MECHANICAL IDENTIFICATION OF ANISOTROPIC PROPERTIES OF COMPOSITES

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SUMMARY: This paper deals with the experimental identification of parameters governing the elastic properties of composite plates. The approach is based on the processing of the heterogeneous strain fields which are provided by well chosen mechanical tests. These fields are measured by particular optical setups developed in-house and are briefly described herein. The identification procedure itself is based on a specific use of the principle of virtual work. Examples of measurements of in-plane, bending and through-thickness stiffness components illustrate the approach.

KEYWORDS: full-field measurements, identification, mechanical characterization, optical methods, principle of virtual work.

INTRODUCTION

The design of composite structures first requires the determination of the mechanical characteristics of the materials to be used. Such characteristics are difficult to determine in the particular case of composite materials for the following reasons:

- the number of independent parameters to be determined is high because of the anisotropy and the heterogeneity. Hence several tests have to be performed to measure them. For instance, even within the simple framework of the linear elasticity, the number of independent parameters which completely characterize an uncoupled anisotropic plate is important in the general case: twelve instead of the two well-known coefficients of isotropic plates (Young's modulus and Poisson's ratio);
- these coefficients are direction dependent as well as often variable from one point of the structure to another. They also depend on the manufacturing process that is used. This tends to increase the number of tests to be performed;
- the anisotropy gives rise to the so-called 'parasite effects' that can disturb the results provided by usual tests, especially when shear properties are to be determined.

These features point out that the design and running of suitable testing procedures is essential for a better knowledge, and therefore a better use of composite materials.

The aim of the paper is to describe the main theoretical, numerical and experimental aspects of a novel general approach developed for identifying the stiffness properties of composite materials and structures. Contrary to the usual approach that relies on basic mechanical tests such as tension or shear tests, based on the questionable assumption of *homogeneous* strain fields within beam like specimens, the present approach focuses on *heterogeneous* strain fields over plate like specimens. These heterogeneous strain fields have to be measured all over the structure and processed. In the present case they are measured with optical methods specifically developed in-house. The heterogeneity of the strain fields is no more a drawback but an advantage since several mechanical parameters are involved in the deformation, and therefore are identifiable by use of a suitable processing of the strain fields. Furthermore, the traditional concepts of mechanical tests and experimental samples are considerably modified and enlarged.

The theoretical aspects of the identification procedure are described in the first section of the paper. The main features of the specific optical techniques that have been developed are then given. Finally, several examples of practical characterization of composite plates illustrate the interest of the present approach.

THEORY

Introduction

The first basic step of the reasoning is the fact that *heterogeneous* strain fields instead of *homogeneous* ones will be used to characterize the material mechanical properties. In practice, these fields will be measured onto the tested specimens with optical techniques. As a result, the input data to run the identification become the *whole* strain field onto the surface of the tested specimen. For instance, if a camera captures the field, a set of *many thousands* of experimental points is available to perform the identification of the model.

This particular feature must be fully taken into account when processing the data. In the usual approaches based on fields processing, the strategy is based on iterative numerical procedures that minimize the difference between both the measured and the computed response of the tested specimen with respect to the unknown parameters ([1] for instance). However, only a small number of experimental points is used in this approach: in practice only the nodal points of the mesh are taken into account and the remaining experimental information available at the other points is unused.

Similar strategies have been proposed with dynamical testing methods. A certain set of natural frequencies of vibrating plates is first measured. A model of the specimen is then built up with the finite element or the Raleigh-Ritz method and various iterative numerical procedures are proposed in the literature to extract the unknown parameters from both the measured frequencies and the model. This approach became popular in the last decade (see for instance [2] [3] [4]), but it seems that only the bending properties of laminated plates can be reached with such methods: in-plane or complete through-thickness properties cannot be obtained, even though promising results have been recently published for the through-thickness shear moduli [5].

Principle of virtual work and characterization of composite plates

The basic idea of the method proposed herein is to write the global equilibrium of the tested specimen with the well-known principle of virtual work.

$$-\int_V \sigma_{ij}\varepsilon^*_{ij}dV + \int_{\partial V} T_i u^*_i dS = 0 \qquad (1)$$

where V is the volume of the tested specimen, ∂V its boundary, σ the actual stress tensor, ε^* the virtual strain tensor, T the surface load density and u^* the virtual displacement field associated to ε^*. The actual stress field over the tested specimen writes as a function of the actual strain field components ε_{kl} with the classical stress/strain relationship

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \qquad (2)$$

where the C_{ijkl} are the unknown stiffnesses. Feeding Eqn (2) in Eqn (1) leads to

$$-\int_V C_{ijkl}\varepsilon_{kl}\varepsilon^*_{ij}dV + \int_{\partial V} T_i u^*_i dS = 0 \qquad (3)$$

Eqn (3) is in fact a linear equation where the stiffnesses C_{ijkl} are directly the unknowns. In the following examples, Eqn (3) is developed to take into account the geometry of the tested plate and the in-plane, bending or through-thickness stiffness components then appear as unknowns (A_{ij} or D_{ij} for instance).

The idea is then to propose a set of *explicit expressions* for the virtual field that is to be used in the principle of virtual work to obtained a set a independent linear equations [6]. This point is illustrated in Fig. 1 for a plane problem and three different virtual fields.

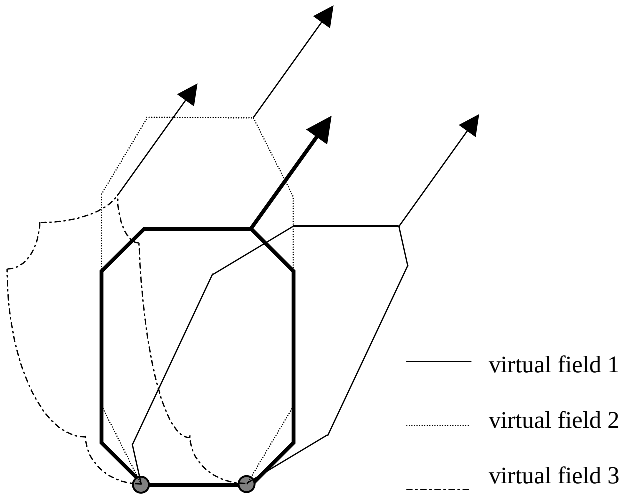


Fig. 1. Internal and external forces work virtually with three different virtual fields. Three linear equations involving the in-plane stiffnesses are obtained.

In theory, one must find at least as many virtual fields as unknown stiffnesses to set up a linear system. This system is then inverted to determine the unknowns. Two problems arise however in practice. First, one must design a mechanical test that provides an heterogeneous stress field through out the specimen and that is such that the unknown stiffnesses play some equivalent role so that they can be identified. Second, a set of independent admissible virtual fields is to be found out to obtain independent linear equations. It has been checked that these two constraints cannot be jointly satisfied in every case, depending on the nature of the unknowns (bending, in-plane, through-thickness). As a result, two main different strategies have been developed:

- in the first strategy (called strategy 1 in the following), *several* different experimental tests are carried out on the same specimen. Each of them emphasizes the contribution of some of the unknowns only. These unknowns are determined applying the principle of virtual fields with a small set of independent and simple virtual fields;
- in the second strategy, only *one* experimental test is performed and the whole set of unknowns is directly determined from it. Either the whole stress field onto the specimen virtually works with the fields that have been retained (strategy 2-a-), or some areas only of the specimen work (strategy 2-b-), according to the shape of the specimen and the location of the loading. The problem in strategies 2-a- and 2-b- is to select a more important number of virtual fields than in strategy 1, but the main advantage is to perform one test only.

Three major consequences must be emphasized at this stage. First, no analytical solution is required to determine the unknown stiffnesses. Second, no finite element calculation is to be used to compute the cinematic fields since they are measured. Finally, the procedure absolutely requires reliable and accurate optical techniques to measure these cinematic fields.

The main features of the optical techniques that have been developed in-house are given in the next section.

OPTICAL METHODS

An essential feature of the identification method described here is that a kinematic *field* has to be measured : displacement field, strain field, slope field… depending on the test performed. Thus, optical methods become almost unavoidable as they are often the only way to gain access to these fields. Moreover, the recent developments in video acquisition and computer hardware, as well as in data processing software, have resulted in an excellent synergy for applications to mechanical investigation. Also, the spreading of the phase-stepping technique allowing accurate fringe processing has resulted in efficient implementation of optical methods.
The possibility for non-experts to use these methods in the mechanical workshop rather than on specific optical tabletops depends on two specific features: easiness of the setup tuning and insensitivity to vibrations. Speckle methods are now widespread, because they meet to some extent those requirements (and also they do not require any surface preparation). They suffer from a major inconvenience, namely the spatial noise inherent to the stochastic nature of the recorded intensity, characterized by a signal-to-noise ratio of 1. Interferometric setups are often quite difficult to tune, and affected by vibrations. Moreover, they are often too sensitive (down to a few nanometers for displacement measurements), and thus inadequate in the field of mechanical engineering, because their inherent sensitivity is related to the wavelength and cannot be adjusted.
In our laboratory, we mainly used to methods which turned out to be fairly well adapted to our goals. The first one is the grid method for in-plane displacement measurements, the second one is deflectometry for out-of-plane slope measurements. Both methods are easy to implement, insensitive to vibrations and their sensitivity can be adjusted. We systematically used phase-stepping, for which an extensive work on the processing algorithms has been carried on [7].

Grid method

In this method, a grid, *i.e.* a regular pattern of black and white parallel straight lines, is deposited onto the specimen surface. The reflected intensity pattern is periodic, and the first

Fourier component of this intensity profile can be detected by phase-stepping. A thin layer of white paint is sprayed onto the surface and the grid is then transferred. Commercially available transferable grids used for artwork can be used. We generally used a grid of pitch 0.6 mm. When the specimen is loaded, the grid lines move and the phase of the line profile is changed. The displacement u_x orthogonal to the lines is related to the phase by the formula :

$$\phi = \frac{2\pi u_x}{p} \tag{4}$$

where p is the grid pitch. When the two components of the displacement are to be measured, a crossed line pattern is necessary. In that case, spatial smoothing of the recorded image along one direction allows to remove the lines orthogonal to that direction, and vice-versa [8]. In our experiments, we used either *temporal* phase-stepping or *spatial* phase-stepping. In the first case, a motorized translation stage is used to move the CCD camera sideways in N equal steps over a distance equal to the grid pitch, so that N phase-stepped images of the grid are recorded. In the second technique, only one image is required and the zoom lens magnification is chosen so that the pitch of the grid imaged onto the CCD sensor corresponds to N contiguous pixels. We found that the phase-stepping technique routinely allowed obtaining an accuracy better than $2\pi/100$ on the phase measurement. This corresponds to 6 µm in terms of displacement with a grid pitch of 0.6 mm.

Deflectometry

This technique is used for the measurement of slope fields one a bent plate. It can be explained very simply using ray optics, although a more precise description using wave optics is also possible. The surface has to be covered with a thin layer of resin so that some amount of specular (*i.e.* mirrorlike) reflection exists. This layer is obtained by pressing the plate and the resin between two glass plates. It is very thin (less than 0.01 mm) and its influence on the mechanical behaviour of the studied plate can therefore be neglected. The principle is then to illuminate the surface by a collimated beam. The local slopes modify the direction of the reflected rays, following Snell's law of reflection.

This principle is sketched in Fig. 2. The plate is illuminated by a collimated beam obtained from a point light source LS located at the focus of the field lens FL. After reflection, all rays having the same given direction (*e.g.* rays reflected at points A and B) converge at the same point of coordinates (ξ,η) of the focal plane of the lens FL, with:

$$\xi = 2f\frac{\partial w}{\partial x}, \quad \eta = 2f\frac{\partial w}{\partial y} \tag{5}$$

where w is the deflection.

If a vertical slit S (*i.e.* aligned with the η axis) is placed at that point, the light coming from points where the local x-slope is different is blocked. So, x-slope contours are observed. In order to have more information at once, the slit can be replaced by a filter of sinusoidal transparency. The obtained slope contour pattern looks very similar to classical interference fringes, apart from the fact that they are much more stable. Indeed, low frequency vibrations induce mainly rigid body translations which do not change slopes.

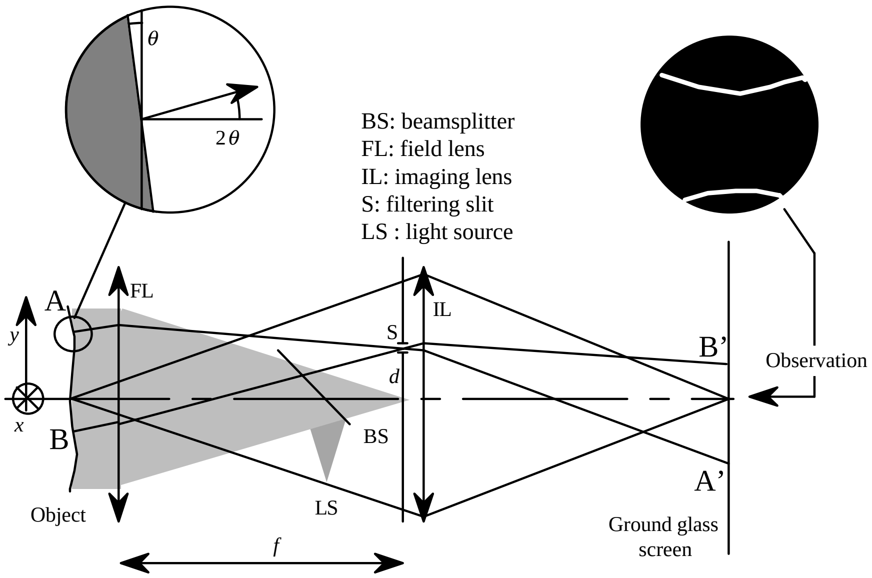


Fig. 2. Schematic of the deflectometric setup, using a filtering slit. A slope contour is observed on the screen.

Once a grid has replaced the slit, it is very easy to achieve phase-stepping by translating this grid in its plane. The final setup for the characterization of the bending rigidities of circular plates is presented in Fig. 3. For sake of simplicity, the beam splitter has been eliminated, simply by introducing a small angle between the incident and reflected rays.

One major feature of this setup as compared to Fizeau interferometry, apart from its insensitivity to vibrations, is that the sensitivity is inversely proportional to the grid pitch, and so it can be adjusted to the needs by choosing the proper pitch. We commonly used pitches in the range 1 to 2 mm. With a 50 cm focal length of the field lens and a phase detection sensitivity of $2\pi/100$, a sensitivity of $2.5\ 10^{-5}$ rad (or 25 nm per mm) is obtained.

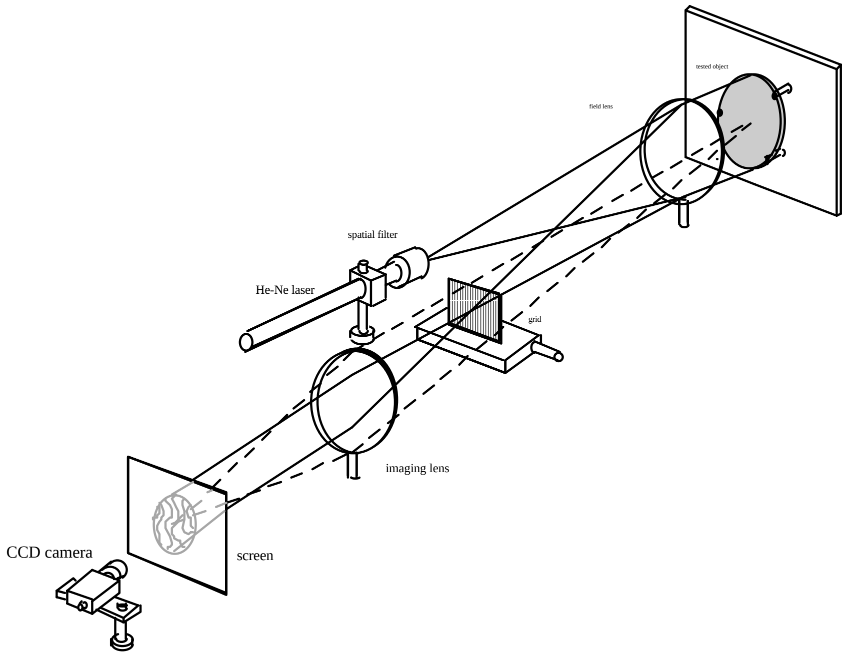


Fig. 3 Deflectometric setup for measuring the slope field on a bent plate.

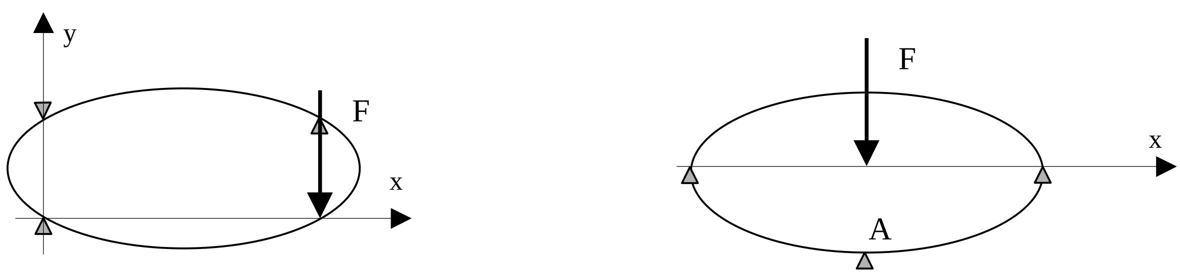
EXAMPLES

The aim of this section is to present some examples of composite characterization with the previous strategies. For obvious reasons, it is not possible to describe here the setups in details and to comment all the results. Hence, only the main features will be given and references are provided for further information.

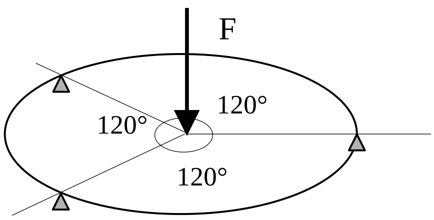
Bending stiffness of composite plates

The present approach was first applied to static plate bending problems. The problem is here to determine the six bending rigidities of laminated plates. In practice, the tested plate is circular (diameter: 150mm, typical thickness: 2mm). Strategy 1 is here adopted. The plate is subjected to two different tests. The first one is the torsion or anticlastic test (see Figure 4-a-). This test is well-known for square plates since an analytical solution is available in this case. For circular plates however, the analytical solution remains unknown. Such a shape was adopted nevertheless because the procedure does not require any analytical solution. Moreover, it is possible to perform many different tests on the same plate rotated in the mechanical device in order to get a redundant set of elastic parameters that can be then optimized. The anticlastic test provides the bending shear compliance as well as the eventual shear coupling terms. The second test is the three-point bending test (see Figure 4-b-). The plate is supported on two cone-shaped supports located at the end of a diameter and the plate is loaded at the center of the plate. The support in point A ensures the stability of the plate. The longitudinal stiffness along the x-direction mainly contributes to the mechanical response of the plate. This parameters can therefore be determined. The Poisson's effect as well as an eventual shear coupling are also emphasized. The same approach performed on the plate rotated through 90 deg. in the setup provides the same stiffnesses, but along direction y. For all these tests, the virtual fields that are used are the most simple ones in bending, that is three independent quadratic polynomials. In conclusion, the procedure allows the determination of the complete bending compliance matrix of the tested plate from only one plate specimen. Full details concerning these tests can be found in Ref. [9] [10].

More recently, the above approach has been modified to measure the invariant elastic parameters that govern the bending elastic behavior of the plate. It has been demonstrated [11] that the supports and loading can be located at some particular points in such a way that the invariant quantities (the U_i with the usual Tsai's notation) can be directly measured by combining the tests in Figs. 2-a- and 2-c-. Strategy 1 is used in this case with the same quadratic virtual fields as in the above example. This strategy has been successfully applied on carbon/cyanate plates [12]. In these cases of static bent plates, the slope contours are provided by a deflectometric set-up [13]. Curvature are obtained by numerical differentiation.



a- anticlastic test   b- three-point bending test



c- average isotropic state of stress

Fig. 4: Basic bending tests for the measurement of bending properties of composite plates.

Dynamical tests have been also recently developed to determine the bending stiffnesses. The shape of the plate is here a square. The natural frequencies and the first natural modes are measured and processed with the same virtual fields as above. Strategy 1 is also used in this case. The main advantage is here to model the problem without any assumption concerning the shape of the modes since they are measured, contrary to most of the similar methods developed for vibrating plates that are based on the processing of the natural frequencies only, the mode shapes being computed with an approximate method like the finite element method or the Rayleigh-Ritz method. The drawback of our approach is the fact that only thin plates (thickness<1mm) can be tested because the magnitude of the deflection is no more measurable with thicker plates. Carbon/epoxy plates have been successfully tested with such an approach [14] [15]. Typical results are shown in Table 1, where expected values of the normalized bending stiffnesses (*i. e.* stiffnesses computed with the classical lamination theory from the ply stiffnesses and angles) and measured ones are compared.

	D^*_{11}	D^*_{22}	D^*_{12}	D^*_{66}	D^*_{16}	D^*_{26}
Expected	89.4	45.6	3.10	4.96	0	0
Measured	89.8	47.0	4.24	5.07	-1.92	-0.47

Table 1 : Expected and measured normalized stiffnesses of a $[0, 90]_s$ carbon/epoxy 100x100x1 mm^3 plate, in GPa.

Both sets of parameters are in good agreement. The most important difference is found for the D^*_{12} term. This result is typical of this type of global approach. It is consistent with experimental results obtained with other identification methods described in the literature. The main reason is the fact that this parameter, which is directly derived from the major Poisson's ratio, does not in general significantly influence the strain and stress fields within any tested specimens where heterogeneous stress fields take place. Consequently, this parameters cannot be accurately identified with any global identification methods.

In-plane stiffnesses of composite plates

Since in-plane and bending properties of composites plates are generally different, the components of both the in-plane and bending matrices must be measured separately. Concerning the in-plane properties, they are generally obtained with different usual standard tests like the in-axes and off-axes tension tests or the Iosipescu shear test. Applying the present approach, one can measure the whole set of components with one test carried out on only one specimen [16]. The shape of the specimen is here a "T" cut in the composite plate to be characterized. This specimen is tested in a tensile machine (Figure 5).

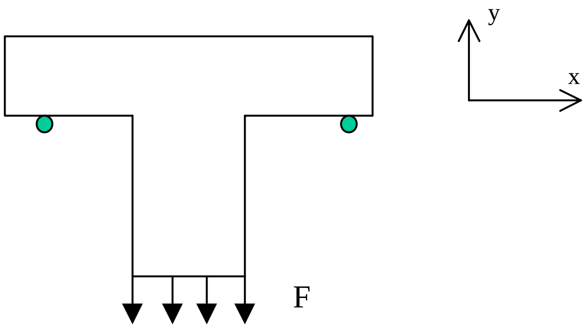


Fig. 5: T-shaped specimen for the in-plane characterization of composite plates.

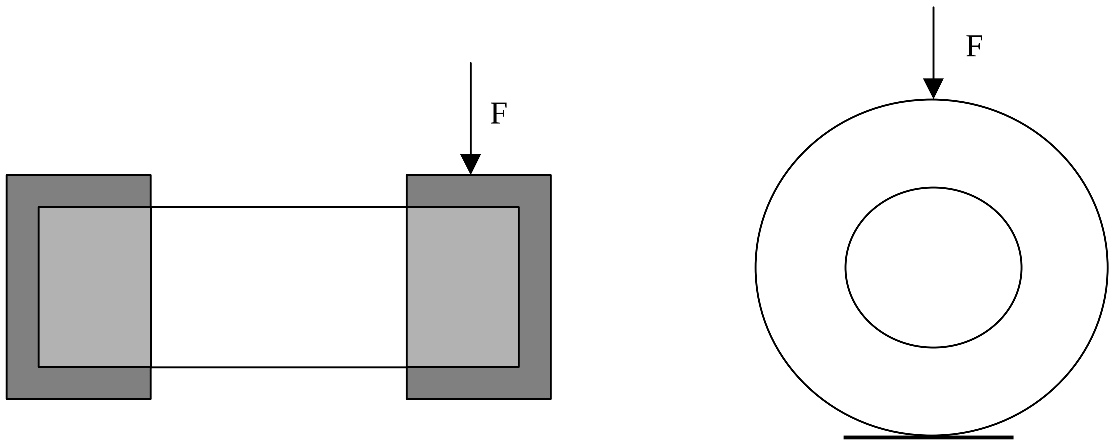
The location of the supports is such that the vertical part of the specimen behaves approximately like a tensile specimen while the horizontal part behaves approximately like a short beam under three-point bending. The in-plane longitudinal stiffness along direction y as well as the Poisson's ratio are mainly involved in the vertical part. The longitudinal stiffness along direction x and the shear modulus are mainly involved in the horizontal part. As a result, the whole set of unknown stiffnesses is involved in the specimen (assuming that the plate is orthotropic). Strategy 2-a is used in this case: the virtual fields emphasize the contribution of some of the unknown parameters in particular areas of the specimen only. For instance, a virtual shear is applied on the horizontal part of the specimen, providing a linear equation where only the in-plane shear stiffness is involved. Because of the shape of the specimens, orthotropic plates are characterized contrary to the above bending tests where completely anisotropic plates can be tested. Typical results obtained with F. E. simulations of the identification method are shown in Table 2 (complete results are described in Ref. [16]). As can be seen, both sets of results are very close. Recently, this method has been experimentally implemented for the characterization of woven glass-epoxy plates [17]. The results were satisfactory, apart the Poisson's ratio that could not be measured accurately. This conclusion is consistent with the above bent plate characterization method.

	A^*_{11}	A^*_{22}	A^*_{12}	A^*_{66}
Expected	130.91	10.07	3.02	5.00
Identified	131.20	10.07	3.03	5.00

Table 2 : Expected and identified normalized in-plane stiffnesses of a unidirectional carbon/epoxy plate, in GPa.

Through-thickness stiffnesses

The through-thickness properties of laminated composites are difficult to measure. They are however absolutely necessary to design properly thick composite structures that are nowadays used increasingly in ground transportation for instance. It has been shown recently through some numerical simulations that such properties can be determined with the present approach applying strategy 2-b.



a- Unnotched specimen in a Iosipescu fixture b- Ring under compression

Fig. 6: basic tests for the through-thickness characterization of laminated structures.

If through-thickness properties of thick composite plates are investigated, the idea is to cut a Iosipescu specimen through the thickness. The geometry is however slightly modified since the specimen is a straight beam *without notch*. The idea is to use a Iosipescu setup to produce not a pure shear stress state, but a complex one where all the through-thickness stress components are roughly of the same order of magnitude. Applying the present approach with strategy 2-b- and four well chosen independent virtual fields the four through-thickness of thick laminated plate can be measured [18].

In the same way, through-thickness stiffnesses of composite tubes can be identified. First, a ring is cut in the tube to be tested. This tube is then subjected to a unique compression test where the four unknown independent trough-thickness stiffnesses are involved. Applying the present approach with strategy 2-b-, the four unknowns can be determined. Full details concerning this approach can be found in Refs. [19] [20]. Finally, a first attempt of measuring the parameters governing a non-linear shear response has been recently performed with this method [21].

CONCLUSIONS

The main features of a general approach allowing the characterization of composite plates are described in this paper. The procedure itself is based on a relevant use of heterogeneous stress fields that take place in composite specimens subjected to suitable mechanical tests. Specific optical setups have been developed in order to assess these fields onto the tested specimens. Three different types of examples dealing with in-plane, bending and through-thickness stiffness components measurements are described in this paper.

The main advantage of the present procedure is its ability to derive an important number of stiffness components from a small number of plate like specimens and tests. Moreover, no questionable assumption is made on the displacement or strain field since they are measured, contrary to most of the classical approaches available in the literature.

In the near future, the identification procedure will be extended to the identification of non-linear properties of composites and coupling terms of particular unsymmetric fabrics. The relevance of some strength criterion could also be investigated. The specific optical methods developed in-house will also be improved to increase their accuracy by measuring directly strain fields instead of displacement fields for instance.

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