Novel Strain Based NDE (SBNDE) methodology for online inspection and prognostics of composite sub-structures with manufacturing induced defects: final report

J. M. Dulieu-Barton (JMB) (PI), O.T. Thomsen (OTT) (CI) and I. Sinclair (IS) (CI)

Faculty of Engineering and the Environment, University of Southampton (UoS), UK

Executive summary

To save time and reduce wastage it is essential that an inspection technology is developed that can be used to intervene at the manufacturing stage and provide high fidelity data for model based prognostic capability (beyond simply sizing defects) to further inform the decision process of 'accept', 'rework', 'repair' or 'scrap'. To this end a novel inspection procedure for cured composite components was developed, which has the ability to provide high fidelity local strain/stress data to inform model-based prognostics and define how a given defect will evolve under service load. The novelty is based on the ability to simultaneously measuring the strain and a stress measure or metric in the vicinity of a manufacturing defect or intrinsic subsurface artefact incl. variability of fibre volume fraction and fibre orientation, wrinkles, etc, and not just the geometry and size.

To apply the fundamental conceptual idea successfully significant innovation is required to mimic the service loading mode on **high value manufactured components**, e.g. aerospace components, so the strain/stress distribution in the neighbourhood of the defect is representative. Knowing the strain/stress distribution gives additional information and inputs to models and, along with the component material properties, enables a prognosis on if and how the defect would grow.

To understand the mechanisms contributing to material heterogeneity in **high volume manufactured parts**, a study of discontinuous compression moulded composite materials was conducted. Surface strains and stresses have been extracted and X-ray CT has been used to quantify volumetric variability in local resin volume content and distribution of local fibre orientations. A novel approach has been demonstrated that allows (very) rapid and potential in-situ manufacturing inspection of parts based on vibration based loading with the potential to link the complex response from the material surface to be linked to the manufacturing procedure.

The feasibility study took place over 9 months from 1st April 2017 to 31st December 2017. The primary part of the funding was for a Research Assistant, Dr Daniel Bull who was funded for 5 months from the Hub funding and 1 month from UoS sources. The funding also covered some of the costs associated with using the testing and imaging facilities at UoS and some of the consumable items to manufacture tests rigs used during the project period. The funding also covered some of Dr Daniel Bull's travel and accommodation costs associated with his participation in the ICCM21 (Xi'an, Chine 2017). The costs of the other dissemination activities associated with the feasibility study and carried out by OTT and JMB were covered by UoS.

Project aim, objectives and next steps

The overarching aim is to devise is a system that can be deployed alongside current inspection approaches in the production environment. When defects or subsurface artefacts including variability of fibre volume fraction and fibre orientation have been detected, the system would be deployed to determine if the component is fit for service, requires repair or is scrapped. The system would be flexible, portable, lightweight and robust. The objectives of the feasibility study were:

(i) To establish the underlying physical principles, and to demonstrate the viability of the experimental methodology based on combining thermoelastic stress analysis (TSA) and digital image correlation (DIC) and collecting data simultaneously.

(ii) Demonstrate that the data necessary for the model based prognosis system could be obtained by demonstrating the viability of the approach at a sub-structural level.

It has been fully demonstrated that DIC and TSA can be used simultaneously to collect data from composite components.

The approach has been demonstrated on a high value carbon fibre reinforced aircraft composite component, and it has been shown that the results can be linked to the findings of high fidelity prognostic FE models, with defect geometry defined by X-ray CT. The work has been presented at ICCM21 and in various other fora (see below). A journal paper is in preparation, a first draft (under review by JMB and OTT) has been prepared and is attached (not for circulation). This work was carried out in conjunction with Bath and Bristol Universities and shows how the TSA and DIC data can be linked to high fidelity models. A key outcome of this work is that a Programme Grant application has been submitted to EPSRC, the outline has been accepted and is now progressing to full proposal stage; the focus of the PG is on structural response and certification of composite aerostructures, and not to inform the manufacturing process.

The approach has also been demonstrated on materials typical of those used in high volume manufacturing made from carbon fibre/epoxy discontinuous compression moulded preforms. The work has linked observations from X-ray CT to the mechanical response, and has demonstrated that the combination of DIC and TSA for assessment of the material quality/performance shows great promise. In particular it is possible to predict the localised stiffness variations, linked to local variability of fibre volume fraction and fibre orientation, throughout the preform. This indicates that the manufacturing control process could be directly informed/updated using the technique. It has also been demonstrated that the technique can be portable (i.e. no need for a test machine to load the components) by exciting the component briefly at its resonant frequency. The work on the discontinuous material will be presented at the Society for Experimental Mechanics conference in the US in June 2018, and a journal paper is also in preparation (an outline based on the SEM paper is attached).

The PhD study is focusing on developing a low cost infra-red camera for TSA. The work has revealed in the first 9 months what the scientific challenges are in developing the technology further, and provided the first steps in developing signal processing routines that will address the challenges. This work will be presented at the SAMPE2018 conference in Southampton in September.

A key scientific and novel outcome was fully integrating DIC and TSA techniques thus objective (i) has been achieved. The key challenge was in collecting the data simultaneously using lock-in processing for the DIC. Although the lock-in DIC was developed at UoS previously, it had not been deployed on a realistic component and not combined with TSA, which was achieved here and fulfilled objective (ii) of the feasibility study. The strain measurements from the DIC and the thermoelastic response, which is dependent on the local fibre orientations and fibre volume fractions have provided strong indication of identification of stiffness distribution and resin-rich volumes. To move this into the production environment it is necessary to remove the need for a test machine. It has been demonstrated that a vibration based approach to create loading at the specimen resonant frequency can be used on the high volume manufactured parts. The deformation required is small and is only applied for a few seconds and hence does not damage the part.

The technology developed in the feasibility study is new and the next steps will provide practical demonstrators based on a realistic high volume manufactured and high value manufactured components loaded either naturally or by excitation at their resonant frequency. Although the feasibility has been demonstrated, the work is at very low TRL and requires further EPSRC funding from the Hub as a core project to fully demonstrate that direct measures taken from an as manufactured composite components can be used to inform the manufacturing process. The focus of the further funding will be to link the TSA/DIC outputs directly to the how the material is formed during manufacturing. In draft paper 2 we have shown that by combining TSA and DIC there is a direct link to the stiffness changes in the discontinuous material, which warrants further investigation. It will also be necessary to reduce the costs of TSA and significant steps towards this are being achieved through a PhD study that would input into the work full proposal. A strong consortium with a focus on manufacturing of composite components both high value and high volume will be established to seek further funding from the future composites manufacturing hub. Luxfer have indicated their support to input into the high value manufacturing part of the project and are interested to understand if the combined TSA/DIC technique could be used to inform the consistency of the filament winding approach for overwrapped pressure vessels. We are yet to identify a collaborator from the high volume parts but it has been agreed with Professor Nicholas Warrior of Nottingham University that his team would be willing to collaborate on this aspect of the work. It is intended to submit the full proposal to the Hub in April 2018, with a start date of June/July 2018.

Outputs

1. Bull, D.J., Dulieu-Barton, J.M., Thomsen, O.T, Butler, R., Rhead, A.T., Fletcher, T.A. and Potter, K.D., "Reshaping the testing pyramid: utilisation of data-rich NDT techniques as a means to develop a 'high fidelity' component and sub-structure testing methodology for composites", Proc 21st International Conference on Composite Materials, Xi'an, China, 2017, 10 pages.
2. Dulieu-Barton and Thomsen O.T., "Towards a new paradigm for high-fidelity testing and integrated multi-scale modelling of composite substructures and components". Invited presentation at International Symposium "Novel Composite Materials & Processes for Offshore Renewable Energy" (Cork, 1 September 2017):
3. Dulieu-Barton and Thomsen O.T., "Towards a new paradigm for high-fidelity testing and integrated multi-scale modelling of composite substructures and components". Keynote presentation at 2nd International Symposium on Multiscale Experimental Mechanics (ISMEM 2017), DTU, Denmark, 8-9 Nov 2017.
4. Dulieu-Barton and Thomsen O.T., "Towards a new paradigm for high-fidelity testing and integrated multi-scale modelling of composite substructures and components". Seminar at University of Illinois at Urbana-Champaign, USA (9 June 2017).
5. Dulieu-Barton and Thomsen O.T., "Towards a new paradigm for high-fidelity testing and integrated multi-scale modelling of composite substructures and components". Seminar at Beijing Jiaotong University (9 August 2017).
6. Dulieu-Barton and Thomsen O.T., "Towards a new paradigm for high-fidelity testing and integrated multi-scale modelling of composite substructures and components". Seminar at Beijing Institute of Technology (10 August 2017).
7. Dulieu-Barton and Thomsen O.T., "Towards a new paradigm for high-fidelity testing and integrated multi-scale modelling of composite substructures and components". Seminar at Northwestern Polytechnic University, Xi'an (20 August 2017).

8. Bull, D.J., Thomsen, O.T and Dulieu-Barton, J.M., “Understanding heterogeneity in discontinuous compression moulded composite materials for high-volume applications”, to be presented at SEM Annual Conference, Greenville, USA.
9. I. Jiménez-Fortunato, Bull, D.J., Thomsen, O.T and Dulieu-Barton, J.M., “Towards integrating imaging techniques to assess manufacturing features and in-service damage in composite components ”, to be presented at SEM Annual Conference, Greenville, USA.
10. Bull, D.J., Butler, R., Rhead, A.T., Fletcher, T.A., Potter, K.D., Smith R.A., Dulieu-Barton, J.M., and Thomsen, O.T “First steps for reshaping the testing pyramid: integrated testing and modelling approach”, journal paper in preparation (see attached).
11. Bull, D.J., Thomsen, O.T and Dulieu-Barton, J.M., “Characterising the performance of discontinuous compression moulded carbon fibre materials using full-field imaging techniques”, journal paper in preparation (see attached).