FULL FIELD NON-DESTRUCTIVE EVALUATION OF COMPOSITE STRUCTURES USING VIBRATION BASED LOADING

Rachael C. Tighe[1] and Janice M. Dulieu-Barton[2]

[1]Faculty of Engineering and the Environment, University of Southampton, Southampton, UK.
Email: [1]R.C.Tighe@soton.ac.uk, [2]janice@soton.ac.uk

Keywords: Non-destructive evaluation, thermoelastic stress analysis, digital image correlation, vibration loading, full field techniques.

Abstract

The present work provides a step towards a combined strain based non-destructive evaluation procedure able to identify and quantify the effect of defects more fully, particularly when examining component performance in service applications. Complimentary information is extracted from thermoelastic stress analysis, which provides stress data, and digital image correlation, which provides displacement data from which strain may be derived. Thermoelastic stress analysis provides high spatial resolution but provides a stress sum, which is not a failure criterion. Digital image correlation can be limited in spatial resolution but provides component strains. If these datasets are brought together it may then be possible to say something about the remnant life of a component. Vibration based loading enables both techniques to be used outside the laboratory. A lock-in digital image correlation approach enables the use of low cost detectors to obtain high spatial resolution data using a lower frame rate and without the need to synchronize to loading. Glass fibre reinforced plates have been used to demonstrate the approach where excited mode shapes have been identified. Work is progressing to develop the approach to enable accurate defect quantification.

1. Introduction

Thermoelastic stress analysis (TSA) is an established active thermographic approach which uses an infrared detector to monitor the surface temperature of a component as it is subjected to cyclic loading in the elastic region of the material. The thermoelastic effect relates this temperature change to the sum of the principal stresses [1]. Digital image correlation (DIC) tracks features on the surface of a material to establish a displacement field which may then be converted to a strain field [2]. DIC is limited in spatial resolution and so areas with high displacement or strain gradients, such as around defects, are not well resolved, without resorting to high magnification optics and hence limiting the field of view. TSA has high spatial resolution but can only provide the principal stress sum, which is not a failure criterion. By using the two techniques a more complete picture of the structural response to loading is obtained.

Laboratory based loading for TSA and DIC is typically imparted using a test machine. The signal processing in TSA uses a lock-in algorithm to relate the cyclic loading to the recorded temperature change. To use DIC to monitor deformations during a cyclically loaded event typical approaches are to increase the frame rate of the detector, often at the sacrifice of spatial resolution, or to synchronise data capture to load peaks [3]. These approaches either reduce the information gathered during testing or add complexity to experimental arrangements. The current work uses a lock-in algorithm as in TSA to create lock-in DIC (LIDIC) [4]. LIDIC enables high spatial resolution cameras with lower frame rates to be used to collect such data. Using the lock-in approach for both data collection sets enables higher

Excerpt from ISBN 978-3-00-053387-7

frequency excitations to be used such as in the current work where a vibration-based loading system is used.

In [4] strain data is extracted using a single camera setup examining in-plane strains in a Brazilian disc, the present paper uses the lock-in approach with stereo DIC to study the mechanical behaviour of composite components. Composite plates are subject to resonant frequency loading using a portable loading device, i.e. 'remote loading'. Complimentary information is extracted from the TSA, giving a stress map, and the LIDIC, giving a displacement map. Ongoing work seeks to improve the spatial resolution in the LIDIC around features in the plates to enable strain data to be extracted and more detailed information around defect sites to be collected. The work provides a step towards a combined strain based non-destructive evaluation procedure able to identify and quantify the effect of defects more fully, particularly when examining component performance in service applications.

2. Methodology

2.1. Specimens and preparation

GFRP plates were manufactured using a 300gsm E-glass unidirectional epoxy prepreg. The plates were manufactured using three plies of the material [0, 90, 0], to give a plate thickness of 0.9 mm, with 0 along the short axis of the plate. Three of the plates contained simulated defects including a fold, a ply cut transverse to the fibres and a section of the ply removed – referred to as 'box cut'. All simulated defects were created in the central ply. The rig comprised a steel frame that clamps the plate to a stand to model a fully built in plate. The dimensions of the unclamped area were 330 x 203 mm.

In TSA it is preferential to have a high and uniform emissivity surface. This is typically obtained by coating the surface of components with a thin layer of matt black paint. In DIC it is necessary to have a random pattern on the surface of a component which has sufficient contrast to enable tracking of the plate deformation. This is typically in the form of a spray paint speckle pattern. It is generally accepted [5] that a white background with black speckles provides a higher level of contrast and the white background has a naturally higher grey level variation thus adding to the uniqueness of a subset compared to a black background. However when a white background speckle pattern was used an increased amount of reflections were visible in the thermal data. Therefore a black background with white speckles was selected, which did not have a noticeable effect on the TSA.

2.2. Experimental set-up and data collection

A schematic of the experimental set up is provided in Figure 1. The load was imparted into the plates using a permanent magnet shaker (LDS V201) which was positioned below the plate and attached using a rigid stinger. The stinger was positioned at the location of the expected peak of displacement for the second mode as it was possible to excite both first and second modes from this positon. A strong connection was made between the plate and the stinger using beeswax; this enabled easy removal and repositioning. A signal generator was used to excite the shaker while the reference signal for lock-in processing was collected using a force transducer attached to the stinger. The data and reference signal were recorded using the appropriate white light or IR detector software. TSA was undertaken using a FLIR SC5000 IR detector capable of a maximum full frame rate of 383 Hz and has a listed thermal sensitivity of 20 mK. By using the lock-in technique this may be reduced to the order of 4 mK. The software used to collect and process the TSA data were Altair and Altair LI respectively. 3D DIC was carried out using two LaVision E-lite 5 MP cameras with 50 mm Nikon lenses. The data were collected and processed using the DaVis software. The DIC data were then exported to Matlab where the lock-in processing was performed.

Excerpt from ISBN 978-3-00-053387-7

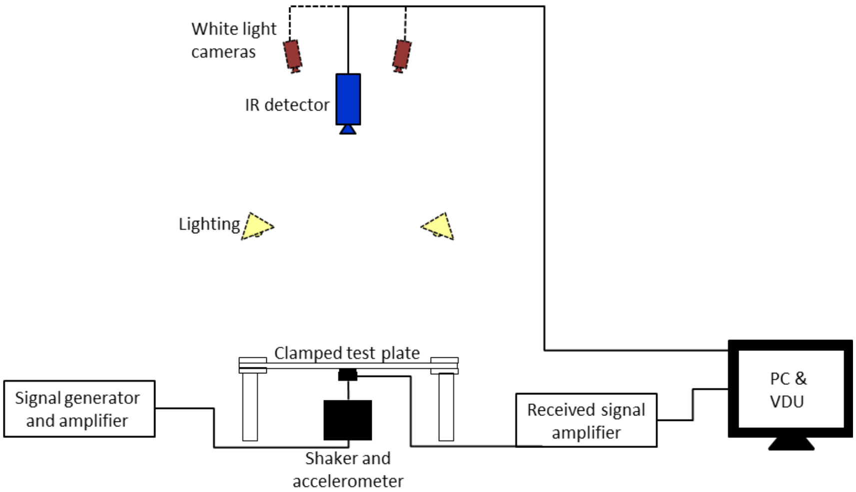

Figure 1. Schematic of experimental set-up.

Excitation and data collection parameters used in the experiments are given in Table 1. The integration time or exposure time was set to 700 μs for both IR and white light cameras to avoid blurring.

Table 1. Excitation and data collection frequencies for mode one and mode two excitation.

Mode	Excitation frequency (Hz)	TSA frame rate (Hz)	TSA data collection duration (s)	DIC frame rate (Hz)	DIC data collection duration (s)
1	90	383	5.2	1.5	200
2	110	383	5.2	1.5	200

3. Results

3.1. Control plate

The results for the GFRP control plate excited at its second mode are presented in Figure 2. In Figure 2a TSA data is presented as ΔT/T data which is directly related to the sum of the principal stresses and in Figure 2d LIDIC data is presented in terms of out of plane displacement. Line plots taken horizontally across the centre of the plate in both data sets are shown in Figures 2b and e. Finally the phase data relative to the reference data collected from the force transducer for both data sets is also shown which illustrates the synchronisation of the load signal and the reconstructed displacement / recorded IR signal.

The effect of the stinger is apparent in the thermoelastic data where large concentrations in the response are visible in the ΔT/T data and the line plot, as indicated in Figure 2a. This concentration around the stinger location causes a bias in the TSA data compared to the expected form of two peaks of similar magnitude and shape. Aside from this concentration the TSA data appears to show the expected pattern for the excitation of the second mode in the control plate. The LIDIC displacement data also captures the mode shape. A decrease in spatial resolution is to be expected when comparing LIDIC and TSA as TSA uses each pixel recorded as a data point where as LIDIC requires pixel subsets thus reducing the number of data points. The LIDIC line plot taken across the plate provides a mode shape closer to that expected however it highlights that the stinger location is limiting the displacement of the left peak thus leading to a lower displacement measurement. This corresponds with the high stress concentration found in the TSA data. As expected the two halves of the plate are found to be out of phase with each other due to the second harmonic excitation. The TSA phase data in

Excerpt from ISBN 978-3-00-053387-7

Figure 2c is highlighting where the stress changes are position on one half of the plate and negative on the other or vise versa while the LIDIC phase data in Figure 2f highlights the displacement on one half of the plate is positive while the other is negative and vice versa due to the excited vibration mode The control plate modal excitation data sets give confidence in the success of the under sampling and lock-in approach used in the DIC data collection.

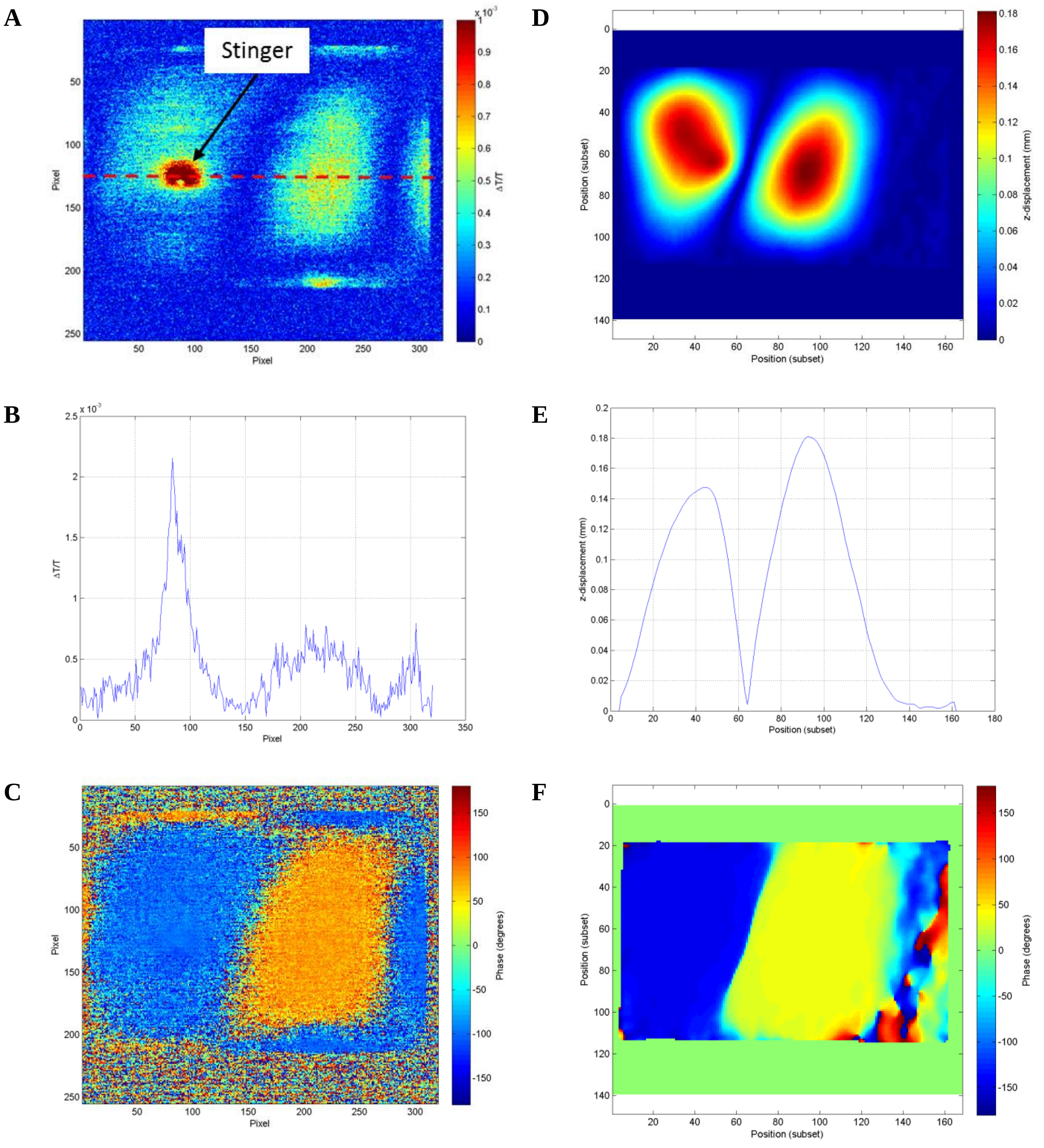

Figure 2. GFRP control plate second mode – TSA data a) ΔT/T, b) ΔT/T horizontal profile at pixel 130 and c) phase data; LIDIC data d) z-displacement, e) z-displacement horizontal profile at subset 70 and f) phase data.

Excerpt from ISBN 978-3-00-053387-7

3.2. Damaged plates

The TSA ΔT/T data for the GFRP plates with the box cut and ply cut in the central ply is provided in Figure 3. The plate is excited at the same frequency as the control panel at 110 Hz, i.e. the expected natural frequency of an undamaged plate to allow comparison of the response of a damaged and undamaged component. The mode shape in the box cut plate shown in Figure 3a is very different to that obtained for the control panel. The TSA data for the box cut plate, identifies the edges of the cut (highlighted by the yellow box) as there is a local change in stiffness where the region of material has been removed. The stress concentration created by the ply cut is also identified by TSA as shown in Figure 3b.

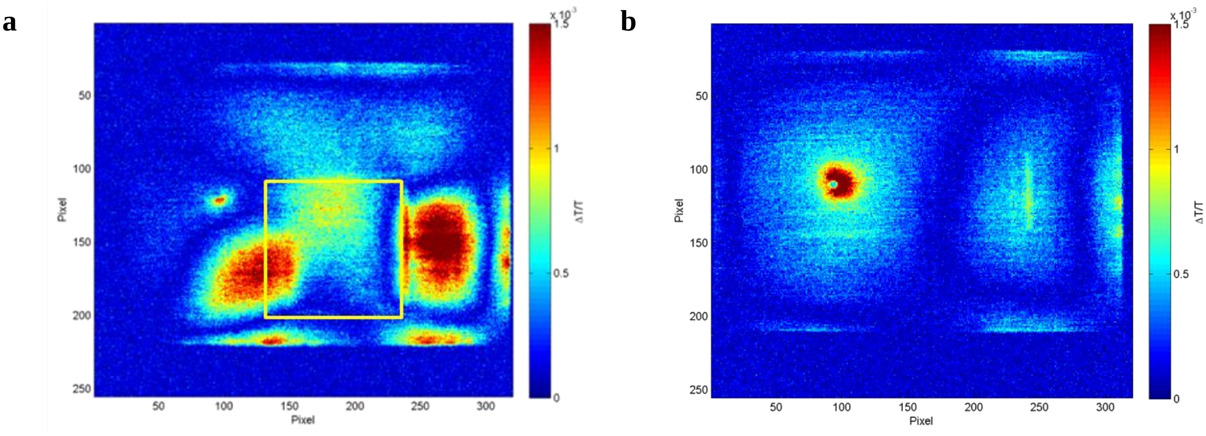

Figure 3. TSA data for a) box cut (yellow box highlights cut area) and b) ply cut plates.

4. Conclusions

TSA and LIDIC have been successfully used to identify mode shape of vibration loaded GFRP plates enabling data to be captured at loading frequencies far greater than the LIDIC sampling rate. It has been shown that through selection of the correct sampling parameters it is possible to apply a lock-in algorithm to reconstruct the data and produce lock-in DIC taken during a dynamic cyclically loaded test. The present work is the first step towards using such low cost cameras for LIDIC. While mode shapes have been identified in the control plate using LIDIC the means to accuratly identify damage using LIDIC is ongoing. Initial trials have shown that the excited mode shape created can mask the damage during LIDIC reconstruction. Future work will focus on addressing this by: firstly, increasing the spatial resolution particularly examining the ply cut plate where sharp strain gradients are present. Secondly, the overall mode shape must be removed from the data to reveal only the effect of the defect and enable the strain concentrations caused by defects to be extracted.

References

[1] Dulieu-Barton J.M., Thermoelastic Stress Analysis, in: Rastogi P., Hack E. (Eds.), Optical Methods for Solid Mechanics, Wiley, 2012.

[2] Chu T.C., Ranson, W.F., Sutton, M.A. and Peters, W.H. Applications of digial-image-correlation techniques to experimental mechanics, *Experimental Mechanics*, 25: 232-44, 1985.

[3] Risbet, M., Feissel, P., Roland, T., Brancherie, D., and Roelandt, J.-M., Digital image correlation technique: application to early fatigue damage detection in stainless steel, *Procedia Engineering* 2: 2219-2227, 2010.

[4] Fruehmann R.K., Dulieu-Barton, J.M., Quinn, S. and Tyler, J.P. Digital image correlation applied to cyclically loaded components. *Optics and Lasers in Engineering*, 68: p. 149-59, 2015.

[5] Crammond, G., Boyd, S.W., and Dulieu-Barton, J.M., Speckle pattern quality assessment for digital image correlation, *Optics and Lasers in Engineering*, 51: 1368-1378, 2013.

Excerpt from ISBN 978-3-00-053387-7