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Optimising test sequences for robust material identification using a data assimilation approach

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Abstract — This study investigates the optimisation of test sequences for robust material identification. Traditional approaches for constitutive behaviour characterisation usually consist in a sequence of independent identification problems, each one considering one single experiment and a small subset of parameters. Conversely, data assimilation approaches consider all measurements stemming from all experiments at once. This work demonstrates the potential of data assimilation to improve multiple parameters identification by optimising the experimental set-up of the tests sequence.

Keywords — Identification, Inverse methods, Optimisation, Full-field measurement, Uncertainties.

Introduction Image-based full-field measurements have had a significant impact on material characterisation, by providing a wider range of data compared to traditional mechanical tests (*e.g.*, strain measurements using strain gauges). For constitutive parameters identification, full-field measurements opened new paradigms, one of those being the possibility of identifying various parameters at once [1, 2]. However, it has also introduced challenges such as determining parameter sensitivity within the measured field, and quantifying uncertainties affecting these parameters, in relation with data noise [3]. Consequently, there is a growing interest in exploring different test configurations to take advantage of full-field measurements, while addressing their specific requirements. In this context, optimal tests design aims at improving parameter identification by reducing uncertainties through the development of innovative test approaches. One possible approach is to modify the loading path, for example by imposing load cycles, or to modify the geometry of the sample, typically by adding holes or notches. Nevertheless, when it comes to optimal tests design, the principal challenge is not only in solving the optimisation problem itself, but also (and above all) in the definition of a cost function that objectively improves identification. For a deeper understanding of the issue of optimal tests design, we propose to consider a simplified scenario by means of a toy problem.

Methods In this scenario, we follow the ASTM standard test procedure for determining in-plane tensile properties of composite laminates [4], which includes four moduli. Three tensile tests are performed, each test coupon being designed with a different lay-up. The layups are of the form $[+\theta, -\theta]_{2S}$ for all coupons, with stacking angles of 0° , 90° and 45° respectively. The tensile tests are assumed to produce a uniform strain state throughout the coupon, so local strain measurements are made using strain gauges. Another strong assumption for the processing of the tests results is that each test is independent of the others. Under these hypotheses, the classical laminate theory provides straightforward expressions for the identification of the constitutive parameters, using the local strain measurements. This approach is advantageous as it allows easy processing of the data thanks to simple relationships, and does not assume any covariance between the parameters. Nevertheless, it requires a large number of experiments and specimens, with relatively limited instrumentation, meaning that each test provides little information concerning the studied material. In order to benefit from the whole data produced throughout the testing procedure, we propose a different approach: we consider all measurements as potentially contributing to the identification of all four parameters. In other words, we do not consider the three tests are independent

one of the others. We believe that this approach is consistent with the objective of identifying the in-plane tensile properties of a single material (or ply). This is done by using a data assimilation framework, in the sense that we aggregate data from all measurements (*i.e.*, the measurements stemming from all three tests). More precisely, the methodology involves modelling the tests using classical laminate theory, and solving an identification problem based on these simulated data.

Returning to the objective of optimal test design, it can be highlighted that including all measurements in the identification problem relaxes the constraints on laminate angles. This allows for the exploration of alternative test designs to improve parameter identification. In this work, we propose to retain the same number of tests in the sequence, yet using different stacking angles. With regard to the optimisation itself, it is necessary to determine a quantity that shall be minimised. In accordance with standard practice, the covariance matrix of the identified parameters is studied as a measure of uncertainty [5, 6]. Consequently, the focus is on adjusting the coupons stacking angles to minimise the covariance matrix over the entire test series. Nevertheless, it should be acknowledged that minimising a matrix is not a straightforward process. A common approach is to examine the eigenvalues of the matrix in question and to derive a scalar quantity from those values. A number of criteria have been proposed. For instance, reducing the largest eigenvalue ensures that the uncertainty associated with the initially worst-identified parameter will not increase. However, it does not guarantee the identification of the remaining parameters will not deteriorate compared to the initial design. Another criterion is to use the determinant of the matrix, which may not enhance the sensitivity to all parameters.

Results In our study, we chose to focus on minimising the trace of the covariance matrix, which is a novel and interesting criterion for uncertainty reduction. Using the trace of the covariance matrix proves to be advantageous for uncertainty minimisation as it includes all eigenvalues equally. While it could be argued that the determinant also includes all eigenvalues, the key difference is that the trace sums the eigenvalues whereas the determinant multiplies them. Opting for summation rather than multiplication helps to avoid artificially lowering the criterion while actually degrading the solution. The results indicate that using the trace as a criterion to reduce the covariance matrix, and subsequently the uncertainties, is a favourable approach. Based on the chosen optimisation framework, the methodology successfully identifies sequences of angles that could improve the identification of ply in-plane tensile properties.

Discussion and Conclusion The application of this study to a simplified scenario, following the ASTM standard test procedure, highlights the interest of using a data assimilation framework for parameter identification. Optimal design of experiments can therefore benefit from such an approach, by attempting to reduce the uncertainties of the identified parameters. This work also demonstrates the utility of multiple objectives (including the trace and determinant) in a multi-objective optimisation setting. This approach may prove beneficial in exploring the design space and identifying different locally optimal designs. Subsequent work will be conducted in the near future to demonstrate the interest of this framework for more complex examples.

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