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Identification and characterization of damaged fiber-reinforced laminates in a Bayesian framework

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Abstract. Non-destructive testing of damaged composite laminates modeled from the homogenization of fiber-reinforced polymers has always been and still is a challenge, both by its underlying complexity and the difficulties encountered in the quantification of uncertainties related to the identification and characterization of defects. In order to provide a rigorous framework that accepts data from different modalities and allows data fusion as well, we propose here a Bayesian neural network (BNN) [1] with two input streams, with a focus on local inter-layer delaminations identification and characterization.

Keywords. thermography, composites, Bayesian neural network, data fusion

Composite materials are widely used in numerous fields, ranging from the automotive industry to green engineering, due to their low cost and lightness. Additionally, their superior strength/ and stiffness/weight ratios vs. traditional materials make them appealing. Yet their non-destructive testing may be highly challenging, with the need for more modeling and computational imaging, before envisaging sound laboratory-controlled experimentations.

Active thermography as a contactless procedure is more and more used for the inspection of isotropic workpieces, refer to [2] and references therein, but an increasing volume of contributions appears on fibered laminates, with a strong emphasis on carbon-fiber-based ones, those exhibiting high anisotropic behavior due to their thermal conductivity function of orientation, e.g., [3], as illustrated in the recent review [4].

The above stated, focused on thermographic modalities of inspection, one needs (i) proper mathematical and physical models of damaged laminates, (ii) versatile enough codes that can provide a good amount of accurately simulated data when those assumed to be inspected by both modalities, and last but not least, (iii) efficient computational imaging tools that can use in an optimized fashion the information provided by the data. The three-fold challenge is strong and from the start one needs simplifications.

The first simplification is that intact laminates are homogeneous per horizontal ply and exhibit within each ply a uniaxial anisotropic behavior, which is manifested by a transverse and a longitudinal thermal conductivity.

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The second simplification is that damages generally can be seen as thin flat delaminations occurring between plies, which are amenable in thermography (in the case of a flash lamp as a heat source at least) to an extension of the Truncated Region Eigenfunction Expansion (TREE).

The third simplification is that one has available imaging tools that can cope with data provided by the modality(ies). Data fusion can be approached in the context of an active thermography procedure with the use of two (or more) IR cameras capturing the temperature evolution on the top and bottom surfaces of the part, which can be considered as two fusionable data streams, making data fusion more readily available. So, if data simulated on a host of damages, double-stream convolutional neural networks (CNN) appear as the way forward, also having insurance that brute force codes (FEM) could always provide good data, if the semi-analytical algorithms were to fail in some cases. This approach was shown highly effective in [8].

However, because of the large number of parameters included in a deep learning model, many questions arise about their initialization, while other questions also arise about the quantification of uncertainties as well as the existence of a physical framework in what may look like a black box. To tackle this problem, BNNs have become highly attractive due to their ability to quantify uncertainties [9]. Thus, the combination of knowledge related to the data and the Bayesian model should allow a rigorous and precise identification, while ensuring a detailed characterization, reinforced by quantification of the uncertainties.

To conclude, this investigation aims at pointing out that semi-analytical solutions are indeed capable at least in simple enough cases (thin inter-layer delaminations) to yield proper data to mimic thermographic inspections, once accounted for homogenization of the intact structures. Then, data can be used and/or fused like was done by the authors and co-workers in breast imaging [8], [10] but in a Bayesian realm enabling uncertainty quantification.

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