Quantifying Damage Propagation in Composites Using Uncalibrated Thermoelastic Stress Analysis

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ABSTRACT
The complexity of composite materials creates a challenge when monitoring and predicting the remnant life of damaged structures. This work demonstrates a non-contact technique that uses uncalibrated thermoelastic stress analysis (TSA) for tracking damage in composites under cyclic loading. TSA maps of the components surface were collected throughout the duration of each test and feature vectors were extracted from the maps using orthogonal decomposition. The difference between feature vectors at different stages of the tests were used to detect small changes in the TSA maps as a result of damage development. The technique has been successfully applied to a range of coupon geometries, including plate specimens with a 45° slot and a hole. The approach provides a methodology to monitor damage within composite components as it develops in the form of delaminations and surface cracking. It was demonstrated that the full-field uncalibrated TSA data can be used for the development empirical models that have the potential to enable predictions of damage propagation and remnant life. Such techniques applied to complex structures could improve our understanding of how large structures degrade and predict their future performance.
Keywords: Thermoelastic Stress Analysis, Carbon fibre composite, Fatigue, Empirical model, Structural health monitoring

INTRODUCTION
Carbon-fibre composites have a good strength to mass ratio and have received significant interest for their application within a large range of industries including automotive, construction and aviation. As an example, Airbus used carbon-fibre composites within their A350F model, helping contribute to a reduction in fuel consumption of 20% when compared to their existing equivalent payload metallic model [1]. Although it is desirable to use composites within structures, the complexity of composite materials creates a challenge when designing and predicting the remnant life of such structures. The complexity arises from the orthotropic material properties and the variability in the way damage initiates and propagates. Remnant life and residual strength predictions are further complicated when the structure has been subjected to damage. Generally, when damage or defects are located within composite components, the part is often replaced or repaired [2]. Such repairs often result in an increase in the structural mass while replacement of the component drives up cost and waste.

Work by *Christian et al. (2018)* showed how changes in measurements of strain fields in damaged composite components acquired using digital image correlation can be used for locating damage and making predictions of residual strength [3]; demonstrating a route towards using full-field measurement techniques for improving composite structural prognoses. This study explores the application of TSA measurements on composite structures to assess components and make predictions of remnant life. TSA is a well-established thermography technique for quantitative evaluation of stresses in isotropic structures [4] and as a sensitive technique for monitoring crack development in metallic components [5]. TSA maps acquired for isotropic materials, loaded under adiabatic conditions, can be calibrated to provide quantitative values of surface stress [4]; while for orthotropic materials, such as the carbon fibre reinforced polymers (CFRP) used in this study, calibration is more complicated due to the need to resolve the stresses in the plies of the laminate [6] and may change with damage. However, calibrated TSA is not necessary for condition monitoring, as demonstrated by *Amjad et. al (2022)* who used uncalibrated measurements of TSA to monitor damage development in aluminium coupons under non-adiabatic conditions [7].

In this study, their technique has been successfully applied to a range of composite coupons with different geometries. The approach provides a methodology to monitor damage within CFRP components as it develops in the form of delaminations and surface cracking. Data collected from across all coupon geometries, has been used for the development of an empirical model that could enable predictions of damage propagation and remnant life.

EXPERIMENTAL METHODS
Composite specimens were produced using unidirectional prepreg RP542-4 (PRF, UK). The prepreg was laid up to produce uncured laminates with dimensions of 145mm by 245mm and a [45, -45, 45, -45, 45, -45]$_s$ layup was used, resulting in

laminates with 12 plies. Cured laminates were cut into 40mm by 220mm coupons using a water jet cutter. After cutting, the specimens had features machined into their centre and had square 40mm glass fibre reinforced polymer tabs bonded to their ends. A single coat of graphite paint (Graphit33, Kontakt Chemie, Belgium) was applied to reduce unwanted reflections and glare. Typical specimens can be seen in Fig. 1a.

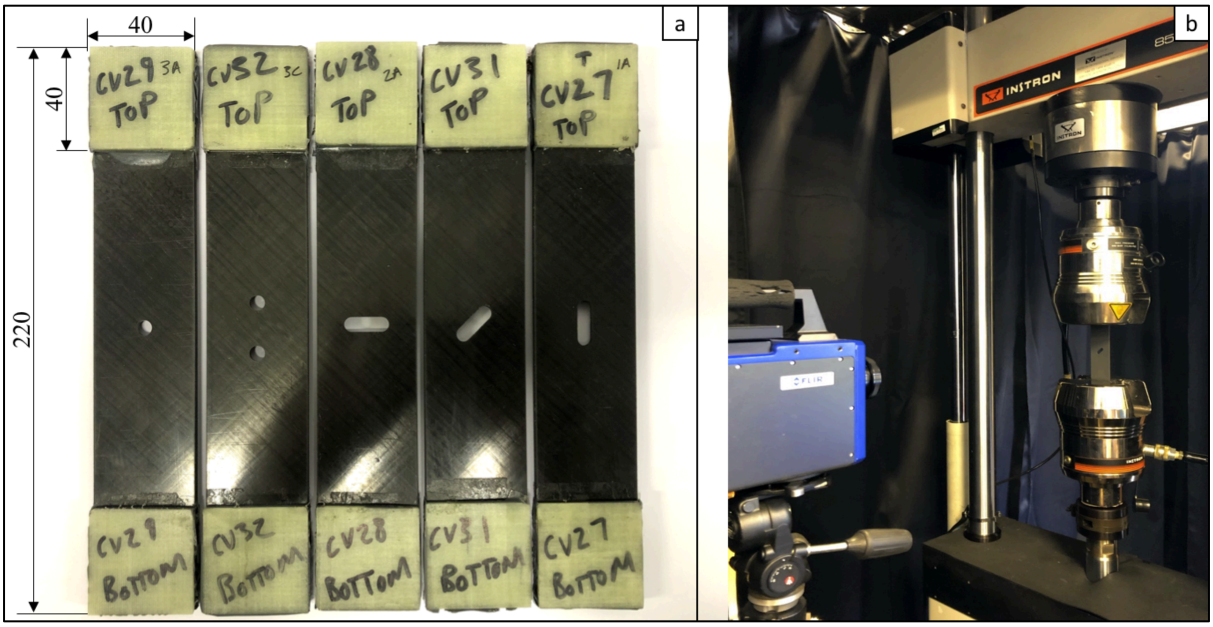

Fig. 1 *– a) Manufactured specimens before graphite paint was applied (dimensions in mm). b) Experimental setup*

Specimens were cyclically loaded in an Instron 8501 universal testing machine (Instron, Buckinghamshire, UK). A standard test setup is shown in Fig. 1b. 19Hz sinusoidal loads were applied to all specimens, with the amplitude and mean loads chosen such that the stress ratio R (Fmin/Fmax) = 0.1. Load values were adjusted for the different geometries to allow for damage development on a reasonable timescale, i.e., < 10 hours (684×10^3 cycles). The specimens were loaded to failure and TSA maps were collected at 6 second intervals using a DeltaTherm 1780 system (Stress Photonics, Madison WI, USA), which combines a SC7650 cooled infrared photon detector (FLIR, OR, USA) with DeltaTherm processing software. Exemplar uncalibrated TSA maps from the coupon geometries shown in Fig. 1a are illustrated in Fig. 2.

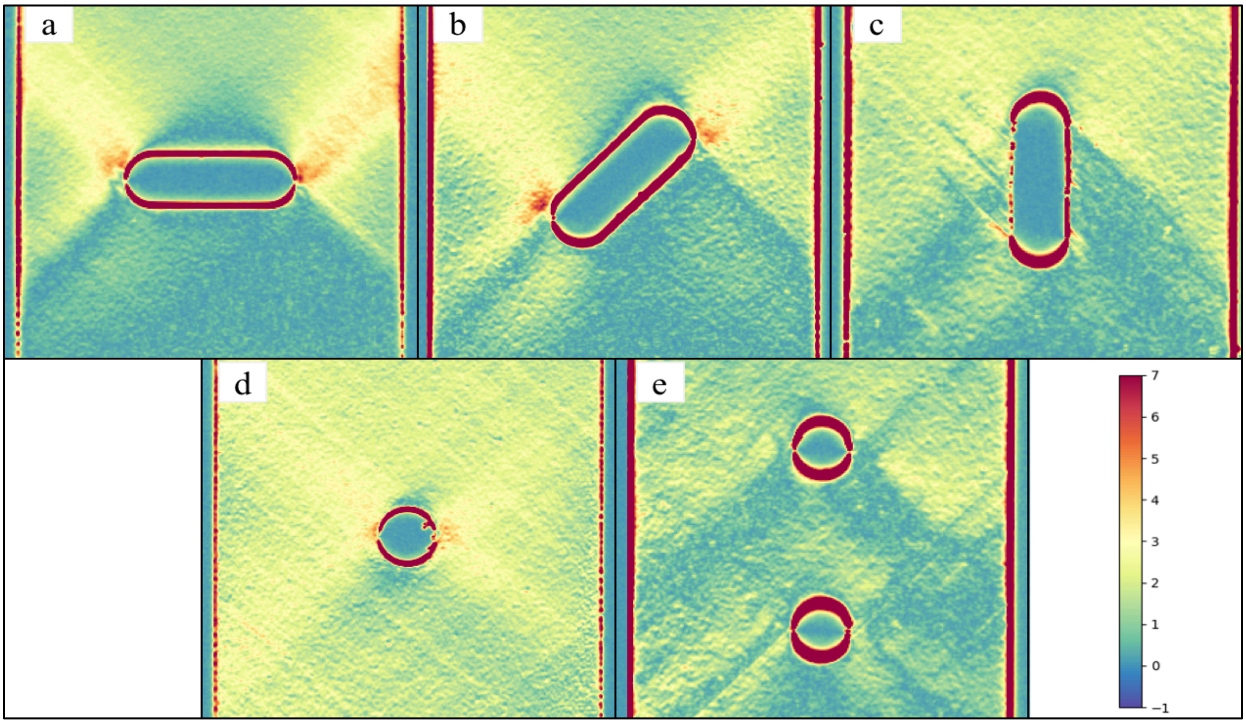

Fig. 2 *- Exemplar uncalibrated TSA maps from all specimen geometries. Colour scale indicates uncalibrated TSA units. a) 90° slot, b) 45° slot, c) 0° slot, d) One hole, e) Two holes. In all cases the specimens were 40mm wide.*

The dimensionality of the TSA maps was reduced by projecting them onto a set of discrete 2D Chebyshev polynomials [8]. This resulted in a map being represented by a comparatively small number of coefficients which were then collated into a feature vector representing the stress-field on the specimen at a particulate instant in time. Time-varying feature vectors can be used to monitor the change in the uncalibrated TSA maps that occurs as damage propagates and develops in the selected regions [5, 7]. The Euclidean distance between the initial feature vector at the start of the test and subsequent feature vectors was calculated to provide a scalar value referred to as the feature vector difference (FVD). FVD can be used as a damage metric for tracking changes in the uncalibrated TSA data from the initial (reference) feature vector as a result of damage development in the form of delaminations and cracking.

RESULTS AND DISCUSSION

Due to the inherent variability of composite materials microstructure, there was a large range of cycles to failure across the same geometry specimens for identical loading conditions; however, similarities between the magnitude of the FVD and lifespan of the specimens indicated that there was a correlation whic could be exploited for the derivation of an empirical model. Empirical models were developed using training datasets for same geometry specimens using Gibbs sampling performed with the software JAGS [9]. A sample empirical model for 90° slotted specimens (Fig. 2a) can be seen in Fig. 3.

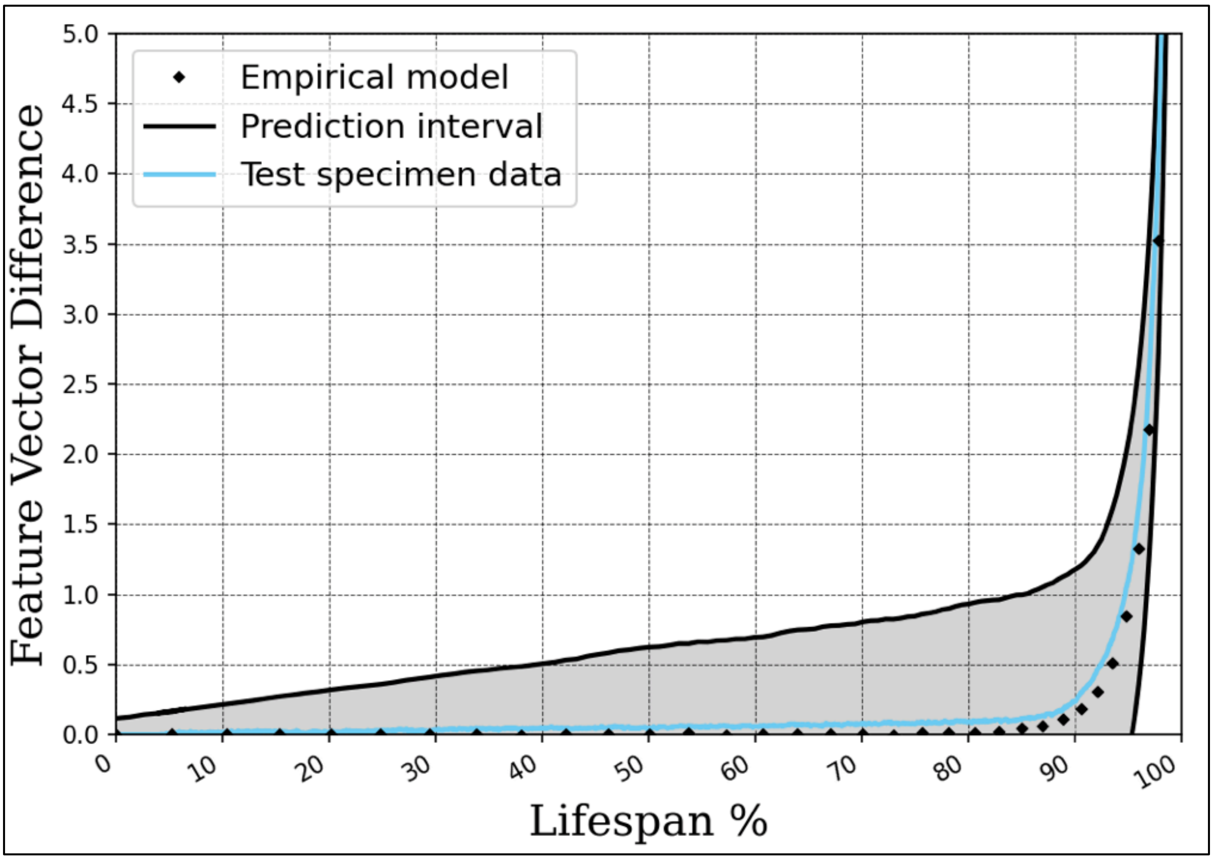

Fig. 3 *- Predictions from an empirical model for a 90° slotted specimen shown as black diamonds. Model prediction interval is shown as the black solid lines. Blue solid line shows corresponding test dataset that was not used for training the model.*

The model in Fig. 1 can be seen to follow the trend of the test data set successfully, illustrating that by using such models there is the potential to predict the remnant life of composite components using uncalibrated TSA measurements. Model performance was assessed by using Leave One Out Cross Validation (LOOCV) on the specimen datasets by using their FVD values to determine lifespan predictions from the model. The results from the LOOCV indicate that the model's performance improved towards the end of a test when the specimen is transitioning from steady state damage growth to fast fracture and failure.

CONCLUSION

Work on applying a strain-based defect assessment to components with complex geometries has been performed through fatigue loading carbon fibre composite coupons with different geometries and collecting and processing full-field TSA measurements. It has been shown that the full-field uncalibrated TSA data can be used to successfully track damage development over time through quantitative measurements of a feature vector difference (FVD) between initial and current maps of data. The potential to predict the remnant life of composite components using uncalibrated TSA measurements was demonstrated through the development of an empirical model.

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