Pervasive Stress Imaging for Experimental Validation of Structural Digital Twins

Nik Rajic[123a], Chris Brooks[1], Kheang Khauv[3], Ayman Mukhaimar[24], Ruwan Tennakoon[24], Fabio Zambetta[24], and Pier Marzocca[24]

[1] Defence Science and Technology Group, 506 Lorimer Street, Fishermans Bend, Australia,[2] School of Computing Technology and School of Engineering, RMIT University, Melbourne, Australia, [3] 1 MILLIKELVIN, 22B Trade Park Dr, Tullamarine, Australia, [4] Sir Lawrence Wackett Defence and Aerospace Centre, RMIT University, Melbourne, Australia

[a]nik.rajic@rmit.edu.au

Abstract. This paper describes a new approach to the experimental validation of structural models which has the potential to support the development of structural digital twins. The approach consists of two complementary elements: (1) a compact microbolometer based thermoelastic stress imaging capability with a paired visual sensor and (2) a computational framework for the transformation of experimentally obtained pervasive 2D stress imagery into a comprehensive 3D stress map. The utility of this new approach is demonstrated using a 3D-printed human mandible as a test subject. A 3D finite element model prediction of the thermoelastic response and bulk stress distribution is compared to a corresponding experimentally obtained 3D representation for an incision load case. The implications of this capability for the digital enterprise are discussed.

Background.

The structural certification of a new aircraft requires the undertaking of an exhaustive full-scale structural test program. One of the objectives of such a program is to provide empirical data for the experimental validation of structural modelling used to predict airframe life. While this data is traditionally obtained from electrical resistance strain gauges, supplementation with imagery from in situ thermoelastic stress analysis (TSA), particularly in structurally critical areas where high stress gradients preclude the use of gauges, can provide a significantly improved basis for validation, as demonstrated in the Joint Strike Fighter test program [F-35]. In that program and other similar cases (e.g. [2]), TSA was applied selectively to known areas of concern, which were identified by analysis or prior instances of structural failure. With the recent development of a multi-point TSA scanning capability [3] this approach can now be applied more pervasively, and therefore much earlier in a test program when it can have greater impact on activities including strain gauge placement, early model testing and refinement, and targeting of structural inspection and long-term monitoring.

This new pervasive approach was demonstrated recently in a full-scale fatigue test of an F/A-18 centre-barrel structure [3]. In this test, TSA imagery containing 100 million pixels was acquired using a multi-point system and then overlaid on a 3D digital representation of the structural geometry obtained via laser scanning, using a bespoke image superimposition algorithm developed for this purpose [4]. Fig. 1 provides an illustration of the stress-superimposed representation obtained using this capability, the 3D version of which can be viewed and analysed using virtual reality.

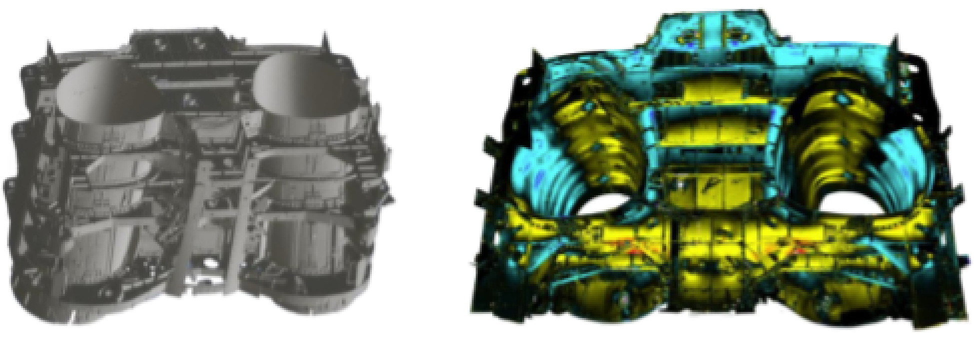

Fig. 1 3D CAD representation of an F/A-18 centre-barrel structure alongside a front-on view of a 3D stress superimposition consisting of over 100 million stress measurements obtained from the structure while undergoing a cyclic wing bending load case [3]. Warm hues correspond to tension and cold hues to compression.

Discussion.

While this capability was developed to support airframe full-scale structural testing, it is applicable to other platforms and other operational domains, i.e. civil, maritime, space etc. One of the more interesting potential uses is in support of structural digital twin (SDT) development.

An SDT is a dynamic, virtual representation of a physical structure, such as an aircraft, ship, submarine, bridge, prosthetic etc., that can mirror important characteristics and behaviours under various operational conditions. It integrates real-time data from sensors and other sources to continuously update and simulate the structure's state, enabling real-time monitoring, predictive maintenance, performance optimisation, and decision-making support. The potential benefits of an SDT are significant, and include reduced platform sustainment and operating costs, as well as increased availability, safety and life. Of course, these benefits are contingent on an SDT having the necessary level of fidelity and predictive capability, which may be challenging to obtain if airframe full-scale structural testing is any guide; where despite considerable investment and effort in structural model development and validation, unpredicted structural test outcomes, up to and including catastrophic failure, are not uncommon. It is reasonable to surmise therefore that experimental validation will be as central to the development of SDTs as it currently is to aircraft structural certification. Arguably, the predictive capability necessary to fully deliver on the promise of an SDT may require an even higher standard of experimental validation.

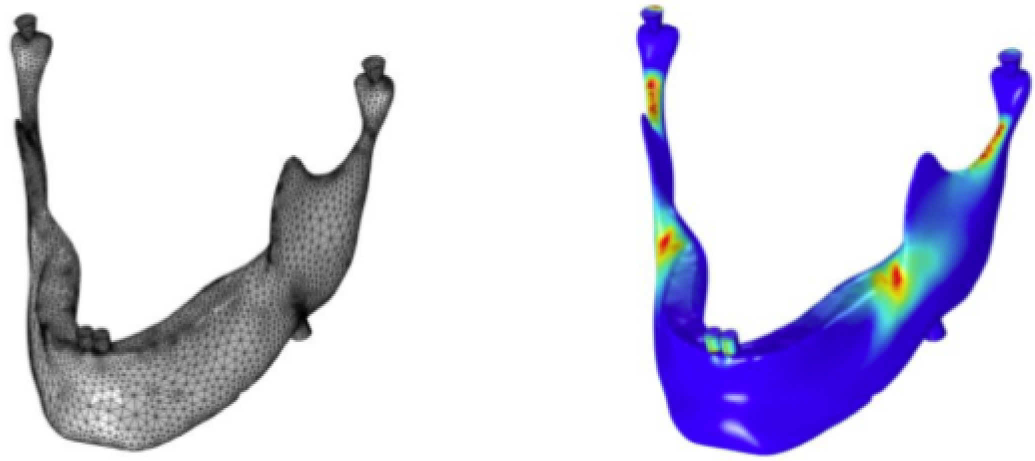

Fig. 2 Finite element mesh representation of a 3D printed human mandible and a corresponding bulk stress distribution for a load case involving incisor engagement with a rigid object, where warm hues correspond to elevated tensile stress.

This presentation will demonstrate how a pervasive stress imaging approach combined with 3D visualisation can support a requirement for rigorous experimental validation. The test subject is a synthetic human mandible, which was selected for two main reasons. Firstly, it contains sufficient geometric complexity to showcase the generality of the approach, and secondly, it was produced using additive manufacturing which is another revolutionary Industry 4.0 technology that poses challenging structural certification problems that the present validation approach could help to overcome. Figure 2 shows a finite element mesh representation of the mandible subject and a corresponding prediction of the bulk stress distribution for a simple incisor engagement load case.

In this presentation, multi-physics finite element predictions of stress state and thermoelastic response will be compared to corresponding 3D representations obtained experimentally from the physical structure using the described approach. Experimental data is sourced from a new stress-imaging device that contains both infrared and visual channels that are paired to facilitate rapid superimposition of stress imagery on digital CAD representations of a physical structure. The presentation will describe the key hardware and software components of this capability, discuss the main sources of discrepancy between 3D predictions and experimental observations of stress state and how such discrepancy can guide model improvement and refinement, and finally it will canvass some of the implications of this capability for the digital enterprise and Industry 4.0 more generally.

References

[1] N. Rajic, D. McSwiggen, M. McDonald, and D. Whiteley, *In Situ Thermoelastic Stress Analysis – An Improved Approach to Airframe Structural Model Validation*, Quantitative Infrared Thermography Journal, 16(1), 2019. 119-128

[2] N. Rajic., D. Rowlands, and K. A. Tsoi., *An Australian perspective on the application of infrared thermography to the inspection of military aircraft.* 2nd International Symposium on NDT in Aerospace 2010. 2010.

[3] N. Rajic, C. Brooks, S. van der Velden, P. Muir, K. Khauv, A. Mukhaimar, R. Tennakoon, F. Zambetta, and P. Marzocca, *A stress imaging capability for the digital enterprise*. In AIAC 2023: 20th Australian International Aerospace Congress: 20th Australian International Aerospace Congress (pp. 32-38). Melbourne: Engineers Australia.

[4] A. Mukhaimar, R. Tennakoon, N. Rajic, F. Zambetta, P. Marzocca, R. Hoseinnezhad, C. Brooks, S. Van Der Velden, and K.Khauv. *Stress visualization in geometrically complex structures using Thermoelastic Stress Analysis and Augmented Reality*. In Proceedings of the 29th ACM Symposium on Virtual Reality Software and Technology, pp. 1-2. 2023.