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# Data fusion and non-destructive testing of damaged fiber-reinforced laminates

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**Abstract.** Efficient strategies for non-destructive testing of damaged composite laminates modeled from homogenization of fiber-reinforced polymers could involve fused data. Here, those are from electromagnetic and infrared thermographic modalities, for which semi-analytical models of the interaction are available. Focus is on inter-layer delaminations. Paths forward are outlined, mostly within the realm of Bayesian approaches and of convolutional neural networks, both of wide breadth and the second ones not involving too many prior regularization factors.

**Keywords.** Electromagnetics, thermography, composites, data fusion

Composite materials are widely used in automotive industry, aeronautics, and green engineering, since low cost, light weight, and of large strength/ and stiffness/weight ratios vs. traditional materials. Yet their non-destructive testing may be highly challenging, with 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 inspection of isotropic work pieces, refer to [1] and references therein, but an increasing volume of contributions appears on fibered laminates, with strong emphasis on carbon-fiber-based ones —those exhibiting strong anisotropic behavior due to their thermal conductivity function of orientation, e.g., [2]— as illustrated in the recent review [3], with deep learning coming also to the fore [4]. In rather sharp contrast, electromagnetic probing of such composite structures appears much less studied, possibly since standard eddy-current probes tend not to work so well for carbon-fiber-based laminates, and may call for tailor-made sensors [5] in the MHz range and beyond, so as usual eddy-current hypotheses fail.

The above stated, focused on thermographic and electromagnetic 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) computational imaging tools that can fuse in a proper way the information which those data provide independently, with the benefit of absence of registration since the structure is unchanged during testing. The three-fold challenge is strong and simplifications are needed.

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The first simplification is that intact laminates are homogeneous per horizontal ply and exhibit within each ply an uniaxial anisotropic behavior, which is manifested by a transverse and longitudinal dielectric permittivity or thermal conductivity, being underlined that one has the joint benefit that first-order electromagnetic homogenization [6] holds close to the same in thermography.

The second simplification is that damages generally can be seen as thin flat delaminations occurring between plies, which is not too demanding for the electromagnetic Green-dyadic-based semi-analytical approaches in [7], while they are amenable in thermography (in the case of a flash lamp as heat source at least) to extension of the Truncated Region Eigenfunction Expansion (TREE), so far applied to isotropic laminates [1], since only the heat equation is impacted by the uniaxial behavior.

The third simplification is that one has available imaging tools that can cope with data provided by the two modalities. So, if data simulated on a host of damages, double-stream convolutional neural networks (CNN) appear 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] for fused ultrasound and microwave imaging, if enough physics within it to guide to sound solutions, with the additional advantage that a stand-alone solution with a single modality can always be developed. With now the advantage of far less data needed than with CNN, the Bayesian framework as also devised for breast imaging in [9] enables in principle to bypass the need of many priors on regularisation factors (those are produced in effect during the construction of the maps of the damages) while there should be good profit in the Bayesian formalism to draw from the assumption of thin delaminations.

To conclude, this preliminary investigation aims at pointing out that data fusion should enable testing of carbon-fibered-based laminates. Semi-analytical solutions are indeed capable at least in simple enough cases (thin inter-layer delaminations) to yield proper data to mimic electromagnetic and thermographic inspections, once the intact structures properly homogenized. Then, data from both modalities could be fused, e.g., in deep learning and Bayesian realms, as inspired, e.g., from [8,9].

## References

- [1] A. Ratsakou *et al.*, Shape reconstruction of delamination defects using thermographic infrared signals based on an enhanced Canny approach, *Infrared Phys. Technol.* **111** (2020), 103527.
- [2] S. Bard *et al.*, Influence of fiber volume content on thermal conductivity in transverse and fiber direction of carbon fiber-reinforced epoxy laminates, *Materials* **12** (2019), 1084.
- [3] F. Ciampa *et al.*, Recent advances in active infrared thermography for non-destructive testing of aerospace components, *Sensors* **18** (2018), 609.
- [4] Z. Tong *et al.*, Automated defect detection in CFRP using flash infrared thermography and deep learning method, *2nd European NDT & CM Days*, Prague, *NDTnet 2021-12* (2021), 10 pp.
- [5] H. Heuer *et al.*, Review on quality assurance along the CFRP value chain – Nondestructive testing of fabrics, preforms and CFRP by HF radio wave techniques, *Composites Part B*, **77** (2015), 494–501.
- [6] C. Li and D. Lesselier, On homogenization of fiber-reinforced polymers, *Radio Scie. Lett.* (2022), to appear, 5 pp.
- [7] Y. Zhong *et al.*, Fast calculation of scattering by 3-D inhomogeneities in uniaxial anisotropic multilayers, *IEEE Trans. Antennas Propagat.*, **62** (2014), 6365-6374.
- [8] Y. Qin *et al.*, Breast imaging by convolutional neural networks from joint microwave and ultrasonic data, *IEEE Trans. Antennas Propagat.* (2022), Early Access, 12 pp.
- [9] Y. Qin *et al.*, Fused microwave and ultrasonic breast imaging within the framework of a joint variational Bayesian approximation (2022), submitted.