Final Year Project Showcase Batch-2021
Year 2025

Department: Civil Engineering Programme: Civil Engineering	
1	**Project Title:** Evaluating Bond Behavior Between GFRP Reinforcing Bars and Concrete **Project Idea** The project is based on exploring the behaviour of Glass Fibre Reinforced Polymer (GFRP) bars with respect to their bond with concrete, which are a relatively new alternative to the conventional reinforcing steel bars for construction purposes. Steel as a reinforcing material is prone to corrosion, while GFRP being non-metallic is an excellent choice as corrosion resistant reinforcement. The bond behaviour of GFRP bars was explored using uncoated, fine sand coated and coarse sand coated bars was experimentally explored with concrete. The behaviour of fine sand coated was found to be the best among the three. To compliment the experimental results, a machine learning based analytical model was developed using the data published in the literature. The model employs advanced regression algorithms, with the Random Forest Regressor providing accurate predictions of bond strength. Compatison of both experimental and analytical model was performed with existing codal predictions. Comparison with empirical design codes was performed. It was found that the ACI 440.1R-15 tends to overestimate the bond strength, while CSA S806-02 aligns more closely with experimental results. The experimental bond-slip curves also correspond well with the modified BPE analytical model. Moreover, the replacement of steel with GFRP ecnourages sustainable construction through low carbon emissions for each element being constructed using GFRP.
2	**Process** The study was conducted starting with a literature and code review, comparing bond models and test methods from ACI 440.1R-15, CSA S806-02, Okelo, and Lee et al., along with a survey of recent beam-end and hinged-beam test results for FRP bars. Beam-end specimens were designed using 12 mm ribbed GFRP bars (ultimate tensile strength ≈ 600 MPa, E ≈ 39 GPa) in three surface morphologies,non-coated, fine sand-coated (< 0.15 mm), and coarse sand-coated (< 1.18 mm),and two concrete grades (27.6 MPa and 41.37 MPa), with 30 mm clear cover (≈ 2.5d) and 72 mm embedment length (6d). Specimens were cast in wooden molds per RILEM configuration, with careful masking of unbonded zones and quality control of sand coatings, demoulded after casting, and cured for 28 days. Each specimen was instrumented with LVDTs connected to a DAQ system, then tested on a UTM using a hinged setup to convert flexural loading into axial pull at the bar, following the RILEM beam-end method, under incremental loading to failure. The experimental matrix comprised 20 specimens,10 for each concrete grade,with repeated samples for each surface type, and measurements included load–slip response, failure modes, and post-test observations. Experimental bond strengths and bond–slip curves were benchmarked against empirical models (ACI, CSA, Okelo, Lee) and the modified BPE (mBPE) bond–slip model. A predictive modelling framework was also developed by combining literature and experimental datasets, applying preprocessing (StandardScaler/RobustScaler, OneHotEncoder), and training multiple regressors (Random Forest, Gradient Boosting, XGBoost, ElasticNet, Ridge) alongside a stacking regressor, evaluated using an 80/20 train–test split and cross-validation. .
3	**Outcome** Twenty RILEM beam-end specimens showed three failure modes: bond/pull-out, concrete shear/cracking, and surface de-bonding. Higher concrete strength (41.37 MPa) increased bond strength by ≈10.6% over 27.6 MPa. Fine sand coating gave the best performance, followed by coarse sand and non-coated bars. ACI 440.1R-15 over-predicted bond strength, while CSA S806-02 was closer to experimental results. Bond–slip curves matched the mBPE model. The stacking-based machine learning predictor ($R^2 \approx 0.883$) performed well, with Random Forest as the top individual model.
4	**Evidence (Theoretical Basis)**

	• **Test protocol:** RILEM beam-end configuration was deliberately chosen because it better replicates bending-induced tensile stresses in members compared with pull-out tests. Instrumentation (LVDTs, DAQ) captured local slip and global response. • **Analytical checks:** Compared ACI and CSA semi-empirical equations against measured τ (bond stress), and fitted the mBPE local bond-slip law to experimental curves for validation of curve shape and residual branch. • **Data-driven validation:** ML model trained on literature + experimental inputs captures multi-parametric effects (f'c, bar surface, db, embedment) that single empirical equations may miss — useful for interpolation within tested parameter ranges.
5	**Competitive Advantage or Unique Selling Proposition** (Industry, Innovation & Infrastructure and Sustainable Cities & Communities) The study supports SDGs on Industry, Innovation & Infrastructure and Sustainable Cities & Communities by promoting durable reinforcement solutions for corrosive environments, reducing maintenance and extending service life. Replacing steel with FRP in such conditions lowers repair frequency and embodied carbon over the structure's lifecycle, aided by thinner, corrosion-resistant sections. Tests showed fine sand coating and higher concrete strength improved bond by ~10%, with mBPE fitting and an ML predictor providing validated tools for optimising anchor and development lengths. These advantages reduce whole-life costs, speed feasibility checks, and open market opportunities in coastal, marine, chemical, and precast applications through a combined testing–design package.
a	**Attainment of any SDG** (e.g. How it is achieved and why it is necessary for the region) Supports *Industry, Innovation & Infrastructure* and *Sustainable Cities & Communities* in Pakistan, where coastal cities (e.g., Karachi, Gwadar, Ormara) and industrial hubs face severe reinforcement corrosion due to marine salts and industrial pollutants. Using GFRP reinforcement extends service life and reduces the need for frequent maintenance, which is critical for budget-constrained public infrastructure.
b	**Any Environmental Aspect** (e.g. carbon reduction, energy-efficient, etc.) In Pakistan, steel production is energy-intensive and largely dependent on imported raw materials, increasing both carbon emissions and foreign exchange outflow. Replacing steel with GFRP in high-corrosion zones reduces repair frequency, lowers embodied carbon, and decreases demand for cement and steel over the life cycle — directly supporting Pakistan's climate and import-reduction goals.
c	**Cost Reduction of Existing Product** Lower maintenance & extended service life in aggressive environments reduce whole-life costs vs steel reinforcement (qualified by the observed bond performance improvements and model predictions). Embedding the ML tool into design practice speeds early feasibility checks.
d	**Process Improvement which Leads to Superior Product or Cost Reduction, Efficiency Improvement of the Whole Process** (e.g. What is the issue is current process and what improvement you suggests) Scale testing should expand the dataset by varying embedment lengths, bar diameters, and environmental conditioning (wet/dry cycles, salt exposure) to broaden model applicability. Collaborating with GFRP manufacturers to produce bars with tighter diameter and surface tolerances (vs. the current 11–12 mm variation) would reduce scatter and improve calibration accuracy. The ML model can be integrated into a user-friendly design tool (GUI or Excel add-in) that takes f'c, db, surface type, and embedment length to predict τ and recommend development length with safety factors. A FEM–ML hybrid approach could use parametric FE simulations to generate synthetic data for under-tested regions, extending prediction coverage. A pilot application using optimized GFRP (fine-sand coating + specified concrete) in a small structure, such as a precast utility tank or coastal parapet, could validate performance in-service. Finally, publishing results comparing ACI, CSA, and ML predictions, and engaging with standards bodies, would help advance GFRP design guidance.
e	**Expanding of Market share** (e.g. how it expand and what is the problem with the current market In Pakistan and many developing regions, the reinforcement market is dominated by conventional steel, which, despite its availability and familiarity, faces severe durability issues in coastal, marine, and chemically aggressive environments, leading to high maintenance costs and reduced service life. GFRP bars remain underutilized due to limited local testing data, lack of national design guidelines, and perceptions of high cost and unproven performance. This project addresses these barriers by providing

	locally validated experimental results and a predictive machine learning design tool, enabling confident specification of GFRP in corrosive environments. Market growth can be driven by demonstration projects highlighting durability benefits, training workshops for engineers, partnerships with precast manufacturers, and eventual inclusion in design codes to secure GFRP's formal market position alongside steel.	
f	**Capture New Market** (e.g. Niche market or unaddressed segment) Coastal + marine structures, bridge decks subject to de-icing salts, chemical plants, precast elements for rapid deployment (precast tanks, utility structures). The validated ML tool + simplified test validation protocol form a marketable package (testing + design advisory).	
g	**Any Other Aspect** N/A	
6	**Target Market** (Industries, Groups, Individuals, Families, Students, etc) Key stakeholders include infrastructure owners and agencies such as road and bridge authorities and port authorities, who can benefit from longer-lasting, corrosion-resistant structures. Contractors and precast manufacturers can adopt GFRP for durable precast elements and faster installation. Design consultancies and structural engineers can leverage the data to optimize development lengths and anchorage for FRP-reinforced members. Research laboratories and standards bodies can use the findings for further validation, supporting updates to design codes and accelerating industry adoption.	
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10	**Pictures (If any)**	  Shear Failure  De-bonding Failure  Pull-out Failure