Investigation into the Strength of Adhesive Joints at Cryogenic Temperatures Using a Modified Arcan Fixture

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Abstract. The magnet found within an MRI machine consists of epoxy infused superconducting wire coils, bonded to glass fiber reinforced polymer (GFRP) rings. Operating at 4K, electromagnetic forces produce complex stresses at the coil-GFRP interface. A modified Arcan fixture (MAF) can be used to assess the deformation and failure in and around the joint under shear and combined compression-shear loading, similar to in-situ loads. This is done at ambient conditions as a benchmark, and then at cryogenic temperatures, using a specifically designed cryostat that isolates part of the specimen from the test fixture. Control specimens were manufactured and used to measure the stiffness and strength of the same epoxy resin used in the magnet. It is observed that the contemporary specimens' stiffness and failure load increases with decreasing temperature. For specimens at the same temperature, the failure load was lower than that of the control specimens. Hence, the various failures observed at ambient and cryogenic temperatures are examined and the potential reasons behind the differences discussed.

Possible Sessions

16. Novel Experimental Techniques, 19. Optical and DIC Techniques From the list, 1. Adhesive and welded joints

Introduction

The key component of an MRI scanner is the magnet, which is composed of superconducting wire coils, adhesively bonded with epoxy resin into glass fiber reinforced polymer (GFRP) rings. To energize the magnet and create the necessary magnetic field, it is encased in liquid helium to facilitate cooling to 4.2K. However, the activation of this field means that powerful electromagnetic forces are exerted on the inert GFRP rings. This interaction creates intricate bi-axial stress distributions at the adhesive bond between the components, which may lead to propagation of damage incurred during manufacturing and/or transportation. Moreover the sudden cooling of the magnet, known as a 'quench', the coiled wire rapidly transitions to a non-superconducting state, releasing stored energy and rapidly boiling the surrounding cryogenic liquid. Understanding the limits and responses of the bond between the coil section and the GFRP rings is critical. To mimic the loading modes a modified Arcan fixture (MAF) [1] is employed that replicate the operational stresses. This fixture is used first to examine the materials shear properties, shown in Fig. 1, and then by adjusting the loading configurations, the rig can simulate combined compression-shear forces, providing valuable insights into the behaviour of the bond under various stress states. With the development of a suitable cryostat, these tests can be repeated at cryogenic temperatures to generate a failure envelope for the adhesive bond under conditions similar to operation.

The aim of the present research is to investigate the ability of the MAF to produce range of biaxial and shear stress states on an adhesive bond. DIC is used to obtain the strains in the vicinity of the bond and from this the bond stiffness and strength is identified at ambient and cryogenic temperatures.

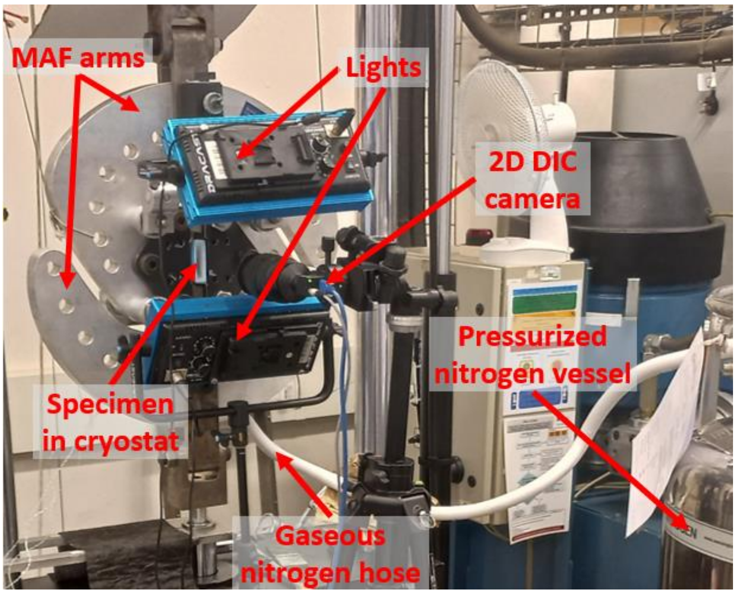

Figure 1: MAF shear configuration with cryogenic testing capabilities and full field observations

Experimental Method

Specimens. Control specimens are manufactured from pairs of bright mild steel plates, adhesively joined with the same epoxy used in the magnet, with a bond area equivalent to the magnet specimens. For the magnet specimens, a waterjet cutter is used to cut 30mm thick blocks of magnet, containing equal amounts of GFRP and infused coil about the adhesive bond. Both ends of these specimens are then encased in epoxy resin to form a small gauge width and reduce the opportunity for deformation and failure to occur within the clamped region of the specimen. A speckle pattern for the DIC is applied with spray paint to all specimens.

Test Method. A single camera is used for 2D DIC, capturing images at 1 Hz. Static images are taken to find the noise floor of the system at ambient and cryogenic temperatures. The load is then applied at 0.5 mm/min until failure. A novel cryostat design utilizes gaseous nitrogen as the cooling agent, flowing onto and around the back of the specimen. On the opposing side, a viewing tube and window create a thermal gradient between the specimen and outside to mitigate condensation building up on the outside of the window.

Results

Control specimens. Due to the available spatial resolution, strain windows overlap the adhesive bond and the steel adherends. Therefore, instead of extracting the strains directly from the DIC calculated strain fields, virtual bi-axial extensometer can be placed along and overlapping the bond. This is used to calculate the engineering shear strain (γ_{xy}) and can be plotted against the maximum shear stress (τ_{max}) to calculate the stiffness. The strain maps show a uniform distribution of shear strain along the bond with no other strain components present. The shear modulus of the epoxy resin at ambient and cryogenic temperatures was calculated as 1.31 GPa and 5.00 GPa respectively. Less deformation of the bond at cryogenic temperatures implies that the fracture is more than at ambient temperature tests. The shear strength of the epoxy at ambient and cryogenic temperatures was identified from stress strain curves as 15.5 MPa and 31.3 MPa respectively.

Magnet Specimens. The same procedure for obtaining the strain was adopted as for the control specimens. Table 1 shows the strain maps just before failure with the green dashed line indicating the adhesive bond, it can be seen that the shear strain remains the dominant strain component, but the transverse normal (peel) strains are significant.

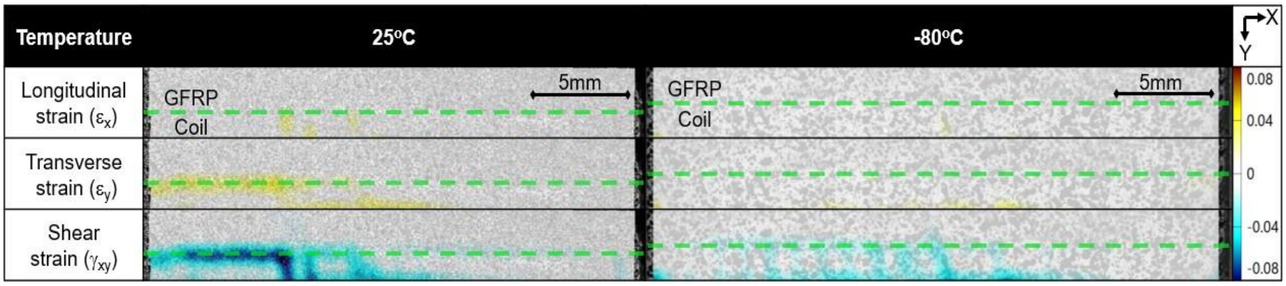

Table 1: Strain maps just before failure under shear loading

The adhesive bond is not as constrained as in the control specimens and the deformations are higher. The strain maps show the strain is distributed in the epoxy between the wires, as well as in the adhesive bond. Clearly highlighted in the specimen at ambient temperatures, the deformation transfers from the adhesive bond and the 1st row of wires. Because of this and the peeling stresses are present, forcing premature failure with the crack propagating into the adherend as it follows the path of least resistance. It is observed that the shear failure stress increased from 17.1 MPa to 21.9 MPa. The failure mechanism changes to an almost pure shear failure at cryogenic temperatures and is most likely due to the increased stiffness in the adherends leading it to act more like the control specimens. As well as the failure mechanism dependency on temperature, it is also dependent on the applied load and various initiations are observed under combined compression-shear loading.

Conclusion

A test methodology has been established to evaluate the in-situ bi-axial loading experienced by an adhesive bond found within an MRI magnet experienced at ambient and cryogenic temperatures. A novel cryostat has been designed to fit with the MAF to facilitate testing specimens at cryogenic temperatures. The testing of control specimens, using the fixtures shear configuration, produced a uniform shear strain distribution along the bond. At lower temperatures the shear modulus and strength increased by 280% and 110% respectively. When applying the test methodology to the magnet specimens, complex strain distributions and fracture mechanisms were observed. Although similar at ambient temperatures, the failure stress of the control specimens was much greater than the magnet specimens. This can be attributed to better adhesion between the epoxy and steel, and the presence of other crack paths available in the magnet coils. In the control specimen's deformation and failure can only occur in the well-defined manufactured plane of epoxy.
Further work includes the use of different loading hole pairs to extend the failure envelope, as well as. continuous development of the cryostat to enable lower testing temperatures, for longer periods of time.

References

[1] T. Laux, K. W. Gan, J. M. Dulieu-Barton, and O. T. Thomsen. Ply thickness and fibre orientation effects in multidirectional composite laminates subjected to combined tension/compression and shear. *Compos Part A Appl Sci Manuf*, 133, 2020.