The use of full-field measurement methods in composite material characterization: interest and limitations

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Abstract

An overview of the use of full-field measurement techniques for composite material and structure characterization reported in the recent literature is presented in this paper. The features of the main types of measurement techniques are first briefly described. Specific advantages of using these techniques in a context of composite material characterization are then highlighted. Critical issues that require further research and development are finally examined.

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1. Introduction

During the two last decades, the improvement in image processing with microcomputers has caused non-contact measurement techniques to become more and more popular in the experimental mechanics community. Some full-field measurement techniques like moiré, interferometry or photoelasticimetry were known and used beforehand. These techniques suffered however from the non-automatic processing of the fringe patterns they provided, leading to some heavy, boring and unreliable by-hand manipulations before obtaining relevant information in terms of displacement or strain. In the recent past, thanks to the dramatic advances in microcomputer and camera technology, many research groups devoted to optics, experimental mechanics or data processing have been developing suitable techniques based on the use of optical devices, digital cameras, algorithms and softwares which automatically process images. These techniques directly provide displacement or strain contours onto specimens under testing. Temperature fields are also available thanks to infrared scanning cameras. Such measurements constitute in fact a new type of tool for researchers in mechanics of solids, which is especially interesting in the field of composite material characterization. Indeed, composites present some features like heterogeneities at different scales which render such full-field measurements very attractive.

It must be emphasized that the above techniques of strain/displacement components deliver extensometric informations of deformed surfaces. It is somewhat different of similar approaches devoted to morphology characterization of materials. In this last case, images are captured directly or through a microscope, digitized and processed to obtain various geometrical properties of the surface under investigation. Percentage and orientation of fibers [1], morphological features of braided composites [2], microcrack properties [3] are some examples of use of this type of image analyses but this point is not addressed in this paper.

The aim here is to examine the interest and the limitations of full-field measurement techniques in composite materials characterization. The main techniques available and their main features are presented in the first part of the paper. Their application in the field of composite material characterization is addressed in the second part. The numerical processing of these fields to identify parameters of constitutive equations is eventually discussed in the last part of the paper.

2. Full-field measurement techniques

Several types full-field techniques have been proposed and used in composite material characterization in the last decade. The nature of the measurements can be
Displacements are measured with various techniques [4], for instance speckle [5], speckle interferometry [6], geometric moiré [7], moiré interferometry [8], holographic interferometry [9], image correlation [10] or grid method [11]. Strain can be obtained by numerical differentiation of the above displacement fields with suitable algorithms [12] or directly, for instance with speckle shearing photography [15] or by moiré fringes shifting [16]. These techniques can be classified according to various criteria based on the nature of the physical phenomenon involved. For instance, non-interferometric (speckle, grid method) and interferometric (speckle interferometry, moiré interferometry) techniques [17] are the two main categories of techniques which are discussed below. Note that temperature fields can also be measured with infrared cameras [18,19,20], but the features of this technique are not recalled below.

2.1. Displacement field measurement techniques with non-interferometric methods

2.1.1. Speckle photography

When a rough surface is illuminated with a coherent light, the rays are scattered in all directions and at all distances from the surface. The scattered waves distribution displays a random spatial variation of intensity called speckle pattern which contrast mainly depends on the degree of coherence of the incident radiation and the surface roughness. The scattered rays are usually collected with a lens and focused on a screen. Speckle patterns are in fact randomly coded patterns, which carry information about the surface under investigation. Moreover, if the surface undergoes changes, the position and the irradiance of the pattern are changed. Techniques that monitor the positional changes of the speckles are classified under speckle photography. The displacement field is obtained by calculating the so-called cross-correlation function \( \rho(x,y) \), where \( \rho_0(x,y) \) and \( \rho(x,y) \) are, respectively, the intensity distribution before and after loading of the specimen. Such calculations are carried out with suitable algorithms after digitizing the image captured by a camera. The main advantage of the speckle method is the ability to measure large and out-of-plane displacements. Several books or review articles are devoted to this technique [21–24] for instance.

2.1.2. Image correlation

Generally, it does not matter how the speckles are formed in the above method. Hence, incoherent light can be used. Surfaces under investigation can therefore be prepared with white painting and sprayed with a black aerosol. This leads to a random structured aspect, which can be observed with a digital camera. In this case, the speckles can be considered as physically attached to the surface unlike the above laser speckles. Since incoherent white light is used, neither laser nor specific optical device are required. Moreover, the preparation of the surface is very simple and the displacements are easily obtained by matching different zones of two images captured before and after loading of the specimen. This image processing is performed with the same type of algorithms as above. This method is therefore easy to use and straightforward, as illustrated by the literature on this subject [10,25–27] for instance, but its sensitivity is lower than laser speckle because of larger speckle size. This method is popular thanks to its simplicity.

2.1.3. Geometric moiré and grid method

Analyzing the evolution of a regular network of equispaced and parallel lines which deform is the base of the grid and moiré methods. In the first case, the network is physically attached to the surface of the specimen [28] whereas it is obtained with some geometric methods in the second one. For instance, in-plane moiré fringes [29–31] are obtained by superposing a grating applied to a surface and a second one called reference grating. When the specimen is loaded or moved, a fringe pattern is generated since the location of the lines relative to the reference grating changes. These fringes represent the component of the displacement normal to the reference grating. Out-of-plane displacements normal to the surface plane are represented by the fringes of a shadow moiré [32]. In this case, fringes are obtained by superposing a grating placed in front of the surface and its shadow. Such optical arrangements are used in practice to determine the deflection field of bent or vibrating plates. Finally, slopes are determined with reflection moiré [33]. In this case, fringes are produced by superposing a grating placed in front of the surface and its shadow.

2.2. Displacement field measurement techniques with interferometric methods

Interferometric methods increase sensitivity of the above methods by more than one order of magnitude. They are however susceptible to environmental disturbances like vibrations because of their high sensitivity. Moiré interferometry and electronic speckle pattern interferometry (ESPI) are the two main methods which have been developed for displacement measurement.

2.2.1. Moiré interferometry

The superposition of two coherent laser beams of light provides interference and fringes which can be considered as regular reference grids which frequency is usually greater than 1000 lines/mm. Moiré interferometry is based on the same physical phenomenon as the above geometric moiré methods, but it can be observed that the grating frequency is much greater. This method therefore extends the possibilities of the moiré method to the submicron level [8]. First, a specimen grating has to be imprinted onto the surface of the specimen. The grating is obtained by exposing a photographic
plate to a two-beam interference pattern. The resulting fringes overcoated with a thin layer of aluminum are then transferred to the specimen with a layer of epoxy. The reference grating is also obtained via two-beam interference. The superposition of these two gratings provides moiré fringes from which in-plane displacement are deduced. Out-of-plane displacements can also be measured [34]. In this case, the reference grating is placed perpendicular to the surface. The superposition of the first beam generated by reflection from the specimen surface and the second one reflected from the reference grating provides moiré fringes since the first beam is distorted by the out-of-plane deformation of the specimen. Consequently, the fringes here are contours of the out-of-plane displacement.

2.2.2. Electronic speckle pattern interferometry

ESPI is based on the coherent addition of the scattered light from the specimen surface and a reference laser beam [5,35,36]. The phase changes within one speckle because of the object displacement are coded by the reference beam with the assumption that the microstructure is modified. The displacement field is extracted by correlation of two speckle patterns, one taken before and one taken after object displacement. The method requires surfaces, which scatter light. Hence neither grating nor smooth surface are necessary.

2.3. Strain field measurement techniques with interferometric methods

Only a few techniques directly provide strain fields among which the shearing interferometry is the most popular. The principle of shearing interferometry is to interfere an optical wavefront with a shifted copy of itself [37]. The resulting fringes are related to the gradient of the optical phase from which the gradient of the displacement are deduced. Strain components or local rotations are therefore directly obtained from these measurements. Various devices have been proposed in the literature to create this shearing effect [14,38–42]. Ligtenberg proposed a double-exposure method to measure curvatures of bent plates [43]. These quantities are directly proportional to the surface strain components thanks to the Love-Kirchhoff assumption [44]. Various optical set-ups providing curvature fields are described in Ref. [45].

2.4. Choosing a method

All the above methods have been used in various applications of experimental mechanics. An important question for the user is the optimal choice of the method for a given problem. The answer is not easy to find for different reasons:

- the published work is scattered over several journals, making it difficult for a reader to have ready access to the information.
- vocabulary and physical phenomena involved in these techniques come from other fields than mechanics like optics or data processing. This causes most of potential users to feel uneasy when reading the description of the optical arrangements and choosing a method becomes therefore troublesome.
- the output from a full-field measurement system is optical data like speckle or fringes in which the information is encoded. These data must therefore be processed by a programme to provide displacement or strain patterns, giving rise to a black box in which the different steps are often confuse and cannot always be clearly distinguished.
- the metrological features of any system should be defined and characterized but extensive data sheets from manufacturers are generally not available. Indeed, the word ‘accuracy’ is too general and some important notions coming from metrological aspects should be clarified. For instance, any data sheet should at least quantify the following properties: sensitivity, uncertainty of the measurements, repeatability, resolution, spatial resolution [46]. This task is however somewhat difficult to perform because most of the arrangements are in-house designed.

Moreover, some extrinsic parameters of the optical methods themselves influence the results like the displacement or strain gradients in the field or the performance of the digital camera used for capturing the fields. Some studies are devoted to the evaluation of the accuracy of full-field measurement systems [47,48], but such a concern is too seldom taken into account in the literature. Standards in this field should have to be urgently proposed to define some objective criteria, which would be useful to calibrate and to compare the methods through round robin confrontations or benchmarks for instance. It should be pointed out that the Versailles Project on Advanced Materials and Standards (VAMAS) which is directly involved in pre-standards research activities has launched a Technical Working Area called ‘TWA26 Full Field Optical Stress and Strain Measurements’ which is devoted to the development of standards for the use of full-field stress and strain measurement techniques [49]. Some documents dealing to the evaluation of non-contact systems are already available [46–48,50,51]. These papers show that the first problem is to properly define the terminology, showing that the community of experimental mechanics and composite materials has still much effort to spend before correctly using calibrated systems.

- programmes which process the images provide very attractive colorful displacement or strain patterns which often fascinate the user, avoiding relevant questions concerning the above issues.

2.5. Image processing

A common property of most of the above methods is that they produce a fringe pattern as output. The quantity
of interest (in-plane displacement, deflection, strain) is coded at the scale of the fringe period. These fringes must therefore be analyzed to convert them into a continuous phase map directly proportional to the quantity of interest. For a more accurate evaluation than just counting the fringes, the phase fringe pattern has first to be filtered and processed. Since this pattern contains discontinuities due to the wrapping of the phase modulo 2π, it must be unwrapped and finally correctly scaled. The recent connection between image digital processors, optical test arrangements and microcomputers has opened new possibilities for automatically processing these patterns. Various algorithms are available and described in Refs. [52,53] for instance. It must be emphasized that the situation here is somewhat similar as the situation for the systems themselves described above. Indeed, the softwares provided with optical set-ups often appear like ‘black boxes’ for the users who are therefore unable to correctly estimate their capabilities. For instance, the influence of noisy data on the final quantity provided by the softwares remains often unknown.

3. Application to the composite material and structure characterization

3.1. Introduction

In the last volume of the international journal *Experimental Mechanics* [54], 19 papers over 61 reported the use of full-field measurement techniques, showing an important interest of the community of experimental mechanics for these methods. Full-field measurements are well suited to analyze the specific mechanical properties of composite materials because of their anisotropic and heterogeneous nature. Papers found in the literature which report the use of full-field measurement techniques for composite material and structure characterization can be classified for instance according to the link between measurements and modeling. Seven groups were found applying this criterion. The link between measurements and modeling presently increases from one category to another:

1. non-destructive testing and inspection;
2. verification of boundary conditions applied to tested coupons;
3. experimental evidence of local gradients due to material heterogeneities;
4. cracking characterization;
5. verification of assumptions under which theoretical or numerical models are built;
6. validation of models;
7. identification of constitutive parameters.

Some recent examples belonging to the above categories are presented in the following sections.

3.2. Non-destructive testing and inspection

Full-field measurement techniques are used in non-destructive testing and inspection since a defect induces as a singularity in a field which can easily be detected [55]. In composites materials, these defects may be due to the manufacturing process (delaminations for instance) or to the degradation of the structure during its live (damage, impacts, macrocracks, etc.). Waldner [56] detected a localized damage within the foam of a sandwich structure due to an impact which did not damage the skin. The specimen was slightly heated with an infrared lamp and the deformation during cooling was detected with ESPI and shearography, showing the location of the impact. Indeed, the defect causes a strain concentration, which manifests itself in the form of fringes lying close together. The same procedure was used to evaluate the influence of removing paint from a sandwich part with a strong pulsed laser [57] and to detect a simulated flaw in an epoxy patch [56]. The influence of the location of the defect on the size of the disturbance of the field was investigated, showing that defects closer to the surface induced a larger deformation than defects located below [58,59]. The resolution of ESPI allows the detection of damaged zones in terms of small cracks due to fatigue for instance, as shown in Ref. [56]. Some compact set-ups are now available and make it possible to use them in an industrial environment [60–63] for instance.

The infrared thermography is also a very good tool for damage analysis. The analysis of the thermal changes of the specimens during a test allows a qualitative monitoring of the damage evolution. Thermal maps were used for instance in Ref. [64] to analyze the static notch sensitivity of various GFRP specimens in terms of damage evolution. In Ref. [65], typical defects like glue infiltration, water ingress and disbonds were detected on the blade of a wind turbine made of sandwich composite structure. The use of thermography in order to detect defects in sandwich structures is illustrated in various papers [66–68] for instance. Note finally that the determination of the fatigue limit of various materials among which composites can be performed with infrared thermographic techniques [69–72].

3.3. Verification of boundary conditions applied to tested coupons

Full-field measurements often reveal parasitic effects that occur during testing composite materials: misalignments of the grips, heterogeneous strain fields or local effects near the loading zones are immediately detected. For instance, it is well-known that designing a test which leads to a state of pure shear stresses a difficult task. Concerning sandwich structures, the shear properties are determined through some usual tests like bending [73] or shear tests [74]. Some parasitic effects occur however during these tests like the indentation under the loading points [75], the bending
of the loading steel plates [76] or the influence of free edges [77]. In Ref. [78], the grid method and its companion software ‘Frangyne’ developed by Surrel [79] were used to quantify these two last effects during an ASTM C273 shear test [74]. The heterogeneity of the shear strain field was clearly highlighted as well as the existence of local transverse tensile stresses near the free edge, which initiate early failure. A similar study has been carried on the off-axis test on composites [80]. The heterogeneity of the shear strain field due to the grips was highlighted and this parasitic effect was reduced thanks to oblique tabs [81]. In the same way, the correlation method was used to assess the heterogeneity of the strain field in fabrics subjected to a shear test [82].

3.4. Experimental evidence of local gradients due to material heterogeneities

Composite materials are heterogeneous at different scales. This leads to some local variations of strain components around their average values. Only these quantities are measurable with usual transducers like strain gauges because of their too high spatial resolution. Evidence of local variations of the strain field in a composite is however important because they may initiate cracks for instance. These variations have been observed in different studies, for instance by Post and co-workers with moiré interferometry. In Ref. [83], the through-thickness longitudinal displacement field in various bent specimens was measured with moiré interferometry. Stiations and zigzag fringes were clearly highlighted through the thickness of unidirectional composites under five-point bending. This is the consequence of high-localized shear strains in resin-rich zones between adjacent plies. Shear strain through the thickness of quasi-isotropic stacking sequences under three-point bending were deduced from the longitudinal displacement field, showing free-edge shear strains in region of normal stresses, especially near the top and bottom of the specimen. The shear strain variation due to the cyclic variation of shear compliance of individual plies was also clearly pointed out. The same technique was used to measure the strain field onto thick composite coupons under compression [84]. Very important variations were observed. Note that curved surfaces can also be investigated with the same technique, as shown in Refs. [85–87] where the ply-by-ply deformation of composite plates at the cylindrical surface of a hole in a specimen under tension/compression is examined. Very local phenomena can also be investigated with full-field measurement techniques. For instance, the failure mechanisms in laminates with dropped plies was studied in Ref. [88] with moiré interferometry. The strain gradients near a ply drop of an enlarged specimen were measured. More recently, the tension/bending coupling effect in the warp and fill yarns and the shear strain concentration in resin-rich regions were observed thanks to the grating shearography method [14,89]. Significant local variations of the strains were detected. Similar conclusions were obtained with ESPI [90].

3.5. Cracking characterization

Full-field measurements are very useful to detect cracks. These cracks appear indeed as singularities in a displacement field. The magnitude of the displacement jump along a direction perpendicular to a crack provides its width. Thanks to the resolution of most of the techniques described in Section 2, crack widths of some micrometers only can be measured. Using full-field measurements is especially effective in the case of brittle materials where multicrocking appears since the location of the cracks is not known a priori. For instance, the grid method [91] and image intercorrelation [92] were used to measure the width and the profile of cracks in a concrete structure reinforced with composite materials. These results were used to build up some relevant models describing the mechanical response of such structures. Cement-based composites with steel fibers were also investigated in Ref. [93]. In this study, multicrocking of specimens under three and four-point bending was studied in terms of relationship between loading and number of cracks, crack width and crack profile.

3.6. Verification of assumptions under which theoretical or numerical models are built

Numerical models used for computing stresses in composite materials are often built under some assumptions concerning the displacement and strain fields. For instance, the calculation of the transverse shear in laminated structures is usually carried out under some assumptions concerning the through-thickness displacement field. The classical laminated theory assumes that straight lines perpendicular to the mid-plane remain straight after loading [94], Thimoshenko or Mindlin theories that these straight lines remain straight but not perpendicular to the mid-plane, more refined theories that a warping appears, leading to a non-uniform through-thickness shear strain and stress components. Reddy proposed a cubic horizontal displacement distribution [95,96] whereas Touratier suggested a sine repartition [97,98] to model this warping. This warping is locked at the center of bent beams in any case [99]. The relevance of these different assumptions was verified and discussed by measuring the displacement field through the thickness of bent composite beams, either with the grid method [100] or with ESPI [101], highlighting the influence of the span-to-depth ratio on their validity.

3.7. Validation of models

Full-field measurement techniques are efficient tools to validate theoretical models when heterogeneities are involved. For instance, a theoretical model describing the post-buckling response of composite I-sections was
This model was then verified by measuring the out-of-plane deflection of web and flange due to buckling during compression tests on columns [103]. The shadow moiré method was used in this study to measure the deflection field due to buckling. In the same way, the influence of joining techniques on the response of assembled composite beams was investigated with moiré interferometry and compared with some theoretical models in Ref. [104]. A meso-model based on the anisotropic damage theory was proposed in Ref. [105] to evaluate the degradation state in a laminate. This model was then validated through full-field measurements performed on bi-axial specimens with intercorrelation.

### 3.8. Identification of constitutive parameters

Procedures which allow the identification of constitutive parameters from heterogeneous strain fields are very promising. They allow indeed the determination of several constitutive parameters from a reduced number of tests. Two main difficulties arise however. First, an amazing amount of measurements must be processed since the input data is a field, that is up to some hundreds of thousands of measurements and the question is to manage this unusual quantity of information. Second, no direct relationship is available between measurements and unknown parameters. Specific procedures have therefore been proposed in the recent past. The main features of two of them are described below.

#### 3.9. Conclusion

Various applications of full-field measurement techniques for composite material and structure characterization have been described in this section. The link between measurements and modeling increases from one case to another as illustrated in Fig. 1, showing the interest of this type of measurements for a better understanding of the mechanical response of composites.

### 4. Identification

#### 4.1. Introduction

The determination of parameters of constitutive equations of materials is usually obtained thanks to mechanical tests for which the loading conditions and the specimen geometries are such that homogeneous stress/strain fields take place [106]. In this case, a simple relationship between applied loading and local strain measurements directly provides the unknown parameters. It is however well-known that such pure states of stress/strain...
are often difficult to obtain in composite materials because of their anisotropy and their heterogeneity at different scales. Moreover, the number of unknown parameters which characterize these anisotropic materials—even in linear elasticity—is much more important than in the case of isotropy, leading therefore to a more important number of mechanical tests to measure them. Finally, the manufacturing conditions influence the final mechanical properties of composite materials, but taking out test samples from large industrial structures may often be unacceptable. For all these reasons, an increasing interest is found in the literature in methods allowing the identification of parameters of constitutive equations from testing configurations leading to heterogeneous stress/strain fields, either for composites or other materials. From a practical point of view, the main breakdown is the relaxation in the demands in terms of specimen geometry and loading conditions, leading to much more freedom in the nature and in the location of the applied loading as well as in the shape of the specimens to be tested. For instance, such strategies allow the design of experiments in which the conditions are much closer to those of practical or industrial situations. From a theoretical point of view, a much more important number of parameters influence the heterogeneous stress/strain field, leading to their possible identification if suitable procedures are available. This leads to a reduced number of tests and specimens to get the maximum number of constitutive parameters. Finally, parameters can be determined in testing configurations in which complex loading paths are introduced. For all these reasons, this type approach is very attractive but the main problem here is the lack of analytical solutions for the stress/strain/displacement fields, leading to the lack of relationship between measurements and unknown parameters.

In the recent past, several strategies have been proposed to extract constitutive parameters from heterogeneous strain fields, either for composites or for other materials. Such a problem is often referred as inverse problem in the literature. The corresponding direct problem is the determination of the stress/strain/displacement fields when the geometry, loading distribution $f$ and constitutive equations are known (see Table 1). In the inverse problem, the parameter identification is carried out within the framework of constitutive equations which are a priori assumed to be relevant. The displacement or strain fields are known as well as the geometry of the specimen geometry and the resulting force $F$ applied to the specimen. The aim here is to describe the headlines, the advantages and the limitations of two strategies found in the literature to solve this inverse problem, namely updating finite element models and the virtual fields method.

### 4.2. Updating finite element models

The finite element method provides displacement/strain/stress fields in almost any case of loading conditions, specimen geometry and constitutive equations. It is therefore the most popular numerical solution of the direct problem. It has been also used as a tool for solving iteratively the inverse problem, leading often to so-called mixed experimental/numerical methods. In this case, a first calculation is performed with an initial set of constitutive parameters. Nodal displacements are collected and compared to their experimental counterparts. The difference is quantified with an objective function, which is often the sum of the squared differences between numerical and experimental data. The idea is then to minimize iteratively this estimator with respect to the constitutive parameters. Many optimization algorithms are available for minimizing this objective function. They are based on the numerical calculation of a sensitivity matrix, which allows the step-by-step determination of new sets of constitutive parameters. The procedure stops when the objective function is lower than a given threshold value. Such procedures have been successfully simulated for instance by Hendricks [107] and used for the determination of anisotropic bending rigidities of wooden plates [108]. More recently, promising results have been obtained by Meuwissen [109,110] for the determination of the plastic response of some metals. They are displacement fields were measured in this case with the image correlation technique. Allix and Vidal [111] reduced the number of iterations necessary to reach convergence and improved the quality of each iteration using the so-called LATIN method (Large Time INcrement method) [112,113]. It is clear that this type of approach can also be used for anisotropic materials. In the same way, LeMagorou et al. [114] optimized the loading conditions in terms of location of the applied forces to determine the constitutive parameters of the elastic/viscoelastic response of wooden plates under bending.

The two main drawbacks of this type of approach are (i) the fact that the procedure is a ‘numerical black box’ build with the suitable solution of the direct problem and an objective function in which the physical meaning is not sufficiently present [115], (ii) often the computing time since iterative calculations are required, (iii) the fact that boundary conditions in terms of tractions must often be known to perform the calculations. Indeed, only the resulting force $F$ applied to tested specimens are measurable in practice whereas the loading repartition $f$ is required in the finite element model apart in the cases of concentrated forces.

### Table 1

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<tr>
<th>Direct problem</th>
<th>Inverse problem</th>
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<tr>
<td>Geometry</td>
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<td>Loading distribution $f$</td>
<td>Resulting force $F$</td>
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<td>Type of constitutive equations</td>
<td>Type of constitutive equations</td>
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<td>Constitutive parameters</td>
<td>$u$ or $\varepsilon$</td>
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<tr>
<td><strong>Unknown</strong></td>
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<tr>
<td>$u$, $\varepsilon$, $\sigma$</td>
<td>Constitutive parameters</td>
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</table>
4.3. The virtual fields method

This approach has been proposed in Ref. [116]. It clearly departs from the above ones since it is direct and does not require any iterative calculation in many cases. The basic idea is rather simple since it consists in writing the global equilibrium of the tested specimen with the principle of virtual work. Introducing the constitutive equations and particular virtual fields leads to an equation where the constitutive parameters only are unknown, provided that the strain fields are measured, either directly or indirectly, by numerical differentiation of measured displacement fields for instance. The idea is then to write the principle of virtual work with different and independent virtual fields. This leads to a system of equations in which the constitutive parameters are unknown. If at least as many virtual fields as unknowns are chosen and if the constitutive parameters write as polynomials of the strain, like in the cases of elasticity and damage, the system becomes linear and the unknowns are directly determined after inversion of the system. This approach has been simulated and applied in various cases of composite materials characterization in the recent past [116–131] for instance. The key point here is the choice of the virtual fields, since an infinity of virtual fields verifying the principle of virtual work is available. A method has been recently proposed to optimize the choice of the virtual fields with respect to the sensitivity to noisy data [132–135]. This dramatic improvement renders the virtual fields method much more easy to implement and reliable. The main advantages of this method are (i) its directness in many cases and (ii) the fact that the influence of the above problem posed by the boundary conditions can be avoided by choosing virtual fields in which only the resulting forces $F$ virtually work. The main limitation is the reduced number of results obtained in the non-linear case, but this point is presently under progress [136] for instance.

5. Conclusion

Thanks to recent advances in the sensing technology and image processing, various techniques are now available to measure displacement, strain or temperature fields during mechanical tests on composite materials and structures. The major breakthrough here is the possibility to detect heterogeneities which can be due to different phenomena: defects or cracks within material, mechanical set-ups causing parasitic effects, strain gradients due to distributed mechanical properties for instance. Full-field measurement techniques are very attractive and it is therefore expected that they will increase their presence and acceptance in mechanical characterization of composites in the near future. Different technologies have emerged and found a niche where they can offer specific performance but it should be noted that quite a few have evolved into commercial products till now. More research is still required to calibrate the different techniques or image processing softwares, to propose reliable black-box units requiring little experience to operate and to develop robust procedures that allow the determination of constitutive parameters from these fields which constitute in fact a new type of data.

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