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A methodology to estimate the fiber tow position during the fiber placement manufacturing processes of FRP laminates to homogenize the laminate's permeability

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Introduction

Automated manufacturing of composites is growing rapidly owing to the advances in preforming, monitoring and control technologies to improve the production efficiency, reduce costs, and ensure consistent geometric accuracy [1]. In dry fiber placement process, dry tows are placed on the lower mold and then impregnated with a resin in a subsequent step after mold closing. The position of fiber tows in a laminate has a significant impact on the laminate's permeability [2]. Advances in the real time monitoring techniques to precisely locate tow positions [3] and in numerical models to estimate the laminate's permeability [4] - and its variability leading to resin flow irregularities (and thus defects) - will enable positioning of the tow in the next layers to minimize the permeability variability. Consequently, the mechanical properties of the manufactured laminate will be enhanced since the defects such as voids will be mitigated.

The objective of the present work is to develop a methodology to achieve a uniform out-of-plane permeability across a fiber-reinforced polymer (FRP) laminate, thereby maximizing the average permeability while reducing its variability. This approach provides a computational tool to mitigate the risk of void formation, which is prevalent in regions exhibiting rapid permeability changes, such as a low permeability zones adjacent to a high permeability zones.

Methodology

A virtual dataset was generated consisting of 54 000 samples, which represent the cross-section binary image of [0/90] laminates. The through-thickness permeability of each laminate was then estimated using a convolutional neural network (CNN) developed in ref. [4] and a circuit analogy for homogenization of permeability of multiple layers.

The variational alignment framework [5] was employed to effectively integrate two latent spaces from different modalities to achieve the main objective. The framework is composed of three variational autoencoders (VAE) models (see Fig. 1.a): transition branch, auto-encoding branch, and variational alignment branch. These VAEs facilitate transitions from permeability pattern to fiber tow positions of a laminate, as well as direct mapping from fiber tow positions to its decoded counterparts. The hyperparameters of each VAEs were optimized using the Optuna Python library [6]. Subsequently, the effect of hyperparameters on the optimization process was investigated, highlighting their influence on model performance. Additionally, the quality of the hyperparameter tuning process was then evaluated to ensure the robustness of the optimization framework.

From a current fiber tow position of a laminate, its permeability and the inverse permeability are estimated. The latter is then encoded in the latent space of the transition branch. Subsequently, the nearest data point in the current latent space is selected, and mapping it to the latent space of the autoencoding VAE via the variational alignment VAE. The nearest data point in the auto-encoding VAE's latent space is then selected. The permeability of the selected data point is then combined with the permeability pattern of the analyzed laminate. The improvement of the combined permeability pattern is indicative of a successful result, which in

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turn provides a promising candidate (i.e. the fiber tow position of the subsequent layers). Conversely, if the result is deemed unsatisfactory, the selected data point is mapped to the transition VAE, and the process is repeated.

Results

A virtual manufacturing process involving 10 000 laminates of $[0/90]_5$ was conducted to analyze the proposed methodology. The analysis demonstrated the improvement of the laminate's permeability, see Fig 1.b. The mean permeability of the proposed laminates is higher than that of the original laminates. Moreover, the proposed laminates exhibit a lower standard deviation of permeability, reflecting reduced variability. This reduction enhances the homogeneity of the permeability, which is crucial for minimizing the risk of void formation and thus for ensuring uniform mechanical behavior throughout the laminate. Additionally, the distributions of both the mean and standard deviation of permeability for the proposed laminates are narrower compared to those of the original laminates. The findings suggests that the proposed laminates have more consistent and uniform permeability pattern in the proposed laminates. The code is accessible via: https://github.com/COMMA-TUD/LSPO.

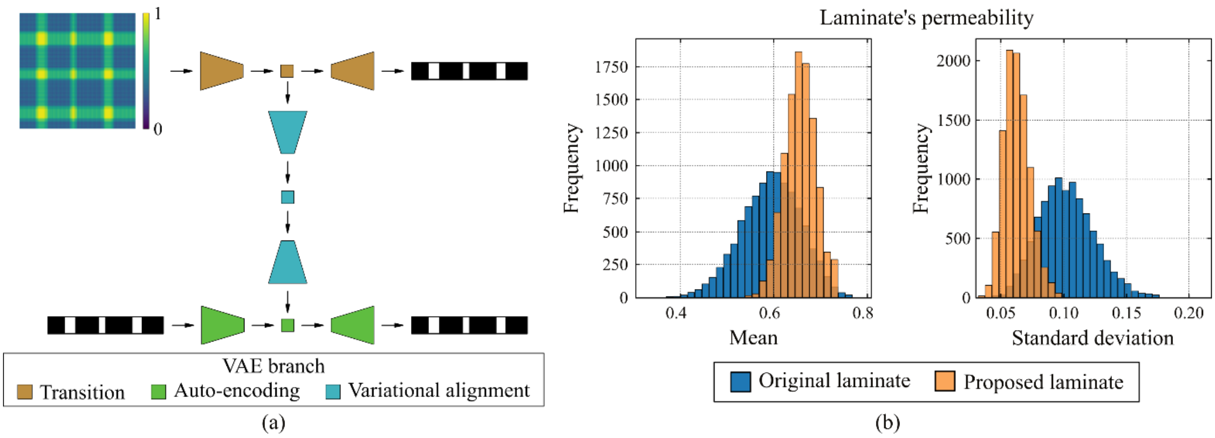

Figure 1: a) Schematic representation of the variational alignment framework, b) mean and standard deviation evolution in a 10-layer $[0/90]_5$ laminate and improvements when the next 2 (optimized) layers placed.

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