USING MACHINE LEARNING TO PREDICT FIRE RESISTANCE OF FRP STRENGTHENED CONCRETE BEAMS

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Fiber-Reinforced Polymer (FRP) materials are increasingly utilized over conventional repair techniques for reinforced concrete due to their advantageous properties, including lightweight, high strength, and corrosion resistance. However, these materials are susceptible to degradation under fire conditions, which can weaken the polymer resin, reduce material strength and stiffness, and ultimately compromise structural integrity. Given the necessity of assessing the fire resistance of FRP-strengthened beams, traditional evaluation methods, despite their accuracy, are constrained by significant time and resource demands. To overcome these challenges, several ML-based prediction models have been developed, offering a more efficient and accurate alternative, further optimized through advanced methods.

A comprehensive dataset, encompassing geometric, material, and loading parameters alongside fire resistance outcomes from both experimental and numerical studies, was compiled. During the preprocessing phase, all input parameters were retained despite low individual correlations, as their combined effects were found to significantly influence model performance. Six ML models, including both ensemble methods including Light Gradient Boosting (LGB), Random Forest (RF) and traditional algorithms including Decision Tree (DT), K-Nearest Neighbour (KNN), Linear Regression (LR), and Polynomial Regression (PR), were developed and evaluated using Python in Google Colaboratory. The models were optimized using Grid Search for hyperparameter tuning, ensuring that the best combination of hyperparameters was identified to maximize model accuracy. Additionally, K-fold cross-validation was employed to assess model performance across multiple data splits, mitigating overfitting and ensuring robust predictions.

The LGB model emerged as the most accurate, achieving an R^2 value of 0.9230 and a mean CV score of 0.9345, outperforming traditional ML models by a considerable margin. Ensemble models such as LGB and RF demonstrated exceptional generalizability, with CV scores below 2%, indicating strong potential for application in real-world scenarios. To further elucidate the factors influencing model predictions, Explainable AI (XAI) techniques such as SHAP analysis were employed, identifying key factors such as loading ratio, depth of insulation, and tensile steel reinforcement area as significant contributors to fire resistance. It has been concluded that ensemble models, particularly LGB and RF, provide a highly accurate and efficient method for predicting the fire resistance of FRP-strengthened concrete beams. This research underscores the limitations of traditional correlation analysis in high-dimensional datasets and highlights the critical role of machine learning in advancing fire resistance prediction methodologies. Further, the efficiency, and applicability of these ML models in real-world scenarios can be enhanced by training these models over a wider range of datasets.

Keywords: Ensemble Machine Learning, Fire Resistance, FRP Strengthened Concrete Beams, Machine Learning

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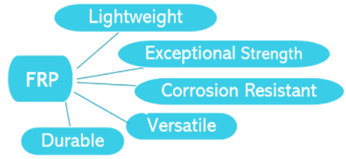
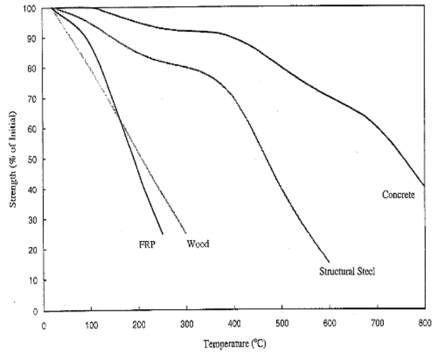
Background

FRP-Strengthened Concrete Beams



Challenges related to experimental and numerical methods

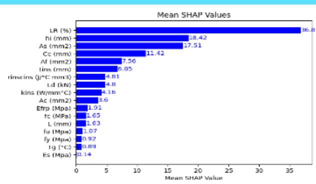
Costly | Time Consuming | Resource Intensive



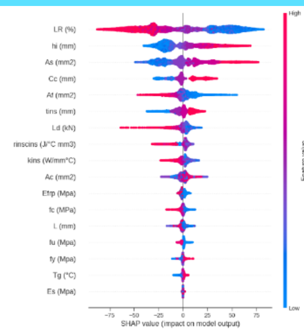
Strength degradation of FRP when exposed to fire

Methodology

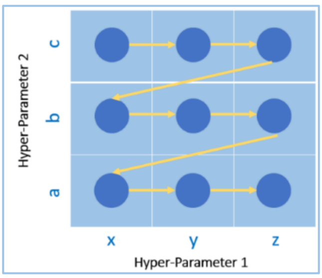
Collecting Database → Processing Data → Developing ML Models → Performance Evaluation → Model Optimization → Obtaining and Interpreting Results



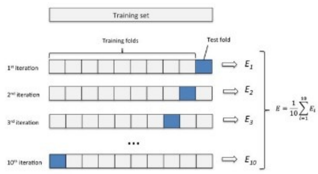
SHAP Feature Importance Plot



SHAP Summary Plot



Grid Search Optimization



Working Principal of K-fold Cross Validation

Results

ML Model	R^2 value	Mean CV score	Standard deviation of CV scores	RMSE	MAE
LGB	0.9230	0.9345	0.0052	20.55	9.81
RF	0.9094	0.9181	0.0090	22.29	11.23
KNN	0.8765	0.8811	0.0063	26.04	14.55
DT	0.8461	0.8562	0.0112	29.06	15.42
PR	0.8238	0.8283	0.0116	31.09	21.26
LR	0.6646	0.6753	0.0122	42.91	32.80

CONCLUSIONS

- Ensemble models like LGB and RF give a high accuracy (>90%) in predicting fire resistance outperforming traditional ML models
- Correlation analysis has limitations in complex datasets and it might miss important interactions between features
- SHAP analysis identified impact of key parameters:
  - Negative: Loading ratio, FRP area, total applied load
  - Positive: Steel reinforcement area, insulation depth, concrete cover
- FRP modulus, glass transition temperature of FRP and yield strength of steel reinforcement exhibit lesser influence