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IDENTIFICATION OF DAMAGED ZONE IN COMPOSITE MATERIALS USING DISPLACEMENT FIELD MESUREMENTS

Elodie Péronnet[1(*)], Olivier Dalverny[2], Hélène Welemane[3], Sébastien Mistou[4]
[1, 2, 3, 4]PRES Université de Toulouse, INP, ENIT-LGP, Av. d'Azereix, BP1629, 65016 Tarbes Cedex, France.
[1]DAHER SOCATA, Aéroport Tarbes-Lourdes, 65290 Louey, France.
[(*)]*Email:* elodie.peronnet@enit.fr

ABSTRACT

This work presents an identification strategy of local elastic properties of orthotropic carbon-epoxy laminates for aviation industry. Based on global and local stages of study, this methodology uses the Finite Element Model Updating (FEMU) method as identification technique with simulated kinematic fields corresponding to tensile test response. The aim of this paper is to predict the spatial variation of elastic plane properties and to deduce the localization of damaged zones.

Keywords: Identification strategy, Finite Element Model Updating method, orthotropic composite structure, virgin material properties, damaged zone localization

INTRODUCTION

One of the main challenges in composite design and development is to be able to compute the damage state at any point of a composite structure during a complex loading. In this context, the knowledge of the spatial distribution of the material properties provides a quantitative estimation of the damage level and localization. Generally, such investigation is made in the context of Non Destructive Testing (NDT) through experimental measurements of acoustic transmission or reflection ultrasound waves (Péronnet, 2012a; Garnier, 2011; Mouritz, 2000; Yashiro, 2007; Ledru, 2009; Boyer, 1993), square pulse or sinusoidal or pulse thermal waves (Péronnet, 2012b; Péronnet, 2011a; Guibert, 2007; Ibarra Castanedo, 2005; Choi, 2008) or densimetric fields (Péronnet, 2011b; Brault, 2011; Carmona, 2009; Schilling, 2005; Bayraktara, 2008).

The work presented here intends to access to such spatial distribution of properties through the analysis of kinematic fields and by means of the finite element model updating method. Such iterative technique has many interesting advantages for structural analysis and industrial requirements, including the numerical framework, the ability to explore complex shapes and loads and a treatment based on surface measurement without any assumption on volume distribution (Grédiac, 2004; Avril, 2008).

A number of studies have already been conducted in this sense for isotropic materials either with elastic or elasto-plastic behaviour (Fazzini, 2011; Claire, 2004; Avril, 2007; Crouzeix, 2008; Pannier, 2006) and elastic orthotropic materials (Lecompte, 2007; Leclerc, 2009; Rikards, 2001; Vautrin , 2009). Yet, all existing works investigate the case of media that are considered as macroscopically homogeneous (that is without any spatial variation of their macroscopic elastic properties). The main contribution of this paper is then to propose an extension of the FEMU identification method to the context of damaged orthotropic materials. Damage is associated here to internal defects inducing local degradation of the virgin material and leading to a spatial variation of the material elastic properties. Studied media can accordingly be considered as macroscopically heterogeneous. The aim is to identify form kinematic fields the local orthotropic elastic properties, to deduce their spatial variation and then to determine the damaged zone within the material.

In a first step, the methodology is implemented for simulated kinematic fields in order to validate the procedure without any additional disturbance related to experimental acquisition. The composite structure including a defect is modeled by an association of two parts with different material properties (Fig. 1); the part 2 corresponds here to the "damaged" zone compared with the virgin material of part 1. To predict the spatial variation, the methodology adopted in the present study is based on global and local FEMU identification steps as described on Fig. 2. This paper intends to explain the two first steps involved in such methodology and to illustrate them on the case of orthotropic composites (carbon-epoxy laminates) for aviation with kinematic fields corresponding to tensile tests.

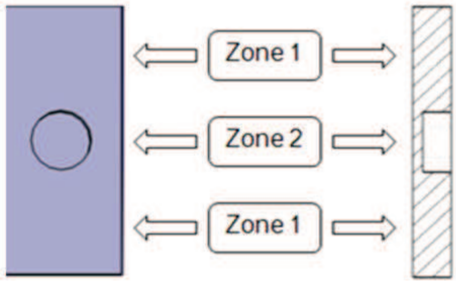


Fig. 1: Composite structure with two parts of different material properties

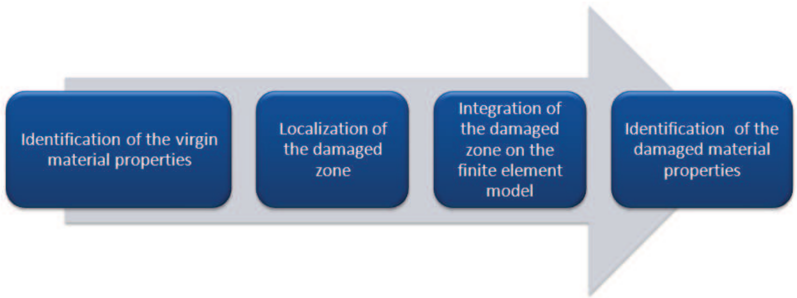


Fig. 2: Global and local identification procedure

IDENTIFICATION OF THE VIRGIN MATERIAL PROPERTIES

The FEMU identification technique implemented by M. Fazzini associates the Abaqus Finite Element (FE) code (Fazzini, 2011). The specific algorithm written in Python language follows the flowchart presented in Fig. 3. A particular attention has been paid to the matching of the kinematic fields grid and numerical one through the determination of neighboring points and interpolation functions. The cost function minimization is based on the Levenberg-Marquardt algorithm.

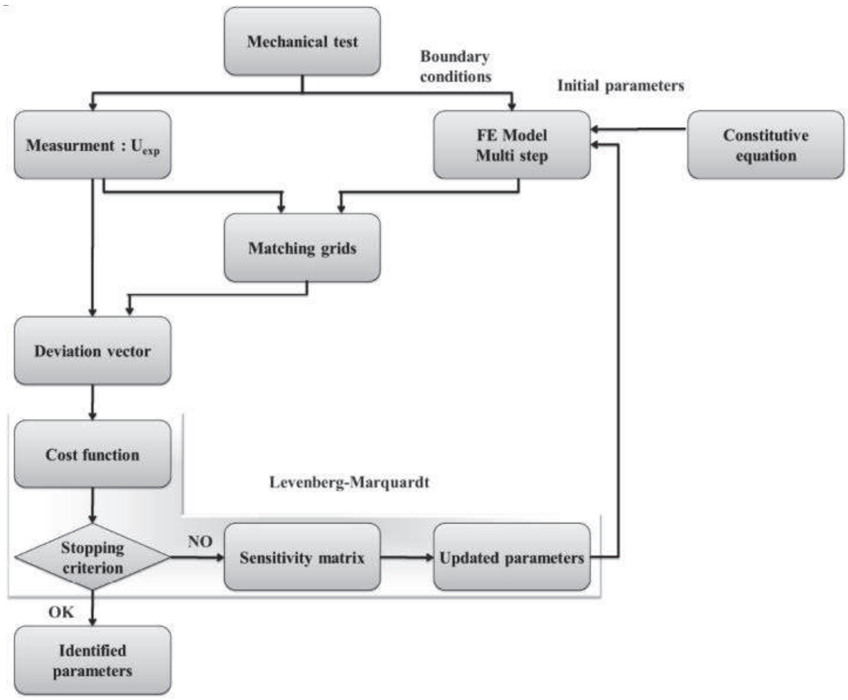


Fig. 3: Identification procedure based on FEMU technique (Fazzini, 2011)

Such procedure has been used for the identification of virgin properties of orthotropic carbon-epoxy laminates for aviation industry. Their four in-plane elastic properties have been determined by means of kinematic fields corresponding to an open-hole tensile test. Such mechanical solicitation generates a heterogeneous strain field localized near the hole that stimulates the whole strain components (Molimard, 2005).

The input data from which identification is done are the displacement fields on the specimen surface. In our case, these data are given by numerical simulation with Abaqus but are yet designed in what follows as “experimental” in order to clarify the link with classical application of FEMU method. Precisely, the numerical “experimental” model is a 3D laminated solid that allows a representation consistent with the real material structure. For such a representation, each ply is modeled with its material orientation and its material properties. On the other hand, the simulated model to be identified is a 3D homogeneous solid which allows to obtain the four in-plane global elastic properties of the composite structure. This global identification step is carried out on a 2000 points interest zone and follows the flowchart in Fig. 4.

Such methodology has been applied for a six plies ($[45/0/45]_s$) carbon-epoxy laminated composite structure in G0926/RTM6. It should be noted that the capability of the virgin material properties identification is validated for different configurations of the laminated composite (plies stacking and orientation, components properties) through a comparison with the Kirchhoff-Love theory. Stability and convergence of the algorithm are checked for each considered parameters (Péronnet, 2012c).

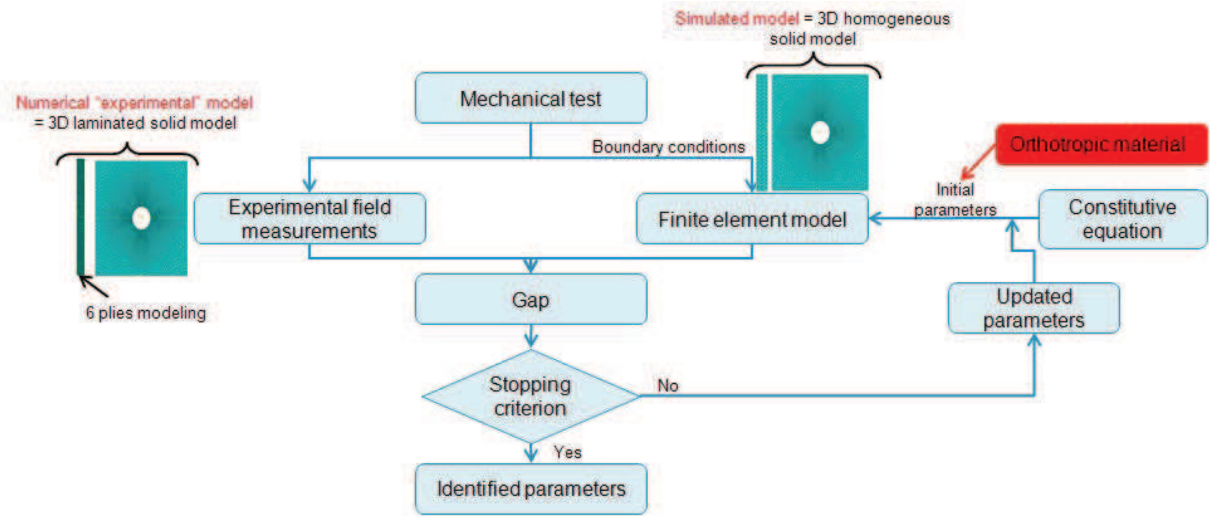


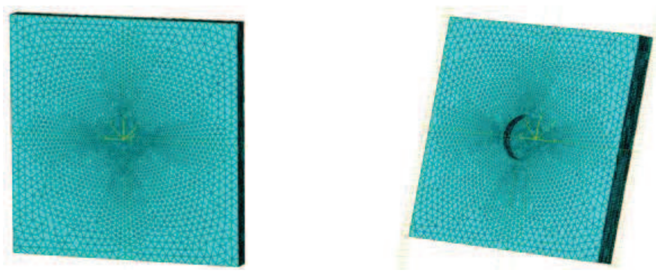
Fig. 4: Virgin material properties identification flowchart

Table 1: Calculated and identified virgin material properties for our composite plate

	E_1	E_2	G_{12}	ν_{12}
Parameters given by Kirchhoff-Love theory	37849 MPa	37849 MPa	21817 MPa	0.438
FEMU identified parameters	37131 MPa	37547 MPa	19874 MPa	0.44

LOCALIZATION OF THE DAMAGED ZONE

The localization of the damaged zone (step 2 in Fig. 2) is given by the calculated gap between the responses ofthe virgin material with constitutive parameters identified at the previous step (Fig. 5a) andthe damaged structure including a virgin zone and a 6 mm diameter circular open-hole defect (Fig. 5b).



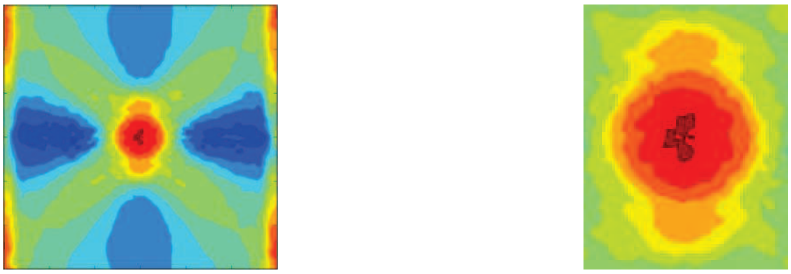
(a) Virgin material model (b) Damaged structure

Fig. 5: Models for the damage zone localization

At this stage, the difficulty lies in the choice of the kind of mechanical response that provides the most relevant feature for the determination of the damaged zone shape. Following classical analyses on errors assessment, the Von Mises equivalent strain has been considered as the representative feature of each situation. A specific algorithm in Python language has been put in place to perform automatically the following steps:

- generate the virgin model and the damaged structure,
- launch the Abaqus job of each model and extract automatically the three in-plane components of strain fields (ε_{11}, ε_{22}, ε_{12}),
- compute in each point of their grid the equivalent Von Mises strain of both models,
- compute the gap between the two models by means of interpolation calculations in order to compare same geometrical points of the structure.

At the end, the equivalent strain error map is plotted (Fig. 6), showing a localized zone with highly different response that corresponds to the defect zone of Fig. 1.



(a) Global equivalent strain error map

(b) Local equivalent strain error map

Fig. 6: Equivalent strain error maps

DIMENSION OF THE DAMAGED ZONE

From the local equivalent strain error map, an image processing developed by a specific application in GIMP (Ostertag, 2007) and Image J softwares (Ferreira, 2010) allows to describe precisely the damaged zone outline. This image processing is composed of three steps as illustrated in Fig. 7.

Fig. 7: Image processing procedure

The first step of the image processing consists in putting in grayscale the error map with GIMP software (Fig. 8). Such software allows indeed a grayscale representation with black and white extrema, which is of particular interest for this quantitative step.

(a) Global grayscale error map

(b) Local grayscale error map

Fig. 8: Grayscale error maps

From the local grayscale error map, a thresholding step is also achieved with GIMP in order to capture the damaged zone outline. This implies to affect the value 0 to the chosen thresholded range and the value 1 outside this range, and allows to display only a certain range of gray level.

The damaged zone shape is known as circular and the equivalent strain error map is derived from tensile test. Therefore during the thresholding step, a specific attention is given on two gray levels which are the one just before circular shape deformation and the other one with the first circular shape deformation (Fig. 8).

(a) Circular shape threshold

(b) Non circular shape threshold

Fig. 8: The two thresholding maps

From these thresholding maps, an image processing with Image J software has been developed in order to obtain automatically each shape outline (Fig. 9) together with each shape size (largest and smallest diameters).

(a) Circular shape outline

(b) Non circular shape outline

Fig. 9: The two outline maps

Table 2: Shape size dimensions

	Largest diameter	Smallest diameter	Average diameter
Circular shape size	5.32 mm	4.9 mm	5.11 mm
Non circular shape size	8.18 mm	5.36 mm	6.77 mm

Concerning the quantitative aspect, the size of the identified damaged zone corresponds with an error of 1% to the one of the defect introduced. Indeed, the mean diameter between the two shape average diameters is about 5.94 mm (for 6 mm in reality). This result should be taken sparingly as the capability of this image processing procedure will be validated on other case studies in order to prove its robustness. Nevertheless, as first result, it is interesting and hopeful.

CONCLUSION

This work lays the early stages of a new methodology for the identification of damaged zones within orthotropic composite materials from kinematic fields. The first step consists in the identification of the virgin material properties, namely for laminated composites of the four in-plane elastic properties, by means of the analysis of a 2000 points interest zone on a open-hole tensile specimen. The first results demonstrate a good agreement with classical laminates theory.

The second step deals with the localization of the damaged zone using the gap between the reference (virgin material) and the damaged structure responses. An automatic procedure based on image processing of the equivalent strain error map accounts for the localization and size of the damaged zone. Again, one obtains a good accuracy with the defect introduced in the structure for calculation.

This work needs now to be completed, especially the implementation of the identified damaged zone within the finite element model (step 3 of Fig. 2) and the identification of degraded properties (step 4 in Fig. 2). The latter should be achieved with the same procedure as for the virgin material. Many simulation cases will also be required in order to ensure the stability and consistency of the procedure. In a final stage, the methodology should be extended to kinematic fields derived from experimental tests.

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