Performance Based Review and Fine-Tuning of TRM-Concrete Bond Strength Existing Models

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ABSTRACT

Textile reinforced mortars (TRMs) are new composite materials which were considered as a proper alternative for fiber reinforced polymers (FRPs) to strengthen various structural elements. In comparison to FRPs, the TRMs have more fire resistance, more environmental consistency and are safer the structural elements because of their better bond to substrate and various failure modes. There are a lot of existing models to calculate the bond strength between TRMs and concrete substrate. But, most of them originated from the FRP-concrete bond models and are not accurate enough to estimate the TRM-concrete bond strength. In this paper, new TRM-concrete bond models were calibrated to predict the bond strength between various TRM composites and the concrete substrate. To achieve this goal, a database including 221 experimental direct shear tests were compiled and a simple existing model was selected to be calibrated via soft computing techniques. It was found that the presented novel models could be accurately utilized to anticipate the TRM-concrete bond strength with various types of fibers and different geometrical features with R value of 0.6909 and NMAE error value of 12.62%.

Keywords: Textile reinforced mortar (TRM); Fiber reinforced polymer (FRP); Bond strength; Calibration process; Soft computing techniques.
1. Introduction

Most of the concrete structures experience damages during their life time. These damages usually start with initial cracks and the these cracks propagate and will cause the whole structure to collapse [1–3]. To prevent such catastrophic collapses, the researcher proposed external bonded (EB) composite systems as useful techniques to strengthen the structural elements. Among different EB systems, the fiber reinforced polymer (FRP) composites are the most known strengthening systems with various advantages such as high strength to weight ratios, compatible geometrical features and easily installing procedure [4–7].

Although the FRP composites have a lot of merits, some of the disadvantages of them such as high sensitivity to fire, brittle manner in conditions with high temperature changes, non-environmental friendly manufacture process and their failure mode which is usually contains detachment a part of the concrete substrate with the FRP strips, make the researcher to find a more proper alternative for the FRP composites [8]. The textile reinforced mortar (TRM) composite was the selection of those researchers in which the epoxy resin in FRP composites was replaced with mineral mortar grouts. The TRM composites have all advantages of FRP composites and moreover reduce their side effects [9].

As the failure modes in TRM composites are more complicated with respect to FRP composites, most of researchers started to conduct deep experimental tests to undertake the bond behavior between TRM composites and different concrete substrates [10,11]. Most of the conducted test to study the TRM-concrete bond behavior were designated to direct shear (DS) tests. In DS tests, a strip of TRM composite should be attached to one face of a concrete block and by fixing the concrete block as the substrate, the strip of TRM composite should be pulled out until the detachment of the TRM composite from the concrete substrate or rupture of the fibers in the TRM composite. Various DS tests with different kinds of fibers such as carbon [12], glass [13], aramid [14], basalt [15], and PBO [16] were reported in previous studies. In many other investigations, the researchers proposed some empirical models to predict the bond strength between the TRM composite and the concrete substrate [17–20]. Most of the previously proposed TRM-concrete bond models were adopted from FRP-concrete bond models and were obtained based on some limited experimental data. As a result, the previous empirical TRM-concrete bond models can not be utilized as a general model and they have high values of errors. The goal of this paper is to calibrate a simplified TRM-concrete bond model based on a comprehensive complied DS tests data.

2. Research objective

Literature has shown that many experimental and analytical efforts have been conducted to investigate the bond behavior between textile reinforced mortar and concrete substrates. The most of existing analytical models provided to estimate the TRM-concrete bond strength originated from previous models proposed for predicting the FRP-concrete bond strength. Moreover, some analytical efforts have been done to propose updated models for estimating the TRM-concrete bond strength based on limited local experimental data. As a result, the
performance of existing TRM-concrete bond strength models is still a challenging question for researchers. In this paper, it is tried to review the existing TRM-concrete bond strength models and select the simplest one to conduct the calibration based on soft computing techniques and improve its performance based on a comprehensive database including 221 experimental direct shear tests. As this paper aims to keep the original form of the selected existing model, the performance of the proposed model is not comparable to other calibration models without any limitation in the form of the proposed equation. The research flowchart is depicted in Fig. 1.

3. Existing TRM-concrete bond models

There are some known existing models to calculate the TRM-concrete bond strength. In this paper, to present a closed form simple equation, the simplest existing analytical model were chosen from the literature. Maeda et al. [20] had proposed the following equation to estimate the TRM-concrete bond strength:

$$P_u = 110.2 \times 10^{-6} \cdot E_f \cdot t_f \cdot b_f \cdot l_e$$  \hspace{1cm} (1)

Where, in Eq. (1), the $E_f$, $t_f$, and the $b_f$ are respectively the modulus of elasticity of fibers, thickness of fibers, and width of fibers in TRM composites. The $l_e$ is the effective bonded length which can be calculated from the Eq. (2) presented below:

$$l_e = e^{6.13 - 0.580 \ln(E_f \cdot t_f)}; \hspace{1cm} E_f (GPa), \hspace{0.5cm} t_f (mm)$$  \hspace{1cm} (2)

In this paper, the Eq. (1) has been selected to be calibrated via different soft computing techniques. The performance of the resulted fine-tuning models will be compared to the original presented models by Maeda et al. [20].
4. The experimental TRM-concrete bond database

In this study, a database including 221 experimental direct shear tests were compiled from various researchers. As presented in Fig. 2, the input parameters in the compiled database were modulus of elasticity of fibers ($E_f$), thickness of fibers ($t_f$), the width ($b_f$) and bonded length ($L_b$) of fibers in TRM composites, the compressive strength of concrete substrate ($f_c$), and the width of concrete block ($b$); Whereas the output is the bond strength between TRM composite and the concrete substrate ($P_a$). Table 1 presents the input and output ranges and the number of specimens in each reference, and the Table 2 reports the statistical features of the compiled database in this paper.

Table 1
Experimental database

<table>
<thead>
<tr>
<th>Reference</th>
<th>$b$ (mm)</th>
<th>$f_c$(MPa)</th>
<th>$t_f$(mm)</th>
<th>$b_f$(mm)</th>
<th>$L_b$(mm)</th>
<th>$E_f$(GPa)</th>
<th>$P_a$(KN)</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iorfida et al.[21]</td>
<td>120</td>
<td>15</td>
<td>0.064</td>
<td>43</td>
<td>100 to 400</td>
<td>70</td>
<td>0.93 to 1.16</td>
<td>4</td>
</tr>
<tr>
<td>Awani et al. [22]</td>
<td>150</td>
<td>55</td>
<td>0.095</td>
<td>75,100 &amp; 150</td>
<td>75,100 &amp; 150</td>
<td>230</td>
<td>8.38 to 38.72</td>
<td>18</td>
</tr>
<tr>
<td>D'Ambrisi et al. [16]</td>
<td>100</td>
<td>16.1</td>
<td>0.046 &amp; 0.092</td>
<td>100</td>
<td>50 to 200</td>
<td>271</td>
<td>5.5 to 15.6</td>
<td>7</td>
</tr>
<tr>
<td>D'Antino et al. [23]</td>
<td>125</td>
<td>42.5</td>
<td>0.37 to 0.83</td>
<td>34 to 80</td>
<td>100 to 450</td>
<td>270</td>
<td>1.50 to 9.18</td>
<td>21</td>
</tr>
<tr>
<td>Tran et al. [24]</td>
<td>100</td>
<td>41</td>
<td>0.0445</td>
<td>100</td>
<td>250 to 400</td>
<td>270</td>
<td>10.46 to 10.95</td>
<td>4</td>
</tr>
<tr>
<td>D'Antino et al. [25]</td>
<td>125</td>
<td>47.4</td>
<td>0.046 &amp; 0.05</td>
<td>60</td>
<td>330 &amp; 450</td>
<td>74,273 &amp; 288.4</td>
<td>1.43 to 6.01</td>
<td>7</td>
</tr>
<tr>
<td>Sneed et al. [26]</td>
<td>125</td>
<td>33.5</td>
<td>0.092</td>
<td>34,60 &amp; 100</td>
<td>100 to 330</td>
<td>206</td>
<td>6.73 to 21.02</td>
<td>7</td>
</tr>
<tr>
<td>Ombres [27]</td>
<td>125</td>
<td>30.4</td>
<td>0.046 &amp; 0.091</td>
<td>70</td>
<td>150,200 &amp; 250</td>
<td>271</td>
<td>2.4 to 8.1</td>
<td>8</td>
</tr>
<tr>
<td>D'Antino et al. [28]</td>
<td>125</td>
<td>33.5</td>
<td>0.092</td>
<td>60 &amp; 80</td>
<td>330 &amp; 450</td>
<td>206</td>
<td>3.36 to 9.14</td>
<td>4</td>
</tr>
<tr>
<td>Raoof et al. [29]</td>
<td>100</td>
<td>14.7 to 32.8</td>
<td>0.095 to 0.38</td>
<td>80</td>
<td>50 to 450</td>
<td>225</td>
<td>7.72 to 49.19</td>
<td>40</td>
</tr>
<tr>
<td>Carolni et al. [30]</td>
<td>125</td>
<td>40.9</td>
<td>0.046</td>
<td>80</td>
<td>330 &amp; 450</td>
<td>270</td>
<td>7.71 to 8.49</td>
<td>4</td>
</tr>
<tr>
<td>Sneed et al. [31]</td>
<td>125</td>
<td>47.4</td>
<td>0.0455 &amp; 0.05</td>
<td>55 &amp; 60</td>
<td>100 to 450</td>
<td>72.4 &amp; 228</td>
<td>0.54 to 2.16</td>
<td>8</td>
</tr>
<tr>
<td>Ombres [32]</td>
<td>125</td>
<td>31.5 &amp; 40.9</td>
<td>0.095</td>
<td>50</td>
<td>100 to 450</td>
<td>200</td>
<td>7.23 to 9.89</td>
<td>7</td>
</tr>
<tr>
<td>Carozzi et al. [33]</td>
<td>250</td>
<td>20.8 to 68.8</td>
<td>0.014 to 0.22</td>
<td>50 to 100</td>
<td>50 to 260</td>
<td>56 to 263</td>
<td>1.1 to 21.4</td>
<td>17</td>
</tr>
<tr>
<td>Gonzalez-libereros et al. [34]</td>
<td>125</td>
<td>59.3</td>
<td>0.05</td>
<td>55</td>
<td>100 to 450</td>
<td>72.4</td>
<td>0.635 to 2.16</td>
<td>4</td>
</tr>
<tr>
<td>Gonzalez et al. [35]</td>
<td>125</td>
<td>59.3</td>
<td>0.046</td>
<td>75</td>
<td>100 to 450</td>
<td>101.5</td>
<td>5.80 to 1.85</td>
<td>4</td>
</tr>
<tr>
<td>Sneed et al. [36]</td>
<td>125</td>
<td>42.5</td>
<td>0.092</td>
<td>34,40 &amp; 60</td>
<td>100 to 330</td>
<td>206</td>
<td>1.50 to 6.50</td>
<td>8</td>
</tr>
<tr>
<td>Sneed et al. [37]</td>
<td>125</td>
<td>31.5</td>
<td>0.092</td>
<td>50</td>
<td>330</td>
<td>205</td>
<td>9.13</td>
<td>1</td>
</tr>
<tr>
<td>Zou et al. [38]</td>
<td>115</td>
<td>25.79</td>
<td>0.092</td>
<td>60</td>
<td>330</td>
<td>206</td>
<td>5.86</td>
<td>1</td>
</tr>
<tr>
<td>Zou and Sneed [39]</td>
<td>115</td>
<td>25.79</td>
<td>0.084 &amp; 0.162</td>
<td>50</td>
<td>30 to 240</td>
<td>190</td>
<td>6.80 to 17.32</td>
<td>10</td>
</tr>
<tr>
<td>Younis and Ebead [40]</td>
<td>150</td>
<td>30</td>
<td>0.046 &amp; 0.048</td>
<td>100</td>
<td>75 &amp; 100</td>
<td>60,80 &amp; 270</td>
<td>3.34 to 10.75</td>
<td>6</td>
</tr>
<tr>
<td>Younis and Ebead [41]</td>
<td>150</td>
<td>30</td>
<td>0.045 &amp; 0.047</td>
<td>100</td>
<td>75 to 200</td>
<td>80,240 &amp; 270</td>
<td>3.34 to 29.5</td>
<td>18</td>
</tr>
<tr>
<td>D'Antino et al. [28]</td>
<td>125</td>
<td>26.9 &amp; 33.5</td>
<td>0.092</td>
<td>60 &amp; 80</td>
<td>330 &amp; 450</td>
<td>206</td>
<td>3.36 to 9.09</td>
<td>5</td>
</tr>
<tr>
<td>D'Antino et al. [42]</td>
<td>125</td>
<td>59.3</td>
<td>0.043 &amp; 0.047</td>
<td>55 &amp; 60</td>
<td>100 to 450</td>
<td>72 &amp; 270</td>
<td>0.54 to 2.16</td>
<td>8</td>
</tr>
</tbody>
</table>
5. Calibrated TRM-concrete bond strength models

New TRM-concrete bond strength models were proposed in this section based on the compiled experimental direct shear tests database reported in Table 1. The proposed models were aimed to improve the accuracy and performance of the selected existing TRM-concrete bond strength model (Maeda et al. [20]). Thus, for calibrating the general simplified models, $P_{u_{Cal\_I}}$ and $P_{u_{Cal\_II}}$ as presented in Eqs. (3) and (4) respectively, a generalized reduced gradient nonlinear approach was implemented to provide the best coefficients ($C, \alpha$ and $\beta$) that minimize the root mean square error (RMSE) as the objective function. The achieved results are presented in Table 3.

$$
P_{u_{Cal\_I}} = C \cdot 110.2 \times 10^{-6} \cdot E_f \cdot t_f \cdot b_f \cdot l_c^{\alpha}
$$

$$
l_c = e^{b \cdot 0.13 + 0.580 \ln(E_f \cdot t_f)} ; \quad E_f (GPa), \ t_f (mm)
$$

$$
P_{u_{Cal\_II}} = C \cdot 110.2 \times 10^{-6} \cdot E_f \cdot t_f \cdot b_f \cdot l_c^{\alpha}
$$

$$
l_c = e^{\alpha + \beta \ln(E_f \cdot t_f)} ; \quad E_f (GPa), \ t_f (mm)
$$
Table 3
The results of calibration technique.

<table>
<thead>
<tr>
<th>Proposed Model</th>
<th>C</th>
<th>α</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{u,\text{Cal,},I}$</td>
<td>0.1517</td>
<td>1.4129</td>
<td>1.2374</td>
</tr>
<tr>
<td>$P_{u,\text{Cal,},II}$</td>
<td>1.0037</td>
<td>6.2637</td>
<td>0.6448</td>
</tr>
</tbody>
</table>

By applying the results of Table 3, the generalized reduced gradient nonlinear method as the calibration method for $P_{u,\text{Cal,}\,I}$ and $P_{u,\text{Cal,}\,II}$ proposed models are presented in Eqs. (5) and (6), respectively.

$$P_{u,\text{Cal,}\,I} = 0.1517 \times 110.2 \times 10^{-6} \cdot E_f \cdot t_f \cdot b_f \cdot l_e^{1.4129}$$

$$l_e = e^{1.2374 \times 6.13 - 0.580 \ln(E_f \cdot t_f)} \quad ; \quad E_f (GPa), \ t_f (mm)$$

$$P_{u,\text{Cal,}\,II} - 1.0037 \times 110.2 \times 10^{-6} \cdot E_f \cdot t_f \cdot b_f \cdot l_e$$

$$l_e = e^{6.2637 - 0.6448 \ln(E_f \cdot t_f)} \quad ; \quad E_f (GPa), \ t_f (mm)$$

To compare the performance of the two proposed calibration models ($P_{u,\text{Cal,}\,I}$ and $P_{u,\text{Cal,}\,II}$) with other statistical methods, a multi linear regression (MLR) technique is also applied to estimate the TRM-concrete bond strength via reported database in Table 1. The general equation for the MLR technique ($P_{u,\text{MLR}}$) is presented in Eq. (7):

$$P_{u,\text{MLR}} = \alpha \cdot b_c + \beta \cdot f_c + \varphi \cdot t_f + \delta \cdot b_f + \lambda \cdot l_e + \eta \cdot E_f + C$$

The obtained parameters in MLR technique are presented in Table 4. Eq. (8) shows the simplified MLR proposed model ($P_{u,\text{MLR}}$).

Table 4
The results of MLR technique.

<table>
<thead>
<tr>
<th>Proposed Model</th>
<th>α</th>
<th>θ</th>
<th>φ</th>
<th>δ</th>
<th>λ</th>
<th>η</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{u,\text{MLR}}$</td>
<td>-0.0766</td>
<td>-0.1554</td>
<td>19.2451</td>
<td>0.1937</td>
<td>-0.0156</td>
<td>0.0058</td>
<td>13.0192</td>
</tr>
</tbody>
</table>

$$P_{u,\text{MLR}} = -0.0766b_c - 0.1554f_c + 19.2451t_f + 0.1937b_f - 0.0156l_e + 0.0058E_f + 13.0192$$

Some of the regular performance and error evaluation parameters such as the correlation coefficient (R), the coefficient of determination ($R^2$), Mean Squared Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), Normalized Mean Squared Error (NMSE) and Normalized Mean Absolute Error (NMAE) presented in Eqs. (9) to (16) [43–48], were selected to evaluate the performance of existing and proposed models. The evaluation results are presented in Table 5 for various TRM-concrete bond strength models.
\[
R = \frac{\sum_{i=1}^{n} (A_i - \bar{A})(F_i - \bar{F})}{\sqrt{\sum_{i=1}^{n} (A_i - \bar{A})^2 \sum_{i=1}^{n} (F_i - \bar{F})^2}}
\]

(9)

\[
R^2 = \left(\frac{\sum_{i=1}^{n} (A_i - \bar{A})(F_i - \bar{F})}{\sqrt{\sum_{i=1}^{n} (A_i - \bar{A})^2 \sum_{i=1}^{n} (F_i - \bar{F})^2}}\right)^2
\]

(10)

\[
MSE = \frac{1}{n} \sum_{i=1}^{n} (A_i - F_i)^2
\]

(11)

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (A_i - F_i)^2}
\]

(12)

\[
MAE = \frac{1}{n} \sum_{i=1}^{n} |A_i - F_i|
\]

(13)

\[
MAPE = \frac{1}{n} \left[ \frac{\sum_{i=1}^{n} |A_i - F_i|}{\sum_{i=1}^{n} |A_i|} \right] \times 100
\]

(14)

\[
NMSE = \frac{\frac{1}{n} \sum_{i=1}^{n} (A_i - F_i)^2}{\max(A_i) - \min(A_i)} \times 100
\]

(15)

\[
NMAE = \frac{\frac{1}{n} \sum_{i=1}^{n} |A_i - F_i|}{\max(A_i) - \min(A_i)} \times 100
\]

(16)

where \(A_i\) represents the obtained experimental value, and \(F_i\) shows the predicted value, \(n\) is equal to the number of the studied data, \(\bar{A}\) is the mean observed values, and \(\bar{F}\) is the mean predicted values. The comparison of predicted TRM-concrete bond strength values with corresponding experimental results for direct shear tests and the measured to predicted ratios are presented in Figs. 3 and 4, respectively. In Fig. 3, the ideal fit line (shown with a continuous purple line) indicates how the results were located accurately.
Table 5
The performances and error evaluation of existing and calibrated models.

<table>
<thead>
<tr>
<th>Method</th>
<th>R</th>
<th>R²</th>
<th>MSE</th>
<th>RMSE</th>
<th>MAE (MPa)</th>
<th>MAPE (%)</th>
<th>NMSE (%)</th>
<th>NMAE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maeda et al.</td>
<td>0.6676</td>
<td>0.4456</td>
<td>71.80</td>
<td>8.47</td>
<td>6.37</td>
<td>134.44</td>
<td>147.59</td>
<td>13.10</td>
</tr>
<tr>
<td>P_u_Cal_I</td>
<td>0.6909</td>
<td>0.4774</td>
<td>64.75</td>
<td>8.05</td>
<td>6.14</td>
<td>106.43</td>
<td>133.09</td>
<td>12.62</td>
</tr>
<tr>
<td>P_u_Cal_II</td>
<td>0.6902</td>
<td>0.4763</td>
<td>67.78</td>
<td>8.23</td>
<td>6.41</td>
<td>128.97</td>
<td>139.33</td>
<td>13.17</td>
</tr>
<tr>
<td>P_u_MLR</td>
<td>0.6398</td>
<td>0.4093</td>
<td>72.77</td>
<td>8.53</td>
<td>6.68</td>
<td>124.91</td>
<td>149.57</td>
<td>13.73</td>
</tr>
</tbody>
</table>

Fig. 3. The predicted vs. obtained TRM-concrete bond strength in different models: a) P_u_Cal_I; b) P_u_Cal_II; c) Maeda et al. and d) P_u_MLR.
The presented result in Table 5 and Figs. 3 and 4 show that for TRM-concrete bond strength, proposed $P_{u, Cal\_I}$ model resulted in R value of 0.6909 and NMAE value of 12.62%, which can be included as the most accurate model. Additionally, the proposed $P_{u, Cal\_I}$ model obtained better R value of 0.6902 but gained more NMAE error value of 13.17% in comparison to existing Maeda et al. model (respectively equal to 0.6676 and 13.10%). Based on the results, the $P_{u, MLR}$ model was not successful to outperform the existing Maeda et al. model. The outcomes can be confirmed by the histogram of absolute percentage error frequencies shown in Fig. 5.

6. Conclusions

In this paper, new TRM-concrete bond models were calibrated to predict the bond strength between various TRM composites and the concrete substrate. Two calibrated models named $P_{u, Cal\_I}$ and $P_{u, Cal\_II}$ as well as a multi regression model named $P_{u, MLR}$ model were conducted to estimate the TRM-concrete bond strength. To achieve this goal, a database including 221 experimental direct shear tests were compiled and a simple existing model was selected to be calibrated via soft computing techniques. Based on the achieved results, the following conclusion could be drawn:

- Among the calibrated models, the $P_{u, Cal\_I}$ model outperforms all other models with R value of 0.6909 and NMAE error value of 12.62%. The calibrated $P_{u, Cal\_II}$ model gained more R value of 0.6902 but higher NMAE error value of 13.17% in comparison to existing Maeda et al. model (0.6676 and 13.10%, respectively).
Fig. 5. The histogram of absolute percentage error frequency in different TRM-concrete bond strength models.

- Opposite to the obtained result from calibrated models conducted by a generalized reduced gradient nonlinear approach by minimizing the root mean square error (RMSE), the proposed multilinear regression model ($\text{Pu}_\text{MLR}$) was not successful to outperform the existing Maeda et al. model. The obtained R and NMAE values for $\text{Pu}_\text{MLR}$ model was 0.6398 and 13.73% respectively.

- The proposed generalized reduced gradient nonlinear approach by minimizing RMSE values was a capable technique to calibrate the existing Maeda et al. model to estimate the TRM-concrete bond strength with higher accuracy and lower error values.

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Conflicts of interest

The authors declare no conflict of interest.
Authors contribution statement

HJ, ZN, DRE: Conceptualization; HJ, ZN: Data curation; HJ, DRE: Formal analysis; ZN, HJ: Investigation; HJ, DRE: Methodology; MRE: Project administration; ZN: Resources; DRE: Software; MRE: Supervision; HJ, DRE: Validation; HJ, DRE: Visualization; HJ: Roles/Writing – original draft; HJ, DRE: Writing – review & editing.

References


