Prediction of Moisture Saturation Levels for Vinylester Composite Laminates: A Data-Driven Approach for Predicting the Behavior of Composite Materials

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Abstract: This paper introduces a comprehensive, data-driven method to predict the properties of composite materials, such as thermo-mechanical properties, moisture saturation level, durability, or other such important behavior. The approach is based on applying data mining techniques to the collective knowledge in the materials field. In this article, first, a comprehensive database is compiled from published research articles. Second, the Random Forests algorithm is used to build a predictive model that explains the investigated material response based on a wide variety of material and process variables (of different data types). This advanced statistical learning approach has the potential to drastically enhance the design of composite materials by selecting appropriate constituents and process parameters in order to optimize the response for a specific application. This method is demonstrated by predicting the moisture saturation level for vinylester-based composite laminates. Using 90% of the available published data available as the training dataset, the Random Forests algorithm is used to develop a regression model for the moisture saturation level. Variables considered by the model include the manufacturing process, the fiber type and architecture, the fiber and void contents, the matrix filler type and content, as well as the conditioning environment and temperature. On this training data, the model proved to be a good fit with a prediction accuracy of $R^2_{training}$=94.96%. When used to predict the moisture saturation level for the remaining unseen 10% of the compiled data, the model exhibited a prediction accuracy of R^2_{test}=85.28%. Furthermore, the Random Forests model allows the assessment of the impact of the different variables on the moisture saturation level. The fiber type is found to be the most important determinant on the moisture saturation level in vinylester composite laminates.

Keywords: Data-driven, composite materials, statistical learning, behavior prediction.
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INTRODUCTION

Due to their light weight and high performance, composite materials are being increasingly used in structural applications in key industries such as aerospace, automotive, energy and infrastructure [1]. Predicting and characterizing the behavior of composite materials is a key problem in materials research and development. Mico- and macro-mechanical models have been developed to predict some of the critical properties of composite parts, such as the elastic modulus, based on constituent materials properties (i.e. reinforcing fibers and resin). However, these models often consider ideal microstructures and perfect interfacial conditions that limit their accuracy. Other phenomenological constitutive models were developed to predict different properties of composites by utilizing analytical expressions that describe the observed physical phenomena. For instance, the hindered diffusion model is known to accurately capture the moisture absorption behavior of a variety of polymer composites [2]. Nevertheless, these models usually depended on several empirical parameters that are recovered, using experimental data, and as such, are very specific to the studied composite type [2].

For several decades, considerable research has been conducted towards experimentally characterizing composite materials based on constituent materials and process variables. The ultimate goal being to facilitate the design process for these materials to withstand different loads encountered during their life-span for specific applications. Yet, each of these investigations is focused on a precise combination of constituent materials. For instance, many studies focus on a specific type of reinforcement such as glass fibers or carbon fibers, with a specific type of polymeric matrix such as epoxy or vinylester, among others [3]. In addition, these studies often consider one manufacturing process while investigating the effects of process parameters on the composite behavior, or alternatively examine the effect of different manufacturing processes on the fabricated composite parts [4]. Other studies focus on the effects of external conditions, such as hygrothermal or environmental history, on the behavior of the studied composites [5].

While there is an abundance of published body of work on composite materials behavior, each study presents a unique viewpoint that is specific to either (i) constituent materials including fiber type and architecture and matrix with high impacts on the moisture saturation level in vinylester-based laminates. The remaining variables have very little effect on the output variability.

TABLE 2. Impact of explanatory variables on the moisture saturation level.

Variable	Reinforcement Type	Void Content	Manufacturing Process	Matrix Filler Type	Conditioning Temperature	Matrix Filler Content	Conditioning Environment
%IncMSE	19.50	7.39	6.13	4.47	3.88	3.84	3.43

For instance, the most important variable by far is observed to be the reinforcement type. Since only glass and carbon fibers were encountered in the database, it follows that moisture saturation levels are fundamentally different between the two types of reinforcement. This can be explained by the different sizings commercially applied to each fiber type, combined with a much higher moisture absorption rate along the fibers [10,11]. Void contents and manufacturing process are also found to influence significantly the moisture saturation levels for vinylester-based composites. This is expected since voids serve as storage locations for water molecules [2], and the manufacturing process would define, more or less, the level of void content in the fabricated composite [15]. What was not expected however, is that fiber content and conditioning environment and temperature did not seem to influence extensively the moisture saturation level of vinylester based composite laminates. These findings would be of great interest while designing vinylester-based composite parts, especially when the intended application involves immersion in water or a humid environment.

CONCLUSION

A data-driven approach is proposed to predict the properties of composite materials. The approach, based on advanced statistical learning techniques applied to the collective knowledge in the composite materials field, involves 3 phases. First, a comprehensive database is compiled from published research articles. Second, the Random Forests algorithm is used to build a predictive model that explains the investigated material response based on a several material and process variables. Third, the predictive performance of the built model is assessed, and the importance of the used explanatory variables is assessed.

This approach is demonstrated on predicting the moisture saturation level of vinylester-based composites. Using 90% of the compiled data as the training dataset, the Random Forests algorithm is used to develop a predictive model for the moisture saturation level. Variables considered by the model include the manufacturing process, the fiber type and architecture, the fiber and void contents, the matrix filler type and content, as well as the conditioning environment and temperature. The model showed a predictive accuracy of $R^2_{training}$=94.96% on the training data, inferring that the variables almost fully explain the variation in the moisture saturation levels. The model displayed a predictive performance of R^2_{test}=85.28% on the unseen 10% of the compiled data. Furthermore, the impact of the different variables on the moisture saturation level can be assessed using the random forest model. The reinforcement type is found to be the most important determinant on the moisture saturation level in vinylester composite laminates.

This proposed approach has the potential to drastically enhance the design of composite materials by leveraging the available published data in the composite material field to select appropriate constituents and process parameters in order to optimize the response of a composite part for a specific application.

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