PREDICTION AND UNCERTAINTY QUANTIFICATION OF MECHANICAL PROPERTIES OF HOMOGENISED WOVEN COMPOSITES

G.N.C. Ariyasinghe [1], H.M.S.T. Herath [1, *]

[1] Department of Civil Engineering, University of Moratuwa, Moratuwa

Woven composites are widely used among many industrial applications due to their unique properties and understanding how these woven composites behave under certain conditions enables us to predict their responses and design efficient solutions. This prior knowledge can be acquired through experimentation and computer simulations. In instances such as in aerospace applications, where experimental investigations are challenging due to the difficulties and constraints present in providing microgravity conditions, computer simulations are the preferred approach. These simulations assume ideal conditions but whenever these models are brought into the physical world, they tend to exhibit unexpected behaviour and the main reason for this deviation is the uncertainty introduced at many stages of the application.

The research provides a framework for providing predictions and to quantify the uncertainty of the mechanical response when a two-ply carbon fibre woven composite laminate composed of T300-1k fibres and Hexply 913 epoxy resin are subjected to material uncertainty. The mechanical properties of the homogenised woven composite are expressed through the ABD stiffness matrix and obtained using a computer-simulated Representative Unit Cell (RUC).

The predictions and uncertainty quantification are carried out by using Supervised Machine Learning (ML) techniques employing Gaussian Process Regression (GPR). In GPR, the input variables are assumed to be correlated, and the output variables are modelled as a distribution over functions, rather than a single function. The mean and covariance of the output distribution are then computed using Bayesian inference, which allows for the predictions and quantification of uncertainty in the output space.

The input space introduces uncertainties to the model through the Latin Hypercube Sampling technique which was propagated through the RUC to obtain the outputs to create the sample database. Model training and testing were carried out on the created database. The evaluation of the fit was carried out based on the Normalised Root Mean Squared Error (NRMSE) values and model validation was carried out using the repeated k-fold cross-validation technique.

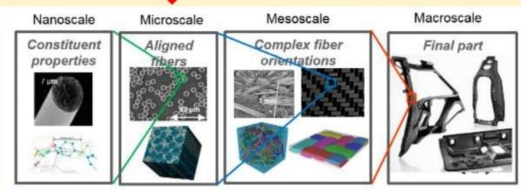
The evaluation of different kernel functions revealed that some covariance functions exhibited superior performance compared to others. The NRMSE values obtained during model training reflect the sensitivity of mechanical properties to constituent material properties. Notably, A12 and A66 of the ABD stiffness matrix exhibited higher errors and lower sensitivity in comparison to other stiffnesses. Comparing various ML techniques based on previous research, GPR models consistently outperformed Artificial Neural Networks (ANNs) and Linear Regression, particularly for specific stiffnesses. The GPR model showcased robust extrapolation capabilities, offering accurate predictions within 10% variations despite being trained for 5% uncertainty. This study also concluded that the model's predictions remained within narrow variation ranges for different uncertainty levels in constituent material properties.

Keywords: Woven Composites, Gaussian Process Regression, Machine Learning, Prediction, Uncertainty Quantification

[*] Correspondence: sumuduh@uom.lk

PREDICTION AND UNCERTAINTY QUANTIFICATION OF MECHANICAL PROPERTIES OF HOMOGENIZED WOVEN COMPOSITES

1. Background



Hierarchical nature of carbon fibre

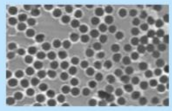
Microscale uncertainty sources

- **Material properties**
- Fibre orientation
- Fibre volume fraction

Uncertainties introduced at different scales will be propagated through the scales along the hierarchy of woven composites

Composite used for the research → **Two ply inter-woven Carbon fibre composite**

- **T300-1k fibre**
- **Hexply 913 resin**



2. Research Methodology

Data

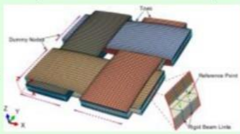
Input

Material property uncertainty

Fibre — Resin

16 input features

Multiscale model



Representative unit cell

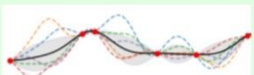
Output

ABD stiffness matrix

$$\begin{bmatrix} A_{11} & A_{12} & & & & \\ A_{12} & A_{22} & & & & \\ & & A_{66} & & & \\ & & & D_{11} & D_{12} & \\ & & & D_{12} & D_{22} & \\ & & & & & D_{66} \end{bmatrix}$$

8 output targets

Model training



Gaussian Process Regression

$f(x) \sim GP(m(x), k(x, x'))$

Kernel functions → The prior

Trained model ← The posterior

Maximum Log Marginal Likelihood

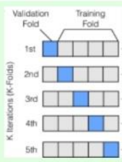
Model testing and validation

Model fit evaluation

The Normalized Root Mean Squared Error (NRMSE)

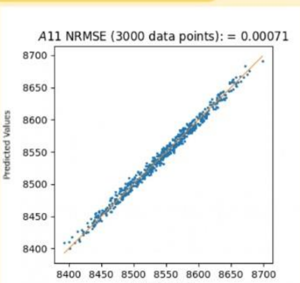
Model validation

The Repeated K-fold Cross Validation

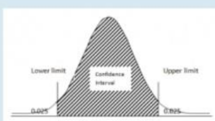


3. Results

Prediction



Uncertainty quantification



95% confidence interval of predictions

	Error percentage for 5% material property variance	
	Lower bound	Upper bound
A11	-1.8	1.9
A12	-0.6	1.0
A22	-2.0	1.7
A66	-0.5	0.6
D11	-2.3	2.2
D12	-0.7	0.5
D22	-2.3	2.3
D66	-0.4	0.6