside and edge to edge. The worth case scenario is going to happen with partially outside tab position when the transverse stress at ungripped tab parts reaches the tensile strength and triggers the delamination [9].

There are few studies on optimizing the above parameters to yield failure inside gauge section and correspondingly highest failure strain, with different levels of success. The present work examines different tabs and specimen geometries suggested in the literature and proposes a novel arrow shape design to find a suitable design that minimizes the stress concentration and yields the highest failure strain. Four different end tab geometries, namely, straight, bevelled, arrow shape and continuous tabs, and two different specimen geometries, rectangular and dogbone shape are used to find a suitable design for tensile testing of UD composites.

Materials and test features

Tensile tests were performed on high-modulus carbon/epoxy composite, with a nominal fiber modulus of 425 GPa and a failure strain of 1.1% [10]. The UD laminates $[0]_{10}$ were fabricated from an HS40/736LT prepreg tape (North Thin Ply Technology, Switzerland) and cured in an autoclave. The nominal cured thickness of the specimen is 0.5 mm. The E-glass/epoxy is used for all the end tabs except the continuous end tab which is co-cured with the specimen and made from 0° UD S-glass/epoxy. Table I summarizes the properties of the specimen and end tabs material either measured or calculated by Chamis' formulae [11].

Six different geometries were tested at a displacement rate of 1 mm/min. Figure 1 shows the geometries and dimensions of all six specimen designs. The gripping force was set to 25 kN. To measure the strain, digital image correlation was used to capture the whole gauge section speckle pattern of the specimen. The pictures were taken in an interval of 0.5 seconds when synchronized with the load cell.

Table I. Properties of UD carbon/epoxy and S/E-glass/epoxy.

Material	**UD laminate****	**S-glass/epoxy**	**E-glass/epoxy***
Layup	$[0]_{10}$	$[0]_4$	$[0/90]_s$
Thickness (mm)	0.5 (±0.02)	0.6	2
Nominal volume fraction (%)	50	50	50
E_{11} (GPa)	250.5 (±19)	45.6	28.2
E_{22} (GPa)	4.9	5.6	28.2
E_{33} (GPa)	4.9	5.6	10.3
$\nu_{12} = \nu_{13}$	0.34	0.27	0.27
ν_{23}	0.30	0.27	0.27
$G_{12} = G_{13}$ (GPa)	2.6	3.2	3.1
G_{23} (GPa)	1.9	2.1	3.1

*The number of plies is unknown

**Measured thickness and longitudinal elastic modulus (E_{11}) (± means standard deviation)

Results and discussion

The results (see Figure 2 and Table II) show that the measured failure strains in specimens without end tabs are lower than in specimens with straight end tabs by about 9 %. The main reasons for these lower values are the combination of high stress concentrations and surface damage in the gripped section due to the serrated surface of the wedge grips. The main result of these sets of tests is the necessity of using end tabs to perform the tensile test on UD composites especially high strength materials.

Changing the bevel angle from 90° (straight end tabs) to 2° does not show a considerable difference in the failure strain. Several specimens, that had minor tab debonding, displayed higher strain values. In general, decreasing the bevelled angle increases the probability of tab debonding due to a lack of grip pressure and higher transverse stress at the forward edge of the end tab [12]. Moreover, the manufacturing process of the bevelled end tab with a consistent bevel angle is not straightforward.

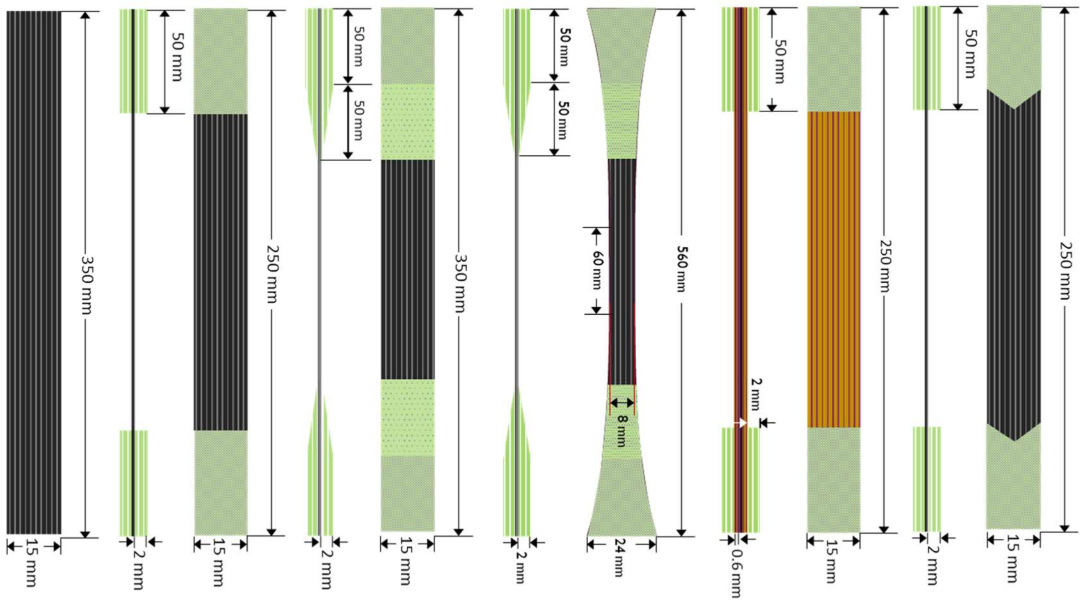

Figure 1. Geometry of specimens drawn to scale within each specimen, but at different scales for the different specimens.

The results in Figure 2 and Table II show that the specimen with continuous tabs has one of the highest average failure strains. Compared to the ASTM standard specimen with rectangular end tabs, the failure strain increases by 8.5% on average. However, the stress measurement in the hybrid specimen is not straightforward and needs back-calculation. Moreover, the thickness of the central carbon fiber layer is not uniform in the case of the co-curing specimen and continuous tabs.

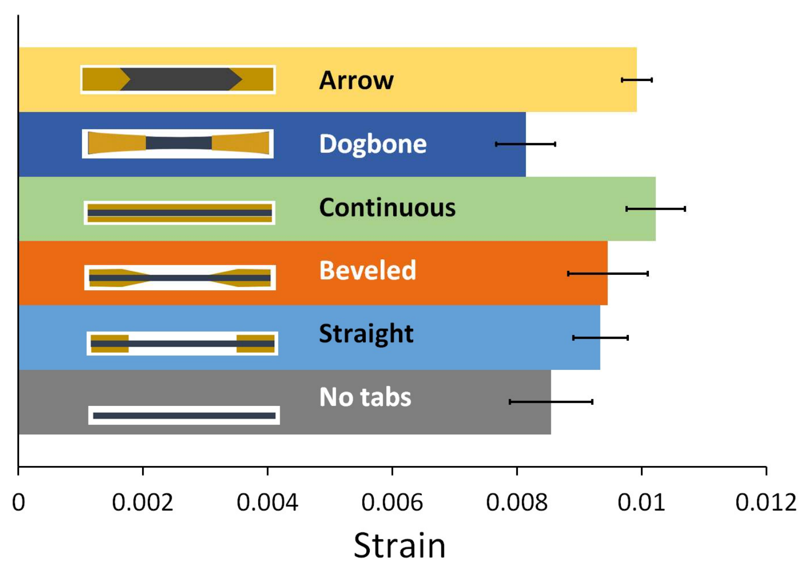

Figure 2. Comparison of failure strain of carbon/epoxy UD laminates for different samples

The dogbone shaped specimen provides uniform stress distribution in the gauge section and removes the stress concentration from the gauge section. However, manufacturing damage and longitudinal splits are potential damage modes that can trigger premature failure in this specimen geometry. Increasing the radius of curvature can help to avoid longitudinal splitting or at least delay it up to higher load levels. As Figure 2 and Table II present, the failure strain of the dogbone shape specimens was the lowest of all specimen designs. Cutting the dogbone shape specimen may cause damage to the virgin specimen that demands extra caution. The splitting that initiates at a lower load level could propagates through the length and yield premature failure.

The arrow shape end tab also provides the highest strain failure (see Figure 2) along with the continuous tab. The arrow shape end tab has a few advantages compared to continuous tab: it does not need special preparation and the stress can be measured directly. The arrow shape end tab distributes the stress concentrations over the width and partially allows Poisson's contraction. Compared to ASTM standard specimen with straight end tabs, the arrow shape increases the average failure strain by 6.1%.

Table II. Results of individual and average tensile tests for all designs.

Design	Failure strain (%)	Tensile strength (GPa)	Average		Standard deviation	
			Strain (%)	Strength (GPa)	Strain (%)	Strength (GPa)
No end tab	0.93	1.73	0.84	1.85	0.069	0.10
	0.87	1.81				
	0.80	1.95				
	0.78	1.90				
Rectangular end tab	0.92	2.40	0.93	2.33	0.043	0.14
	0.89	2.29				
	0.92	2.24				
	0.85	2.10				
	0.99	2.21				
	0.95	2.55				
	0.94	2.43				
	0.94	2.38				
Tapered end tab	0.89	2.06	0.94	2.15	0.066	0.32
	0.89	1.84				
	0.90	1.93				
	0.98	1.60				
	0.90	2.24				
	0.90	1.86				
	1.03	2.67				
	1.00	2.42				
	1.06	2.53				
	0.91	1.96				
	0.91	2.26				
	1.03	2.42				
	0.86	2.14				
Continuous end tab	0.99	1.85	1.00	2.02	0.047	0.145
	1.00	2.10				
	1.05	2.05				
	0.98	2.01				
	1.05	2.11				

	1.07	2.23				
	0.91	1.72				
	0.99	2.09				
	1.00	2.08				
	0.99	2.00				
Arrow-shape end tab	0.98	2.006	0.98	2.23	0.029	0.17
	1.02	2.44				
	0.93	2.05				
	0.99	2.25				
	0.99	2.30				
	0.98	2.35				
Dog-bone shape	0.91	2.10	0.84	1.94	0.053	0.14
	0.84	1.97				
	0.82	1.75				
	0.78	1.92				

Conclusions

Different tensile test specimens with UD carbon fibers were investigated to define the test method that yields the highest failure strain. More valid data can be achieved by avoiding or minimizing stress concentrations near end tabs owing to the combination of geometric discontinuity and orthotropic nature of the specimen and end tab materials. The experimental results show the benefit of using end tabs for tensile testing of UD composites. Bevelled tabs can help to reduce the stress concentration in the case of no tab debonding at the bevelled part. However, the failure strain of ASTM standard specimen with rectangular and bevelled end tabs are statistically the same. The failure strain of dogbone shape specimen was the lowest most likely due to damage in the pristine specimen and premature splitting. The continuous tabs and arrow shape end tabs lead to the best results in this test series. The continuous end tab eliminates the stress concentrations in the specimen. The drawbacks of the continuous tab are the need for back-calculation of the tensile strength and thickness variation in the case of co-cured tab and specimen. The arrow shape end tabs provided a smooth transition of stress and spread the stress concentrations through the width.

FEM analysis will be performed to optimize the end tab geometry to further reduce the stress concentrations and hence increase failure strain.

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