Characterisation of filament wound carbon fibre composites through open-ended pressure testing

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Abstract. Composite pressure vessels (CPVs) are typically designed utilising a maximum fibre stress failure criterion to determine their failure pressure. This method requires reliable and accurate fibre direction stress and strain data; however, standard composite material characterisation methods are limited regarding their application on filament wound material, which is often the manufacturing method of choice for CPVs. An alternative method based on the pressurisation of open-ended composite tubes is investigated, which enables characterisation of the as manufactured material properties. A methodology is described, which incorporates the design of a test rig able to withstand 1000 bar pressure, with a Digital Image Correlation (DIC) approach designed for use during in-situ testing of the tubes. The DIC methodology allows image capture up to failure alongside synchronisation of data from the pressurisation system. It is demonstrated that the novel system is able to determine the failure properties of the material.

Introduction

Composite pressure vessels are a key storage solution for compressed gaseous hydrogen, with type IV vessels being common because of their light weight and higher gravimetric efficiency potential compared to other vessel types. Type IV vessels consist of 3 components: metallic boss(es), polymer liner, and a composite shell. The composite shell (typically carbon fibre) is the main load carrying component and its design is driven by the operating pressure of the vessel.

CPVs are commonly designed considering a monotropic model for their composite shell. The model assumes that the CPV's pressure bearing capacity is solely governed by the composite fibre-direction properties, including fibre strength and fibre stiffness [1]. Therefore, accurate fibre-direction material properties are vital for accurate CPV design. Standard material testing methods, such as tensile testing of flat panels or split-disk testing of NOS rings, present some limitations regarding their application to filament wound (FW) material, typical of CPVs. Flat panels, although manufacturable using specialised filament winding (FW) tools, are not truly representative of typical FW parts [2]. The fibres are tensioned differently and cutting of the panels will release residual stress developed in the curing process. Split-disk testing allows as-wound rings to be tested, but the method induces bending and promotes premature failure [3].

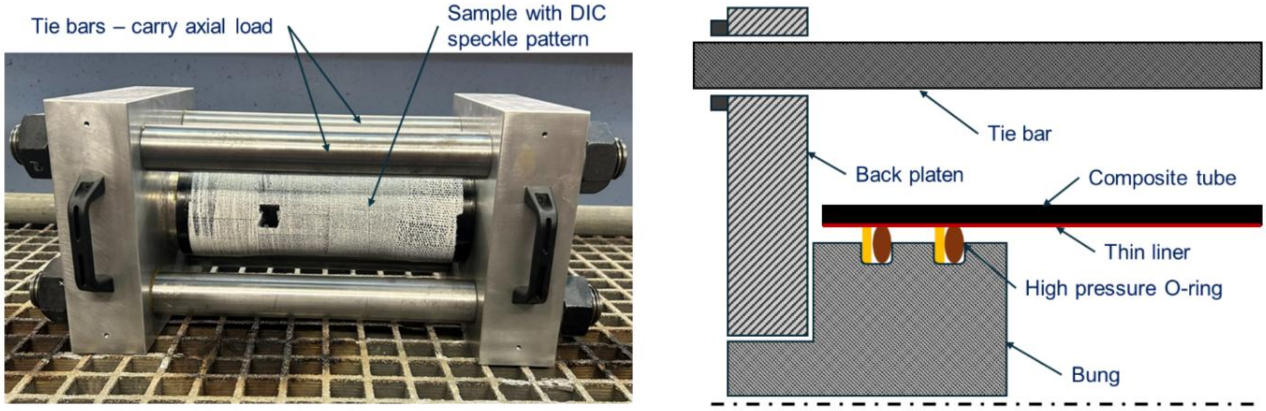
Because of the limitations mentioned above, the use of a method based on the internal pressurisation of hoop-wound tubes is investigated, for the characterisation of FW material fibre-direction properties. The pressure testing rig s designed to minimally constrain tubes during pressurisation, whilst withstanding 1000 bar pressure, allowing the samples to be tested in a pure hoop-stress state, i.e. 1:0 hoop to axial stress. This method of 'open-ended' pipe testing is a route towards testing truly representative FW parts using a desired load case where the entire part is uniformly loaded over the gauge length.

Test method

Open-ended test rig. The open-ended test rig, shown in Fig. 1a has been designed to test tubular specimens with an internal diameter of 100 mm, a total length of 300 mm and a gauge length of 100 mm. Samples are pressurised with water and can be tested up to a safe maximum pressure of 1000 bar.

Composite tubes are internally fitted with bungs that support and seal on the tubes internal face using two O-ring seals, as shown in Fig.1b. This design allows the sample to axially and radially deform as desired during pressurisation, creating a pure hoop-stress state. The axial load from the internal pressure is carried by 4 tie bars parallel to the test specimen. Each tube is fitted with a thin polymer liner to prevent leakage through any matrix cracks and ensure fibre failure is achieved.

Digital Image Correlation. During testing, strain vs pressure data is collected using a stereo Digital Image Correlation (DIC) system synchronised with the pressurisation rig. Pressure tests are undertaken in a non-ideal environment for DIC. Key challenges include equipment damage from debris & water following a burst event, tight/limited equipment space, inadequate lighting, and suitability of auxiliary connections. A key novelty of this research is the bespoke DIC set-up using affordable machine vision cameras and a built-in protection system enabling strains to be obtained over a wide viewing area during the pressure test, up-to the final failure event.



(a) (b)

Figure 1. (a) assembled open-ended pressure rig with sample prepared for digital image correlation. (b) Cross section of assembled rig showing internally fitted bungs.

Results

Multiple pressure tests have been completed alongside successful image captures for DIC. Good correlation between the DIC strains and surface-mounted strain gauges confirms the accurate performance of the DIC system, as shown in Fig 2. Analysis of the collected data alongside Finite Element Analysis (FEA) results can be used to give insight into the specimens' behaviour/ performance during testing.

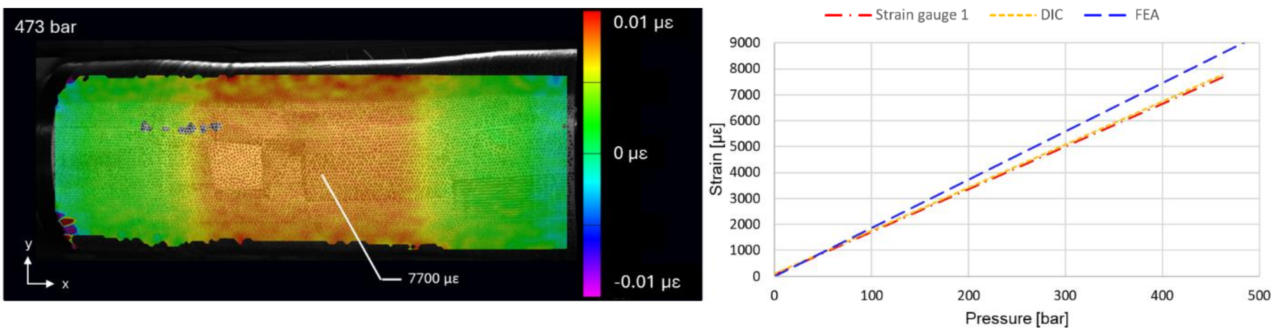


Figure 2. DIC of field of view ε_{yy} (hoop) surface strain capture immediately before burst event and correlation between DIC, surface strain gauge, and FEA model for ε_{yy} (hoop) strain.

Conclusion

A methodology based on internally pressurising tubes presents a testing route that can avoid the limitations of other standard testing techniques for the characterisation of filament wound composites. The use of an open-ended pressure rig alongside a bespoke DIC system to burst test composite tubes has been shown to be a feasible alternative, with good quality DIC strain data captured up to the final failure event. Further development of this methodology can lead to a testing regime for an improved characterisation of the fibre direction properties of FW composite materials.

References

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