IS THE STANDARD FOR TENSILE TESTING OF UNIDIRECTIONAL COMPOSITES OPTIMAL?

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Keywords: Unidirectional composites, Tensile testing, Gripping tabs, Finite elements, Optimal tab design

ABSTRACT

Tensile tests allow for preliminary mechanical characterisation of composite materials, but the standard recommended specimens (ASTM and ISO) often fail improperly near the grip leading to underestimation of the tensile strength and conservative component design. Reliable results in tensile testing can be obtained by avoiding or reducing stress concentrations near the grips. To this aim, the present study exploits FE analysis to assess potential end tabs designs and find an optimal specimen configuration that yields the maximum failure strain. The optimal design results, with circle-shape end tabs, are compared with the experimental tests and numerical models of ASTM standard test specimen and two promising approaches in the literature, namely, continuous tab and butterfly specimens.

1 INTRODUCTION

The standards (ASTM and ISO) for tensile testing for unidirectional (UD) composites recommend using a rectangular specimen with rectangular or tapered end tabs (woven or unwoven E-glass/epoxy with a $[0/90]_{ns}$ and at 45° with loading direction). However, failure near the grip is likely to happen with the standard methods [1,2]. FE analysis showed that the end tabs introduce stress concentrations owing to geometric discontinuity and limiting the Poisson's contraction. To have acceptable failure inside the gauge section, these stress concentrations need to be avoided or minimised.

Some authors suggest alternative methods, such as butterfly (or dog-bone) specimens [3,4] and continuous tabs [5]. Butterfly or dog-bone-shape specimens eliminate stress concentrations from the gauge section, while stress concentrations remain near the gripped sections which are far away from the gauge section. However, for UD composites, the discontinuity of the fibres introduces shear stress in the curved section leading to longitudinal splitting [6]. The longitudinal splitting can be minimised by increasing the radius of the curved section [4,7,8] or reinforcing the specimen in the transverse direction [4]. In continuous tabs, proposed in [5], the specimen is sandwiched between two UD laminates with considerably higher failure strain than the specimen. The continuous tabs protect the specimen from stress concentrations in the gripped section and from surface damage caused by the serrated surface of the grips. Finite element analyses revealed that with adequate continuous tab thickness, the stress concentrations in the grip section stay away from the specimen. Experimental data support the FE analysis where the specimen with continuous tab showed the highest failure strain compared to the specimen with rectangular end tabs [5] and other specimen designs [6]. However, the challenges in manufacturing and measurement of stress make the proposed method less compelling to replace the standard one.

Finite element analysis [9–11] was utilised to optimise the end tabs, considering the effect of end tab geometry (different tapering) and material on stress concentrations in the gripped section. The effect of test setups such as grip misalignment on stress concentrations was also investigated [10]. Since UD composites are much weaker in transverse and shear than longitudinal loading, a slight misalignment could lead to a significant reduction in UD tensile properties. However, the numerical prediction of the potential design was not validated with experimental measurements.

The present work exploits FE analysis to examine potential end tab designs to perform reliable tensile tests. To better understand the source of stress concentrations, the actual set-up of tensile testing, including grip and plunger, was simulated. Then, an optimal design is examined, and the results are compared with the ASTM standard test method and two promising approaches in the literature, namely, continuous tab and butterfly specimens.

2 MATERIAL AND METHODS

2.1 Carbon fibre unidirectional composite

UD thin ply carbon fibre/epoxy HS40/736LT prepreg (North Thin Ply Technology, Switzerland) has been used for this study. The nominal failure strain of HS40 fibres is 1.1%. The $[0]_{10}$ laminate was manufactured in an autoclave with an average thickness of 0.5 mm after curing. Woven fabric E-glass/epoxy was used for the end tabs, while $[0]_4$ UD S-glass/epoxy was used for the continuous tabs (SCG75, Hexcel). The specimen and continuous tabs were cured together. Despite having different resin systems, the curing cycles of both materials were compatible. Table 1 summarises the material properties of the specimen and end tabs.

Material	HS40/736 LT	E-glass/epoxy
Layup	$[0]_{10}$	0/90 woven
Thickness (mm)	0.5	2
Nominal V_f (%)	56	50
E_{11} (GPa)	250.5	28.2
E_{22} (GPa)	4.9	28.2
E_{33} (GPa)	4.9	10.3
$\nu_{12} = \nu_{13}$	0.34	0.27
ν_{23}	0.3	0.27
G12 = G13 (GPa)	2.59	3.1
G23 (GPa)	1.87	3.1

Table 1: Properties of specimen and end tab materials.

2.2 Experimental tensile test features

Tensile tests were performed on six different designs at a displacement rate of 1 mm/min [6]. Fig. 1 shows the geometries and dimensions of four of them adopted here for the detailed numerical simulations. The gripping force was minimised to reduce stress concentrations while avoiding slipping during the test. The gripped force was set at 42.5 kN for continuous tabs, 14 kN for butterfly, and 25 kN for the other two designs.

The average surface strain was measured using digital image correlation. The full gauge length speckle pattern of the specimen excluding the area near the end tabs was captured with a digital camera (with a lens Schneider Kreuznach componon-S 2.8/50). The averaging was done for the region of interest with VIC-2D software. Pictures were taken every 0.5 seconds synchronised with the load cell of the machine.

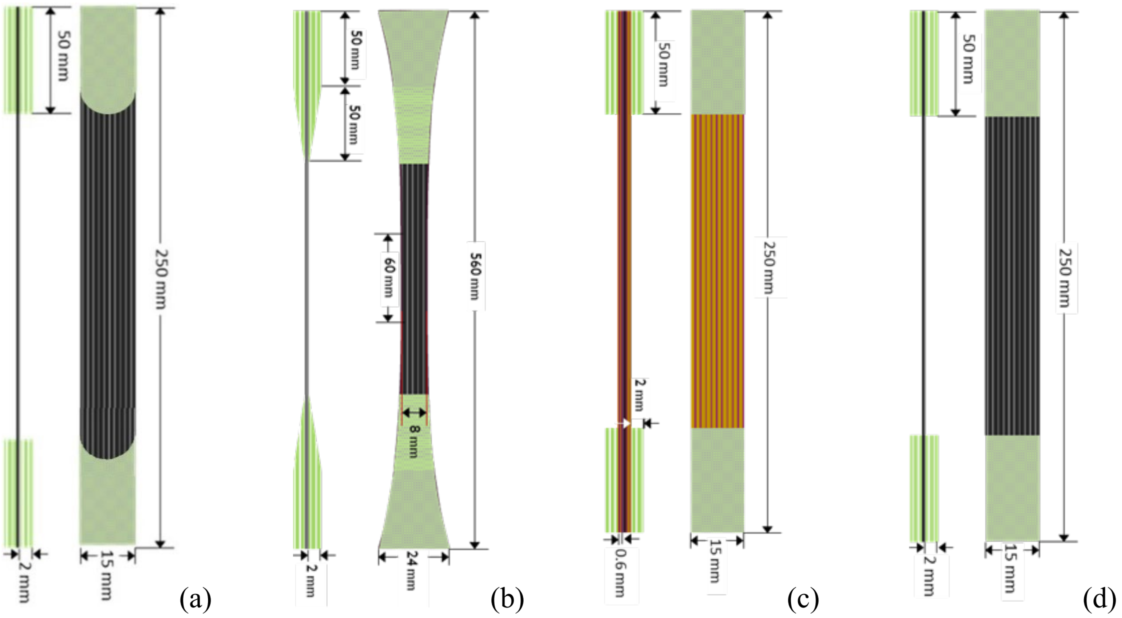

Figure 1: Geometry of specimens (different scales for the different specimens): (a) circle-shape end tabs, (b) butterfly end tabs, (c) continuous end tabs, (d). rectangular end tab (ASTM).

2.3 Finite element modelling features

A quarter of the specimen (symmetry in thickness and transverse direction) was modelled and analysed in ABAQUS™. All materials were modelled as transversely isotropic, linearly elastic, 3D homogenous solids.

To better understand the source of stress concentration, the actual test setup was simulated including grip components (see Fig. 2a), namely a plunger, cylinder, and a wedge grip (as suggested in [9,11]).

The plunger and cylinder interact with the grip by locking the specimen. This motion provides the contact pressure for gripping the specimen. A high friction value of 0.8 was considered between the grips and specimen, while a low friction coefficient value of 0.16 was adopted between steel components.

In this model, perfect bonding between specimen and end tab was assumed and the adhesive was not modelled to enable a conservative estimation.

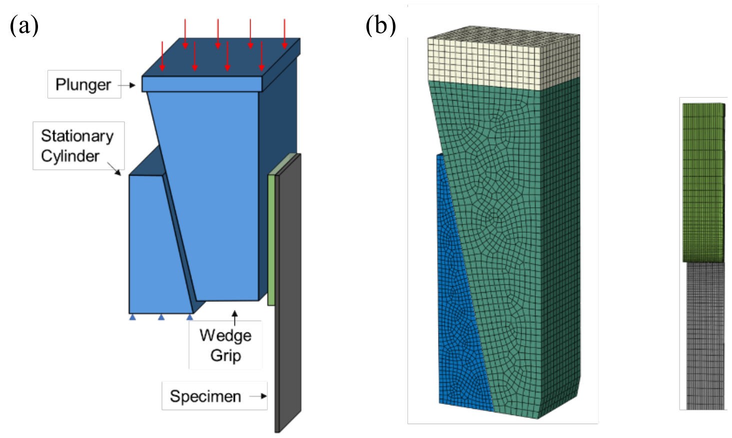

Figure 2. Finite element model of the tensile test setup: a) boundary conditions and b) mesh density.

Linear hexahedral brick elements with full integration (C3D8) were used to mesh the model. A dense mesh was adopted close to the edge of the end tabs and specimen-end tabs interface (see Fig. 2b).

The tensile test was simulated in two steps: (1) inward displacement of the plunger by 0.75 mm to lock the grip with the specimen and simulate contact pressure, (2) displacement of the cross-section in the centre of the specimen in the longitudinal direction by application of 1% strain.

3 RESULTS AND COMPARISON

Fig. 3 shows the results of FE analysis on longitudinal stress concentration of different end tabs and specimen designs. The end tab and specimen designs can significantly reduce the magnitude and material volume experiencing stress concentrations. The butterfly design completely removes the stress concentration from the gauge section (Fig. 3a). However, the stress concentrations presented at the open end of the fibres in the curved section trigger splitting. The circle-shape end tab (Fig. 3b) reduces the stress concentration and smears it out over a certain length rather than being localised in one cross-section such as the rectangular specimen (see Fig. 3c). The continuous tabs eliminate the stress concentrations from the layer of interest and could therefore lead to the highest failure strain (see Fig. 3d).

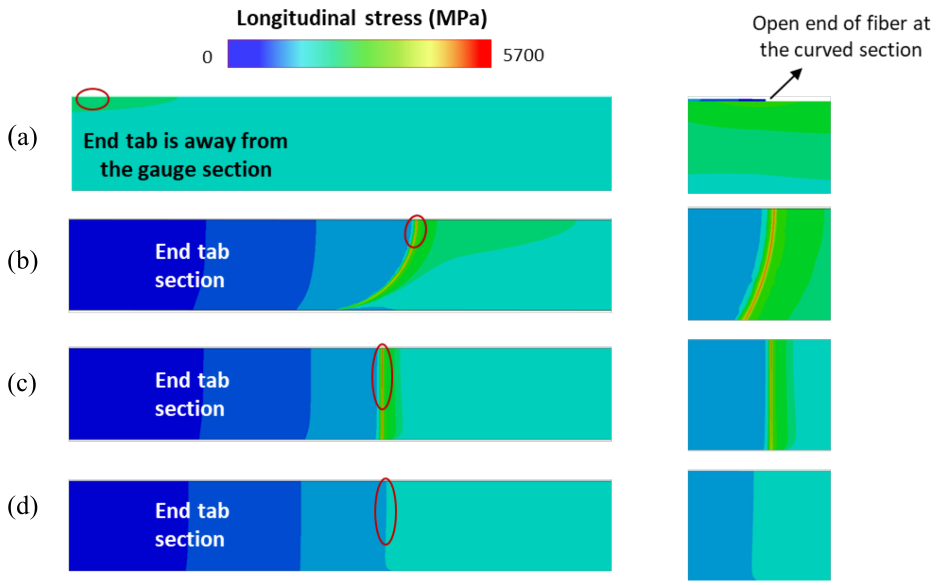

Figure 3: Longitudinal stress concentration in the specimen: (a) butterfly, (b) circle-shape end tabs, (c) continuous tabs and (d) rectangular end tabs.

FE analysis on different end tab designs shows that the circle-shape end tab reduces the stress concentration and hence could lead to a higher failure strain than conventional and non-conventional end tab designs. Fig. 4 shows the experimental stress-strain diagrams of 7 specimens with circle-shape end tabs. The average value of failure strain increases by about 9.3% compared to rectangular end tabs (ASTM). Fig. 5 compares the experimental failure strain of the ASTM standard specimen with continuous tab, butterfly specimen, and circle-shape end tab. The butterfly specimen has the lowest failure strain. This is due to the longitudinal splitting, which initiates above 75% of the failure strain and spreads throughout the entire sample as the load is further increased (see Fig. 6a). The splitting hinders the butterfly benefits by reducing the geometry to the rectangular shape and results in premature failure [6]. The continuous tab and circle-shape designs have the highest value of failure strain (Fig. 5). The p-value of less than 0.05 confirms a statistically significant difference between ASTM standard design with these two designs. However, the direct measurement of the stress in the specimen with continuous tab requires back calculation. In the case of co-curing the specimen and tabs, the thickness of the specimen can vary over the width, which makes stress back-calculation an even greater challenge (see Fig. 6b). Therefore, the continuous tab is not recommended to measure the tensile strength of UD composites.

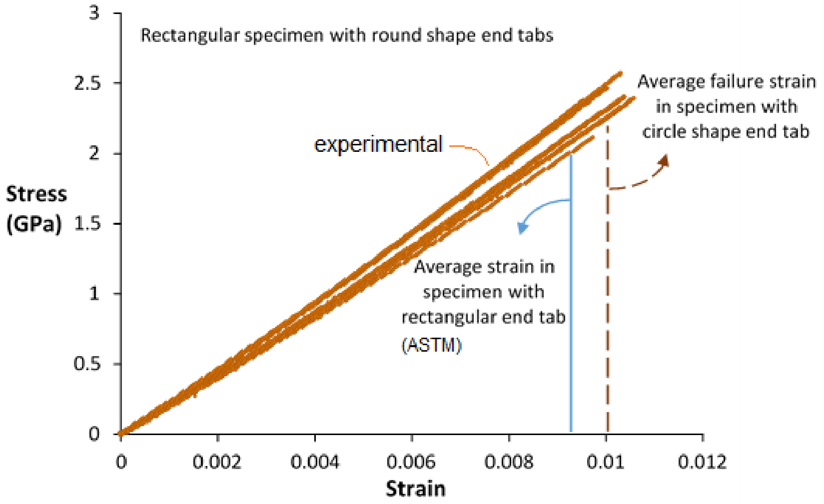

Figure 4. Experimental stress-strain curves of specimens with circle-shape end tabs, in comparison with average failure strains for specimens with rectangular end tabs (ASTM).

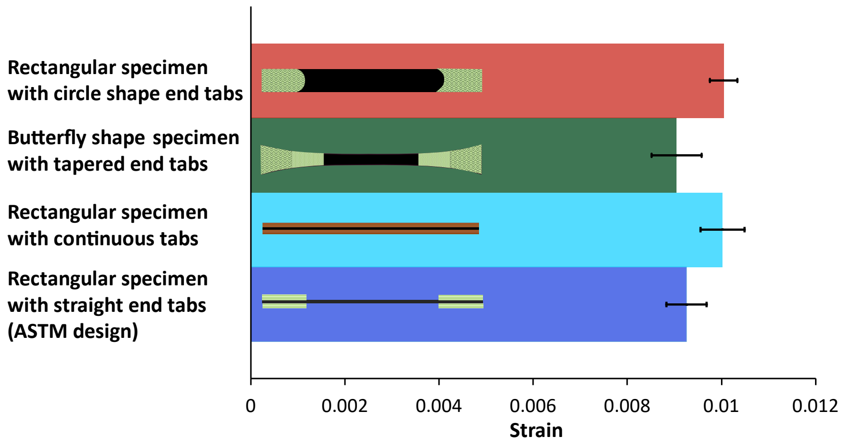

Figure 5. Measured failure strain of different designs.

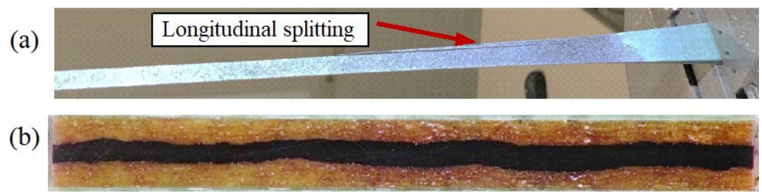

Figure 6. Issues in performing a tensile test on (a) butterfly, and (b) continuous tab specimens.

4 CONCLUSIONS

This work examines a possible alternative for tensile testing of UD composites by minimising the stress concentration near the end tab region. FE analysis shows the circle-shape end tabs significantly reduce the stress concentration. Based on the experimental data, the following conclusions can be drawn:

- ASTM specimen configuration is not optimal.
- Butterfly specimens lead to premature failure due to longitudinal splitting.
- Continuous tab and circle-shape end tab increase the failure strain significantly compared to ASTM standard test method.
- Continuous tab requires stress back-calculation and in the case of co-curing specimen and tab, the inconsistency of specimen thickness over the width introduces errors.
- The circle-shape tab specimen is a promising approach and is easier to manufacture than continuous tab and butterfly designs.

ACKNOWLEDGEMENTS

The work leading to this publication was performed within the framework of the HyFiSyn project and has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 765881.

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