Predicting the Strength of CFRP-steel joints using Genetic Programming

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Abstract. Numerous steel structures that were built following the industrial revolution, including bridges, off-shore platforms, and many buildings, are carrying excess loads of varying types over those they were originally designed for. Furthermore, the magnitude, pattern, and type of loadings have changed over the years. As a result, these structures need to be strengthened to sustain and convey the increased applied loads and remain in service. Carbon fibre reinforced polymers are a promising material that is gaining popularity in the field of strengthening deteriorated infrastructure as a replacement for conventional strengthening methods such as bolting, riveting, or welding due to its cost effectiveness, good strength-to-weight ratio, and ease of application. This paper proposes a new model to predict the strength of CFRP-steel joints using genetic programming. A number of studies have been carried out to evaluate the bond strength of newly formed composite material, but a lack of calculations for the bond strength with assurance still exists. A prediction model derived using genetic programming to calculate bond strength for both static and dynamic loading scenarios using various bond length, cross-sectional area, and CFRP moduli is thus proposed. The database used in the genetic program software was collated from the existing literature, and both derived models have a high value of R² which demonstrates an acceptable level of accuracy compared to the experimented results.

1. Introduction
Since the late 1800s, steel has been used in infrastructure development, and over the years, a large number of steel structures have been built. These structures were designed to sustain prescribed loads and to endure for particular design lifetimes; however, due to the increase in human demands, traffic loads have been increased in the last few decades, and many steel structures have been subjected to additional live loads which frequently exceed the ones they were designed for. In addition, some steel structures suffer from deterioration due to unforeseen incidents such as vehicle collisions, impact loading caused by explosions, environmental effects, loss of material properties, and exceedance of the design life [1]. Based on these factors, several steel structures are now failing or unable to withstand the new applied loads. Due to this depletion in capacity, some additional structural members are required for strengthening to keep whole structures in service. Traditional strengthening methods include bolting, riveting, or welding steel plates onto joins, member replacement, external post tensioning, and the addition of steel jackets. Along with their benefits, these techniques also bring certain challenges, however; for example, bolting reduces the effective cross section for load transfer, welding requires a controlled environment, and steel jacketing is frequently architecturally unacceptable. In addition, all conventional methods add additional weight to the structure being strengthened, and limited cost effectiveness is also a concern when choosing strengthening methods. Carbon Fibre Reinforced Polymer (CFRP) is a newly evolved composite material that is gaining popularity in the field of infrastructure strengthening due to its unique properties which make it preferable to conventional strengthening methods used for steel. Due to CFRP being relatively new, several studies have focused on evaluating the performance of CFRP-steel joints subjected to different conditions such as loading types and rates, changes in environmental conditions, and type of CFRP used. Although numerous researchers have studied the influence of the above factors on the bond between CFRP and steel [2], there several limits and lacks still face structural engineers. One of the lacks is that no design guidelines are available for CFRP-steel strengthening that illustrate its effective bond length and ultimate design bond strength. This paper aims to bridge the gaps in estimating the CFRP-steel bond strength by implementing genetic
programming (GP), with the data for GP modelling input collected from existing literature [3-9]. Genetic programming has become a popular method for complex modelling of several parameters, and numerous researchers have used this method to successfully solve complex modelling issues.

2. Bond Behaviours between Steel and CFRP

Strengthening of steel structures came into place to maintain such structures in service, and different methods of strengthening have been developed over the years. All these methods have their advantages and disadvantages depending on the circumstances. As a newly approved material, CFRP has certain advantages over most conventional methods due to its high strength, light weight, good corrosive resistance, reduced thermal conductivity and ease of installation. It can also be used where chemicals pose a challenge to steel or where highly flammable substances may be present that limit the use of welding. A thorough literature review was conducted to develop an underpinning of the current scenario of CFRP-steel strengthening.

2.1. CFRP Material Properties

The literature review on the strengthening of steel members revealed two types of CFRP used in most studies, sheet and laminate. CFRP sheets are either single or bi-directional in nature. Conversely, the laminates have a defined width and are cut into desired lengths for use. [6] conducted a review of steel members strengthened with CFRP, finding that the properties of CFRP are generally in the range of 230 and 640 GPa for the elastic modulus and 150 to 450 MPa for the tensile strength.

2.1.1. Effective Bond Length

As the effective bond length is the optimum length of CFRP attached to steel beyond which no further increase in the bond strength can be made, it is necessary to evaluate the effective bond length for a CFRP-steel joint for the calculation of ultimate load carrying capacity and economic considerations. Several researchers [5, 7, 8, 10] have noted that the strength of the bond becomes constant when the effective bond length attains its maximum. A study conducted by [3] utilised commonly used adhesives showed that the type of adhesive used had an impact on the effective length. Samples prepared with Araldite 420 had a higher strength capacity and effective bond length than samples prepared using Sikadur 30.

2.1.2. Adhesives

Two main types of adhesives were used by most of the researchers in CFRP-steel studies [6, 7]. These are Araldite 420 and Sikadur 30. The manufacturers of Araldite 420 claim that it has a tensile strength of 32 MPa, while Sikadur 30 has 30 MPa and 12,800 MPa as typical tensile strength and elastic modulus, respectively [11].

2.2. Proposed Models of Ultimate Strength Calculation

The authors of [6] detailed three different approaches that can be taken into consideration to determine the bond strength; adding the classic model that was developed in the early 1970s gives four options:

- Stress-distribution method
- Bond-slip relationship approach
- Multi-layer distribution model
- Hart-Smith Model

2.2.1. Stress-distribution model

This model was first proposed by [12] and it focuses on Steel-CFRP systems. It is based on the deformation and equilibrium compatibility conditions of the system and one of the key assumptions is the linear elastic behaviour of parent and bonded materials. Stress throughout the adhesive layer is also assumed to be uniformly distributed. This model can be applied to cracked steel beams reinforced with
CFRP, with defects present in the adhesive layer, FRPs with sharp ends acting as stress concentrators, and double lap shear joints [9].

Several parameters of the material properties, such as the Young’s modulus of both the adhesive and CFRP, shear strength, Poisson’s ratio, and shear modulus, along with other bond dimensions, act as functions to predict the bond strength using this model [9]. [13] showed that the stress variation across the layer cannot be ignored, and FEA analysis reflected that these values can be of opposing natures along with same layer.

2.2.2. Bond-slip relationship approach
The bond-slip model plays an important role in both steel and concrete FRP systems. Effective bond length and bond strength can both be calculated using this model. The bond-slip relationship is based on the axial strain measured on the FRP or developed from the load versus displacement curve [14], based on CFRP-concrete systems. The CFRP-steel slip model was initially proposed by [15] based on a study of FRP plates. Later, [3] suggested a homogeneous bi-linear model to cover CFRP-steel plate systems, extending its range. The ultimate strength predictions made with this model were based on CFRP plate width and thickness and the elastic modulus of the CFRP. A bond-slip model was later utilised by [16] to evaluate its applicability to CFRP sheets in terms of deriving the bond strength.

2.2.3. Multi-layer distribution model
The previous models were not applicable to high modulus CFRP with multiple layer arrangements due to their different mode of failure to normal modulus CFRP [8] and failure not occurring along the bond length [9]. [17] proposed the use of strain values across the CFRP layers, which would gradually decrease or dissipate across the layers and away from the joint. [17] suggested evaluating the design capacity for a multiple layer arrangement scenario to calculate the load corresponding to each layer, and then combining them to obtain the ultimate (predicted) capacity of the joint. This load is a function of strain in the layer of interest, the area of the layer actively carrying the load, and the elastic modulus of CFRP.

2.2.4. Hart-Smith model
The Hart-Smith model is a classic model developed by [10]. The model treats a double strap joint as having a symmetrical configuration, and thus can be used to evaluate the effective length of a CFRP-steel bond and its maximum design capacity based on the joint per width length. Detailed derivations based on the classical model can be found in [10].

3. Methodology
To propose a strength model to evaluate ultimate bond strength of CFRP-steel composite joints, parameters such as loading rates, CFRP modulus, effective bond length, adhesive type, section properties, and other related factors that contribute to the bond performance were extracted from published research papers. Collected data were used to form a database for GeneXproTools 5.0, a genetic programming software application that can be utilised to find solutions to optimisation problems. To do this, the software produces the relationships between different input variables in the form of an algorithmic tree expression. Based on the expression tree, an equation can be written to propose a model, which is helpful in terms of determining the influencing factors significant in the strength model of CFRP-steel joints [18].

Genetic programming (GP) is an extension of genetic algorithms (GA), which were first proposed by [19] as an aid to understanding the natural evolutionary phenomenon of “adaptation”. GA was proposed and developed further to allow computers to solve given problems without providing instruction on how to solve those problem [20]. This provided independency to the input, allowing programs to evolve themselves based on the theory of evolution. GA thus follows a Darwinian theory of evolution, based on survival of the fittest. Generally, GA transforms a population of individual objects into new population generation using evolution. In doing so, each individual object is given a fitness
value, then mutations or cross-overs are performed with them, and the next generation is of objects is examined and renumbered until an individual member is evaluated with available fitness value, causing it to be selected as the optimum solution for the full process [20]. The author of [20] developed guidelines for GP as follows:

1. Create initial population with random composition.
2. Run and assign each program with a fitness value depending on performance in solving the assigned problem.
3. Create a next generation of programs by either copying the best performing programs (reproduction), or by encouraging mutations or cross-overs.
4. Process individual programs of the newly created generation.
5. Choose the best performing programs of the previous stage as the potential solutions of the genetic programming.

The usage of GP in the engineering field is gaining popularity in terms of providing acceptable solutions for optimisation issues. GP is usually utilised in difficult and multi-variable dependent modelling scenarios with reasonable assumptions. It is an electronic method that formulates new algorithmic models based on input parameters and produces results in the form of mathematical equations based on an expression tree, as shown in the figure 1. Initially, a complex conventional algorithmic expression was presented by [20], and further development in finalising and producing an equation was given by [21] who proposed another method of calculating the torsional strength of reinforced concrete (RC) beams, and compared the results using their proposed model with other methods suggested in various codes (ACI-318-2005, BS8110, AS3600-2001, TBC-500-2000, EC-2_01,02,03, and CSA-1994). Their comparison showed good performance in the model, which in some cases outperformed the codes. [22] and [23] also successfully used GP in optimisation problems, comparing their models with recommended guidelines and establishing that the proposed models were robust, performed well, and could be used in the field with confidence. Since then, more experiments using genetic programming on CFRP-concrete structures have been conducted; however, for CFRP-steel structures, algorithmic models using genetic programming have been very limited [18].

4. Research Program

The research project involved

- Evaluation of the collected data using GeneXproTools 5.0
- Analysing the results obtained from the software
- Proposing a strength model for CFRP-steel joints using genetic programming, noting its possible limitations discovered when conducting the research.

4.1. Program parameters:

In this research, the GeneXproTools 5.0 software package was used to predict the strength model for CFRP-steel bonds. The modelling was divided into two stages: the first model predicts the bond strength for static applications, while the second model predicts the bond strength for applications with high displacement rates. This is due to the large gap between the loading rates used in the literature, which meant that the modelling could not be incorporated into a single model with sufficient accuracy. The displacement rate ranged from 0.5 mm/min to 300,000 mm/min for static and dynamic scenarios, respectively, creating large gap that could not be bridged by a single model.

In the first model with static loading, the number of inputs used for training was 129, with 14 inputs used for testing of the proposed model. Figure 1 shows the expression tree of the static load modelling, from which an expression can be written. In the expression tree (ET) of this model the d0, d1, d2, and d3 represent CFRP bond length (Lb), cross-sectional area (a), CFRP modulus (Esf), and applied displacement rate (v), respectively. These values are readily available from the initial database and were used in both models, with the only difference between them being applied velocity.
The linking function was chosen to be addition, and the mathematical functions were chosen to be addition, subtraction, multiplication, division, square ($x^2$), cube ($x^3$), square root, cube root, absolute value of $x$, inverse of $x$ ($1/x$), and average of $x$ and $y$ ($\text{avg} \{x, y\}$).

In the second model with dynamic loading, 97 inputs were used for training the model and 14 inputs used for testing the proposed model. Figure 2 shows the expression tree of the proposed model for the calculation of the ultimate bond strength of CFRP-steel joints. In the expression tree (ET), the variables are as per static loading model. The modelling parameters and other information are shown in Table 1. The linking function was chosen to be addition, the mathematical functions are addition, subtraction, multiplication, division, square ($x^2$), cube ($x^3$), square root, and cube root. The modelling parameters and other information are shown in Table 1.

| Table 1. Details of modelling parameters. |
|-----------------------------------------|
| Parameter                  | Value     |
| Loading Type               | Static    | Dynamic   |
| Training Set              | 129       | 97        |
| Testing Set               | 14        | 14        |
| Number of Genes (Sub ETs) | 3         | 3         |
| Linking function          | Addition  | addition  |
| Number of variables used  | 4         | 4         |
| Chromosomes               | 15        | 15        |
| Head size                 | 8         | 8         |
| Lower bound               | -10       | -10       |
| Upper bound               | 10        | 10        |
| Mutation                  | 0.00138   | 0.002     |
| Fitness function          | RMSE      | RRSE      |
| Inversion                 | 0.00546   | 0.00546   |
| Transposition             | 0.00277   | 0.00277   |
| Constants per gene        | 2         | 2         |

5. Results and discussion

As mentioned, the output method of the GP program can offer various methods; however, the expression tree (ET) is the most convenient output from which an equation can be developed. Figures 1 and 2 show the expression tree of the prediction model for calculation of ultimate strength of CFRP-steel bonds under static and dynamic loadings respectively.

From the expression tree in figure 1, the derived equation of the bond strength is as follows:

$$\tau = \left[ a \ast v \ast (L_f + 54.3) \ast (v + 9.84) \right] + \left[ (6 \cdot 24v^2 - 14.14) \ast \sqrt{3.83E_f} \right] + \left[ ^3 \sqrt{(a - 9.52) \ast (E_f - 4868.4) \ast (L_f + a) \ast \left( \frac{E_f}{E_f - 9.1} \right)} \right]$$

Equation 1

However, the expression tree for the dynamic loading model is given in figure 2 and the derived equation of the bond strength is as given below:

$$\tau = \left[ 2L_f(a - 13.45)^2 + \frac{E_f}{a} \right] + \left[ (\sqrt{L_f + a})^3 + (41774.70 - L_f^2) \right] + \left[ \frac{(E_f - v) \ast (L_f - 7.76) \ast (7.76 - a^2)}{88.72L_f} \right]$$

Equation 2
where 
\( \tau \) is the ultimate joint capacity in N; 
a is the area of the CFRP in mm\(^2\); 
\( L_f \) is the effective length in mm; 
\( E_f \) is the modulus of CFRP in MPa; and 
\( V \) is the loading rate in mm/min.

**Figure 1:** Expression tree of the prediction model for the static loading.

**Figure 2:** Expression tree of the prediction model for the dynamic loading.

Both models were validated using the parameters described below; these parameters are the coefficient of determination \( R^2 \), mean absolute error (MAE), root mean square error (RMSE) and root relative squared error (RRSE). The equations are stated below, and the results are tabulated in the table 2:

\[
R^2 = 1 - \frac{\sum(t_i - o_i)^2}{\sum(o_i)^2}
\]

**Equation 3**

\[
MAE = \frac{1}{n} \sum |t_i - o_i|
\]

**Equation 4**

\[
RMSE = \sqrt{\frac{1}{n} \sum (t_i - o_i)^2}
\]

**Equation 5**
\[ RAE = \frac{\sum |t_i - o_i|}{\sum |t_i - \frac{1}{n} \sum t_i|} \]  
\[ RRSE = \sqrt{\frac{\sum (t_i - o_i)^2}{\sum (t_i - \frac{1}{n} \sum t_i)^2}} \]

Equation 6
Equation 7

Among these equations, \( t_i \) is the target parameter and \( o_i \) is the output parameter. The \( n \) represents the number of datasets used in the model.

**Table 2:** Error values of training, testing, and validation phases of the model.

| Phase   |        | \( R^2 \) | MAE   | RMSE  | RAE   | RRSE  |
|---------|--------|----------|-------|-------|-------|-------|
| Static  | Training | 0.93     | 6861  | 8416  | 0.25  | 0.26  |
|         | Testing | 0.94     | 9156  | 10305 | 0.27  | 0.28  |
| Dynamic | Training | 0.97     | 5537.4| 6426.3| 0.14  | 0.16  |
|         | Testing | 0.97     | 6202.7| 7157  | 0.16  | 0.17  |

From table 2, it can be concluded that the predicted values of strength are 93% closer to the actual tested values for the static loading scenario. The dynamic model, on the other hand, can predict the bond capacity to 97% accuracy. In addition, figures 3 and 4 show the correlation between the predicted bond strength versus the actual strength, and it can be seen that there is dense data in values of around 70 kN in figure 3; this can be attributed to the fact that in some joints, this range was the maximum force achieved, and that this bond length can thus be considered the effective bond length of these specimens.

**Figure 3:** Correlation of the training model of static loading.
6. **Summary and Conclusions:**

CFRP is an excellent material and it is becoming ever more attractive in the strengthening field due to its excellent strength to weight ratio, ease of application, and cost effectiveness. The focus of this research project was to examine a method of calculating the ultimate bond strength of CFRP-steel joints using a genetic programming approach to evaluate how well the proposed model fits with a given database. Two models were proposed in this research: the first model was based on static test results investigated in the literature, and the second model copied this with dynamic testing. The variables used in this research were bond length, cross sectional area of the CFRP, displacement rate, and CFRP modulus. The results showed that the predicted strength offered good agreement with the actual values determined experimentally, as a high value of $R^2$ was shown for both models, indicating their accuracy.

7. **References:**

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