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Model for the assessment of bond in corroded steel ribbed bars

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ABSTRACT

The aim of the present paper is to further validate a model proposed for assessing bond strength in corroded and non-corroded steel bars. The model was obtained by applying multiple linear regression analysis to an initial database obtained from literature containing over 650 bond tests: 372 with corroded steel bars. In this paper, a second stage for further validating the model has been conducted with new database consisting of 131 new tests of bond with corroded steel bars resulting in a final database of 500 tests of bond with corroded reinforcing steel bars.

In this model, bond strength is considered as an average stress on the nominal surface of a straight length of a bar over the bond length. The corrosion effect is considered using the cross-section loss (% Cor) considered as uniform corrosion along the bonded length of the bar. In addition to the cross-section loss, corrosion effect in bond is additionally considered with an additional variable that implicitly includes the effect of cracking depending on the range of cross section loss, bond condition and presence of transverse reinforcement.

In the paper, the former formulation proposed in [1] is compared with the formulation adapted with rounded coefficients for the former database, the new database and the combined database with different statistical criteria to compare the accuracy of the bond strength predictions obtained with the model.

Finally, the predictions of the model show a good fitting with the experimental results with the new database and also have a low scatter. This is showing its utility in the safety assessment of bond strength in reinforced concrete members.

1 INTRODUCTION

Corrosion may affect the bond between reinforcing steel bars and concrete and hence the transfer of longitudinal stresses. Since the potential outcome of bond loss could be brittle structural behaviour, the verification of bond strength has a paramount importance in the assessment of corrosion-damaged existing structures [2].

The relevance of this topic has motivated an intense research in this field. The factors affecting bond behaviour due to corrosion include the weakening of concrete confinement due to concrete cover cracking and stirrup corrosion, the presence of corrosion products at the interface and, in ribbed bars, reduction of the bond index due to cross-sectional loss in the reinforcing steel bars [1].

However, the findings reported in the studies conducted on bond strength in corroded steel ([3-5]) diverge rather widely, due to differing corrosion procedures, test specimens and variables analysed and therefore proposed models are not always useful for prediction.

Although in [1] was presented a model that was robustly validated in this paper the aim is to further validate this model with an extended database that not used to derive the model.

2 MODEL AND DATABASES

2.1 Multiple linear regression model

The model proposed here was based on the influencing variables that affect bond behaviour in corroded and non-corroded steel bars and was obtained with multiple linear regression. A detailed explanation of the influencing variables used to defined the model can be found in [1] a also in [6, 7] can be found an extensive literature survey on bond.

The response variable used in the multiple regression model is average or uniform bond strength, $f_{b,0}$, obtained dividing the bar force of the bond tests by the bar surface along the anchorage length, divided by a function of concrete compressive strength, $f_c^{2/3}$. A detailed explanation on the multiple linear regression model can be found in [1]. In this paper, the formulation from [1] used to assess bond strength in corroded and non-corroded steel bars was modified using rounded for the variable *m* and adjusted coefficients for all the exponents of the different variables of the model:

$$f_b = f_c^{0.65}\left(m\left(\frac{1}{\phi^2}+1\right)^9\left(\left(\frac{\phi}{l_b}\right)^2+1\right)^{8.1} e^{-0.12\frac{f_c}{40}}\left(\left(\frac{a}{\phi}\right)^4+1\right)^{0.06}(K_{tr}^2+K_{tr}+1)^{0.5}(\%\,Cor^2+1)^{-0.02}-1\right) \tag{1}$$

The variable *m* of Equation (1) includes variables that takes into account the following aspects regarding to bond strength: Bond condition (good or any other), Confinement (none or stirrups) and Corrosion category (No corrosion, $0 < \%\text{ Cor} \leq 5\%$, $5 < \%\text{ Cor} \leq 20\%$)

Table 1: Rounded values for variable m by bond condition, confinement and corrosion [1]

	Good bond conditions		*All other bond conditions*	
	No confinement	*Confinement*	*No confinement*	*Confinement*
No Corrosion	1.27	1.32	1.24	1.28
0 < % Cor ≤ 5 %	1.24	1.29	1.21	1.25
5 < % Cor ≤ 20 %	1.22	1.27	1.19	1.23

2.2 Databases

The multiple linear regression model was obtained with a database of more than 650 bond tests (372 of them with corroded steel bars). The corroded bond tests were collected after ruling out bond tests with corrosion current densities of over 200 μA/cm^2 and corrosion cross-section losses of more than 20 %. Table 2 gives the range of values for some of the database variables analysed in the former study [1].

Table 2: Range of values of the former database variables for corroded steel bars [1]

	ϕ (mm)	f_c (N/mm^2)	l_b (mm)	l_b/ϕ	c (mm)	c/ϕ	a/ϕ	% Cor	K_{tr}
Min	10.0	18.6	129.0	10.5	12.0	1.0	1.5	0.15	0.0
Max	24.91	57.3	304.0	25.0	48.0	3.42	3.92	19.74	0.13
Mean	15.39	44.03	226.3	14.81	27.95	1.86	2.36	5.59	-

Models may be reliably validated by verifying its outcome with a sample independent of the data used to build it [8]. Normally, this procedure is not an option due to scarcity of available data.

After performing a reliable validation of the model for non-corroded and corroded bars in [1], in this study the model for bond in corroded steel bars wanted to be validated with new tests and therefore an additional database of bond test with corroded steel was collected with more than 250 tests. After ruling out the tests with corrosion current densities of over 200 μA/cm^2 and corrosion cross-section losses of more than 20 % the final bond database with corroded steel bars was formed with 131 bond tests. Table 3 gives the range of values for some of the database variables analysed in this study [1].

Table 3: Range of values for the extended database variables

	ϕ (mm)	f_c (N/mm^2)	l_b (mm)	l_b/ϕ	c (mm)	c/ϕ	a/ϕ	% Cor	K_{tr}
Min	10.0	20.0	50.0	5.0	16.0	1.33	1.83	0.10	0.0
Max	20.0	45.88	200.0	15.50	69.0	5.75	6.25	19.70	0.19
Mean	15.5	32.89	107.75	7.13	52.97	3.64	4.14	8.13	-

3 COMPARISON

3.1 M2010 model

In this study the comparison will be done against the MC2010 [9] model. In MC2010 [9], no explicit formulation is given for assessing bond capacity for corroded steel. Rather, bond strength in corroded steel is classified by bar type (ribbed or plain) and confinement (with or without). Table 4 is provided giving the percentage of the residual basic bond strength, f_{bd}, for sound steel depending on corrosion penetration, P_x, or the equivalent surface crack.

Table 4: Residual bond capacity for corroded steel in MC2010 [9],

Corrosion penetration, P_x [mm]	Equivalent surface crack [mm]	Confinement	Residual capacity (% of f_b)			
			Bar type			
			Ribbed		Plain	
			upper	lower	upper	lower
0.05	0.20 – 0.40	No stirrups	70	50	90	70
0.10	0.40 – 0.80		50	40	60	50
0.25	1.00 – 2.00		40	25	40	30
0.05	0.20 – 0.40	Stirrups	100	95	100	95
0.10	0.40 – 0.80		80	70	100	95
0.25	1.00 – 2.00		75	60	100	90

For obtaining f_b, first is needed to obtain the reinforcement stress with the following equation [9]:

$$f_{stm} = 54 \cdot \left(\frac{f_c}{25}\right)^{0.25} \left(\frac{25}{\phi}\right)^{0.2} \left(\frac{l_b}{\phi}\right)^{0.55} \left[\left(\frac{c_{min}}{\phi}()^{0.33}\left(\frac{c_{max}}{c_{min}}^{0.1} + k_m \cdot K_{tr}\right)\right)\right] \quad (2)$$

The bond strength, f_b, is then obtained dividing the bar force, $f_{stm}A_{s,corr}$, by $\pi\phi l_b$, the bar surface over which the reinforcement stress, f_{stm}, is developed.

The following hypotheses were also assumed to obtain bond strength predictions:

- Bond strength for corroded steel was obtained with the values in Table 4 and Equation (2) for sound steel. Equation (2) was simplified by assuming that the ratio between maximum and minimum cover, $c_{\max}/c_{\min}$, was 1.0.
- Given the mean corrosion penetration, P_x, found for the corroded steel, the percentages in Table 4 were applied to the values obtained with Equation (2). Since Table 4 gives only one P_x value, the reduction of bond strength was applied stepwise. When corrosion penetration was higher than the 0.25 mm listed in Table 4, that maximum was used. Pursuant to this procedure, upper and lower limits were calculated.

3.2 Statistical criteria

Different statistical criteria are used to compare the accuracy of the bond strength predictions obtained with the model from [1], the one with rounded coefficients proposed in this paper (1) and the upper and lower limit of MC2010 to the accuracy of the assessments.

The predicted residual sum of squares (*PRESS*) can be obtained as follows:

$$PRESS = \sum_{i=1}^{n}\left(f_{b,\exp,i} - \hat{f}_{b(i)}\right)^2 = \sum_{i=1}^{n} e_{(i)}^2 = \sum_{i=1}^{n}\left(\frac{e_i}{(1-h_{ii})}\right)^2 \quad (3)$$

where $f_{b,\exp,i}$ is the observed experimental value of bond strength, $\hat{f}_{b(i)}$ is the predicted value of the bond strength of the ith response based on all observations except the ith one, $e_{(i)}$ is the deleted residual or *PRESS* residual and h_{ii} is the weight of each observation in the regression model. Generally, a model with a small value of *PRESS* is preferable to one where *PRESS* is large [1]. Decomposing the PRESS statistic also provides good criteria for model comparisons [10], by means, for instance, of the mean squared error of prediction, *MSEP*:

$$MSEP = \frac{1}{n}\sum_{i=1}^{n} e_{(i)}^{2} \tag{4}$$

The predictive residual mean, *PRM*, can be obtained as follows:

$$PRM = \overline{f}_{b,\exp} - \overline{\hat{f}}_{b(i)} \tag{5}$$

The different variance of predicted residuals, DVPR, can be obtained as follows:

$$DVPR = s_{f_{b,\exp}} - s_{\hat{f}_{b(i)}} \tag{6}$$

DVPR provides information on the orthogonal regression line.

Another criterion for establishing model accuracy is the *M* ratio between the experimental value and the model estimate. The m_i ratio for the i^{th} observation is obtained by dividing the experimental value, $f_{b,\exp}$, by the predicted value, $f_{b(i)}$:

$$m_i = f_{b,exp}/f_{b(i)} \tag{7}$$

3.3 Model results

Table 5, Table 6 and Table 7 provide all the statistical values for the model from [1], the model of Equation 1 and the MC2010 model for the upper and lower bound for the database used in [1], the extended database collected for this study and the combined database.

Table 5: Summary of statistical parameters for bond tests with corroded bars evaluated for the different models for the database provided in [1]

Model	*n*	*PRESS*	*MSEP*	*PRM*	*DVPR*	*ICPR*	*Cut-off point*	μ_M	s_M	*CoV*
Model from [1]	372	512.68	1.38	0.034	0.43	1.09	4.74	1.00	0.27	0.27
Model Eq. (1)		516.67	1.39	-0.0007	0.38	1.11	4.88	0.99	0.27	0.27
Upper limit Eq. (2) MC2010 [9]		1599.52	4.30	-0.56	-1.06	1.67	4.07	1.02	0.47	0.46
Lower limit Eq. (2) MC2010 [9]		1456.08	3.91	0.620	-0.75	1.67	6.11	1.43	0.80	0.56

For the former database the results were discussed in detail in [1]. The only thing that is worth mentioning is that the statistical values obtained with Equation (1) with the rounded coefficients proposed here are almost similar to the ones obtained in [1]. The *PRM* statistic, giving the systematic error of the model is changing its sign but can be assumed as almost zero.

Table 6: Summary of statistical parameters for bond tests with corroded bars evaluated for the different models for the database collected in this study

Model	*n*	*PRESS*	*MSEP*	*PRM*	*DVPR*	*ICPR*	*Cut-off point*	μ_M	s_M	*CoV*
Model Equation (1) New database	131	2224.77	16.98	0.080	1.99	3.61	9.88	1.00	0.47	0.47
Upper limit Eq. (2) MC2010 [9] New database		7709.19	58.85	3.384	2.02	6.58	10.59	1.86	1.37	0.74
Lower limit Eq. (2) MC2010 [9] New database		9663.26	73.77	5.199	2.33	6.43	11.01	2.92	2.34	0.80

In Table 6 can be seen according to the *M* ratio that the model of Equation (1) gives a good prediction for bond strength in corroded steel, with a mean value of 1.0, similar to the prediction given in the former database. In the new database the difference is that the CoV is almost double than the CoV obtained with the former database. The results provided in Table 6 show that the upper limit given in MC2010 [9] has the second best behaviour with respect to the *M* ratio, although with a high conservative bias and a CoV that nearly doubles the CoV of the proposed model (1). The lower limit of MC2010 proves to be overly conservative. For the new database by far the lowest value for the *PRESS* statistic was found for the model proposed (1). The *PRM* statistic showed that the results for the model proposed (1) were on the safe side on average, exhibiting the lowest positive value.

Table 7: Summary of statistical parameters for bond tests with corroded bars evaluated for the different models for the combined database

Model	*n*	*PRESS*	*MSEP*	*PRM*	*DVPR*	*ICPR*	*Cut-off point*	μ_M	s_M	*CoV*
Model Eq. (1) Combined databases	503	2695.40	5.36	0.022	0.81	2.17	6.17	1.00	0.33	0.34
Upper limit Eq. (2) MC2010 [9] Combined databases		8974.63	17.84	0.694	1.08	4.02	5.05	1.28	0.86	0.68
Lower limit Eq. (2) MC2010 [9] Combined databases		11050.8	21.97	1.981	1.40	4.01	3.59	1.86	1.47	0.79

In Table 7 can be seen according to the *M* ratio that the model of Equation (1) gives a good prediction for bond strength in corroded steel, with a mean value of 1.0, similar to the predictions given in the former database and in the extended database. In the combined database the CoV is almost similar to the one obtained with the former database. The results provided in Table 7 show similar behaviour for the upper limit of MC2010 [9] and lower limit as observed in Table 6. Both predictions are overly conservative and with a high bias. For the combined database by far the lowest value for the *PRESS* statistic was found for the model proposed (1).

Figures 1a, 1b, 1c show the experimental bond strength for corroded steel bars versus the values predicted with the proposed formulation (1), the upper and lower limits obtained given in MC2010 [9] respectively.

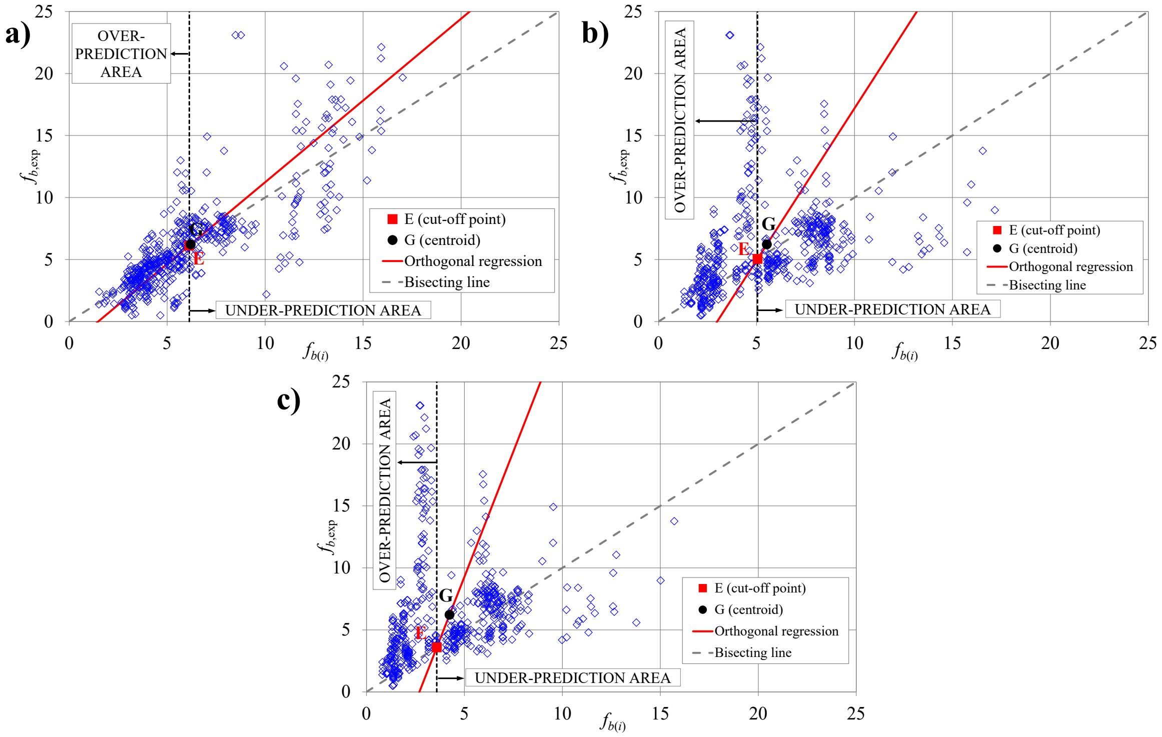

Figure 1: a) Experimental vs. predicted bond strength in corroded steel bars of the proposed formulation (1); b) Experimental vs. predicted bond strength in corroded steel bars of the Upper Limit given in MC2010 [9]; c) Experimental vs. predicted bond strength in corroded steel bars of the Lower Limit given in MC2010 [9]

The cut-off point (point E in Figure 1) is equal to 6.17 in the formulation proposed (1) for corroded steel bars for the whole database (Table 7) meaning that when predicting new values for mean bond strength with the proposed model from this value the mean bond strength predictions will be on the safe side. On the other hand, in the upper and lower given in MC2010 [9] the cut-off point is equal to 5.05 and 3.59 respectively. In this case, on the contrary that was observed in [1] the slope of the orthogonal regression line is not lower than 45 degrees and the predictions from these values will be on the safe side.

Further to the statistical parameters analysed, the model proposed here with Equation (1) shows its robustness giving reasonably good assessments of bond strength with a completely new database.

4 CONCLUSION

The present paper has shown that the formulation for the assessment of bond strength with corroded steel bars proposed in [1] and adjusted in this paper is robust and provides reasonable estimates for bond strength. The new bond test database collected in this study covers a wide range of variables affecting bond strength, such as bar diameter, concrete strength, concrete cover, anchorage length, confinement ratio and corrosion-induced cross-sectional loss as the bond database used in [1] to derive the model. In addition, a number of relevant statistical criteria were used to validate the adjusted model (1) and compare it to MC2010 [9]. In that context, the results obtained by the model proposed are reasonably good in terms of all the statistical criteria analysed for the former database, for the new database and for the combined database. The prediction of the adjusted model fits better with the experimental results and have less scatter than the MC2010 upper and lower bound model for the assessment of bond strength in corroded steel bars. This provides a good indication of its utility for predicting in a safe way bond strength in corrosion-damaged reinforced concrete members.

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