Numerical stochastic study of defects in composite materials: influence of porosity and wrinkles on the mechanical behavior

Hassoun ISHAK [1,2], Alexandre CLEMENT [2], Frédéric JACQUEMIN [2]

[1] Institut de Recherche Technologique Jules Verne, Chemin du Chaffault 44340 Bouguenais, France
Email: hassoun.ishak@irt-jules-verne.fr, Web Page: http://www.irt-jules-verne.fr/
[2] GeM, Institut de Recherche en Génie Civil et Mécanique, Université de Nantes, Centrale Nantes, UMR CNRS 6183, 58 rue Michel Ange 44606 Saint-Nazaire, France
Email: alexandre.clement@univ-nantes.fr, Web Page: http://gem.ec-nantes.fr
Email: frederic.jacquemin @univ-nantes.fr, Web Page: http://gem.ec-nantes.fr

Keywords: Computational mechanics, Probabilistic analysis, Polynomial Chaos, Porosity, Wrinkle

Abstract
Due to their excellent specific properties, composite materials with organic matrix are increasingly used in industry. The manufacturing processes of composite parts may lead to defects which decrease the mechanical properties of the structure. Those parts are thus subjected to systematic long and costly non-destructive testing to detect any defects resulting from manufacturing processes. In case of negative results regarding conservative criteria, the composite components can be considered non-compliant and can be rejected leading to non-negligible economic consequences. In this numerical study we propose to analyze the impact of two types of defect: porosity and wrinkles. Those two defects are, on the other hand, submitted to geometrical uncertainties such as porosity distribution or wrinkles size. The main aim of this work consists in taking into account these uncertainties in order to obtain enhanced physical predictions.

1. Introduction

The use of composite material in the aerospace and the marine renewable energy industry is more and more widespread [1]. Indeed, this type of materials offers best performance because of their remarkable mechanical properties coupled to their lightness. However, when testing the structural composite parts, some defects, linked to the manufacturing process, are detected [2]. These defects may decrease the mechanical properties of the structure. Porosity and wrinkles are among the most common manufacturing induced defects in composites [3, 4]. Although they are from different natures and observed at different scales, they are both submitted to geometrical uncertainties such as porosity distribution or wrinkles shape and size. This numerical study aims at analyzing the impact of these two types of defect in order to get enhanced physical predictions.

In this paper, we adopt a parametric vision of the uncertainties consisting in representing the probabilistic content through a finite set of random variables. The geometry of the voids modeling the porosity is characterized through input random parameters. In the same manner, the shape and size of wrinkles are also represented with random variables. We thus focus on the propagation of the uncertainties based on spectral stochastic methods [5] such as the L2 projection technique which belongs to the so-called non-intrusive approaches [6]. These methods only require the use of deterministic solvers, such as classical finite element softwares, and easily allow parallel computing. The proposed stochastic method will be sum up in section 2.

Excerpt from ISBN 978-3-00-053387-7

The first study of this work will deal with the porosity defect. We work at the microscopic scale where the details of the constituents are geometrically represented. The porosity rate will be modeled with a random variable and represented by voids. The resulting randomness on the mechanical behavior will thus be highlighted.

The second part of the study is dedicated to wrinkle defects which appear at the interface of the ply. We thus work at the mesoscopic scale where ply of composite laminates are characterized by their effective elastic properties. The homogeneous mechanical properties are assumed deterministic whereas the geometry of the wrinkle is submitted to uncertainties. The wrinkle geometry will then be controlled by its height and width which will be modeled with random variables. We thus propose to analyze the influence of these random parameters on local mechanical quantities such as maximum stresses.

2. Mechanical problem

2.1. Static problem

We will study the behavior of a mechanical system that, from an unloaded initial state (the stresses are zero at any point), will reach a new equilibrium state under the action of external forces. The study will be limited to a composite material formed by several materials which are assumed to be linear elastic under small displacements.
The domain $\Omega \subset \mathbb{R}^d$ is subjected to volumetric efforts $\mathbf{f}(x)$ and surface forces $\mathbf{F}(x)$, and specific boundary conditions are applied on its border. The stresses are represented by a second order symmetric tensor denoted $\boldsymbol{\sigma}$ such that the problem writes: find displacement field $\mathbf{u}$ which verifies

$$\mathbf{div}\boldsymbol{\sigma} + \mathbf{f} = \mathbf{0} \tag{1}$$

This equation is completed with the behavior law which links the stress tensor to the second order strain tensor $\boldsymbol{\varepsilon}$

$$\boldsymbol{\sigma} = \mathbf{C} : \boldsymbol{\varepsilon} \tag{2}$$

where $\mathbf{C}$ is the fourth order elastic tensor depending on the material.
Specific displacement and force boundary conditions are added to this problem to ensure the unicity of the solution.

3. Spectral stochastic approach

The stochastic approach based on the probabilistic theory is one of the different existing approaches for modeling uncertainties. In this work, we adopt a parametric view of uncertainties [5,7] consisting in representing the probabilistic content by a finite set of *m* second-order independent random variables $\boldsymbol{\xi} = (\xi_1, ..., \xi_m)$ characterized by their probability measure P_{ξ}. An identification of the input random parameters using existing data or expert judgment may help to characterize the input marginal probability laws which described random vector $\boldsymbol{\xi}$. The propagation of uncertainties, *i.e.* the computation of random output quantities of interest, can be made with various techniques such as Monte-Carlo simulations. In this work, we propose to use spectral approaches which consist in approximating the stochastic solution through a functional representation with respect to the basic random variables.

We denote by $\mathbf{u}(\boldsymbol{\xi})$ the random solution of the model problem. The method leads to seek the response $\mathbf{u}(\boldsymbol{\xi})$ under the form of the following series

Excerpt from ISBN 978-3-00-053387-7

$$\mathbf{u}(\boldsymbol{\xi}) \approx \sum_{\alpha=1}^{P} \mathbf{u}_{\alpha} H_{\alpha}(\boldsymbol{\xi}) \tag{3}$$

where $\{H_{\alpha}(\boldsymbol{\xi})\}_{\alpha=1}^{P}$ refers to a prior basis functions and where the $\mathbf{u}_{\alpha}$ are the coefficients to be determined. Many choices exist for the approximation basis $\{H_{\alpha}(\boldsymbol{\xi})\}_{\alpha=1}^{P}$. We chose the polynomial chaos expansion [8] which is a particular construction of this basis where the H_{α} are multidimensional orthonormal polynomials function of the input random variables.

Several techniques allow the computation of decomposition (Eq. 3) which may be divided into two families: intrusive methods which require modifications of the deterministic solver and non-intrusive methods which do not request such changes. In this work, we use the L^2 projection method [9], which belongs to the non-intrusive family of methods. It consists in defining the approximated solution as the projection of the semi-discretized solution on the stochastic approximation space. The vector solution $\mathbf{u}_{\alpha}$, whose components are the polynomial coefficients of the nodal unknowns, is then computed with a numerical integration procedure such as

$$\mathbf{u}_{\alpha} \approx \sum_{\alpha=1}^{M} \omega_k H_{\alpha}(\boldsymbol{\xi}_k)\, \mathbf{u}(\boldsymbol{\xi}_k) \tag{4}$$

where the $\boldsymbol{\xi}_k$ are the integration points corresponding to particular realizations of the basic random variables and the ω_k are the associated integration weight. For each integration point, the calculation of $\mathbf{u}(\boldsymbol{\xi}_k)$ requires the use of a deterministic solver. In this work we use the classical finite element method through the commercial software Abaqus®.

In practice, we have developed a tool which allows to entirely controlling the probabilistic problem with the Matlab® software. The stochastic pre-processing and post-processing are performed with the Matlab® tool and dedicated Python scripts allow to automatically solve the deterministic problems with Abaqus®.

4. Numerical studies

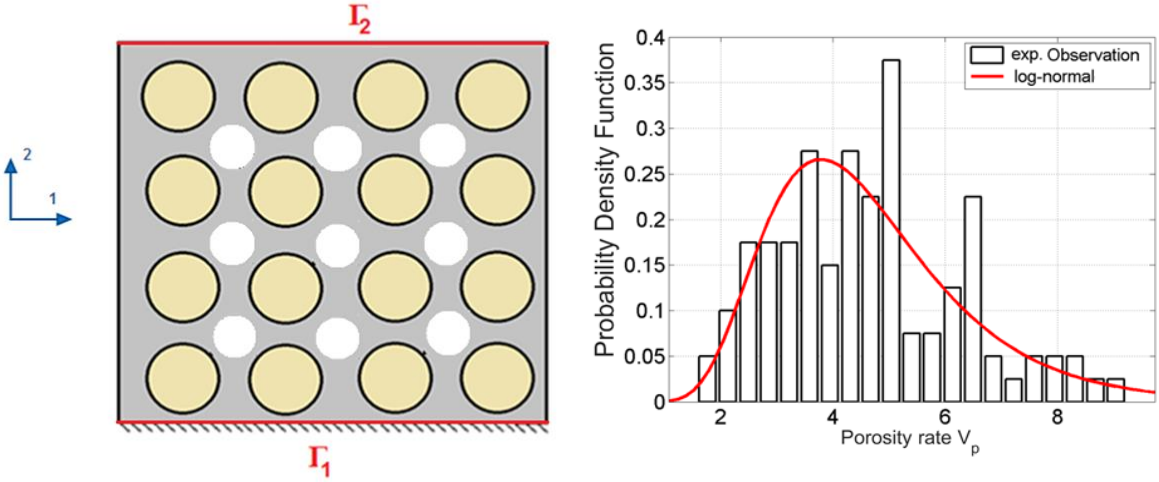
4.1. Porosity defects

4.1.1 Problem definition

In this part, we will conduct a numerical study involving random porosity. We work at the microscopic scale, where we consider a composite material made of an epoxy resin and reinforced with glass fibers with a volume fraction of 50 % depicted on figure 1.(a) The cell characteristic size is 70 μm and the deterministic diameter of the fibers is 14 μm.The material properties are the following ones: E_m = 3 GPa and ν_m = 0.33 for the epoxy resin, E_f = 72 GPa and ν_f = 0.33 for the glass fibers. The boundary conditions are illustrated on figure 1.(a) with an applied strain = 0.5 % on Γ_2.

The objective of this study is to determine the influence of the randomness of the porosity rate on the behavior of the composite. The porosity is represented by voids in the matrix and its rate is modeled with a random variable. Experimental data have allowed identifying this random variable through maximum likelihood estimation. The Log-normal law appeared to be a good candidate as shown on figure 1(b) with a mean = 4.63 % and a standard deviation = 1.65 % leading to a coefficient of variation CoV = 35.7 %. The stochastic approximation space is based on a polynomial chaos of order 2 composed of Hermite polynomials.

Excerpt from ISBN 978-3-00-053387-7

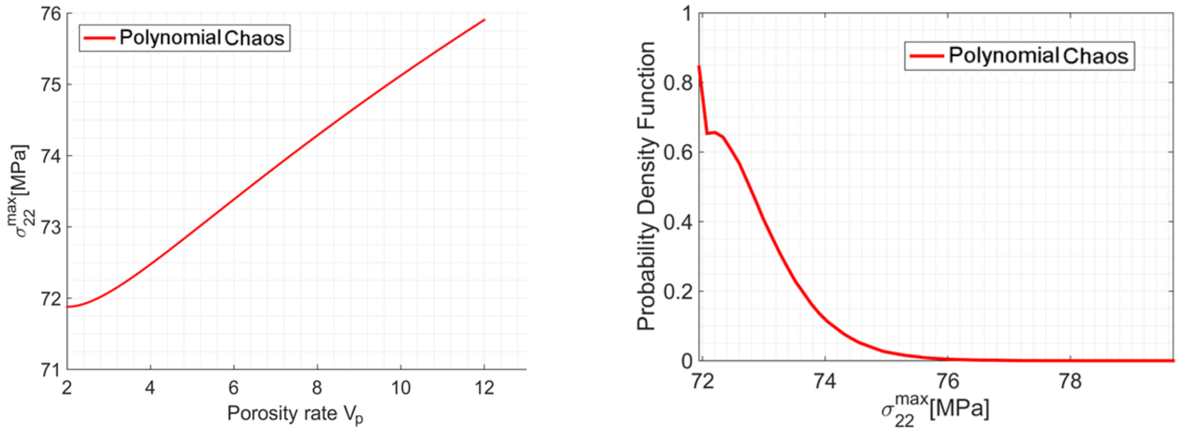


(a) (b)

Figure 1. (a) Geometry and boundary conditions of the porosity problem (b) Probability density function (PDF) of the porosity rate.

4.1.2 Results and discussion

Figure 2 shows the response surface and the probability density function (PDF) of the maximum local stress σ_{22}^{max}. As expected, we can see on figure 2.(a) that the stress level increases with the porosity rate. The PDF of σ_{22}^{max} figure 2.(b) shows that we have a high probability to have a stress level inferior to 74 MPa with P($\sigma_{22}^{max} \leq$ 74 MPa) = 0.86. The coefficient of variation of this quantity is CoV = 1.74 % which is a quite low value comparing to the one we had for the input porosity rate.



(a) (b)

Figure 2. (a) Response surface of maximum stress σ_{22}^{max} function of the porosity rate V_p
(b) Probability Density Function of σ_{22}^{max}.

Excerpt from ISBN 978-3-00-053387-7

4.2. Wrinkle defects

4.2.1 Problem definition

In this part, we will conduct a numerical study involving wrinkle. We thus work at the mesoscopic scale, so we consider a composite material consisting of two plies. The length of each one is 20 mm and its thickness is 3 mm. The first ply is a [0°] unidirectional composite, the second one is a [45°/-45°] ply. A neat epoxy resin fills the gap between the wrinkle and the [45°/-45°] ply. The elastic material properties for all material components are listed in Table 1. The composite is loaded in in-plane compression, as illustrated in figure 3 and symmetry boundary conditions are imposed.
The objective of this study is to determine the influence of the randomness of the wrinkle on the behavior of the composite. We use a parametric representation of the wrinkle geometry basically through its height and width. We did not have yet experimental data for this type of defect and we therefore assume values coming from the literature. The geometrical parameters are thus taken as uniform random variables such that the width $L \in U$ (2.8 mm, 3.2 mm) and the height $A \in U$(0.3 mm, 1.5 mm).The stochastic approximation space is based on a polynomial chaos of order 2 composed of Legendre polynomials.

Table 1. Elastic properties for materials in the composite structure.

Material	E_1 /E_2 (GPa)	G_{12} (GPa)	ν_{12} (GPa)
UD [0°]	41.3 / 10.6	4.2	0.29
PLY [45°/-45°]	11.1 / 10.6	4.2	0.29
Epoxy	3	0.5	0.33

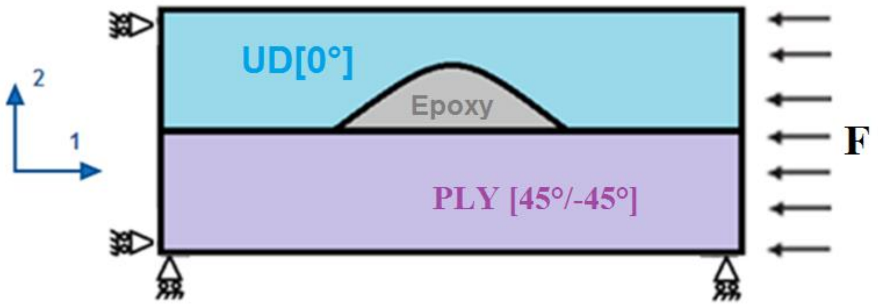
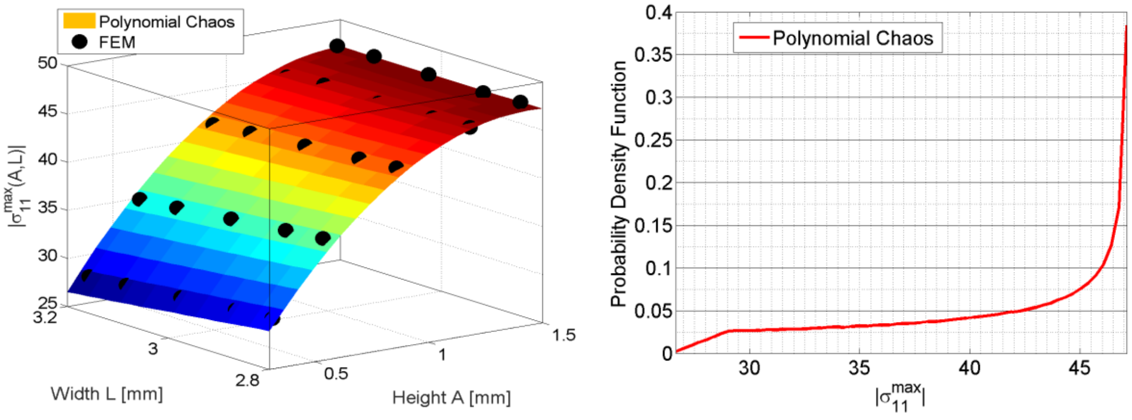


Figure 3. Geometry and boundary conditions of the wrinkle problem.

Excerpt from ISBN 978-3-00-053387-7

4.2.2 Results and discussion



(a) (b)

Figure 4. (a) Response Surface of $|\sigma_{11}^{max}|$ function of the wrinkle height A and width L (b) Probability Density Function (PDF) of $|\sigma_{11}^{max}|$.

Figure 4 shows the response surface and the probability density function (PDF) of the maximum local stress $|\sigma_{11}^{max}|$ where one can observe a good agreement between the polynomial chaos approximated solution and deterministic FEM computations corresponding to particular realizations of the input random variables. As we can see on figure 4.(a), $|\sigma_{11}^{max}|$ increases with the height of the wrinkle. However, the width of the wrinkle has a small impact on this quantity. Moreover, we can see on the PDF of $|\sigma_{11}^{max}|$ (figure 4.(b)) that the probability to find $|\sigma_{11}^{max}|$ inferior to 46 MPa is $P(|\sigma_{11}^{max}| \leq 46$ MPa) = 0.74. Finally, we note a significant variability for this quantity with a coefficient of variation CoV = 14.3%.

5. Conclusions

We have proposed a study of the impact of porosity and wrinkles within composite materials which take into account the variability of these defects. We used a parametric vision of the uncertainties consisting in representing the probabilistic content through a finite set of random variables. We focused on the propagation of uncertainties based on spectral stochastic methods using the L2 projection technique which is a non-intrusive method. We have shown the capability of the proposed approach with two numerical examples leading to parametric and probabilistic results. Further works will be devoted to (i) the use of scale transition methods to take into account microscopic details at a much higher scale without geometrically representing the constituents, (ii) various configurations of random wrinkles and (iii) fatigue damage analyze of the impact of these defects on the behavior of the composite.

Excerpt from ISBN 978-3-00-053387-7

Acknowledgments

This paper is part of the SIMSCEF project managed by IRT Jules Verne (French Institute in Research and Technology in Advanced Manufacturing Technologies for Composite, Metallic and Hybrid Structures). The authors wish to associate the industrial partners of this project: Adwen and DAHER.

References

[1] K.B. Katnam, L.F.M. DaSilva and T.M.Young. Bonded repair of composite aircraft structures: A review of scientific challenges and opportunities. *Progress in aerospace*, 61:26-42, August 2013.

[2] K.D. Potter. Understanding the origins of defects and variability in composites manufacture. *ICCM-17*, Edinburgh, 2009.

[3] A. Caiazzo, M. Orlet, H. McShane, L. Strait and C. Rachau. The effects of marcel defects on composite structural properties. *Composite Structures: Theory and Practice*, 1383:158-187, 2001.

[4] C. Lopes , J. Remmers and Z. Gurdal. Influence of Porosity on the Interlaminar Shear Strength of Fibre-Metal Laminates. *Key Engineering Materials*, 383: 35-52, 2008.

[5] R. Ghanem and P. Spanos. *Stochastic finite elements : a spectral approach*. Springer, Berlin, 1991.

[6] O.P. Le Maître, M.T. Reagan, H.N. Najm, R.G. Ghanem and O.M. Knio. A stochastic projection method for fluid flow. *J. Comput. Phyics*, 181 : 9-44, 2002.

[7] M. Loève. *Probability Theory. I, fourth edition, in : Graduate Texts in Mathematics, vol. 45*. Springer-Verlag, New York, 1977.

[8] D. B. Xiu and G. E. Karniadakis. The Wiener-Askey polynomial chaos for stochastic differential equations. *SIAM J. Sci. Comput.*, 24 (2) :619–644, 2002.

[9] O.P. Le Maître and O.M. Knio. *Spectral Methods for Uncertainty Quantification with Applications to Computational Fluid Dynamics*. Springer, Heidelberg 2010.

Excerpt from ISBN 978-3-00-053387-7