ACCURATE ASSESSMENT OF THE TENSILE STRENGTH OF HIGH-PERFORMANCE CARBON-FIBRE UNIDIRECTIONAL COMPOSITES FOR HYDROGEN STORAGE APPLICATIONS

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Abstract
A next-generation high-performance carbon-fibre-reinforced composite material was tested using two standard tensile test methods to accurately assess its tensile performance for compressed hydrogen gas storage vessels in aircraft. The material was tested in two forms: rectangular unidirectional specimens and ring-shaped unidirectional specimens, both manufactured via filament-winding. The nature of end tabs, a primary parameter in rectangular specimen testing, was investigated, revealing that aluminium end tabs pushed the material to 86.8% of its theoretical strength, while glass-fibre composite end tabs led to failure at 60% of that limit. The split-disk tensile tests on ring-shaped specimens validated the strength results obtained for the rectangular specimens, but only after considering the multiaxial nature of the transmitted load, where a 10% fraction of the maximum reached stress before failure was added to the experimental values to rectify the underestimation of the tensile stress in the circumferential direction. These results demonstrate the compatibility of the two adopted approaches for strength assessment, with the proper consideration of the complex solicitation in the different specimen forms.

1. Introduction
In the context of climate change and pollution challenges, the shift towards cleaner energy sources has spurred significant scientific research in hydrogen in recent decades due to its clean nature [1-3]. This transition not only concerns the shift in energy sources but also requires the development and testing of new materials and technologies to ensure their viability and durability in various hydrogen-related applications. In the aviation industry, which accounts for 2.8% of global CO2 emissions, the evolution towards hydrogen-powered solutions can constitute a significant step towards the decarbonisation of the air transport sector.

To utilise hydrogen effectively, it must be produced and stored in specialised reservoirs. Various storage methods exist, including both chemical and physical approaches, requiring particular vessels adapted to different pressure and temperature ranges.

The evolution of pressure vessel technology from Type I to Type IV underscores the industry's pursuit of lighter and more durable storage solutions. Type IV vessels have become pivotal in applications like aviation, aiming to enhance hydrogen storage efficiency while preserving structural integrity. Composites, in particular carbon-fibre composites, being lightweight and strong, are excellent candidates for hydrogen storage and transport infrastructure. However, ensuring the security aspects of utilising these high-performance materials is crucial.

The mechanical characterisation of high-performance carbon-fibre composites plays a crucial role in designing robust structures such as Type IV hydrogen tanks. This characterisation ensures that materials are utilised efficiently and structures are properly designed without compromising safety measures.

The subject of the mechanical charactersisation of high-performance composite materials constitutes an ongoing key challenge in the domain of composite research. Numerous studies have been conducted with the aim of maximising the potential of composites during testing, dating back a few decades [4-6] and including modern-day efforts [7-9].

In the frame of Clean Aviation's European project CAVENDISH, a state-of-the-art high-performance carbon-fibre-reinforced composite material constitutes the area of study for a large scale lightweight hydrogen gas storage solution for a hydrogen-powered aircraft.

This paper presents the work carried out in the frame of the CAVENDISH project with the goal of properly assessing the strength of the studied composite material using two different approaches of tensile testing, on rectangular and ring specimens.

2. Materials and Methods

2.1. Carbon-fibre-reinforced Composite

The material studied in this paper is a composite material composed of a thermoset epoxy resin matrix reinforced with continuous carbon fibres. The primary material comes in the form of a prepreg. For confidentiality requirements, no further information will be disclosed regarding the nature of the material.

The samples used in the study are manufactured through filament-winding process by MaHyTec SAS to produce both rectangular and ring specimens. Large plates of 300×200 mm^2 of unidirectional carbon-reinforced composite are fabricated by winding the prepreg onto a flat mandrel. This process thus results in 2 flat plates per winding process. These plates are then cut using a Protomax water-jet machine to yield standard rectangular test specimens. The specimens have dimensions 280×18 mm^2 and a thickness of around 1.2 mm.

As for the ring specimens, individually wound rings are manufactured with an inner diameter of 120 mm, a width of 10 mm, and a thickness of 1-1.2 mm. The only machining performed on the ring specimens after their manufacturing consists in sanding their outer surface all along the circumference. This crucial step achieves an important goal; it smoothes out any significant surface roughness over the width and particularly at the rims of the rings originating from the overlap of the prepreg filament during the winding process due to the small width of each individual specimen.

The law of mixtures gives a theoretical estimation of the strength of the studied material, which acts as a rough baseline for the experimentally-targeted levels of stress. This law, however, describes a perfect composite material via the individual performances of its component elements without taking into account numerous aspects involved in the effective strength at the composite scale [10], including both experimental and manufacturing-related factors, such as the considered gauge length, and the fibre distribution inside the material and the localisation of porosities, respectively.

2.2. Tensile Test Methods

Standard test methods are taken as reference for the tensile testing of the described specimens. However, these testing methods often result in the premature failure of the tested material due to localised high stress concentrations in the specimen and the multiaxial nature of the transmitted loading.

For the rectangular specimens, the ASTM D 3039 standard [11] states the use of cross-ply glass-fibre-reinforced-epoxy tapered end tabs to promote specimen failure in the gauge section. A certain number of authors have validated these recommendations in their findings. This study investigates a number of end tab parameters, mainly focusing on the end tab material and geometry, that would have an important impact on the mechanical tests outcome. For this purpose, different groups of rectangular specimens are tested; specimens without end tabs, and specimens with glass-fibre-composite and aluminium end tabs, both with a tapered geometry. Specimens having a relatively low stress level at failure attributable to a material defect are not included in the calculations mentioned in this paper. For example, specimens presenting a crack along the fibre direction crossing the entirety of their gauge sections and continuing deep into the tabbed end where the failure occurred invalidate the results because of the lack of proper fibre-mode failure.

On the other hand, for the ring specimens, the ASTM D 2290 [12] standard for split-disk tensile testing is followed. Even though the nature of the transmitted load in this type of test proves to be multiaxial [13-14] due to the bending moment that appears in the two gauge sections of the ring as the two half-disks are pulled apart, the simplicity of this type of test favours it over other proposed more complex approaches [13, 15-16]. A correction factor for the induced bending moment compensates for the underestimation of the measured material strength during the test; it is assumed that the actual performance of the tested specimen is 110% of that calculated using the experimental data. Considering the gauge volume in the ring specimen during a split-disk tensile test, and moving outwards in the thickness direction, the inner surface of the ring experiences the highest tensile stress as its curvature is straightened under load, and this stress decreases gradually through the material until its outer surface where it undergoes compressive loading. Thus, a value of 10% of the experimental maximum failure strength, corresponding to the mean of the through-thickness stress gradient determined by means of a finite-element simulation, is added to obtain the actual maximum strength.

Figure 1 shows the two types of tested specimens – rectangular specimens with aluminium end tabs and a test-ready ring specimen mounted on the split-disk setup.

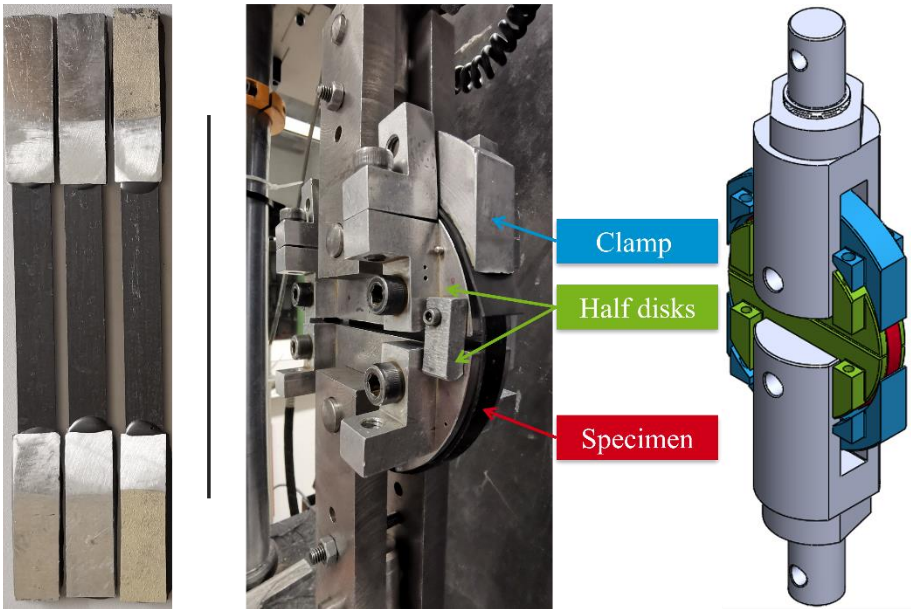

Figure 1. Rectangular unidirectional test specimen with aluminium tapered tabs and a ring specimen mounted on a split-disk setup.

3. Results and Discussion

3.1. Rectangular Specimens

Figure 2 shows a summary of the parametric study conducted on the rectangular specimens comparing different end tab parameters. In this figure, the normalised failure stress of the specimen groups is defined as the ratio of the experimental stress at failure to the theoretical maximum stress of the studied material. The theoretical stress is obtained from the law of mixtures and thus the normalised stress is calculated as follows in Eq. 1:

$$\sigma_{\mathrm{normalised}} = \sigma_{experimental}/\sigma_{theoretical} \quad (1)$$

These results show a disagreement with the recommendations of several works with regards to the type of end tabs. Even though glass-fibre-reinforced composite is commonly found to reduce stress concentrations inside the specimen at the exit of the gripping jaws [4, 7, 17], in this study, specimens equipped with aluminium end tabs performed considerably better, postponing failure until a level of normalised stress of 86.8±5.5% on average, when compared to the glass-fibre-composite end-tab group, which fails at a normalised stress of 60.3±8.0%.The use of aluminium end tabs, thus, led to a 44% increase in the material strength.

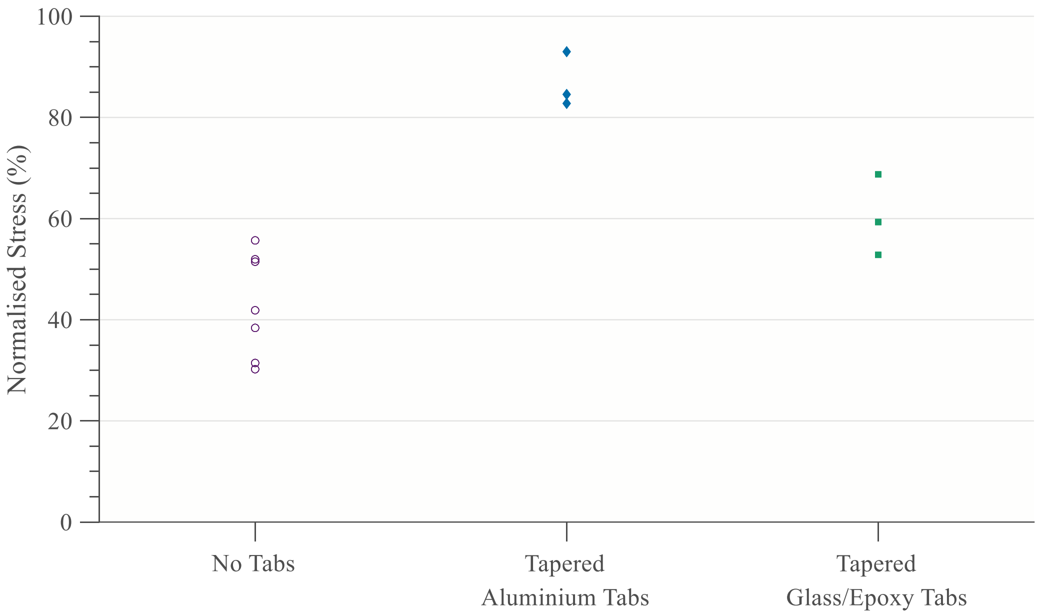

Figure 2. Results of tensile tests for rectangular specimens.

3.2. Ring Specimens

The obtained strength of ring specimens is subject to correction where the experimental data is multiplied by a factor of 1.1 to take into account the bending moment that occurs during the test. Figure 3 shows the corrected failure strength of the tested ring specimens compared to the best-performing rectangular-specimen group equipped with tapered aluminium end tabs.

The mean value of the ring specimen strength at failure is at 82.6±8.7% of the maximum theoretical stress, which is slightly lower than that of the best-performing rectangular specimens, 86.8%. This slight difference of 5% can be attributed to the nature of the load transmission to the specimen in this type of test, and an underestimation of the bending moment that acts as an important weakening factor, thus leading to a false assessment of the material strength due to an early failure.

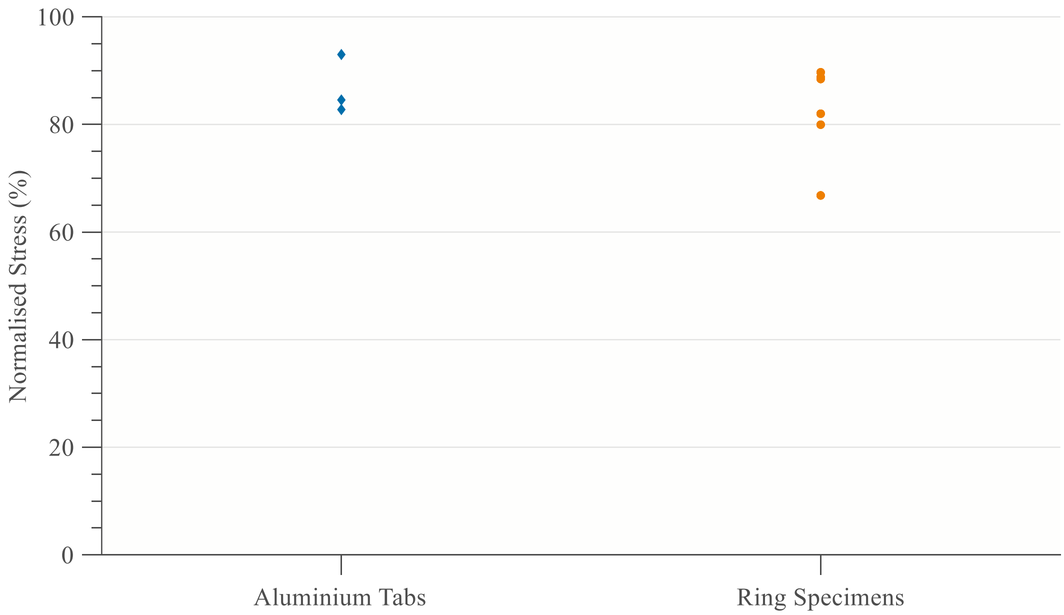

Figure 3. Results of tensile tests for ring specimens.

4. Conclusion

In this study, the strength of a latest-generation high-performance carbon-fibre-reinforced composite material is evaluated using two standard approaches, tensile testing of rectangular and ring specimens. When needed, the adopted ASTM standards for these tests are modified with the aim of reaching the full potential of the tested material.

In the case of rectangular specimens, near-theoretical failure stress levels are properly reached using a suitable specimen preparation protocole, mainly concerning the tabbing material and geometry. Contrary to general recommendations, tapered aluminium end tabs, when compared to glass-fibre-composite ones, result in higher stress levels at failure with a a significant increase of 44%.

With regards to the ring specimens, similar stress levels are obtained at failure as those of rectangular specimens with only a minimal difference of 5%. These stress values are not the experimental data, but rather a revised evaluation of the experimentally-obtained values, multiplied by a compensating factor for the intrusive bending moment that occurs during the standard split-disk tensile test.

These results show a good compatibility of the two adopted approaches for the strength assessment of the studied material with the proper consideration of the complex solicitation in the ring-shaped specimen testing method.

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