Bond assessment of corroded steel bars in structural concrete

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Summary

The present paper proposes a semi-empirical formulation accounting for both pull-out and splitting failures for assessing bond of corroded and non-corroded steel bars. This formulation is obtained by means of multiple linear regression analysis of a database of more than 650 tests of corroded and non-corroded bond tests, including tests performed in a former study [1] and data from literature. The database used includes a wide range of influencing variables regarding to bond, such as bar diameter, concrete strength, concrete cover, anchorage length, confinement ratio and cross-section loss due to corrosion. Several statistical criteria have been used to analyse the proposed formulation and the influence of the explanatory variables. Also a comparison with several formulations, including the proposal of Fib Model Code 2010 for corroded bars is performed. This formulation could be used in the structural assessment of corroded reinforced concrete members.

Keywords: Reinforced concrete, corrosion, Bond, pull-out, splitting, multiple linear regression, assessment of existing structures.

1. Introduction

Corrosion can affect the bond between reinforcing bars and concrete and hence the transfer of longitudinal stresses. Loss of bond normally leads to a potentially brittle type of structural behaviour thus it should be analysed within the framework of the assessment of deteriorated structures to avoid it.

Factors affecting bond behaviour include the weakening of concrete confinement due to cracking of concrete cover and/or corrosion of stirrups, development of corrosion products at the interface and in ribbed bars reduction of the bond index due to cross section loss of steel. In recent years a number of relevant studies have been conducted on bond with corroded steel (e.g. [2], [3], [4]), the findings have diverged rather widely, due primarily to differing test conditions.

In an attempt to address the inconsistencies in the prediction of bond with corroded steel, in a former study eccentric pull-out tests were conducted on specimens subjected to accelerated or natural corrosion as described in [1]. In this study a unified approach for the assessment of bond behaviour of corroded and non-corroded steel bars with a semi-empirical formulation accounting for both pull-out and splitting failures is proposed. The formulation is obtained with a multiple linear regression analysis.

2. Multiple linear regression model for bond assessment of corroded and non-corroded steel bars

2.1 Introduction

Initially to obtain the formulation for bond assessment 849 bond tests with corroded and non-corroded steel bars were collected from scientific literature (references [2], [3], [4] and from [7] to [19], among others). Natural corrosion processes need a long time to develop, therefore a galvanostatic method is normally used in bond tests to accelerate the process. This procedure applies a constant current density in the steel.

In this study only bond tests with corroded steel bars obtained with corrosion rates below or equal to $200 \mu\text{A}/\text{cm}^2$ have been analysed. Higher corrosion rates may yield bond strengths which are not

representative of field conditions. This intensity criteria was obtained taking into account that the maximum corrosion rate measured in highly chloride contaminated members was between 100 $\mu\text{A}/\text{cm}^2$ and 200 $\mu\text{A}/\text{cm}^2$ [5] and also that for the same degree of corrosion current densities higher than 200 $\mu\text{A}/\text{cm}^2$ yield to a significant increase in the strain response and crack width [6] compared to the ones produced with lower intensities closer to natural corrosion intensities.

Moreover, once bond tests with higher corrosion intensity than the maxima were discarded, only 4 bond tests of the database had cross section losses higher than 20% so for the equilibrium of the database these tests were also discarded. Finally, the database analysed comprised 666 bond tests (references [2], [3], [4] and from [7] to [19]) including all the bond tests performed in the former study [1] with the exception of the bond test with lateral pressure because of lack of enough data. The bond test database is classified as follows: 172 bond tests with sound steel bars and no confinement, 122 bond tests with sound steel bars and confinement by transverse reinforcement, 165 bond tests with corroded steel bars and no confinement and 207 bond tests with corroded steel bars and confinement by transverse reinforcement.

Type of bond tests of the database: 66 beam tests, 75 Pull-out tests, 501 eccentric pull-out tests (similar to the one performed in the previous study [1]) and other 24 bond tests with other configurations.

Regarding bond conditions, they may be classified as good in 498 tests while 168 bond tests belong to any of the other bond conditions according to Model Code 2010 [20] (hereafter “MC2010”) provisions. Regarding to the ratio of the embedment length and bar diameter, l_b/ϕ , 583 bond tests are of the so called “long anchorage” lengths, $l_b/\phi \geq 10$. Although the ratios $l_b/\phi < 10$ are not acceptable in design, they are considered in the analysis here because the model aims to be used in the assessment of existing structures where the minimum value is often not attained. Table 1 gives the range of values of some of the representative variables of the bond database used in this study.

Table 1: Range of values of some of the representative variables of the bond database used

	ϕ	f_{cm}	l_b (mm)	l_b/ϕ	c (mm)	c/ϕ	a/ϕ	% Corr	K_{tr}
Min	9,53	16,41	40	3,57	0,00	0,00	0,50	0,00	0,00
Max	34,93	57,30	1117,60	40,0	139,70	10,50	10,00	19,74	0,196
Mean	15,82	41,14	226,34	14,21	30,62	1,96	2,52	-	-

2.2 Variables

The response variable used in the multiple regression model is the uniform bond strength normalized with a function of the concrete compressive strength, $\tau/f_{cm}^{2/3}$. Two additional models were analysed, one based on the normalized steel force and the other based on the steel stress following the formulation of MC2010 [20] that will not be addressed in this paper. The explanatory variables used in the model are based in the different variables detected in previous studies of bond with corroded steel and can be addressed in the following way:

- Categorical variable or dummy considering bond conditions, respectively good or any of the other bond conditions, POS.
- Categorical variable or dummy considering type of confinement, no confinement or confinement by transverse reinforcement, CONF.
- Categorical variable or dummy that takes into account whether there is corrosion or not and also the categories of deterioration, N1_COR and N2_COR.
- Continuous variable considering bar size effect, $\text{Ln}(1/\phi^2 + 1)$.
- Continuous variable considering the effect of the embedment length, $\text{Ln}((\phi/l_b)^2 + 1)$.
- Continuous variable considering the effect of concrete brittleness with increasing concrete strength, $f_{cm}/40$.
- Continuous variable considering the effect of concrete confinement, $\text{Ln}((a/\phi)^4 + 1)$ with

$a = c + \phi/2$ being a the thickness of the concrete tension ring and c the concrete cover.

- Continuous variable considering the effect of confinement due to stirrups, $\text{Ln} (K_{tr}^2 + K_{tr} + 1)$ with $K_{tr} = n_l A_{st} / n_b \phi s_t$ being n_l the number of legs of confining reinforcement crossing a potential splitting failure, A_{st} cross sectional area of one leg of a confining bar, n_b number of anchored bars and s_t longitudinal spacing of confining reinforcement.
- Continuous variable considering the effect of corrosion degradation of the concrete and stirrup confinement, $\text{Ln} ((\% \text{ Cor})^2 + 1)$ with $\% \text{ Cor} = (W_{\text{sound}} - W_{\text{corroded}}) / W_{\text{sound}} \cdot 100$ being W_{sound} the weight of sound steel and W_{corroded} the weight of corroded steel.

Statistical analyses of the multiple linear regression model were performed with the statistical software IBM SPSS Statistics 21 [21]. A more detailed explanation of the multiple linear regression analysis performed is given in [24].

2.3 Formulation proposed

The semi-empirical formulation proposed to assess bond strength for corroded and non-corroded steel bars accounting for both pull-out and splitting failures is:

$$\tau = f_{cm}^{2/3} \left(m \left(\frac{1}{\phi^2} + 1 \right)^{9.052} \left(\left(\frac{\phi}{l_b} \right)^2 + 1 \right)^{8.13} e^{-0.129 \frac{f_{cm}}{40}} \left(\left(\frac{a}{\phi} \right)^4 + 1 \right)^{0.058} (K_{tr}^2 + K_{tr} + 1)^{0.498} (\% \text{ Cor}^2 + 1)^{-0.016} - 1 \right) \quad (1)$$

The variable m includes the dummy variables POS, CONF and N1_COR and N2_COR and takes

Table 2: Values for m depending on bond conditions, confinement and corrosion

	Good bond conditions		All other bond cond.	
	No Conf.	Conf.	No Conf.	Conf.
No corrosion	1,275	1,324	1,235	1,283
$0 < \% \text{ Cor} \leq 5\%$	1,245	1,293	1,206	1,253
$5\% < \% \text{ Cor} \leq 20\%$	1,225	1,272	1,187	1,233

into account the following aspects regarding to bond, see Table 2:

– Bond conditions (good and all other bond conditions).

– Confinement (no confinement and confinement with stirrups).

– Corrosion categories (no corrosion, $0 < \% \text{ Cor} \leq 5\%$, $5 < \% \text{ Cor} \leq 20\%$).

It is important to highlight that $\% \text{ Cor}$ is equivalent to cross section percentage loss, thus $\% \text{ Cor}$ can be obtained from cross section loss without needing to weight Steel bars before and after the corrosion process.

3. Comparisons

3.1 Introduction

The comparison with different statistical criteria of the proposed model (1) and the models from Contecvet [25] and MC2010 [20] was performed between experimental and estimated bond strength of each one of the models. This comparison allows the assessment of the accuracy of the models to predict bond strength. This comparison allows the assessment of the accuracy of the models to predict bond strength.

3.2 Statistical criteria

One of the statistical criteria that has been chosen is the predicted residual sum of squares, *PRESS* statistic, as this allows analysing and measuring the fit of the data to the models in a consistent way [22]. The external or predicted residuals, $e_i(i)$, are the prediction error of an observation not included in the sample. The assessment of $e_i(i)$ is equivalent to calculating the external predictive value, $\tau_{\text{est},i(i)}$, without the use of the i^{th} observation. The predicted residual for the i^{th} observation is defined as follows:

$$e_{i(i)} = \tau_{\text{exp},i} - \tau_{\text{est},i(i)} = e_i / (1 - h_{ii}) \quad ; \quad h_{ii} = 1/n - (x_i - \bar{x})^2 / S_{xx} \quad (2)$$

Being h_{ii} the weight of each one of the observations in the regression model. Together with the expressions of (2) the external predictive value, $\tau_{\text{est},i(i)}$, can be obtained [22]:

$$\tau_{\text{est},i(i)} = \tau_{\text{exp},i} - e_i / 1 - h_{ii} = \tau_{\text{exp},i} - (\tau_{\text{exp},i} - \tau_{\text{mod},i}) / (1 - h_{ii}) = (\tau_{\text{mod},i} - h_{ii} \tau_{\text{exp},i}) / (1 - h_{ii}) \quad (3)$$

Finally, *PRESS* statistic is the sum of the squared external residuals:

$$PRESS = \sum e_{i(i)}^2 = \sum (e_i / 1 - h_{ii})^2 \quad (4)$$

The behaviour of the model is better when the *PRESS* statistic is lower. The decomposition of the *PRESS* statistic gives also good criteria for model comparisons [22]. That is the case of the mean squared predictive error, *MSEP*,

$$MSEP = 1/n \sum e_{i(i)}^2 \quad (5)$$

The predictive residual mean, *PRM*, is the estimation of the systematic error of the prediction of the model and is related to the centroid of the scatter plot.

$$PRM = \bar{\tau}_{\text{exp}} - \bar{\tau}_{\text{est}(i)} \quad (6)$$

The different variance of predicted residuals, *DVPR*, gives information about the orthogonal regression line which minimizes the square sum of the Euclidean distances to the regression line [22]. Positive values of *DVPR* indicate that the experimental variance is higher than the variance of the model predictions.

$$DVPR = s_{\tau_{\text{exp}}} - s_{\tau_{\text{est}(i)}} \quad (7)$$

The incomplete correlation predictive residual, *ICPR*, gives information about the dispersion in each side of the orthogonal regression line.

$$ICPR = \sqrt{2(1-r)} s_{\tau_{\text{exp}}} s_{\tau_{\text{est}(i)}} \quad (8)$$

The orthogonal regression line and its slope can be obtained with the following expressions [22]:

$$\tan(\theta) = \left(\frac{s_{\tau_{\text{exp}}}^2 - s_{\tau_{\text{est}(i)}}^2}{2rs_{\tau_{\text{exp}}} s_{\tau_{\text{est}(i)}}} \right) \pm \sqrt{\left(\frac{s_{\tau_{\text{exp}}}^2 - s_{\tau_{\text{est}(i)}}^2}{2rs_{\tau_{\text{exp}}} s_{\tau_{\text{est}(i)}}} \right)^2 + 1} \quad (9)$$

$$\tau_{\text{exp}} - \bar{\tau}_{\text{exp}} = \tan(\theta) (\tau_{\text{est}(i)} - \bar{\tau}_{\text{est}(i)}) \quad (10)$$

The cut-off point of the orthogonal regression line with the bisecting line of the first quadrant of the experimental-predicted diagram gives information about the zones where the model, on average, is safe or unsafe.

Another criteria to establish the accuracy of the model is obtained with the *M* ratio between the experimental value and the model estimation. For the *i*th observation the *m_i* ratio is obtained dividing the experimental value, $\tau_{\text{exp},i}$, with the predictive value, $\tau_{\text{est},i(i)}$.

$$m_i = \tau_{\text{exp},i} / \tau_{\text{est},i(i)} \quad (11)$$

3.3 Models from literature

In Contecvet manual [25] there is a proposal for the assessment of bond with corroded steel based on the work of Rodriguez et al. [9]. An extensive experimental campaign was undertaken and 3 formulations were proposed, one for corroded steel without confinement, other for corroded steel with confinement by transverse reinforcement and finally one for the assessment of bond with lateral pressure that will not be addressed in this study. The following expressions are used for the assessment of the mean value of bond with corroded steel without confinement and with confinement respectively:

$$\tau_b = 3,00 - 4,76P_x \quad (12)$$

$$\tau_b = 5,25 - 2,72P_x \quad (13)$$

Being P_x the mean corrosion penetration [mm].

In MC2010 [20] no explicit formulation is given for the assessment of bond with corroded steel, bond strength with corroded steel is classified according to bar type (ribbed or plain) and type of

confinement (with or without) and a table is given with the percentage related to the residual basic bond strength, f_{bd} , of a sound Steel depending on the corrosion penetration, P_x , or the equivalent surface crack.

Table 3: Residual bond capacity for corroded steel in MC2010 [20]

Corrosion penetration [mm]	Equivalent Surface crack [mm]	Confinement	Residual capacity (% of f_{bd})			
			Bar type		upper	lower
			Ribbed	Plain		
			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

The basic bond strength in MC2010 [20] is:

$$f_{bd} = \eta_1 \eta_2 \eta_3 \eta_4 (f_{cm}/25)^{0,5} \quad (14)$$

Being η_1 , η_2 , η_3 and η_4 coefficients accounting for, respectively, bar type, bond conditions, bar diameter and characteristic yield strength of the bar.

Expression (14) has been derived from the following general expression of MC2010 [20]:

$$f_{stm} = 54 \cdot (f_{cm}/25)^{0,25} (25/\phi)^{0,2} (l_b/\phi)^{0,55} \left[(c_{min}/\phi)^{0,33} (c_{max}/c_{min})^{0,1} + 12 \cdot K_{tr} \right] \quad (15)$$

The following criteria [20] have been used to derive expression (14) from (15): characteristic instead of mean bond strength has been considered, in (15) minimum concrete cover and detailing has been used and indexes and coefficients have been rounded appropriately.

The statistical criteria of section 3.2 are used to evaluate expressions (14) and (15) given in MC2010 [20]. The following hypotheses are also used:

- Bond strength for corroded steel is obtained with expressions (14) and (15) for sound steel together with the values of Table 3. For simplicity in expression (16) the ratio between maximum and minimum cover, c_{max}/c_{min} , is taken equal to 1,0.
- Considering the mean corrosion penetration, P_x , of the bond tests with corroded steel the percentages of Table 3 are applied to the values obtained with expressions (14) and (15). Table 2 gives only a value of P_x , thus the reduction of bond strength is applied stepwise. When corrosion penetration is higher than the maxima of Table 3, the maximum is assigned. Following this procedure an upper and lower limit is obtained for expressions (14) and (15).

3.4 Statistical validation and comparisons

A rigorous procedure of model validation is to verify the results of the model with an independent sample of the data used to build it [23]. Normally is difficult to conduct this procedure due to the lack of available data that are used for building the model. Thus, an alternative robust procedure to validate the models is to choose a random sample of the observations used to build the model. In this study, two different samples were used, one with bond tests with corroded steel and the other with bond tests with sound steel. One of the tests was taken out for the comparison because it could not be evaluated with the expression (15) given in MC2010 [20] because concrete cover was zero.

293 bond tests with sound steel have been analysed. The comparison was performed between the proposed formulation and the expression given in MC2010 [20]. The summary of the statistics of

Table 4: Summary of statistical parameters for bond tests with sound bars evaluated according to models (1) & (15)

	Model proposed (1)	Model MC2010 [20] (15)
n	293	
$PRESS$	1308,18	4522,56
$MSEP$	4,47	15,44
PRM	0,11	-0,33
$DVPR$	0,37	1,67
$ICPR$	2,08	3,54
Cut-off point	6,99	9,14
μ_M	1,02	0,97
s_M	0,21	0,38
CoV	0,21	0,40

the models is given in Table 4. According to $PRESS$ statistic, the model proposed in this study shows a better behaviour than the MC2010 [20] model for sound bars. The mean squared predictive error, $MSEP$, is nearly 4 times higher in MC2010 [20] model than in the proposed model (1). According to the systematic error of the prediction, PRM statistic, the model proposed (1) is on average on the safe side whereas MC2010 [20] model with a negative value, on average over predicts bond strength. Also in Table 4 the summary of the parameters of the M ratio of both models is given. The model proposed slightly underestimates experimental bond strength whereas MC2010 [20] slightly overestimates it. The model proposed (1) for sound bars

shows a relatively low COV given the large number of influencing variables of bond tests.

372 bond tests with corroded steel have been also analysed. The comparison was performed between the proposed formulation, Contecvet model [25] and upper and lower limit with expressions (14) and (15) of MC2010 [20]. The summary of the statistical parameters of the models is shown in Table 5.

Table 5: Summary of statistical parameters for bond tests with corroded steel of the proposed model, Contecvet model [25] and MC2010 model with expressions (14) and (15)

Model	n	$PRESS$	$MSEP$	PRM	$DVPR$	$ICPR$	Cut-off point	μ_M	s_M	CoV
Model proposed (1)	372	512,68	1,38	0,034	0,43	1,09	4,74	1,00	0,27	0,27
Contecvet (12)(13)		1808,66	4,86	1,38	0,47	1,55	0,79	2,38	14,90	6,27
MC2010 [21] Upper limit (14)		5849,40	15,72	3,56	1,51	0,68	0,36	3,86	1,79	0,46
MC2010 [21] Lower limit (14)		6731,21	18,10	3,87	1,54	0,68	0,07	5,34	3,11	0,58
MC2010 [21] Upper limit (15)		1599,52	4,30	-0,56	-1,06	1,67	4,07	1,02	0,47	0,46
MC2010 [21] Lower limit (15)		1456,08	3,91	0,620	-0,75	1,67	6,11	1,43	0,80	0,56

According to $PRESS$ statistic the model proposed (1) for bond with corroded steel shows the best behaviour, lowest value, by far with respect to the models compared, followed by the lower and upper limit of MC2010 [20] with expression (15) respectively. The mean squared predictive error, $MSEP$, shows also the best behaviour for the proposed model (1) followed by the lower and upper limit of MC2010 [20] with expression (15) respectively and Contecvet model [25]. The model proposed (1) is on average on the safe side with the lower value of PRM statistic followed by the lower limit of MC2010 [20] with expression (15) and Contecvet model [25]. The upper limit of MC2010 [20] with expression (15) has a negative value of PRM statistic showing that on average the model overestimates bond strength.

According to the statistical parameters of the M ratio the proposed model (1) with a mean value of 1,0 denoted a good estimation of bond with corroded steel. As for sound bars, the proposed model (1) shows a relatively low coefficient of variation given the widely scatter of bond phenomena. The upper limit of MC2010 [20] with expression (15) is the next model that gives the better behaviour according to the M ratio although it shows a slightly conservative bias and a CoV that nearly doubles the one of the proposed model (1). All the other models are overly conservative, being the upper and lower limit of MC2010 [20] with expression (14) the most conservative models.

Figure 1 shows the experimental versus predicted diagrams of the proposed model (2), Contecvet model [25] and upper and lower limit of MC2010 [20] with expression (15) for bond tests with corroded steel.

Fig. 1: Experimental vs. predicted bond strength of corroded steel bars: a) proposed formulation; b) Contecvet model [25]; c) and d) upper and lower limit of MC2010 [20] with expression (15)

Considering all the statistical parameters analysed for both sound and corroded steel bars the model proposed shows a reasonably good behaviour for the assessment of bond with sound and corroded steel bars.

4. Conclusions

The present study introduces a semi-empirical formulation for the assessment of bond with sound and corroded steel bars. The formulation proposed has been obtained with a multiple linear regression model of a database that comprises more than 650 bond tests with sound and corroded steel bars including the bond tests performed in a former study [1] and data from literature. The database used includes a wide range of influencing variables regarding bond, such as bar diameter, concrete strength, concrete cover, anchorage length, confinement ratio and cross-section loss due to corrosion.

Different statistical criteria have been used for validation of the model proposed and also for comparison with other models for the assessment of bond with corroded steel, such as those from Contecvet [25] and MC2010 [20]. In comparison with the other models analysed, the model proposed in this study shows a reasonably good behaviour for the assessment of bond as well in case of sound as corroded bars. Finally, the model proposed can be used in a consistent way in the safety assessment of bond of reinforced concrete members.

5. References

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