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Towards the design of a new standard for composite stiffness identification

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ABSTRACT

This paper presents a step towards the design of a novel test for simultaneous identification of all the stiffness components of orthotropic composite materials. A simulator was adopted to numerically simulate the whole identification process. Synthetic images were generated and then processed by Digital Image Correlation (DIC) to calculate the strain fields. The Virtual Fields Method (VFM) was used to identify the material stiffness parameters and error functions were finally defined to evaluate the identification error. Two steps of optimization were applied to obtain the best design variables of different specimens and the optimal DIC processing parameters. Four types of test configuration were simulated including short off-axis tensile test, short off-axis open-hole tensile test, off-axis Brazilian disc and off-axis unnotched Iosipescu test and the most promising configuration was identified.

1. Introduction and state of the art

Composite materials are currently widely used in many sectors of industry thanks to their good performance to weight properties. The design of composite structures requires knowledge of the parameters driving their mechanical behaviour, among which their elastic stiffness components. In many cases, such as for unidirectional or cross-ply/woven laminates, their elastic behaviour can be assumed orthotropic and in a given plane (1–2), the stiffness behaviour depends on four independent parameters: E_{11} and E_{22}, the Young's moduli in the two orthotropy directions, ν_{12}, major Poisson's ratio and G_{12}, the shear modulus.

The identification of these stiffness components generally relies on the use of simple uniaxial tests for which there is an *a priori* knowledge of the stress field (statically determinate tests). For instance, E_{11} and ν_{12} can be obtained from a uniaxial tensile test along the fibre direction and E_{22} from a uniaxial tensile test perpendicular to the fibre direction, according to ASTM standard D3039 for instance [1]. For the shear modulus, several standard techniques are available, like the tensile test on a $[45/-45]_{nS}$ specimen (ASTM D3518, [2]), the double V-notch shear test (ASTM D5379, [3]), the rail shear test (ASTM D4255, [4]) or the off-axis tensile test [5], with oblique tabs for shallow angles [6]. These techniques are well established and based on robust deformation measurements from strain gauges or extensometers. However, they suffer from a number of shortcomings. First, they rely on stringent assumptions on geometry and boundary conditions to ensure the validity of the stress solution. This can cause spurious effects leading to biased stiffness identification [7]. Another issue is that the material has to be in a form that enables easy cutting of such test specimens. This is not so easy when testing in the through-thickness plane [8] for instance. Finally, this procedure is not very efficient as three tests are required to obtain four parameters. This leads to costly test campaigns and to the fact that spatial variations of properties are difficult to address because of the significant amount of test material that is required to perform the three tests.

With the development of full-field deformation measurements like Digital Image Correlation (DIC) for instance [9], new routes for composite stiffness identification have been proposed. The underpinning idea is to exploit the rich field information to conduct more complex tests and use an inverse identification tool to determine the required parameters. Research efforts towards this goal started in the late eighties [10] for plate bending but the bulk of the work targeted at in-plane loading tests dates back to the early 2000. Different types of full-field measurements have been used for this purpose: DIC [11], speckle interferometry [12], moiré interferometry [13] and grid method [14], among the most popular. Displacement or strain fields are then processed using an inverse identification technique to extract the stiffness

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parameters from the measured field data. Several techniques can be used for this purpose as reported in [15]. Finite element model updating (FEMU) consists in building up a finite element model of the test and constructing a cost function as the difference between measured and computed quantities [11,13]. An alternative is the Virtual Fields Method (VFM) which uses the measured strain field to directly extract the stiffness parameters from a specific use of the principle of virtual work [14,16]. Both techniques are nominally equivalent in elasticity, as shown in [17], the VFM being more computationally efficient as no iterative finite element computations are required.

One of the difficulties in using the approach described above is the choice of the test configuration. Sometimes, the test geometry is conditioned by the manufacturing process of the test piece [11,18] but for generic testing of thin plates, the design space for both test geometry and loading is quite wide. Sometimes, the test configurations used with the above methodology have been recycled from existing tests like the open-hole tensile test [13], the Arcan test [19], or slightly adapted as for the unnotched Iosipescu test [12,20]. There have been attempts to design specific tests, for instance a T-shaped specimen loaded in tension/bending [21] but only recently have research efforts been targeted at more systematic specimen optimization. Syed-Muhammad et al. [22] attempted to optimize the load configuration of a rectangular composite plate in bending and validated the results experimentally. Their approach was based on the use of the sensitivity to noise coefficients provided by the optimized VFM [23]. The same procedure has been used for in-plane orthotropic stiffness components in the unnotched Iosipescu test [12] and the modified Arcan test [19].

If such procedures are ever going to be used as new standard tests to replace existing ones, it is paramount that the uncertainty of the identified parameters be realistically evaluated. For this, the simple model of uncorrelated strain noise on which the test optimizations cited above have been performed is not sufficiently realistic. First, strain noise is correlated since all components derive from the measured displacement components and even these are not uncorrelated as they derive from the same subset in DIC, for instance. In reality, the main source of noise is the variation of grey level at each pixel caused mainly by the sensor of the camera. This was considered in [11] in a DIC/FEMU procedure to produce random error maps. However, the random error generated by camera noise is not the only one. A systematic error is also produced from the limited spatial resolution of full-field measurements. Indeed, the data are collected at a certain number of discrete points (subset of pixels in DIC, lines for the grid method) and therefore, high strain gradients are likely to be underestimated by such measurements, all the more since in the elastic regime, extra regularization needs to be included to make the identification noise-robust. This is illustrated in Fig. 16 in [24] for instance.

Because of the complexity of the combined measurement and identification chain, such uncertainty quantification can only be addressed by numerical simulations. Such a simulator was first proposed by Rossi and Pierron [25] using the grid method and recently extended to DIC [24]. Its application to orthotropic PVC foam stiffness identification has enabled both test configuration optimization and realistic confidence interval predictions [26].

The objective of the present paper is to use this simulator to approach in a rational way the design of a potential new test standard to identify the complete set of orthotropic stiffness components in a plane from a single test. Several configurations are explored and related to test parameters, like dimensions or orthotropy axis direction. A sum of the systematic and random errors is calculated as the total identification error. The error arising from the load measurement has been neglected here as it is generally much lower than that arising from the imaged-based strain measurements when the load cell is of appropriate capacity compared to the measured load. Other sources of error such as camera misalignment, lens distortion, non-uniform lighting are not considered in this paper either and will be included in further studies. Detailed simulations are presented in this article to reach a conclusion about the suitability of each of the explored test configurations. Confidence intervals on each stiffness component are also provided. Finally, considerations like ease of specimen preparation or robustness of loading conditions are added to make the final choice of the most promising candidate. This will be the base of future experimental validation before such a test can be proposed to the testing community.

2. Simulation of the experiments

In order to compare different experimental configurations, the whole identification chain has been numerically simulated following the procedures reported in [24,25]. The flow chart of the simulator is shown in Fig. 1.

Firstly, a finite element model is built up to simulate the displacement fields of a loaded specimen, with the input of material properties, geometry and boundary conditions of the real test. Then, the deformed image is obtained by imposing the displacement fields calculated by finite element on the reference image. This uses a subsampling to reduce the interpolation errors, details can be found in [24]. Grey level white noise can be added to both generated images to simulate a realistic image capture. Digital Image Correlation (DIC) is then applied to calculate the strain fields, in the same way as in the real experimental procedure. With the strain fields and applied force, stiffness parameters can finally be identified using the VFM. The identification error can be calculated by comparing the identified stiffness parameters with the reference values used as input in the finite element model. The following provides information about the different steps in this procedure.

2.1. Test configurations

The objective of this article is to compare a few potential tests for robust and accurate simultaneous identification of orthotropic stiffness components, with a view to defining a new standard. As a consequence, this ideal test candidate should not only lead to accurate results but should also involve a specimen which is relatively easy to manufacture and to load. The design space is nearly infinite and to start exploring it rationally, the first attempt

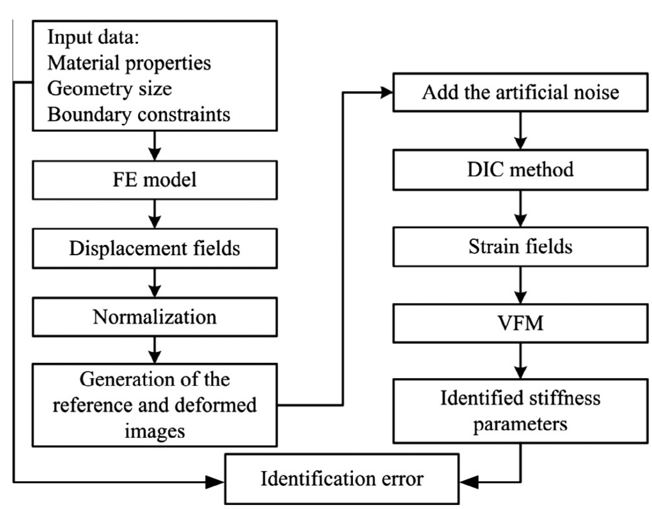

Fig. 1. Flow chart of the identification simulator.