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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%.

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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 results, 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.

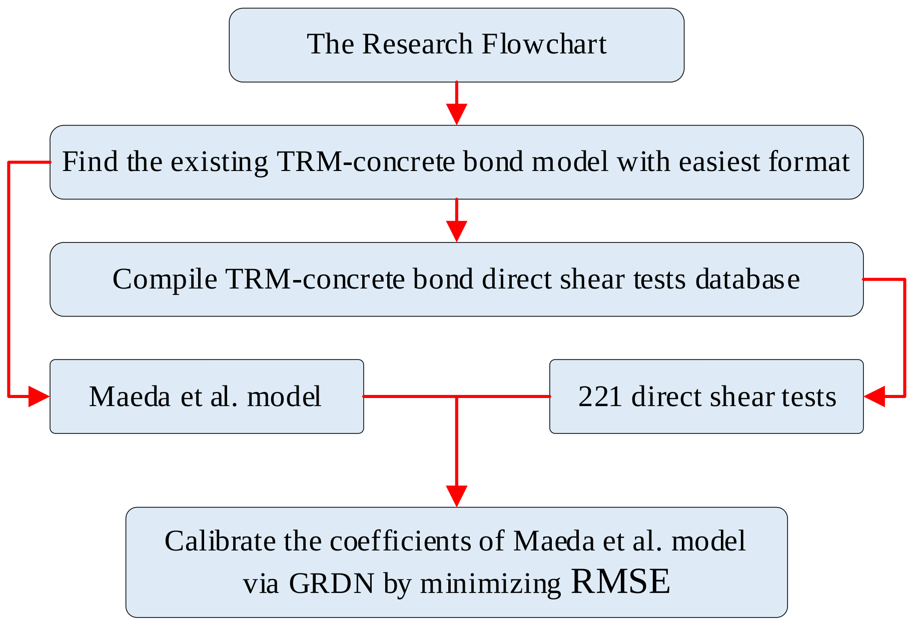

Fig. 1. The research flowchart in this study.

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:

$$P_u = 110.2\times10^{-6}\cdot E_f\cdot t_f\cdot b_f\cdot l_e \tag{1}$$

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 le is the effective bonded length which can be calculated from the Eq. (2) presented below:

$$l_e = e^{6.13-0.580\ln(E_f\cdot t_f)};\quad E_f(GPa),\ t_f(mm) \tag{2}$$

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_u). 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

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

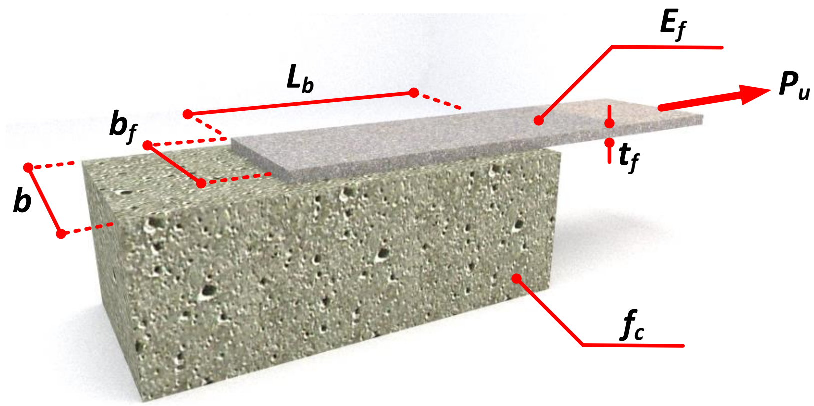

Fig. 2. The inputs and output parameters considered in this study.

Table 2
Statistical properties of the database.

Statistical Methods	b (mm)	f_c(MPa)	$t_f(mm)$	$b_f(mm)$	$L_b(mm)$	$E_f(GPa)$	$P_u(KN)$
Minimum	100	14.7	0.014	34	30	56	0.54
Maximum	250	68.8	0.828	150	450	288.40	49.19
Range	150	54.1	0.814	116	420	232.40	48.65
Average	133.01	36.49	0.153	73.75	213.19	210.47	12.298
SD	37.49	12.46	0.16	23.48	119.89	63.99	11.09
CoV (%)	28.19	34.13	110.37	31.83	56.23	30.40	90.24
Kurtosis	4.56	-0.49	4.08	1.11	-0.75	0.50	0.531
Skewness	2.20	0.37	2.10	0.72	0.60	-1.25	1.21

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, α and β) that minimize the root mean square error (RMSE) as the objective function. The achieved results are presented in Table 3.

$$P_{u\_Cal\_I} = C \cdot 110.2 \times 10^{-6} \cdot E_f \cdot t_f \cdot b_f \cdot l_e{}^{\alpha}$$
$$l_e = e^{\beta\ 6.13 - 0.580 \ln(E_f \cdot t_f)}; \quad E_f(GPa),\ t_f(mm) \tag{3}$$

$$P_{u\_Cal\_II} = C \cdot 110.2 \times 10^{-6} \cdot E_f \cdot t_f \cdot b_f \cdot l_e$$
$$l_e = e^{\alpha - \beta \ln(E_f \cdot t_f)}; \quad E_f(GPa),\ t_f(mm) \tag{4}$$

Table 3
The results of calibration technique.

Proposed Model	C	α	β
$P_{u\_Cal\_I}$	0.1517	1.4129	1.2374
$P_{u\_Cal\_II}$	1.0037	6.2637	0.6448

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

$$P_{u\_Cal\_I} = 0.1517 \times 110.2 \times 10^{-6} \cdot E_f \cdot t_f \cdot b_f \cdot l_e{}^{1.4129}$$
$$l_e = e^{1.2374 \times 6.13 - 0.580 \ln(E_f \cdot t_f)}; \quad E_f(GPa),\ t_f(mm) \tag{5}$$

$$P_{u\_Cal\_II} = 1.0037 \times 110.2 \times 10^{-6} \cdot E_f \cdot t_f \cdot b_f \cdot l_e$$
$$l_e = e^{6.2637 - 0.6448 \ln(E_f \cdot t_f)}; \quad E_f(GPa),\ t_f(mm) \tag{6}$$

To compare the performance of the two proposed calibration models ($P_{u\_Cal\_I}$ and $P_{u\_Cal\_II}$) 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_MLR}) is presented in Eq. (7):

$$P_{u\_MLR} = \alpha \cdot b_c + \beta \cdot f_c + \varphi \cdot t_f + \delta \cdot b_f + \lambda \cdot l_b + \eta \cdot E_f + C \tag{7}$$

The obtained parameters in MLR technique are presented in Table 4. Eq. (8) shows the simplified MLR proposed model (P_{u_MLR}).

Table 4
The results of MLR technique.

Proposed Model	α	β	φ	δ	λ	η	C
P_{u_MLR}	-0.0766	-0.1554	19.2451	0.1937	-0.0156	0.0058	13.0192

$$P_{u\_MLR} = -0.0766 b_c - 0.1554 f_c + 19.2451 t_f + 0.1937 b_f - 0.0156 l_b + 0.0058 E_f + 13.0192 \tag{8}$$

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.

$$R = \frac{\sum_{i=1}^{n}\left(A_i - \bar{A}\right)\left(F_i - \bar{F}\right)}{\sqrt{\sum_{i=1}^{n}\left(A_i - \bar{A}\right)^2 \sum_{i=1}^{n}\left(F_i - \bar{F}\right)^2}} \tag{9}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n}\left(A_i - \bar{A}\right)\left(F_i - \bar{F}\right)}{\sqrt{\sum_{i=1}^{n}\left(A_i - \bar{A}\right)^2 \sum_{i=1}^{n}\left(F_i - \bar{F}\right)^2}}\right)^2 \tag{10}$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(A_i - F_i\right)^2 \tag{11}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(A_i - F_i\right)^2} \tag{12}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|A_i - F_i\right| \tag{13}$$

$$MAPE = \frac{1}{n}\left[\frac{\sum_{i=1}^{n}\left|A_i - F_i\right|}{\sum_{i=1}^{n}\left|A_i\right|}\right]\times 100 \tag{14}$$

$$NMSE = \frac{\frac{1}{n}\sum_{i=1}^{n}\left(A_i - F_i\right)^2}{\max(A_i) - \min(A_i)}\times 100 \tag{15}$$

$$NMAE = \frac{\frac{1}{n}\sum_{i=1}^{n}\left|A_i - F_i\right|}{\max(A_i) - \min(A_i)}\times 100 \tag{16}$$

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.

Method	R	R^2	MSE	RMSE	MAE (MPa)	MAPE (%)	NMSE (%)	NMAE (%)
Maeda et al.	0.6676	0.4456	71.80	8.47	6.37	134.44	147.59	13.10
$P_{u\_Cal\_I}$	0.6909	0.4774	64.75	8.05	6.14	106.43	133.09	12.62
$P_{u\_Cal\_II}$	0.6902	0.4763	67.78	8.23	6.41	128.97	139.33	13.17
P_{u_MLR}	0.6398	0.4093	72.77	8.53	6.68	124.91	149.57	13.73

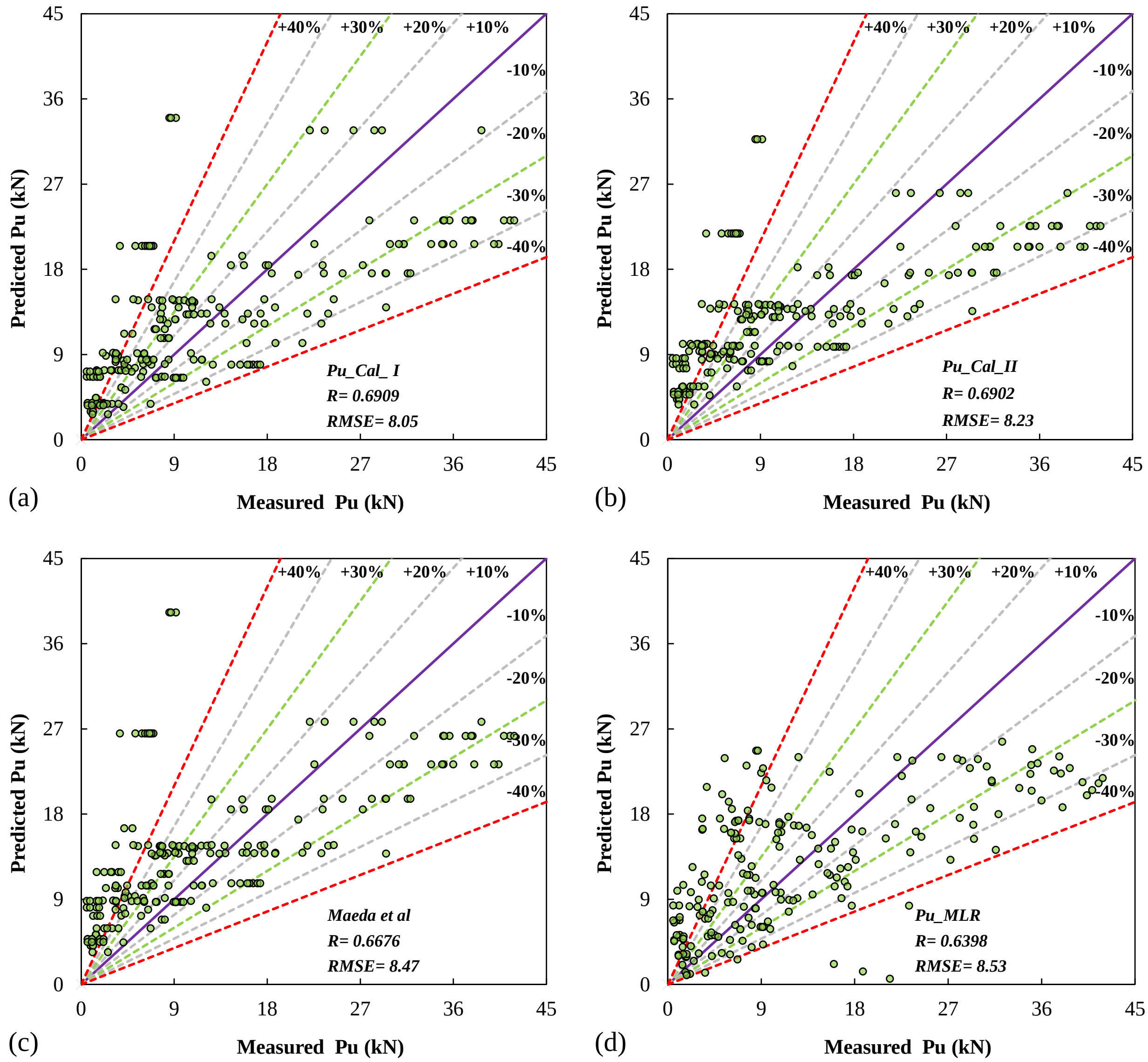

Fig. 3. The predicted vs. obtained TRM-concrete bond strength in different models: a) $P_{u\_Cal\_I}$; b) $P_{u\_Cal\_II}$; c) Maeda et al. and d) P_{u_MLR}.

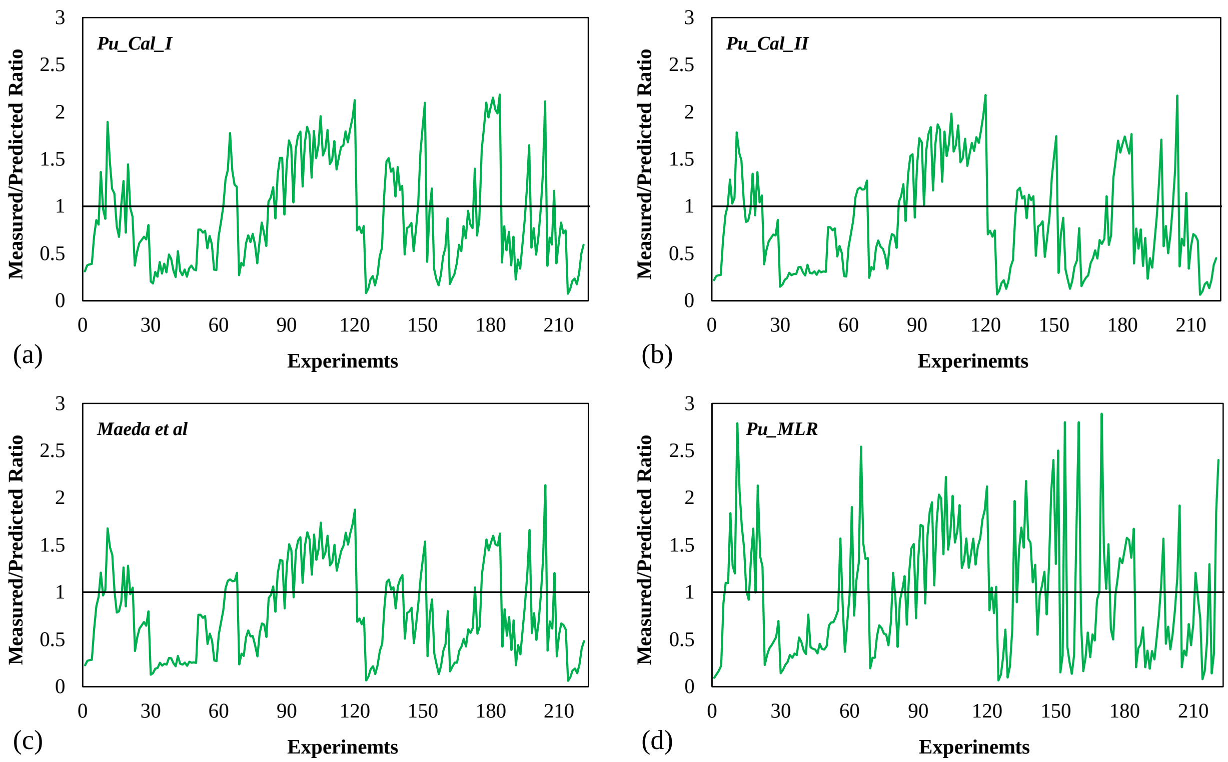

Fig. 4. The measured to predicted ratios of TRM-concrete bond strength in different models.

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).

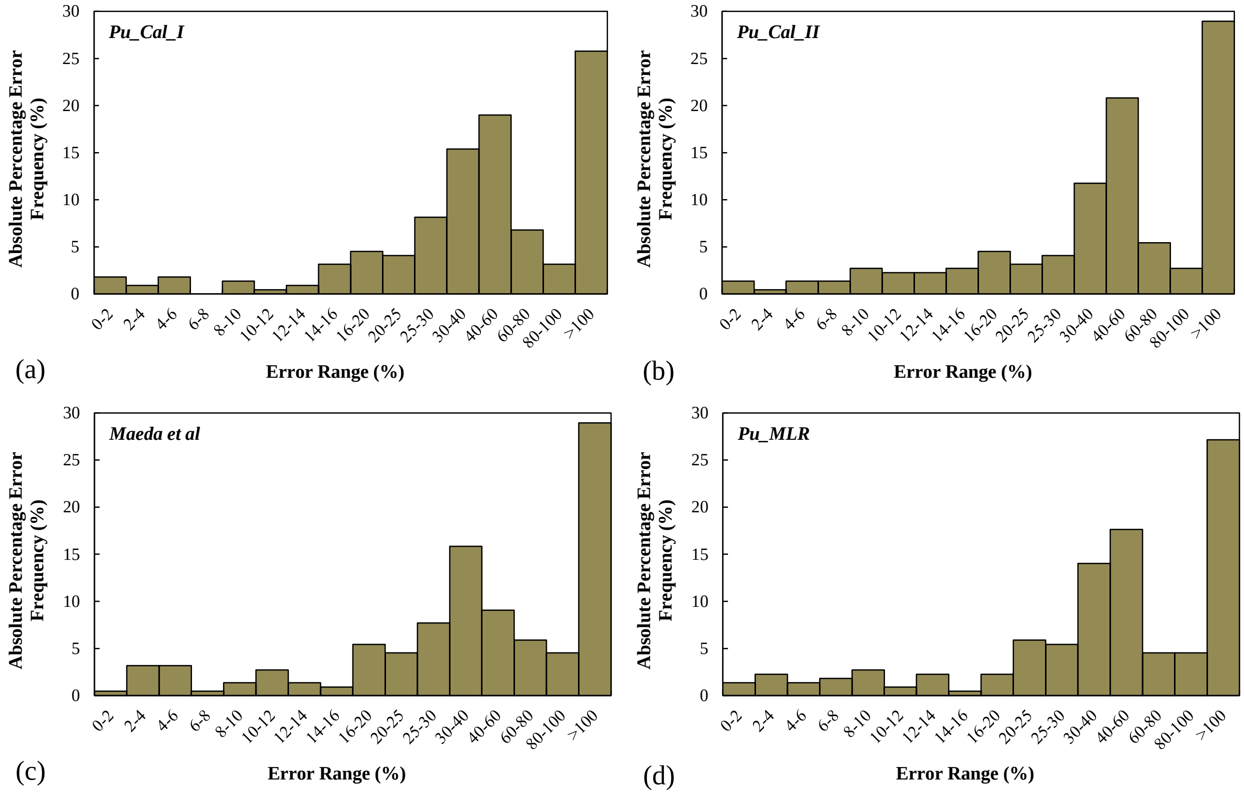

Fig. 5. The histogram of absolute percentage error frequency in different TRM-concrete bond strength models.

- 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 (P_{u_MLR}) was not successful to outperform the existing Maeda et al. model. The obtained R and NMAE values for P_{u_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.

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