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Publication date
2022

Document Version
Final published version

Published in
Proceedings of the 20th European Conference on Composite Materials: Composites Meet Sustainability

Citation (APA)
Sasikumar, A., Ninyerola, J., Ruiz, I., Bessa, M. A., & Turon Travesa, A. (2022). Generation of design allowables on the open hole tensile strength of composite laminates using sensitivity analysis and uncertainty quantification framework. In A. P. Vassilopoulos , & V. Michaud (Eds.), *Proceedings of the 20th European Conference on Composite Materials: Composites Meet Sustainability: Vol 4 – Modeling and Prediction* (pp. 868-874). EPFL Lausanne, Composite Construction Laboratory.

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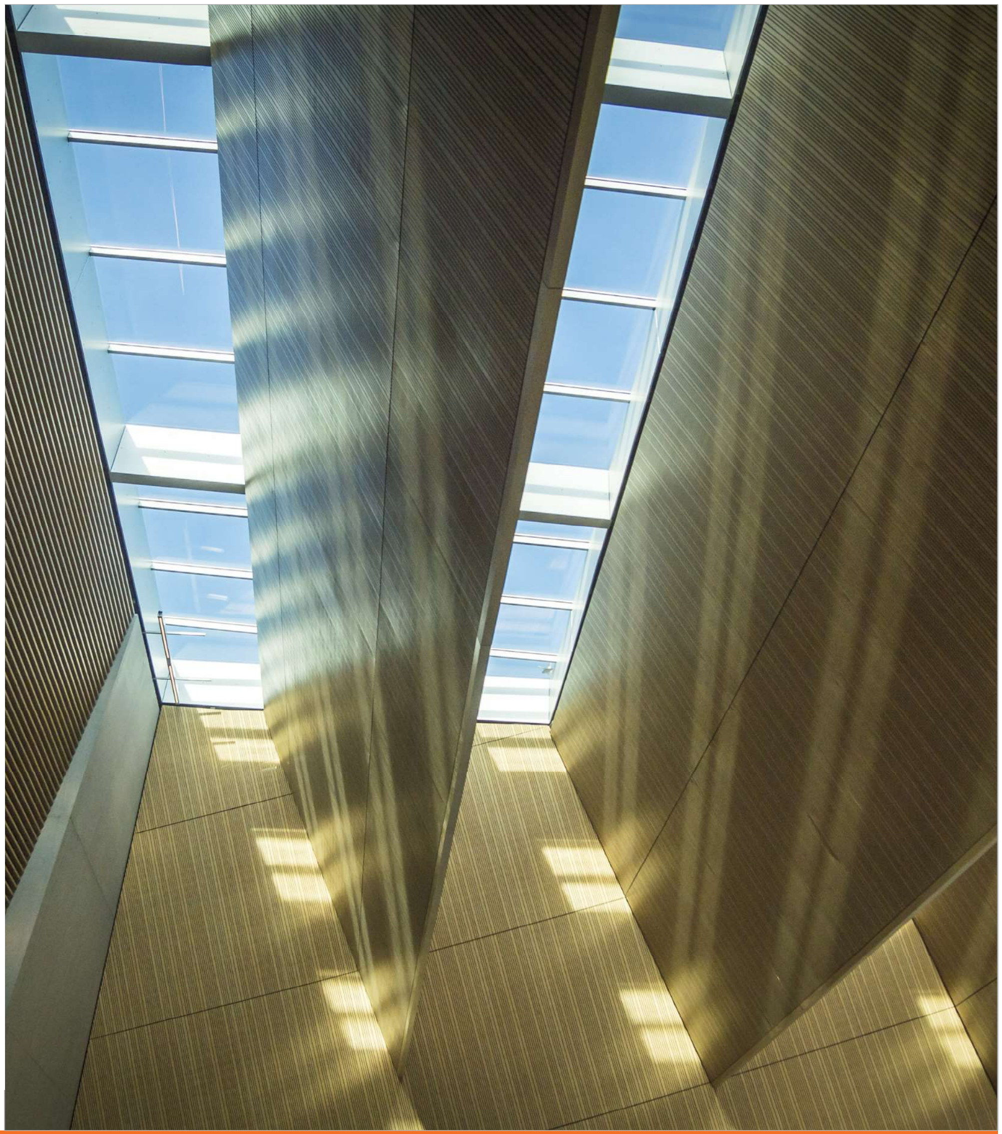

Proceedings of the 20th European Conference on Composite Materials

COMPOSITES MEET SUSTAINABILITY

Vol 4 – Modeling and Prediction

Editors : Anastasios P. Vassilopoulos, Véronique Michaud

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Prof. Véronique Michaud, LPAC/EPFL

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ISBN: 978-2-9701614-0-0
DOI: http://dx.doi.org/10.5075/epfl-298799_978-2-9701614-0-0

Published by :

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1015, Lausanne, Switzerland

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GENERATION OF DESIGN ALLOWABLES ON THE OPEN HOLE TENSILE STRENGTH OF COMPOSITE LAMINATES USING SENSITIVITY ANALYSIS AND UNCERTAINTY QUANTIFICATION FRAMEWORK

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Abstract: *Aeronautical industries are concerned about the cost effective generation of design allowables for composite laminates. Design allowables take into account the variabilities arising from different sources (material, manufacturing, defects etc.,) which are determined using expensive and time consuming experimental campaigns. For rapid certification and costs reduction, it is of high interest for the aeronautical industries to use high fidelity numerical models to compliment the testing. In this work, we use a high fidelity numerical model to simulate open hole tension (OHT) of composite laminate, followed by an efficient global sensitivity analysis and uncertainty quantification and management framework to generate design allowables. In a first step, Morris sensitivity analysis is used to screen the sensitive input material properties that affect the OHT strength. In the second step, machine learning technique is used to create a surrogate model, which is used to obtain the B basis design allowable on the OHT strength.*

Keywords: Design allowables, Virtual testing, Sensitivity analysis, Machine learning, Uncertainty quantification and propagation

1. Introduction

Aeronautical industries confront the challenge of accounting for the various uncertainties related to composite material response. Uncertainties related to composite materials can arise from material properties, manufacturing processes, test setup, specimen geometry, loading conditions, manufacturing defects etc., and need to be quantified to evaluate their influence on the structural performance. Hence, uncertainty quantification and management (UQ&M) approach is used to provide the variability from each input parameter and provide the design allowables on the output (for e.g., strength of the laminate), which adds confidence and robustness to the design and certification process. Contrary to the conventional method of obtaining design allowables through extensive experimental campaigns, industries have started to supplement the experimental tests with virtual tests using high fidelity numerical models that can predict with good accuracies, and also reduces the recurring and non-recurring costs, thereby leading to cost efficient and shorter certification processes.

The failure strength of a laminate depends on the material properties of the fiber-matrix system, laminate configuration, specimen geometry etc. Material properties account to the elastic, strength and fracture properties of both fiber and matrix and the variability in these material properties can significantly affect the structural response of the laminate. To quantify the variability associated to each material property, a statistical distribution of the property is

doi:10.5075/epfl-298799_978-2-9701614-0-0

obtained through experimental testing. Here it is beneficial to screen the sensitive material properties that affect the output, where the identified sensitive parameters can be well characterized experimentally by testing more specimens and thereby obtaining a better statistical distribution.

Global sensitivity analysis has been widely applied over different fields with the idea of identifying the key input parameters that affect the output. Variance based methods are suitable for non-linear complex models but with the drawback of high computational costs. Screening based method is optimum for models demanding high computational cost since these methods require less model evaluations, but with the drawback of providing only qualitative effects. Different authors [1, 2] have performed local sensitivity analysis to identify the key material properties that affects the open hole strength, impact delamination area etc., where the identified sensitive parameters where used to build a response surface for the calculation of the design allowables using UQ&M approach [2].

Recent advances on machine learning has made its way into the virtual testing of composite materials, where the computational expensive numerical simulations can be represented by surrogate models that can predict the response at a relatively cheaper cost [3]. At first, an input test matrix is created using a sampling approach from a defined design space and further, using FEM simulations the output data is generated. This obtained data is used for training and testing the surrogate model using a defined approach. Different machine learning techniques such as Gaussian Process, Random Forest, Artificial neural network have gained prominence towards the building of surrogate models.

In this paper, we aim to define a framework to generate the design allowables on the open hole tensile strength of composite laminate, taking into account of the variability in the material properties. At first, we define a cheap and efficient global sensitivity analysis based on 3D FE numerical model where we identify the sensitive material properties that influence the OHT strength from a total of 21 input material properties. Further, a surrogate model is created from a design space where only the sensitive material properties are varied, where the other parameters are kept constant at their mean values. Gaussian process was used to build the surrogate model, where the relation between the R score and the number of FE simulations required was studied. Once an accurate model was generated, this was employed to estimate the B basis design allowable using the Monte Carlo approach, and was also compared with the Composite Material Handbook 17 (CMH17) [8] approach.

2. Methodology

2.1 Numerical model

We used a mesoscale FE model to simulate the open hole tensile response, where Abaqus/Explicit [6] 3D solid elements (C3D8R) were used to model the plies. The interfaces were modeled using Abaqus finite thickness cohesive elements (COH3D8) [ref]. Progressive intra-ply damage was accounted for with the continuum damage model proposed by Maimi et al. [4,5] The damage activation functions are based on LARC04 failure criteria. The intralaminar model was implemented in a VUMAT user-written subroutine. An intralaminar element was deleted once the fiber damage variable (d1) reached 1. A uniform in-plane element size of 0.5 mm was used for all the elements (both inter and intralaminar) throughout the study. Each ply was modeled as a solid layer with one element through the ply thickness, while the thickness of the cohesive elements was set to 0.01 mm as recommended in the Abaqus documentation. Tensile load was introduced by applying a pre-de displacement at one of the specimen edges while keeping the other edge constrained.

The laminate modeled is a quasi-isotropic laminate with 24 plies of 0.131 mm per ply. The nominal thickness is 3.12 mm and the hole diameter is selected as 2 mm with the in-plane dimensions of 12 mm (width), 24 mm (length) and maintaining a with-to-diameter ratio of 6. The selected material is IM7/8552 and the FE model considers 21 material properties that includes the elastic, strength and fracture properties of both fiber and matrix.

2.2 Sensitivity analysis

In this work, we used the Morris One-At-a-Time (MOAT) [7] screening based sensitivity analysis in order to filter the key material properties. In each model evaluation, only one input parameter is varied at a time and is varied across a selected *p* levels in the grid space. An elementary effect is calculated which provides the ratio of the change in the model output to the input parameter variation. Morris provides two sensitivity measures: μ^*, which provides the overall influence of the input parameter on the output, and σ, which assesses the non-linear or interaction effect of that input parameter with the rest of the parameter. MOAT uses hyper parameters such as p and r which are denoted as the number of levels in the design grid space and the number of repetitions/trajectories, respectively. All the input material properties follow a normal distribution and are varied within ±3 standard deviations for the creation of the input matrix of the sensitivity analysis. We used Morris hyper parameters p=16 and r =20 (defined through a preliminary study) and with 21 material properties, this leads to a total of 440 FE simulations.

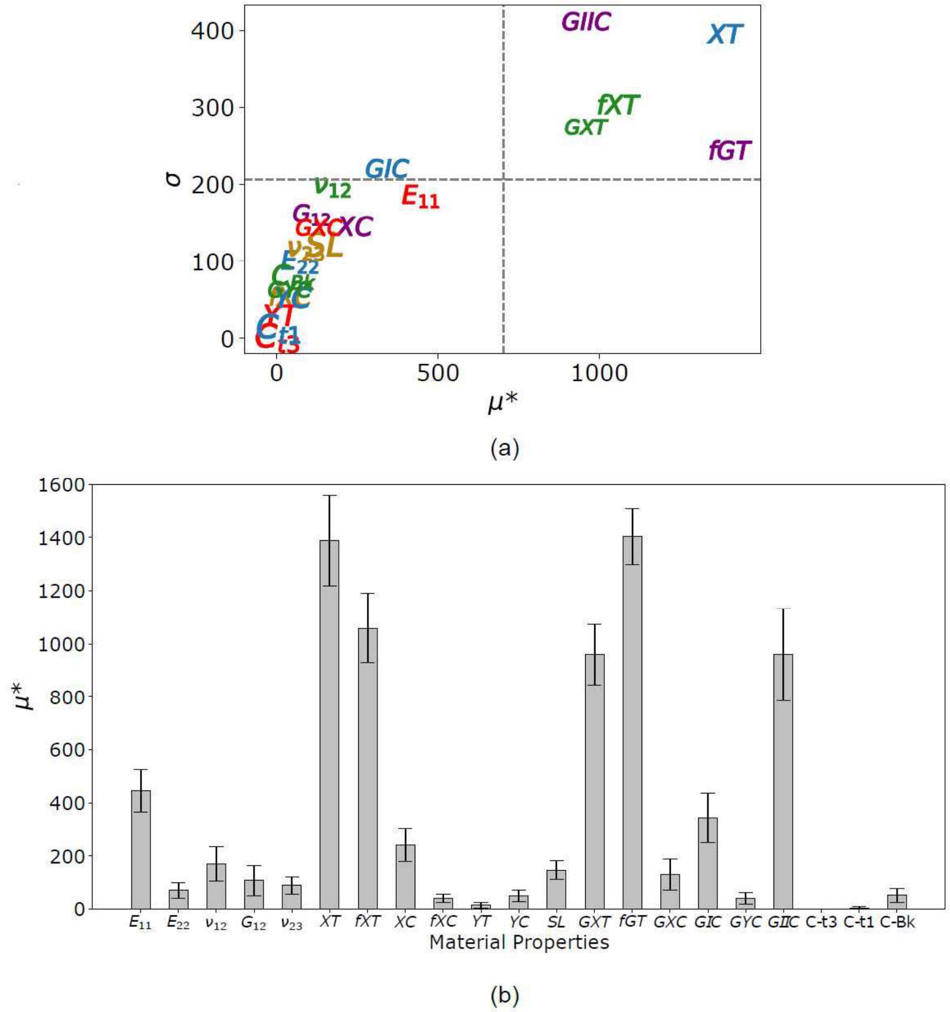
2.3 Metamodel and UQ&M

Latin hypercube sampling (LHS) approach (with max_min criteria) is used for design of experiments, where the identified sensitive material properties from the previous step are the input parameters. The material properties were varied within ±3 standard deviations from their mean value, and the LHS sampling with a 75% of the total samples following a uniform distribution and the remaining 25% following a normal distribution. This will ensure that there are more sample points added to the tail of the normal distribution. An input matrix of 2000 samples (varying the sensitive material properties) was created and then subjected to virtual testing to obtain the OHT strengths. With this data generated, a Gaussian process regression was performed with a train to test ratio of 0.75. This was performed progressively for different number of simulations to obtain the dependence of R score with respect to the number of simulations required. Once an accurate model was obtained, the B basis design allowable was calculated using two approaches: (a) CMH17 [8] approach (b) Monte Carlo simulations (MCS) of n samples to obtain the 10th percentile Empirical Cumulative Distribution Function (ECDF), followed by repeating the process N times and then obtaining the B value as the 5th percentile of the ECDF of the N 10 percentiles.

3. Results and Discussion

3.1 Morris sensitivity analysis

Figure 1 (a) presents the Morris μ^* vs σ plot for the 21 material properties and Figure 1(b) presents the μ^* values along with 95% confidence interval obtained from bootstrapped resampling. Material properties placed on the right top are considered as the sensitive parameters that have a high μ* and σ values. Fiber longitudinal tensile strength (XT), fiber tensile fracture toughness (GXT), mode II interlaminar fracture toughness (GIIC) and fiber tensile cohesive law parameters (fXT and fGT, ratios of XT and GXT in the first branch of the cohesive law) are the sensitive parameters identified through Morris approach.



(a)

(b)

Figure 1. (a) Morris sensitivity analysis results (p=16, r=20) and (b) Morris plot with 95% confidence interval on the absolute mean values obtained through bootstrapped re-sampling.

3.2 Metamodel and Design allowable

As mentioned before, a total of 2000 OHT simulations were performed, where the input matrix was obtained through Latin hypercube sampling (LHS) of the above-mentioned five sensitive material properties. Once the OHT strengths were obtained, this data is used for training the metamodel. The evolution of R score with respect to the number of samples (simulations) was performed as shown in Figure 2. For example, 100 samples (input matrix as well as the OHT strengths) were selected randomly out of the total 2000 samples available. Out of this 100, 75 samples were used to train the model and 25 for the test, which will provide a R score. This process was repeated 100 times, which thus provides 100 R scores and hence Figure 2 shows a box plot of the R-scores for different number of samples selected (ranging from 100 to 2000). Figure shows that the even with a low a number of samples, a good prediction is obtained with an R score more than 0.95. With increased number of samples, the bounds of the R-score keep decreasing (except for the last case).

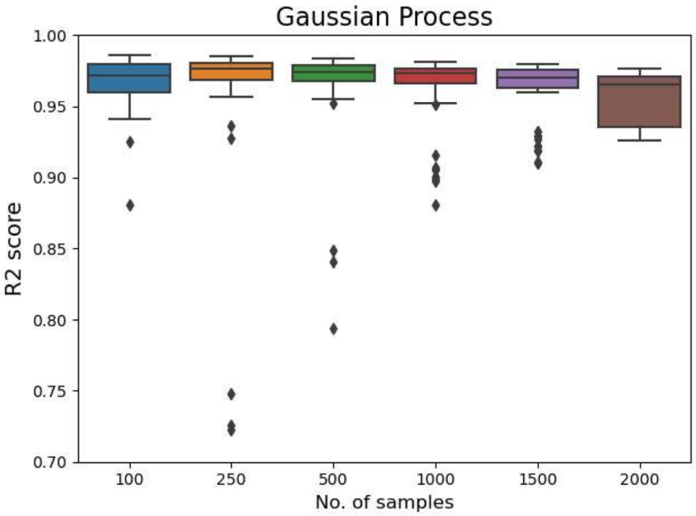


Figure 2. Box plot of the metamodel R-score for increasing number of samples

To estimate the design allowables, two approaches are used. First one is to use the metamodel and perform Monte Carlo simulations (MCS). Here, metamodel built from a sample size of 200 was selected (from Figure 2) and using this metamodel, MCS were performed. At first, MCS of n samples were performed to obtain the 10th percentile Empirical Cumulative Distribution Function (ECDF), followed by repeating this process N times and then obtaining the B value as the 5th percentile of the ECDF of the N 10 percentiles. Figure 3 shows the B value obtained using metamodel and the MCS approach represented using the black dashed line, with $N=10^3$ and $n=10^5$.

In addition, this B value is compared with the CMH17 approach, where the mean and standard deviation of the n samples can be used to calculate the B value (following the guidelines in the Composite Material Handbook 17). Figure 3 shows the B value obtained from the CMH17 approach for different number of samples. For example, for 100 samples case, 100 OHT strengths are randomly selected out of the 2000 simulations to obtain one B value, and this process is repeated 100 times, which provides the box plot of the B value for each case. With increasing number of samples/simulations, the B basis value increases. For a lower number of samples, it provides a conservative B value in contrary to increasing the number of samples. Hence, it's important to find a balance in the approach to have a reasonable computational time and not to have a very low or conservative B basis value.

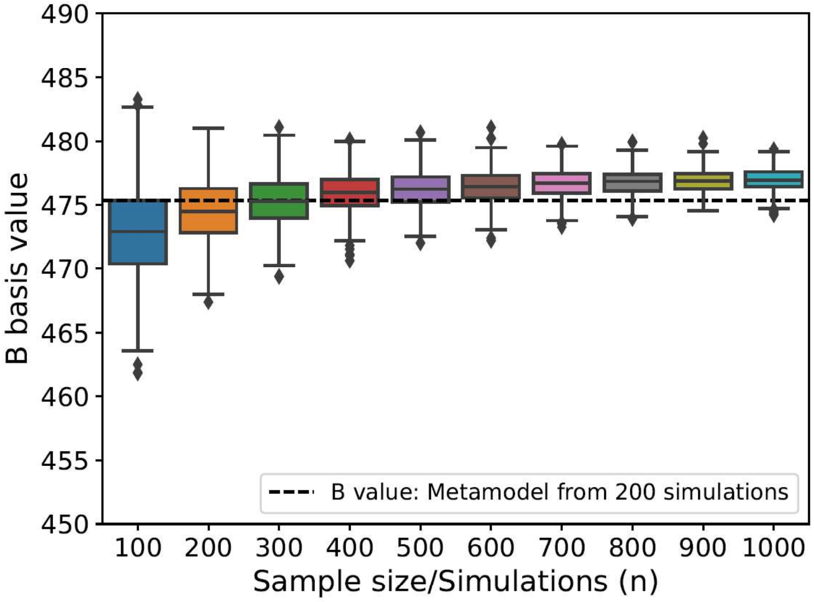


Figure 3. Box plots of B basis values (using CMH17 approach) for n simulations, whereas the dashed line represents the B value obtained from the Monte Carlo simulations of the metamodel (from 200 samples)

4. Conclusion

Aeronautical industries are trying to quantify the various uncertainties associated with composite materials response. Within the framework of uncertainty quantification and management (UQ&M), industries aim to obtain statistical design allowables for different composite tests to quantify the confidence on the design & certification process and structural performance. In this aspect, we propose a framework of sensitivity analysis followed by UQ&M approach to estimate the design allowable on the open hole tensile strength accounting for the uncertainty from the material properties. Morris sensitivity analysis method identified five sensitive material properties out of 21 properties that are influencing the open hole strength. Further to estimate the design allowable on the open hole tensile strength, two approaches were used where the first one is to build a surrogate model (accounting for the variability of the sensitive material properties identified) and compute the B basis value using Monte Carlo simulations, and the second one to use the Composite Military Handbook approach. The results are compared and it is observed that for a low number of samples, CMH approach provides a conservative B value and on the other hand using metamodel approach, there has to be a balance on the computational time required for the creation of the metamodel, which depends on the test case. This proposed framework can help to estimate design allowables, where the experimental tests can be complimented by virtual testing and leading to a more robust and cost efficient designs and more importantly helping to achieve rapid certification processes.

Acknowledgements

This work has been accomplished within the framework of an ongoing EU Horizon 2020 CleanSky 2 Project TREAL (Thermoplastic material allowable generation using a reliability-based virtual modelling platform). This work has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No. 864723. The JU receives support from the European Union’s Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union. The project consortium is formed between Amade (University of Girona), University of Porto and MSC-Xstream, with Airbus as the topic manager.

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