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UNIVERSITY OF Southampton

Faculty of Engineering and the Environment

Institute of Cryogenics

Applying DIC to extract full field thermo-mechanical data from an HTS coil

Wendell Bailey, Jorge Pelegrin, Duncan Crump

Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, United Kingdom.

Introduction

The global contraction of superconducting coils as they cool down to their cryogenic operating temperature is very difficult to model. Racetrack shaped pancake coils present additional geometrical inhomogeneities and stress concentrations that often reduce confidence in Finite Element (FE) models.

Digital Image Correlation (DIC) is a non-invasive optical technique that tracks the displacement of pixelated blocks from a series of digital photographs to measure surface deformation down to one part per million of the field of view. The full 2D or 3D displacement vector fields and strain maps are developed after post processing with software algorithms. The technique is very cost effective and eliminates the subjectiveness of placing/ integrating strain gauges that capture only localised strain data. The application of DIC at cryogenic temperatures is untried and presents new challenges.

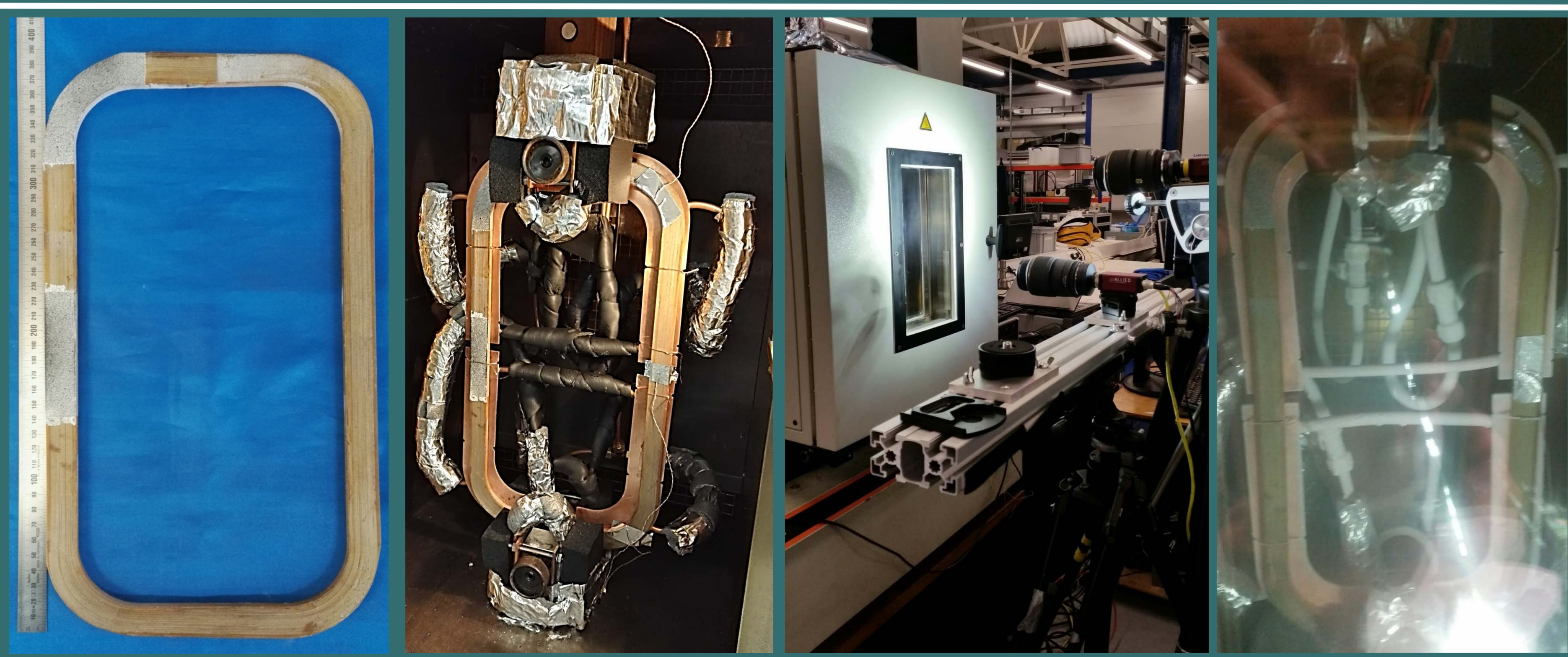

Figure 1. HTS coil and experimental setup

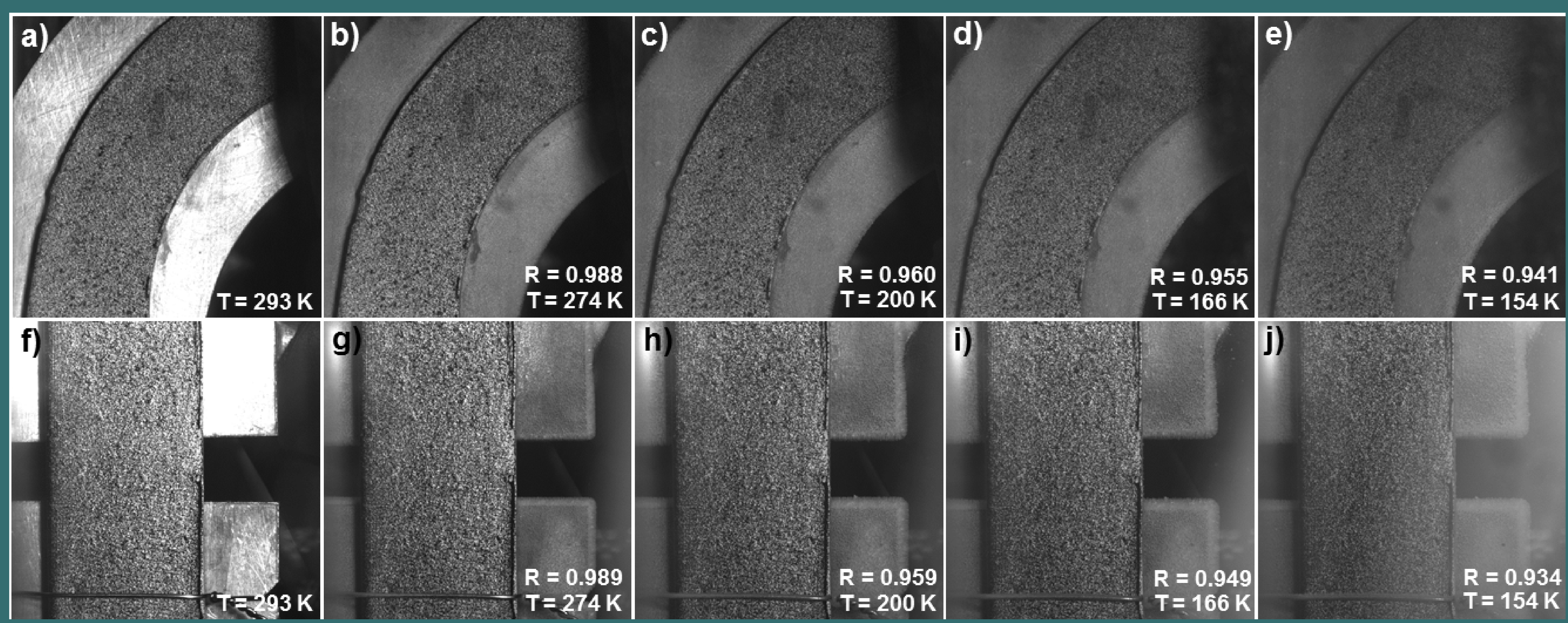

Figure 2. Images taken during the cooling down of the corner and straight sections of the coil

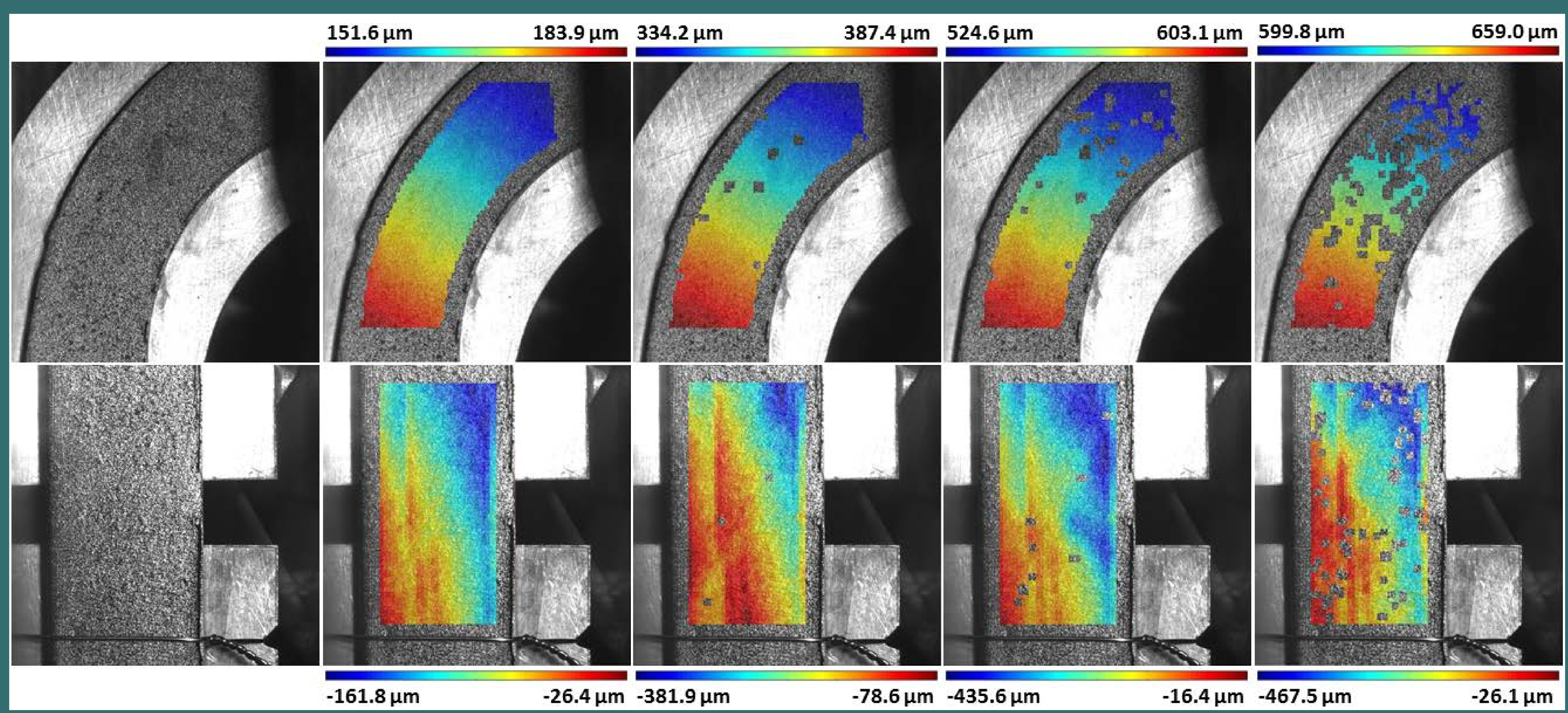

Figure 3. Horizontal displacements obtained after processing the DIC images

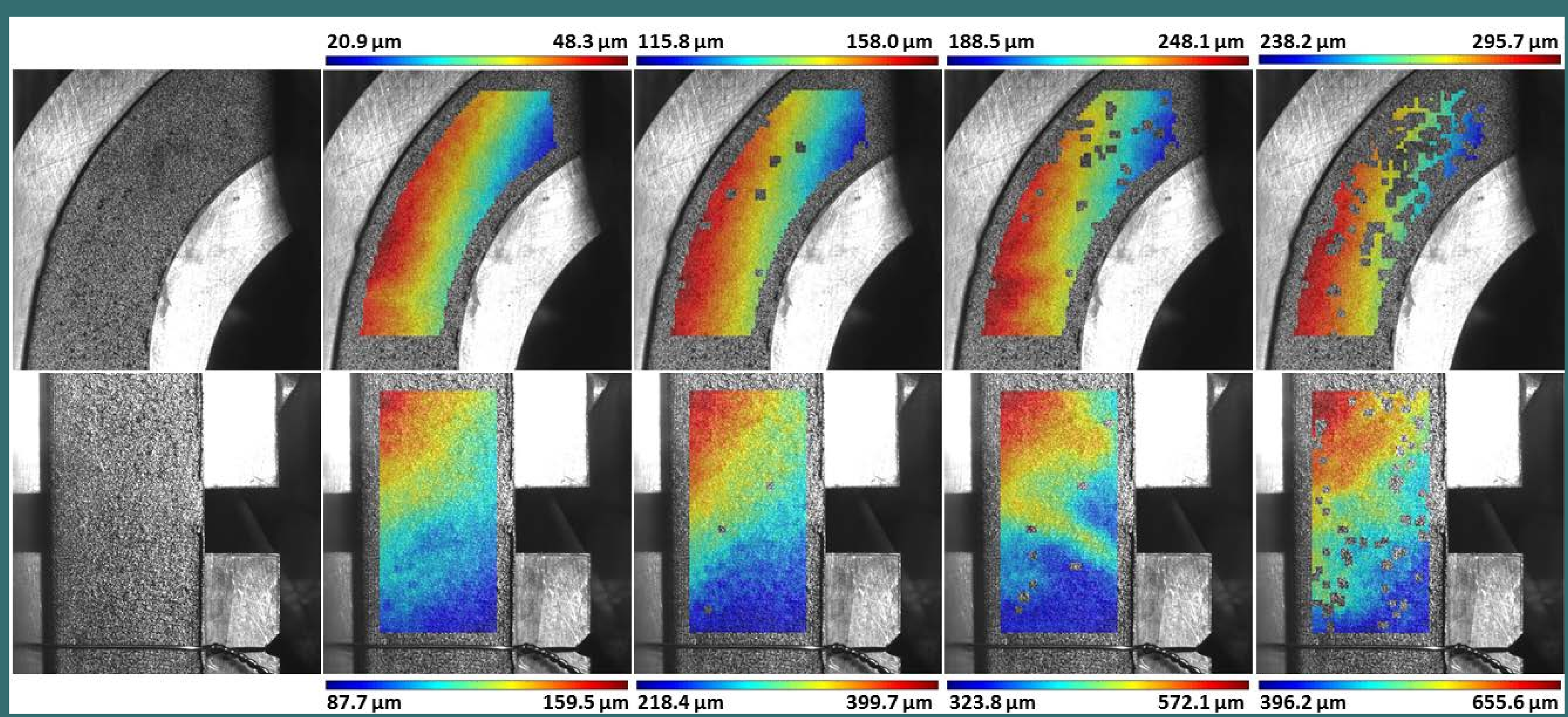

Figure 4. Vertical displacements obtained after processing the DIC images

Methodology

A speckle pattern was applied to a BSSCO superconducting racetrack coil by masking two regions of the coil and spraying a solid layer of matt white paint, followed by a fine spray of black paint to produce small randomly distributed speckles.

The coil was placed inside an environmental chamber and clamped between the vertical jaws in the Instron universal test machine. The chambers force flow gas cooling system was bypassed for a pair of heat exchangers to locally cool the coil by conduction with liquid nitrogen. The heat exchangers were coupled to a split pair of copper rings placed in contact with the rear of the coil.

A separate digital camera focusing on each speckled region was synchronised with LabVIEW software to take an image and record the load measured by the Instron's load cell every minute during cool down. The local temperature of the coil was recorded by thermocouples connected to a data logger.

Results

Figure 2 shows five images taken during the cooling of the coil from 293 K to 154 K. The speckle pattern applied did not crack/ flake and the correlation factor *R* (determined during the post-processing stage and indicates how well the subsets are detected by the software) decreased by very little during cooling. Typically, a correlation factor of > 0.8 is acceptable for strain measurements. Correlation is lost in some regions of the inspected zone at the lowest temperatures due to formation of ice and propagation of cold mist over the coil.

Figure 3 shows how the displacement evolves in the **horizontal direction** during cooling. The magnitudes of the displacements of the straight and corner sections of the coil consistently increase under reducing temperature, but in opposite directions. This may have been influenced by the clamping arrangement of the coil. The displacement is largest in the outer edge of the straight section as the structure tends to bow outwards as its shortens in its vertical length. The displacement in the corner sections tends to follow the direction of the HTS tapes and is lowest close to the upper clamp.

The **vertical displacements** mapped in Figure 4 also increase in magnitude with reducing temperature. The highest displacements occur on the outer edge of the corner as expected. The distribution of the largest displacements recorded in the straight section have been influenced by the copper wire holding the coil against the copper ring.

The software derived strain in the vertical direction is plotted against the corresponding force (N) translated to stress (MPa) in Figure 5 (left). The slope of the stress-strain curve is linear and the coil stiffness $E_{DIC} \approx 1.9$ GPa. This stiffness corresponds well with the elastic stiffness of Stycast 1266 epoxy resin at low temperatures (used for potting the coil), and varies between 1.3 - 2.5 GPa between 293 K and 150 K. It is likely the resin is the most active component in the composite at these low temperatures and strains. Figure 5 (right) plots the strain-temperature curve to determine the coefficient of thermal expansion α. The slope of the DIC curve gives an α value two times smaller than an experimental measurement performed with a dilatometer upon a sample removed from a similar coil. The difference can be accounted for by the retraining of the coil at both ends and small temperature gradients measured across the length of the coil.

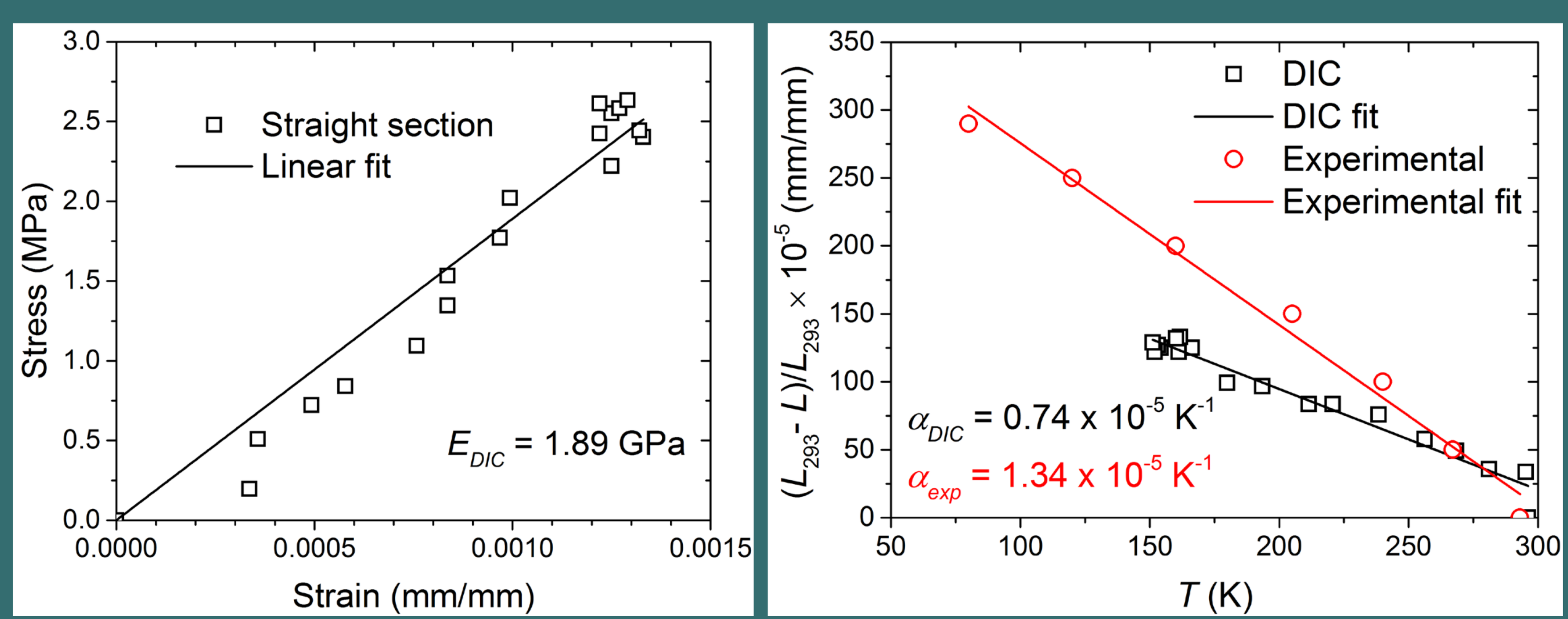

Figure 5. (left) Stress-strain curve and (right) coefficient of thermal contraction obtained from DIC analysis

Conclusions

This novel piece of work has confirmed that DIC can be successfully deployed at cryogenic temperatures. The speckle pattern can survive at these extreme temperatures and provide high fidelity full field data. The displacement and strains that occur in complex components like HTS racetrack coils can be mapped over larger regions to reveal complex interactions that could be missed if applying strain gauges or through a lack of accurate input data install in FE-models.

Post-processing to construct the stress-strain and strain-temperature curves output the coil stiffness induced by reducing temperature (which seems to dictated by the stiffness of the resin) and the linear coefficient of thermal contraction which is influenced by the method used to restrain the coil and measure force. The key changes required to improve the setup include conducting the test in a bespoke vacuum chamber and uniformly supporting and compressing the coil to mimic the configurations deployed in HTS machines.