Al-Rafidain Engineering Journal (AREJ) Vol.28, No.2, September 2023, pp. 18-32

The Optimum Design of RC Beams Strengthened with FRP Materials: A Review

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Received: March 21th, 2023 Received in revised form: April 27th, 2023 Accepted: May 10th, 2023

ABSTRACT

Fiber Reinforced Polymer (FRP) materials have become more popular according to contemporary developments in civil engineering applications. These materials have been used to repair and rehabilitate traditional structures. In turn, the majority of currently used applications are the result of research and recommendations made by fiber composite manufacturers or the experience of the designer. Therefore, optimization techniques try to achieve the best design under different conditions in structural design. An extensive search was conducted on existing research in the literature on applying optimization techniques such as artificial intelligence (AI) methods to reinforced concrete members that were externally strengthened with FRP materials. This paper provides a concise assessment of many studies that have been done in the literature on the behavior and strength of fiber-reinforced concrete elements, particularly in shear and bending scenarios. Each study's methodology and key findings are summarized.

Keywords:

Optimization; FRP materials; Artificial intelligence (AI); Genetic algorithm; Beams; Strengthening.

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1. INTRODUCTION

Reinforced concrete (RC) is a versatile, cost-effective building material. However, RC structures, such as bridge girders, parking garages, buildings, etc., may degrade for a number of reasons, including accidental damage, errors in the design and construction, poor maintenance, exposure to hazardous environmental activities, and damage in the case of seismic events. Replacement and demolition of these dilapidated buildings might disrupt various services and require high budgets. In order to extend the useful life of the structures, procedures for strengthening and restoring them are receiving a lot of attention [1, 2].

Due to the superior characteristics of FRP composites, such as a high strength-to-weight ratio, excellent corrosion resistance, low axial coefficient of thermal expansion, and non-magnetism, externally bonded fiber-reinforced polymer (FRP) materials are a powerful technique for repairing and retrofitting existing concrete structures [3-6]. Besides, when FRP laminates are used to strengthen concrete structures, members don't need to change their dimensions. This means that repair or retrofit work can be done quickly and easily, even while the structure is still in use [4, 7-9]. Significant interest has been demonstrated in using externally bonded fiber-reinforced polymer (FRP-EB) sheets and laminates to reinforce and repair existing reinforced concrete (RC) beams in both flexural and shear, as illustrated in Figure (1). By attaching unidirectional sheets to the surface of maximum tension, FRP can be successfully employed to improve flexural strength. Also, it has been determined that FRP systems are effective for enhancing the shear capacity of beams. Philosophically, FRP fibers should performed perpendicular to potential shear cracks [10, 11]. Figure (2) depicts how FRP is wrapped around the web of the beams using complete or three-sided U-wraps. FRP can also be installed just on the sides, although this is not suggested because there may not be enough bond area for the fibers to reach their full tensile strength [12, 13].

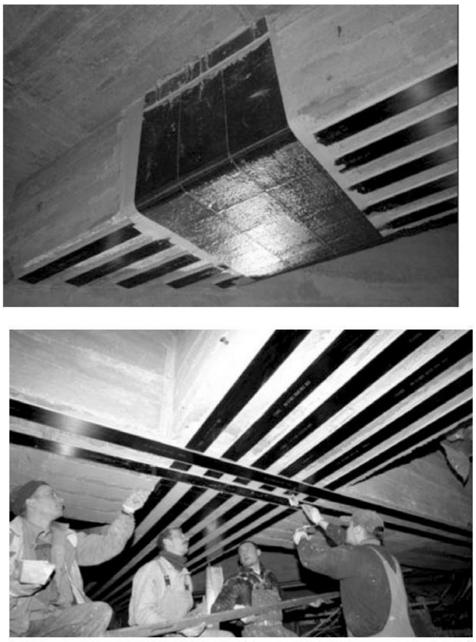


Fig. 1 Flexural and shear strengthening technique [14].

(a) **(b)** **(c)**

Fig. 2 Wrapping arrangements for externally bonded FRP materials: (a) complete wrapping, (b) U-wrapping, and (c) 2-sided bond [13].

Optimization is the process of achieving the optimal results under specified conditions. Structural engineers need to find efficient ways to make decisions, like the optimization technique, to design and build efficient structures. This is because global competition has made reducing the costs of building structures more important than ever. Therefore, the optimization technique and improved computer-aided tools enhance structural systems' conceptual and comprehensive designs.

Over the past few decades, many studies have been done on the possibility of using optimization techniques that rely on artificial intelligence, such as neural networks, genetic algorithms, and others, to predict the performance of any reinforced concrete member strengthened externally with FRP materials under different failure conditions, to get the best design for these members and try to lower the cost of them. But according to the authors' knowledge, the number of published articles in this field is limited. So, this work briefly overviews many of these studies and discusses their most important results.

2. Review of optimizing RC-members strengthened by bonded FRP:

2.1 Optimization methods of RC-beams by bonded FRP

Awad, et al. [15] theoretically reviewed the design optimization techniques used for designing fiber composite members in civil engineering applications, including bridge decks, plates, sandwich panels, bridge girders, box beams, and beams. Where numerous optimization techniques were discussed and compared from each other. The most typical optimization techniques used in the design of fiber composite structures for civil engineering applications were design sensitivity analysis (DSA), Genetic algorithm (GA), Simulating annealing method (SA), Reliability based design optimization (RBDO), Particle swarm optimization algorithm (PSOA),Ant colony optimization (ACO), and Multi-objective robust design optimization (MRDO). The analysis of significant literature showed that the DSA approach was employed with a single objective function. Multi-objective optimization could be conducted using the GA, PSOA, ACO, RBDO, and MRDO methods. Also proposed a methodology for optimization the design RC members strengthened with FRP materials as shown in Figure (3).

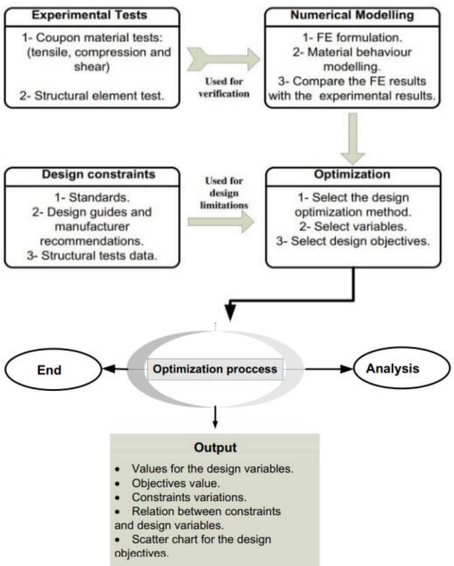


Fig. 3 Proposed design optimization methodology of FRP structures [15].

2.2 FRPs for strengthening RC structures in case of flexure (flexural applications)

Spadea, et al. [16] proposed the Performance Factor criterion to assess the effectiveness of the external anchorage system and the structural performance of CFRP-strengthened composite beams. The performance factor design criterion considers composite beams' deformability and strength. The findings demonstrated that, regarding both strength improvement and deformability, the Performance Factor criterion might realistically depict the overall structural behavior of the CFRP strengthened composite beam. The optimum arrangement and distribution of the external anchorages improve the structural behavior of the strengthened beam.

Gao, et al. [17] presented a numerical analysis, the purpose of the study was to develop a practical guideline for optimizing the design of taper-ended FRP strips. The finite element model (FEM) model was used to confirm that the enhancements in load-carrying capacity and deflection at the failure of RC beams due to tapered FRP strips were caused by reduced stress concentrations at the FRP strip ends. This delayed the start of concrete cracks, leading to concrete cover separation failure. In order to enhance the performance of strengthening RC beams, taper-ended FRP sheets were effectively implemented. Using the critical transition between the separation of concrete cover and crack-driven interfacial debonding as the criterion and the effective bond length as the input, straightforward methods were developed to discover the appropriate, effective taper circumstances. The ideal taper distance for the beams examined was calculated using sample calculations. In the research lab. The ideal taper distance for the experimental beams was estimated using sample computations. They determined that l_{taper}= 57 mm, which was near to the expected 50 mm value based on test outcomes.

Figure (4) shows the configurations of various tapered ends of FRP strips.

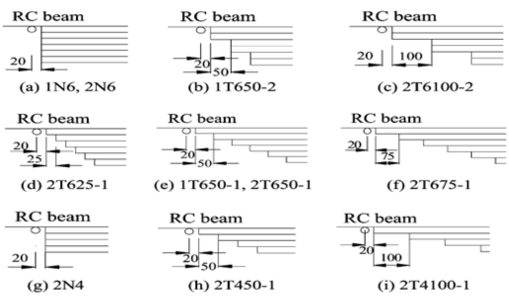


Fig. 4 Arrangements of different tapered ends of FRP strips [17].

Rahman, et al. [18] presented a procedure for optimizing the design of FRP plates for reinforcing RC beams theoretically for the flexural strengthening. The optimization process was created to identify the design factors that result in the lowest possible cost of a structural strengthening system utilizing CFRP plate under the limits imposed by the TR55 code (Concrete Society Technical Report 55 on strengthening concrete structures using externally bonded fiber composite materials). The strategy of optimization was based on genetic algorithms GAs, the formulation of the objective function contains the costs of FRP plate and epoxy adhesive, and in the formulation of constraints, the ultimate limit states and the serviceability limit states were addressed. The outcomes indicated that, compared to the traditional design methodology, the cost-optimal design approach might lead to considerable savings in the amount of strengthening materials needed.

Bennegadi, et al. [19] created a numerical model for the improvement of Hybrid Fiber Reinforced Polymer (HFRP) Plate external reinforcement of RC beams. The ANSYS package was used to create a FE model to examine the performance of beams and sheets regardless of the external reinforcement provided by FRP. The findings showed that the behaviors were most significantly influenced by the use of a FRP plate. As a result, the behavior of the reference beam switches from shear failure to flexural failure when CFRP reinforcement is added. Also, flexural cracks develop for small loads in the zone between the midspan and the load location (constant moment). The total beam volume is significantly decreased as a result of the FRP plate's optimization. The length and thickness of the FRP plate are reduced by 6.7% and 50%, respectively, to achieve an acceptable reinforcement with reasonable weight.

De Munck, et al. [20] demonstrated the possibility of minimizing the cost and weight of hybrid composite-concrete beams through the use of multi-objective optimization theoretically, specifically the use of the non-dominated sorting genetic algorithm (NSGA-II) and a meta-model, MATLAB code was developed to determine the optimum beam section dimensions. Two of the limitations were limited: (i) deflection in the stage of hardened and (ii) load-bearing capacity in the casting process. The deflection in the hardened stage was the most restrictive limitation for optimum beams with a low height and reinforced with a thick CFRP (relatively low weight and high cost). For beams with little CFRP reinforcement and greater height (relatively higher weight and lower cost), loadbearing capability in the casting stage was limited. This was due to the fact that the beam section's load-bearing resistance is proportional to the quantity of reinforcement. The optimization process provides insight into the effect of various parameters, such as span and concrete class, on the weight and cost of the beams. The results demonstrated that a thicker layer of CFRP reinforcement is required for spans that are higher. For beams with a span of 6 meters, a minimum tensile reinforcement of 2.4 mm is required, but a CFRP layer of 1 mm is sufficient for beams with a span of 4 meters. In addition, the investigation revealed that a rise in the concrete class had no effect on the efficiency of the solutions.

Metwally [21] introduced a dependable flexural performance of CFRP-strengthened beams with significant precision using a feed-forward back-propagation neural network containing fourteen input neurons which are span the CFRP qualities, the geometrical properties of the beam, and the reinforcement properties, twenty hidden neurons, and one output neuron which is the capacity of the ultimate load. The research was a simple overview of the ACI 440.2R-08 for the RC beams using FRP laminates regarding flexural strengthening. In a similar way and using the same experimental data, the code's ability to predict the flexural capacity of strengthened beams was also looked into. The analysis demonstrated that the ANN model provides accurate estimates of the flexural capacity of the enhanced members. Also, findings indicated that the ANN model forecasts precise flexural capacity compared to ACI 440 equations. The findings showed that the both effective depth of the beam and sheet length are the main significant factors in estimating the ultimate load capacity of members.

Kaura [22] optimized the supported reinforced concrete beam's FRP thickness requirement using the Generalized Reduced Gradient (GRG) optimization approach. In order to reduce the capacity of RC beams, optimal design charts were established. The graphs might be applied to determine the ideal FRP thickness for various steel reinforcement ratios, dead-to-live load ratios, and FRP elasticity moduli. The findings show that the modulus of elasticity of the FRP material plays a significant role in determining the size of the optimized FRP thickness needed for reinforcing reinforced concrete beams that are exposed to flexural limitations. It was discovered that the optimized thicknesses for FRP were 2.5mm, 1.75mm, 0.75mm, 0.6mm, 0.5mm, and 0.4mm, with elastic moduli of 25 GPa, 50 GPa, 75 GPa, 100 GPa, 125 GPa, and 150 GPa, respectively. The cost of strengthening a reinforced concrete beam for flexural purposes depends on the FRP thickness and elastic modulus value.

Tveit, et al. [23] presented an approach using an analytical tool to lower the cost of materials for a rectangular RC beam strengthened with FRP developed for flexural strength according to the equations of the ACI.1R-15. The cost-optimal function between the area of FRP reinforcement and the effective depth of the cross-sections by establishing a function of the price per meter of the beam was derived. The optimum ratio for a specific FRP and concrete type turns out to be identical for all specified flexural capacities, which can be shown for rectangular cross-sections as a function of cross-section width. Also, this strategy is especially helpful when a project's material prices are high due to the high costs associated with FRP.

Sundar, et al. [24] presented the subject of designing new reinforced concrete beams (RCBs) with proper fiber-reinforced polymer strips (FRPS) selection in order to fully utilize the advantages of FRPS. In order to assess the efficacy of FRPS-glued RCBs where the data was taken from data collected from 69 FRPS-glued RCBs in literature, proposed a mathematical model based on artificial neural networks (ANN). Also, to improve (maximize) both the ultimate load and the deflection ductility and to get the best design parameters for FRPS-glued RCBs, an optimum design approach was made using flower pollination-based optimization simulation of how plants pollinate. It displayed the ideal design parameters for the five FRP-glued RCBs and successfully tested their performance. Figure (5) shows the testing of the beam under two-point loads.

Fig. 5 Assessing the performance of the beam [24].

The results demonstrated that the suggested intelligent beam design tool (IBDT) optimal design is capable of producing designs that are superior to those produced by GA- and PSO-based methods. The experimental outcomes, as shown in Figure (6), also recorded the ultimate load of 364.263 and deflection ductility of 4.864, which as in almost the simulation performances and confirm the proposed design method (PDM).

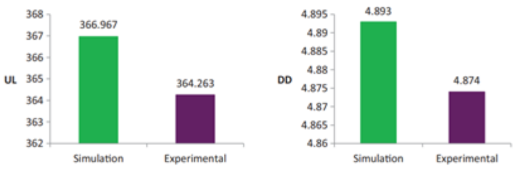


Fig. 6 Experimental comparison of the performances [24].

Kodur and Ahmed [25] recommended strengthening the optimal fire resistance in RC beams with FRP. For the aim of quantifying the impact of different parameters on the fire reaction of beams strengthened with FRP, a macroscopic FE model is used. The results demonstrated that the best fire insulation design for achieving fire resistance in beams spreads from the member soffit to either side of the beam cross-section to a depth equal to double the thickness of the clear concrete cover thickness for the steel reinforcement. Additionally, the ideal insulation thickness for commonly used, commercially available fire insulation is 40 mm to accomplish fire resistance of 3 hours and 20 mm to reach fire resistance of 2 hours.

Zhang and Wang [26] suggested a model for predicting the bond strength between FRP materials and concrete utilizing a metaheuristic-optimized least-squares support vector regression (LSSVR). Also used is a beetle antennae search (BAS) technique to modify the hyper factors of the LSSVR model. The findings demonstrated that the developed LBAS-LSSVR model has relatively good prediction accuracy, as shown by the test set's low root mean square error (1.99 MPa) and high correlation coefficient (0.983). The FRP's width is the factor that responds to bond strength the greatest.

Table 1 illustrates the most prominent results:

Table 1: Flexural applications summary

Research	Results
Spadea, et al. [16]	The Performance Factor criterion might realistically depict the overall structural behavior of the CFRP strengthened composite beam in terms of strength improvement and deformability.
Gao, et al. [17]	Developed a practical guideline for optimizing the design of taper-ended FRP strips for reinforced concrete beams of known dimensions.
Rahman, et al. [18]	Presented an optimization strategy based on genetic algorithms GAs procedure for optimizing the design of FRP plates for reinforcing RC beams for the flexural strengthening.
Bennegadi, et al. [19]	Adopted a 3D-nonlinear numerical model for the improvement of Hybrid Fiber Reinforced Polymer (HFRP) Plate external reinforcement of RC beams. The total beam volume is significantly decreased as a result of the FRP plate's optimization. The length and thickness of the FRP plate are reduced by 6.7% and 50%, respectively
De Munck, et al. [20]	Demonstrated the possibility of minimizing the cost and weight of hybrid composite-concrete beams and showed that a thicker layer of CFRP reinforcement is required for spans that are higher.
Metwally [21]	Showed that the both effective depth of the beam and sheet length are the main significant factors in estimating the ultimate load capacity of members.
Kaura [22]	Optimized the supported reinforced concrete beam's FRP thickness requirement.
Tveit, et al. [23]	Presented an approach using an analytical tool to lower the cost of materials for a rectangular RC beam strengthened with FRP developed for flexural strength according to the equations of the ACI.1R-15.
Sundar, et al. [24]	Designing new reinforced concrete beams (RCBs) with proper fiber-reinforced polymer strips (FRPS) selection in order to fully utilize the advantages of FRPS.
Kodur and Ahmed [25]	Demonstrated that the best fire insulation design for achieving fire resistance in beams spreads from the member soffit to either side of the beam cross-section to a depth equal to double the thickness of the clear concrete cover thickness for the steel reinforcement.
Zhang and Wang [26]	suggested a model for

Research	Results
	predicting the bond strength between FRP materials and concrete

2.3 FRPs for strengthening RC structures in case of shear (shear applications)

Perera, et al. [27] developed a simple technique for estimating the shear strength of beams strengthened with FRP depending on the theory of the strut-and-tie method. An optimization issue based on genetic algorithms was generated in order to determine the optimum solution for the strut-and-tie mechanism. In comparison with predictions made by some design processes, the developed model was calibrated using tested data gathered from the literature.

Perera, et al. [28] presented experimental and theoretical studies for estimating the shear strength of externally bonded FRP- beams. They suggested two artificial intelligence-based methods: estimating the shear capacity using neural networks (ANNs) and using genetic algorithms (GAs) to determine how the shear mechanism functions optimally. The experimental values were compared to the predictions produced by both methods. On the basis of the study and the derived predictions, it is thought that the two offered methods offer a possible alternative way for predicting the shear strength of externally strengthened beams.

Perera, et al. [29] presented a study on the shear strength of RC beams reinforced with FRP. To do this, a database of experimental outcomes was used to construct an ANN that will forecast the shear capacity. When the ANN predictions are compared to the results of experiments and the predictions of other design ideas, the strength values from the artificial neural network are very accurate.

Lousdad, et al. [30] offered a method for resolving edge effect issues that develop during structural strengthening. The technique depends on the geometric optimization of the FRP sheet end that is glued to the RC member. In this regard, an analytical method for determining the interfacial shear stress under various mechanical loads is described. It is expanded by using a model of FEM for a beam strengthened with CFRP, with different configurations, as shown in Figure (7). The results demonstrated that the geometric shape of the plate end section had a significant favorable impact on the decrease of interfacial shear stress where for uniformly distributed loads (UDL), the obtained results indicate a 30%, 39%, and 43% reduction in shear stress reduction for taper, parabolic, and stepped plate end sections, respectively. (UDL), in comparison with concentrated load condition, UDL reduced shear stresses by an average of 12.30%.

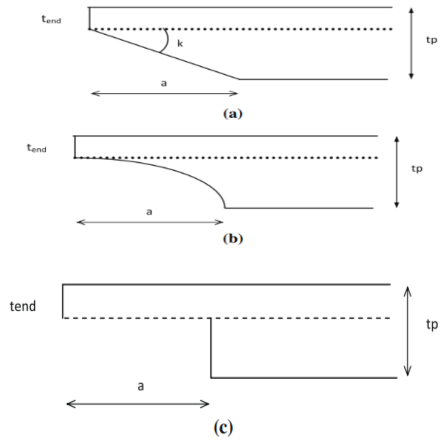


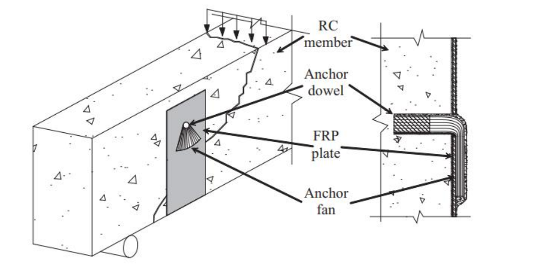
Fig. 7 Geometric shapes of the end section of the plate: (a) taper end section, (b) parabolic end section, and (c) stepped end section[30].

Nehdi and Nikopour [31] proposed simple equations for calculating the shear strength of FRP beams using the genetic algorithms (GAs) technique applied to 212 tested beams available in the literature. The results demonstrated that the totally wrapped system, when compared to other schemes, produces better results for the shear retrofitting of RC beams by enhancing the confinement of the concrete beam section and, as a result, the aggregate interlock. Contrarily, the totally wrapped design offers excellent concrete and FRP bonding characteristics. Additionally, it was demonstrated that CFRP materials, as opposed to GFRP or AFRP, offer greater shear capability when retrofitting RC beams. Moreover, FRP sheet rupture failure is more probably to happen in RC beams with lower shear span-to-depth ratios. Moreover, these beams can give better shear capacity in comparison to beams with larger shear span-to-depth ratios because of the concrete and transverse of the steel rebars.

Perera and Ruiz [32] calculated the enhanced shear strength of RC beams strengthened with FRP using a simple and efficient way of defining improved equations. The equations were found using genetic algorithms in a multi-objective optimization framework that took into account the results of experiments on beams with and without FRP external reinforcement. The shear design standards for strengthening concrete members using FRPs are used to evaluate the performance of the new equations. With this new technique, the divergence between the estimated and measured shear strengths of reinforced concrete beams with and without FRP external reinforcement is simultaneously minimized. New shear design equations have been created using the suggested methodology, and shear strength results computed using these equations are in acceptable results compared with the tests outcomes of members evaluated by various researchers.

Tanarslan, et al. [33] used to retrofit reinforced concrete (RC) beams in shear fiber-reinforced polymer (FRP) that has been externally bonded, wrapped, and U-jacketed. An ANN model was constructed to estimate the shear strength of these beams taking into account the impact of strengthening configurations with different properties. Moreover, the shear span to depth ratio (a/d) ratio's impact on the final state was taken into account by the model. The beams' mechanical, dimensional, and dimensional characteristics, as well as the strengthening material's mechanical properties, were selected as inputs. Using the literature on 84 RC beams, the ANN model was trained, validated, and tested. Analyses were done, and it was discovered that the neural network model, when compared to the experimental findings, was more accurate than the guideline equations and that it could be used successfully for the parameters it covered.

Zhang, et al. [34] investigated twenty-four FRP-to-concrete control joints that were not anchored and three FRP-to-concrete joints that were. Figure (8) represents a commonly installed anchor system in the FRP beam context and lists the anchor's components. The outcomes demonstrated that a single anchor could, on average, increase a joint's strength by 53% above that of a control joint that was left unanchored. Also, an anchor can increase a joint's ability to slip by more than ten times the amount that control joints can slip. An optimum anchor design has been developed based on the criteria of joint strength increase, a post-peak reserve of strength and slide capacity, consistency of failure mode, and amount of fiber material. Additionally, it was decided that the best choice was impregnated carbon anchors made from 200-mm-wide fiber sheets.



(a) U-jacket shear-strengthening (b) Section of FRP anchor and

Fig. 8 Schematic of the FRP-RC member and anchor [34].

Krour, et al. [35] suggested an approach to decrease the interfacial stresses in the beams strengthened with the FRP sheet using fiber orientation. In the first part of the project, the analytical method was focused on the laminate theory. A minimization method was used to find the fiber orientation directly, which lowered the interfacial stresses. The second section was made up of Finite Element Analysis (FEA) to assess the strength of the optimal solution for debonding stresses and to validate the analytical approach. To determine the minimal shear and normal stresses, a MATLAB software was employed. The Matlab minimization procedure uses the Nelder and Mead Nelder–Mead method to minimize an objective function in a multidimensional space. It has been shown that low shear and normal stresses are obtained when all of the fibers in each layer are oriented perpendicular to the longitudinal axis of the CFRP-bonded plate. The least debonding stress-producing fiber orientation is not a good option for strengthening efficiency, according to the finite element analysis.

Lee and Lee [36] provided a theoretical model based on ANN technique for determining the shear capacity of thin FRP-RC flexural members without stirrups. The model takes into account the correlation between compressive concrete strength and shear strength as well as the impacts of effective depth, shear span-to-depth ratio, elastic modulus, and the ratio of FRP flexural reinforcement. In contrast to previous existing equations, the constructed ANN model produced superior statistical parameters with more accuracy, as indicated by comparisons between the forecasted values and 106 test results.

Tanarslan, et al. [37] predicted the contribution of anchoraged CFRP to the shear strength of weak RC beams by using artificial neural networks (ANNs), two back-propagation NN models were created. To assess the efficacy of the ANN models, the predictions from the ANN were compared to the results from the experiments and the results obtained from the reference equations of fib14 and ACI 440. As can be observed, fib14 had the best predictions when compared to experimental outcomes. Also, while ANN predictions and fib14 predictions exhibit a slightly common theme, they are less reliable.

Choi, et al. [38] provided the optimum seismic retrofit technique using FRP jackets for shear-critical columns of three-story RC frames by using a multi-objective optimization technique, the non-dominated sorting genetic algorithm-II (NSGA-II), to optimize the two competing objective functions of the retrofit cost as well as the seismic performance simultaneously. According to the results, the reinforcement positions and amount of FRP reinforcing ply needed to satisfy all the limitations taken into account were discovered as a consequence of using the suggested optimal approach. The shear reinforcement and flexural reinforcement of FRP jackets for columns were used to confirm the prevention of shear failure and the lowering of the inter-story drift ratios of a structure. Also, it has been demonstrated that FRP jackets improve the structure's strength and ductility while preserving the components' original stiffness.

Dehghani and Fadaee [39] assessed the reliability of the torsional strength of beams retrofitted with U-wrap FRP laminate using the Rackwitz-Fiessler method. The reliability of the design process is 2.92, which is less than the goal value of 3.5 used in the calibration of the guidelines. Therefore, future guidelines models may need to use the optimal resistance factor, so the optimum resistance factor is advised to be 0.723 based on the relationship between the average reliability index and resistance factor.

Hanoon, et al. [40] Studied theoretically and experimentally a simple model for assigning the shear strength of deep beams strengthened with CFRP materials depending on the strut-and-tie model. Utilizing a particle swarm optimization (PSO) algorithm, the optimal STM of a CFRP-RC beam was found by looking for the optimal unknown coefficients (stress distribution and concrete tensile stress reduction factors). Debonding and tensile rupture were two CFRP failure modes that were examined by the model. The model was calibrated using tested data and the results of the published works. 366 CFRP-strengthened RC deep beams were brought together to make and test the suggested hybrid (PSO-STM) model. The collected data were split into two groups: one was used to make the proposed model, and the other was used to test it. The first group had 26 beam specimens from the literature and 325 FE models presented by the research. In comparison, the second group had nine beam specimens from their research and six beam specimens from the literature.

A total of 325 simulated FE models and large datasets demonstrated the accuracy of the modified STM. Statistical analysis showed that the coefficient of variation (COV), mean, and correlation coefficient (R2) values were 0.0576, 0.955, and 0.9918, respectively, showing that the values were accurate and consistent. Therefore, the modified STM is believed to have great potential for forecasting the shear strengths of deep beams made of concrete with carbon fiber reinforcement.

Naderpour, et al. [41] created an artificial neural network (ANN) method to predict concrete beam shear strength. The suggested method takes into account the shear span-depth ratio as well as the geometric and mechanical features of cross sections and FRP bars. Using a large database, the proposed method's capabilities were compared to those of other methodologies that have been used in the literature. The results demonstrate that the suggested approach and the experimental database have a high agreement.

Abuodeh, et al. [42] discussed how machine learning approaches could be used to study the behavior of RC beams that have been strengthened in shear by using two-sided-bonded and U-wrapped FRP materials. The neural interpretation diagram (NID) and recursive feature elimination (RFE) algorithm were applied within the validated robust back-propagating neural network (RBPNN) to discover the parameters that significantly influence the prediction of FRP shear capacity. According to the results, the RBPNN with the chosen parameters was capable of estimating the FRP shear capacity more reliably than the RBPNN with the original 15 parameters. Applying RBPNN with RFE and NID individually is a workable method for assessing the strength and behavior of FRP in shear-strengthened beams, according to a thorough parametric analysis.

Al-Rousan [43] developed an analytical model that forecasts the shear capacity of RC beams externally reinforced with CFRP materials. The proposed model offered an acceptable COV that is accurate with expected RC beam behavior and a satisfactory correlation with test results. According to the findings, the experimental/theoretical failure load ratios for the ACI model range from 0.16 to 10.08. The appropriate test/theoretical mean value range of 0.27 to 2.78 is likewise provided by the Triantafillou models. The Colotti model, on the other hand, provides an experimental/theoretical mean value range of only 0.20 to 1.78. Hence, regardless of whether the bonded reinforcement comprises CFRP or steel, the suggested model applies to all externally bonded beams.

Table 2 shows the most important results obtained with regard to the research related to this section:

Table 2: Shear applications summary

The research	Results
Perera, et al. [27]	developed a simple technique for estimating the shear strength of beams strengthened with FRP depending on the theory of the strut-and-tie method
Perera, et al. [28]	Suggested two artificial intelligence-based methods for estimating the shear capacity using neural networks (ANNs) and using genetic algorithms (GAs).
Perera, et al. [29]	Studied the shear strength of RC beams strengthened with FRP.
Lousdad, et al. [30]	demonstrated that the geometric shape of the plate end section had a significant favorable impact on the decrease of interfacial shear stress
Nehdi and Nikopour [31]	demonstrated that the totally wrapped system produces better results for the shear retrofitting of RC beams by enhancing the confinement of the concrete beam section
Perera and Ruiz [32]	Calculated the enhanced shear strength of RC beams strengthened with FRP using a simple and efficient way of defining improved equations.
Tanarslan, et al. [33]	Constructed an ANN model to estimate the shear strength of RC beams strengthened with FRP.
Zhang, et al. [34]	Demonstrated that a single anchor could increase a joint's strength by 53% above that of a control joint that was left unanchored.
Krour, et al. [35]	Showed that low shear and normal stresses are obtained when all of the fibers in each layer are oriented perpendicular to the longitudinal axis of the CFRP-bonded plate.
Lee and Lee [36]	Provided a theoretical model based on ANN technique for determining the shear capacity of thin FRP-RC flexural members without stirrups.
Tanarslan, et al. [37]	Predicted the contribution of anchoraged CFRP to the shear strength of weak RC beams by using artificial neural networks (ANNs).
Choi, et al. [38]	Demonstrated that FRP jackets improve the structure's strength and ductility while preserving the components' original stiffness.
Dehghani and Fadaee [39]	Assessed the reliability of the torsional strength of beams retrofitted with U-wrap FRP laminate.
Hanoon, et al. [40]	Presented a simple model for assigning the shear strength of deep beams strengthened with CFRP materials.
Naderpour, et al. [41]	Created an artificial neural network (ANN) method to predict concrete beam shear strength.
Abuodeh, et al. [42]	Showed how to use machine learning approaches to evaluate the behavior of RC beams that have been strengthened in shear by using two-sided-bonded and U-wrapped FRP materials.
Al-Rousan [43]	Developed an analytical model that forecasts the shear capacity of RC beams externally reinforced with CFRP materials.

2.4 FRPs for strengthening RC structures in case of combination (shear - flexure)

Perera and Varona [44] studied theoretically the use of a genetic algorithm (GA), a method for designing flexural and shear reinforcements of low-cost RC beams strengthened with CFRP plates has been given. The proposed technique reduces the material costs associated with this type of reinforcement while achieving the serviceability and strength standards outlined in the proposed code for the European Community. The optimization technique is performed in a discrete manner by constructing data sets of various FRP configurations based on the manufacturer-supplied market size values. Using penalty functions, the proposed code's restrictions are articulated as constraints included in the problem. The method was checked with two examples, and have been shown that the GA was an easy, systematic, and automatic way of designing RC strengthening systems employing FRP materials. Figure (9) illustrates the flexural and shear strengthening, respectively.

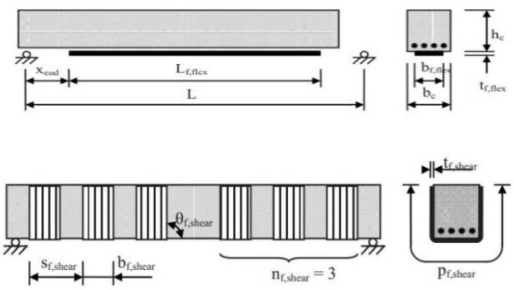


Fig. 9 Flexural and shear strengthening system [44].

Table 3 shows the most important results obtained with regard to the research related to this section:

Table 3: Shear-flexure applications summary

Research	Results
Perera and Varona [44]	Used the genetic algorithm (GA) for designing flexural and shear reinforcements of low-cost RC beams strengthened with CFRP plates.

2.5 Optimization of composite-laminates structures

Callahan and Weeks [45] discussed how to design composite laminates using genetic algorithms (GAS), which are global search procedures based on the mechanics of natural selection. The design variables must be coded as a finite-length string using a finite alphabet according to the GA. The lamina orientations and stacking order necessary to achieve the maximum laminate strength and/or stiffness with the least amount of weight are the design variables in this case. Numerical results were presented in order to show that the evolutionary algorithm can be a practical substitute for conventional search techniques in the design of laminates.

Abachizadeh, et al. [46] implemented continuous ant colony optimization (ACO_R) method inspired by nature for hybrid laminates made of low-strength glass/epoxy and high-strength graphite/epoxy. Where the design variable set consists of the number of surface and core layers, their layouts, and the continuous fiber angles in each layer, the objective functions are the fundamental frequency and cost of the composite, which are to be maximized and minimized, respectively. Findings provided for three separate problems clearly demonstrate that the $ACO_R$was successful in enhancing the outcomes of the problems previously obtained in the literature when employing the ant colony system (ACS), genetic algorithm (GA), and simulated annealing (SA) while considering standard fiber angles.

Awad, et al. [47] used the finite element (FE) approach and the genetic algorithm (GA) technique in order to create a modern FRP sandwich floor with fiberglass skins and modified phenolic core materials, which have a substantially higher density than common sandwich panels. The FE method displayed a rather accurate simulation of the FRP panel's behavior. The cost of the Materials was considered as an objective function with EUROCOMP design limitations and the optimization showed that 0/90^o surface orientations would produce the optimum one-way extended floorboard design.

Axinte, et al. [48] reviewed current optimization techniques for designing composite structures, including the Particle Swarm Optimization Algorithm (PSOA), the Genetic Algorithm (GA), Ant Colony Optimization (ACO), and Simulated Annealing Method (SAM), where stochastic techniques are better for dealing with a mix of discrete and continuous variables, finding the global optimum of a multi-objective function, and designing composite lay-ups using a variety of solutions. When the stochastic techniques were looked at, it was found that these methods have a low rate of convergence, which also depends on the problem. Therefore, it is impossible to compare stochastic techniques because they are highly dependent on the situation. Up until now, GA has been the most widely used approach for find the optimum design of fiber composites structures, followed by SAM.

2.6 prediction the mode of failure of RC-FRPs members

Perera, et al. [49] examined the intermediate crack-induced deboning (IC deboning) experimentally and theoretically, which is formed by the stress concentration at the FRP strip cutoff point of the FRP substrate from the concrete in a sudden way. It also used a structural health monitoring (SHM) technique capable of tracking and detecting damage and deterioration in the earliest phases. The suggested approach was solved using a multi-objective version of the particle swarm optimization technique. A network of sensors was used to collect data in critical areas of the external reinforcement where the number of accessible sensors would limit the number of static strains under applied loads. Furthermore, embedded FRP/concrete interface sensors will also offer a high level of sensitivity to deboning damage due to their proximity to the damage characteristics.

Because they could be readily inserted at the FRP–concrete interface with minimal disruption to the surrounding material, these sensors can give great sensitivity to debonding damage. Repeated finite element models were used to represent the behavior of FRP of RC beams and would significantly increase the computational cost of the damage detection approach. Also, a spectral element model was used in the framework of the model updating problem in the proposed solution because it is accurate and costs less on a simple domain. The findings demonstrated that the simpler spectral model shows less strain in the three load situations, as shown in Figure (10).

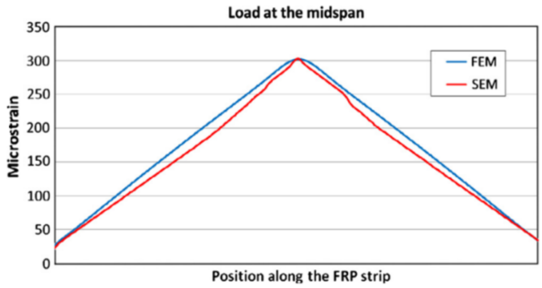


Fig. 10 The distribution of FRP strain under a concentrated loading at the midspan [49].

Li, et al. [50] created A BP neural network model based on the sparrow search algorithm (SSA) in order to increase the precision of determining the debonding strain of FRP-composites reinforced RC beams. The results showed that increasing the concrete strength, the shear-to-span ratio, and the longitudinal reinforcement ratio significantly affects the debonding strain of FRP-strengthened RC beams. The debonding strain is negatively associated with FRP stiffness; as FRP stiffness increases, the debonding strain decreases. Also, the results demonstrated that the SSA-BP neural network model's COV is 13% and the SSA-BP model improves both the code models and the conventional BP neural network in regards to prediction precision and reliability.

2.7 FRPs for strengthening precast RC beams

Van Loon, et al. [51] tried to increase a standard Dutch office building's MPG [Milieuprestatie Gebouwen] rating by lowering the environmental-economic (shadow) costs of its precast RC beams. First, by constructing a cavity in the cross-section of the beam, less concrete was used; second, some of the reinforcement was substituted with a FRP tube. The hollow FRP-RC beams with an elongated oval cavity and flax, glass, and kenaf fiber tubes produced the lowest shadow costs. In this instance, the flax tube's shadow costs were 39% less than those of the hollow RC beam (with an elongated oval cavity); this allowed for the shadow costs of other building components, such as the facade, to be minimized, lowering the building's MPG score. The study also demonstrates the significance of choosing the appropriate FRP type, as hemp fiber tubes caused a 98% rise in shadow costs.

2.8 FRPs for strengthening dapped-ends RC beams

Sas, et al. [52] investigated experimentally and theoretically the most effective design of CFRP composites for reinforced dapped-end beams using parametric analysis based on non-linear finite element modeling. The work concentrated on the effects of 24 externally bonded (EBR), near-surface mounted reinforcement (NSMR) arrangements on yield strain in steel and the capacity and failure mechanism of dapped-end beams after field application and laboratory testing. The variables that were looked into were: (a) the CFRP's inclinations with respect to the beam's longitudinal axis. In agreement with both the field application and the experimental program, alignments of 0 and 45 were chosen. (b) The CFRP materials' mechanical characteristics, high modulus (HM), and high strength (HS) FRPs were used to reinforce the experimentally tested beams. (c) Application of CFRP Layout. The results show that the HM NSM systems can give greater capacity gains than the HM EBR systems, but the HS EBR systems record the greatest overall capacity increases. Also, mechanically anchoring the CFRP might have enhanced the beams' capacity by up to 36% above the reference specimen, which demonstrated that the anchoring length was almost adequate to prevent debonding in the strengthening systems.

3. Conclusions and Recommendations

A significant problem in optimizing reinforced concrete structural members strengthened using FRP appears here, which is the cost of the composite materials resulting from the rehabilitation procedure using these materials. Fortunately, using Artificial Intelligence techniques has overcome these obstacles by allowing the objective function to have the same design variables that should be used in the design limitations (constraints) and the objective function, which could not have been done using traditional optimization methods.

Saving time and effort are the most beneficial outcomes of using these techniques in optimizing such materials. Therefore, many of the recent studies use AI approaches to deal with highly constrained problems, such as designing reinforced concrete members strengthened with FRB, and the resulting outcomes were very comforting and encouraging for these approaches to be used in such problems.

Although some of the familiar structural problems do not need the useful benefit of AI methods in design due to its simple and modest approach, the payoff of AI methods here will not be very noticeable as designing different structural members with non-linear constraints and multi-objective problems. By reviewing the literature, it is clear that the researchers focus on obtaining the optimal structure with the highest possible performance and the lowest possible cost, and this is provided by the use of multiple optimization techniques and methods in the design of FRP reinforced concrete structures.

Also by looking at the literature, it was found that there are many optimization techniques used in the design of composite concrete structures, and among these methods: Genetic algorithm (GA), Simulating annealing method (SA), Reliability based design optimization (RBDO), Particle swarm optimization algorithm (PSOA), the Generalized Reduced Gradient (GRG), beetle antennae search (BAS), Ant colony optimization (ACO), and the non-dominated sorting genetic algorithm (NSGA-II), Where GA and NSGA were used in the multi-objective optimization.

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تاريخ الاستلام: 21 مارس 2023 استلم بصيغته المنقحة: 27 ابريل 2023 تاريخ القبول: 10 مايو 2023

الملخص

أصبحت مواد البوليمر المقوى بالألياف (FRP) أكثر شيوعًا وفقًا للتطورات الحالية في تطبيقات الهندسة المدنية. حيث يتم استخدام هذه المواد لإصلاح وإعادة تأهيل المنشآت التقليدية. من جهة اخرى، فإن غالبية التطبيقات المستخدمة حاليًا هي نتيجة البحث والتوصيات المقدمة من الشركات المصنعة لهذه الألياف أو وفقاً لخبرة المصمم. تحاول تقنيات التحسين تحقيق أفضل تصميم في ظل ظروف مختلفة في التصميم الإنشائي. تم إجراء بحث مكثف على الأبحاث الموجودة في الأدبيات حول تطبيق تقنيات التحسين مثل أساليب الذكاء الاصطناعي (AI) لأعضاء الخرسانة المسلحة التي تم تعزيزها خارجيًا باستخدام مواد FRP. تقدم هذه الورقة تقييمًا موجزًا للعديد من الدراسات التي تم إجراؤها في الأدبيات حول سلوك وقوة عناصر الخرسانة المسلحة بالألياف ، خاصة في حالات القص والانحناء. تم تلخيص منهجية كل دراسة والنتائج الرئيسية لها.

الكلمات الداله :
الامثلية،مواد الفايبر،الذكاء الاصطناعي، الخوارزميات الجينية، العتبات، التقوية.