Practical Bond Model for Corroded RC Bridges

Mattias Blomfors[1, 2], Karin Lundgren[1], Oskar Larsson Ivanov[3], Dániel Honfi[4], and Kamyab Zandi[1]

[1]Division of Structural Engineering, Department of Civil and Environmental Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden
[2]CBI Swedish Cement and Concrete Research Institute, c/o SP, 501 15 Borås, Sweden
[3]Division of Structural Engineering, Lund University, 221 00 Lund, Sweden
[4]Mechanics Research, RISE Research Inst. of Sweden, 400 22 Gothenburg, Sweden

ABSTRACT

Corrosion of steel reinforcement is a common cause of deterioration in reinforced concrete bridges and many existing bridges are damaged to varying degrees. The rate of deterioration of the bridge stock has been shown to increase due to climate change. Unsympathetically, the demand for load-carrying capacity is however often increased with time. Therefore there is an increasing need for reliable methods to assess the load-carrying capacity and remaining service-life of existing infrastructure.

A simple model for the assessment of **A**nchorage in corroded **R**einforced **C**oncrete structures (ARC) has previously been developed. It was originally based on *fib* Model Code 1990 and has been verified with experiments and three-dimensional nonlinear finite element (3D NLFE) analyses for both accelerated and natural corrosion as well as for different degrees of corrosion. The model was applied when assessing two road bridges in Sweden. The investigation demonstrated great cost savings but also areas for improvement, in particular regarding (a) applicability to practical cases and (b) incorporation of uncertainties in the assessment.

The primary focal point of this paper is to present an overview of the development of the ARC model together with recent verifications against a large bond test database as well as foreseen future developments. It was found that the ARC model represents the physical behaviour reasonably well, and gives conservative values of bond strength compared to the bond tests database. In future works, among others, uncertainties of the input variables will be incorporated by means of probabilistic modelling, making way for implementation of the ARC model into semi-probabilistic safety concepts by extraction of modification factors. Overall, with more accurate and reliable assessment methods for corroded RC structures, environmental and economic savings are imminent as more of the potential of existing structures can be realized.

Keywords: bond, anchorage, reinforcement corrosion, assessment, existing structures

INTRODUCTION

Corrosion of steel reinforcement is the most common cause of deterioration in reinforced concrete bridges, Bell (2004). Many existing bridges show significant corrosion damage, from cover cracking to even cover spalling. Wang (2010) analyzed the impacts of climate change on the deterioration of concrete structures, and showed that the deterioration is expected to become even worse in the future. In addition, the demand for load-bearing capacity of bridges often increases over time. Thus, there is a growing need for reliable methods to assess the load-carrying capacity and the remaining service-life of existing infrastructure.

This has been addressed in a number of research projects; some examples on European level are Duracrete (2000), Contecvet (2001), and Sustainable Bridges (2004). Corrosion-induced cracking, spalling and the effects on bond can be modelled with detailed 3D NLFE models, see e.g. Zandi Hanjari *et al.* (2013). However, such models do not yet have any wide application in practice as 3D NLFE analyses are too time-consuming for practical application. Thus, there is a need for simple models and tools for the assessment of existing bridges with direct implication in practice. Development of such a model for the anchorage capacity of concrete structures with corroded reinforcement has been carried out at Chalmers University of Technology with a financial support of the Swedish Transport Administration since 2006. The primary focal point of this paper is to present an overview of the development of the model together with recent verifications against a large bond test database as well as future foreseen developments.

OVERVIEW OF DEVELOPMENTS OF THE MODEL

A simplified one-dimensional (1D) model for the assessment of **A**nchorage in corroded **R**einforced **C**oncrete structures has been established in Lundgren *et al.* (2012); the model is referred to as **ARC1990** model in this paper as it is based upon provisions in Model Code 1990. Major milestones throughout the development phase of the model are shown in Figure 1. The ARC1990 model was originally formulated based on the analytical bond-slip model in Model Code 1990 combined with a parametric study using 3D NLFE analyses and several experiments, see Lundgren *et al.* (2012). The model was later verified by results from test specimens with natural corrosion, Perez *et al.* (2014). Moreover, the model was validated by 3D NLFE analyses and experiments for high corrosion attacks leading to cover spalling, see Zandi (2015). The relevance of the model in a practical context has been demonstrated in a pilot study of two bridges in Stockholm, Sweden; see Nilsson *et al.* (2014a, 2014b) and Lundgren *et al.* (2014). It was shown that for these two bridges, the use of the model reduced the costs by approximately €3 million as unnecessary strengthening could be avoided. Considering that the Swedish Road Administration manages 20 000 bridges and that there are around one million bridges in EU27, of which a great portion are made of reinforced concrete and located in corrosive environments, the potential cost savings for society are enormous, if reliable assessments methods are made available to the engineering practice. The ARC1990 model has been verified against a large bond test database of corroded specimens; this is further discussed in the present paper. Furthermore, the model was reformulated to be based upon *fib* Model Code 2010 and was re-calibrated using the large bond test database, see Blomfors *et al.* (2017). Finally, the ARC1990 model has recently been adopted by *fib* commission 3 – Task Group 3.2:

“Modelling of structural performance of existing concrete structures” – to be included in a planned *fib* bulletin; this paper is therefore meant to serve as a background to the bond model to be implemented in this document.

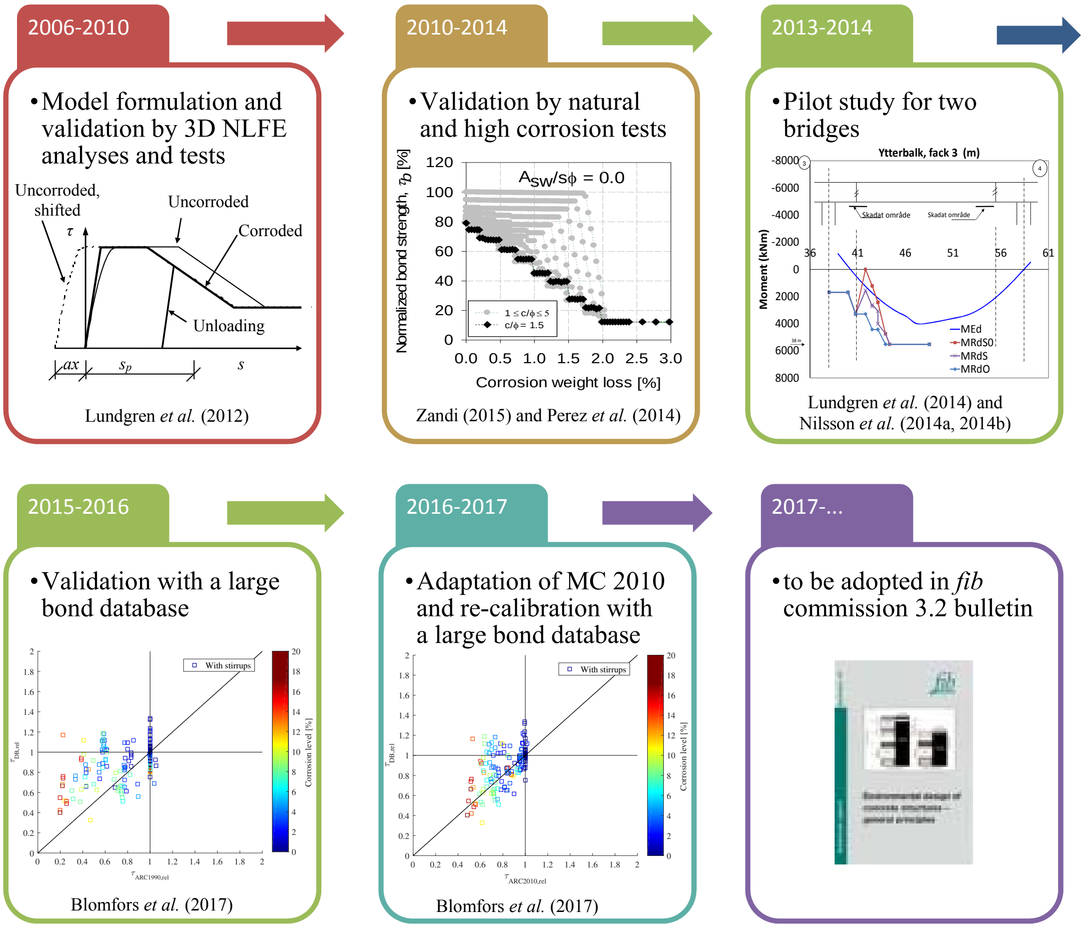

Figure 1. Overview of ARC model developments including major millstones.

FORMULATION OF BOND MODEL FOR CORRODED REINFORCEMENT

In the following, the bond-slip model is shortly presented; for details see Lundgren *et al.* (2012). The model is an extension of the bond-slip model given in the CEB-FIP Model Code 1990, CEB (1993) where parameters for the extreme cases “confined” (i.e. ductile pull-out failure) and “unconfined” (i.e. brittle failure due to cover cracking induced by the radial tensile stress) are given. Lundgren *et al.* (2012) describes a method to interpolate for intermediate cases, which often occur in practice. An interpolation factor k_{uncor} is determined by $k_{uncor} = \max\,(k_{c/d}\,,\ k_{Asw})$ where $k_{c/d}$ is a factor that depends on the cover to bar diameter ratio, and k_{Asw} is a factor that depends on the amount of transverse reinforcement A_{sw}/s according to Figure 2.

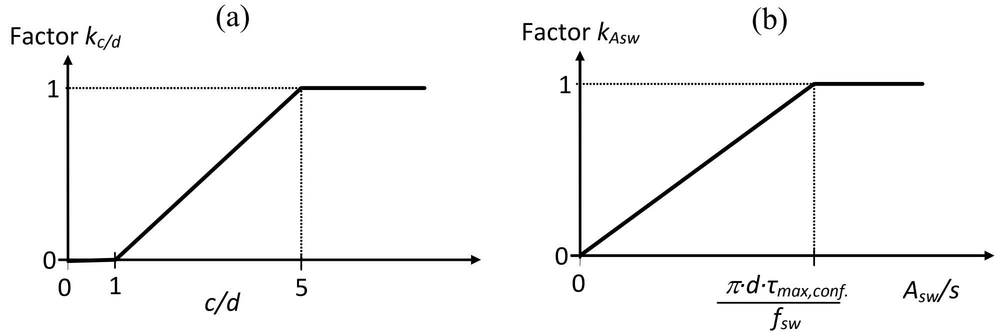

Figure 2. Factors for interpolation between "confined" and "unconfined" case.

For corroding reinforcement, the failure mode can change from pull-out to splitting failure, unless sufficient confinement is provided by efficient transverse reinforcement. This change of failure mode is here accounted for by an interpolation factor k_{cor} that depends on the ratio x/x_{cr}, where x is the actual corrosion penetration and x_{cr} is the corrosion penetration that causes cover cracking. Thus, when the cover is cracked, the remaining bond capacity depends only on the transverse reinforcement. Before the cover is cracked, the cover also contributes to the capacity. To get a numerically stable modelling, a linear decrease from the capacity including the effect of the cover to the capacity only due to the transverse reinforcement is assumed to take place from a corrosion penetration of 85% of cover cracking, see Figure 3 (a). The bond-slip is assumed to be the weighted sum of the bond-slip curves for the "confined" cases, $\tau_{b,conf}$ and "unconfined" cases, $\tau_{b,unconf}$, according to

$$\tau_b = k_{cor} \cdot \tau_{b,conf} + (1 - k_{cor}) \cdot \tau_{b,unconf} \tag{1}$$

The corrosion penetration that causes cover cracking was found by curve fitting to analysis results from the detailed 3D model in Lundgren (2005), as given by the following formula:

$$x_{cr} = 11 \cdot \left(\frac{f_{cc}}{40}\right)^{0.8} \cdot \left(\frac{c}{d}\right)^{1.5} \cdot \left(\frac{d}{16}\right)^{0.5} \tag{2}$$

where x_{cr} is the corrosion level that cracks the cover in µm, f_{cc} is the concrete cylinder compressive strength in MPa, c is the concrete cover in mm, and d is the reinforcement bar diameter in mm. From the results presented by Soto San Roman (2006), it was noted that it was possible to obtain the bond-slip response of corroded reinforcement by shifting the bond-slip curve of uncorroded reinforcement along the slip axis. The explanation is the exhaustion of the confinement resistance by splitting stresses and cracking induced by the corrosion pressure, which is an effect similar to that produced by bar slipping. In Lundgren *et al.* (2012) this observation is introduced in the plasticity formulation of the CEB-FIP bond-slip model by making the hardening parameter dependent on both the plastic slip and the corrosion penetration. With the less formal way to present the model chosen in this paper, the bond-slip curve for corroded reinforcement is simply obtained by shifting the interpolated bond-slip curve by ax along the slip axis, as shown in Figure 3(b). The parameter a is assumed to be a constant, quantified as 8.1, according to Schlune (2006).

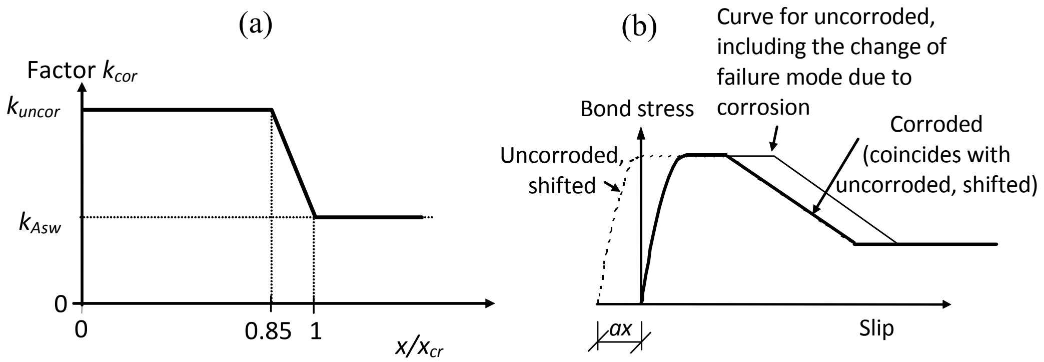

Figure 3. (a) Factor to take a change of failure mode into account for corroding reinforcement, (b) the proposed plasticity model is equivalent to using a "master curve" and adjusting the slip level to the amount of corrosion.

MODEL VALIDATION WITH A BOND TEST DATABASE

A compilation of 500 bond tests was used to validate the ARC1990 model. The database consists of pull-out and beam tests reported in 21 research works: (Al-Sulaimani et al., 1990; Cabrera and Ghoddoussi, 1992; Rodriduez, Ortega and Casal, 1994; Rodriguez, Ortega and Garcia, 1994; Almusallam et al., 1996; Rodriguez et al., 1996; Coronelli, 1998; Mangat and Elgarf, 1999; Stanish, R.D. and Pantazopoulou, 1999; Auyeung, Balaguru and Chung, 2000a; Ghandehari, Zulli and Shah, 2000; Shima, 2001; Lee, Noguchi and Tomosawa, 2002; Ng, Craig and Soudki, 2002; Fang et al., 2004; Horrigmoe et al., 2007; Zandi Hanjari and Coronelli, 2010; Law et al., 2011; Fischer and Ozbolt, 2012; Lin and Zhao, 2016; Coccia, Imperatore and Rinaldi, 2016). Information of the tests includes bar diameter ϕ_m, concrete cover c, embedment length l_b, stirrup content $A_{st}/(s_t \cdot \phi_m)$, yielding strength of stirrups f_{yt}, concrete compressive strength f_{cm}, current density used in accelerated corrosion process v and corrosion level W_c. Included are also the absolute bond strength$\tau_{DB,abs}$, typically calculated as the anchored force divided by the surface area of the bar in the bonded zone, and the relative bond strength $\tau_{DB,rel}$, defined as the ratio between absolute bond strength of the corroded and the un-corroded (reference) test. The current densities vary among the test set-ups, which may influence the bond capacity. Furthermore, also the embedment lengths vary. For short embedment lengths, the absolute bond strength can be seen as the local bond strength. For longer lengths, this no longer holds true. However, the comparison between the computational model and the database results is made by assessing the anchorage capacity through integrating the local bond-stress along the embedment length. The resulting force is then divided by the surface area of the rebar in the bonded zone to obtain the average bond strength, which corresponds to the procedure of determining the bond strength in the tests.

The ARC1990 model was applied to the tests in the database and the results were compared to the experimental data. For cases without stirrups the results are shown in Figure 4 (a). It can be seen that ARC1990 in many cases predicts larger reductions in the bond capacity compared to the database values; these values are clustered on the left hand side in the figure. For cases with stirrups the results are shown in Figure 4 (b).

The results are more distributed (less clustered) compared to the cases without stirrups. However, the tendency of the ARC1990 model to show greater reduction in bond capacity compared to the database values is visible also for the cases with stirrups; this indicates that the model gives conservative values compared to the database, however very much on the safe side.

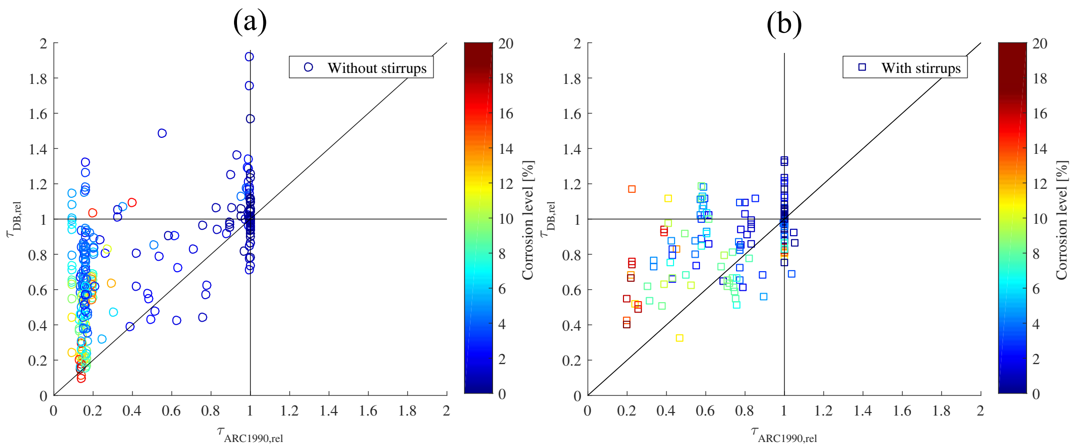

Figure 4. Normalized bond strength from database versus ARC1990 model for specimens (a) with stirrups and (b) without stirrups. The diagonal line corresponds to full agreement.

It is however important to note the influence of scatter in the database of bond tests. Many parameters influence the bond between reinforcement and concrete, and even more parameters in case of corrosion. Due to the large number of influencing parameters, many of which are difficult to control in experiments, the scatter in bond test results with corroded reinforcement is expected to be large. Despite the large scatter, ARC1990 was able to predict the reduction in bond capacity of the experiments in the database. Nonetheless, due to scatter in the test results and since increase in bond capacity due to low levels of corrosion is not included in ARC1990, the comparison between model and test results should be made with some considerations.

CONCLUSION

This paper has presented and overview of the development of a model for the assessment of anchorage capacity of corroded steel bars in concrete, intended for use in engineering practice. The model was compared to a bond test database with varying corrosion levels. Based on the study, the following conclusions can be drawn:

- The overview of ARC model includes several milestone in the development of the model: (1) model formulation and validation by 3D NLFE analyses and tests; (2) validation by natural and high corrosion tests; (3) application of the model in pilot study for two bridges; (4) validation with a large bond database; (5) adaptation of MC 2010 and re-calibration with a large bond database; and (6) the mode is to be adopted in *fib* commission 3.2 bulletin.
- The model represents the physical behaviour reasonably well, however very often it gives too conservative values compared to the test database..

- Considering the many uncertainties related to bond assessment of corroded reinforcement, a probabilistic model should be developed to take the uncertainties of the input parameters and their relevant distribution functions into account and develop reliable distribution functions for the resistance.

FUTURE WORK

Future work will be divided into the following parts: (i) implementation of the *fib* Model Code 2010 in the ARC model; (ii) calibration of modification factors to account for several layers of reinforcement by means of 3D NLFE analyses; (iii) development of a probabilistic ARC model, to incorporate the uncertainties of the basic variables and enable probabilistic analysis of the response; and (iv) calibration of modification factors for the deterministic ARC model, for implementation into the semi-probabilistic safety concepts, e.g. in Eurocode. The use of the assessment model will increase the ability of practicing engineers' to estimate the anchorage capacity in corroded concrete structures. This will make it possible to keep utilizing more corrosion damaged concrete bridges if the ARC assessment model is used.

REFERENCES

Almusallam, A. A., Al-Gahtani, A. S., Aziz, A. R. and Rasheeduzzafar, A. (1996) 'Effects of reinforcement corrosion on bond strength', Cons. and Building Materials, 10(2), pp. 123–129.

Al-Sulaimani, G. J., Kaleemullah, M., Basunbul, I. A. and Rasheeduzzafar (1990) 'Influence of corrosion and cracking on bond behavior and strength of reinforced concrete members', ACI Structural Journal, 87(2), pp. 220–231.

Auyeung, Y., Balaguru, P. and Chung, L. (2000a) 'Bond behavior of corroded reinforcement bars', ACI Structural Journal, 97(2), pp. 214–220.

Bell, B., Sustainable bridges. D1.3 European Railway Bridge Problems, 2004, sustainablebridges.net.

Blomfors M., Coronelli D., Lundgren K., Zandi K. (2017): Engineering bond model for corroded reinforcement. Submitted for publication to Engineering Structures.

Cabrera, J. G. and Ghoddoussi, P. (1992) 'The effect of reinforcement corrosion on the strength of the steel/concrete "bond"', in International Conference Bond in Concrete. Riga, Latvia.

CEB. CEB-FIP Model Code 1990. fib Model Code Concr. Struct. 1990, Lausanne, Switzerland: 1993.

CEB. CEB-FIP Model Code 2010. fib Model Code Concr. Struct. 2010, Lausanne, Switzerland: 2013,

Coccia, S., Imperatore, S. and Rinaldi, Z. (2016) 'Influence of corrosion on the bond strength of steel rebars in concrete', Materials and Structures. Springer Netherlands, 49(1–2), pp. 537–551.

Contecvet, A validated Users Manual for assessing the residual service-life of concrete structures: Manual for assessing corrosion-affected concrete structures, 2001, Instituto Eduardo Torroja.

Coronelli, D. (1998) Bar corrosion in steel-concrete bond: material and structural effects in R/C. Politecnico di Milano, Ph.D. Thesis.

Duracrete, General Guidelines for Durability Design and Redesign. Duracrete. Probabilistic Performance based Durability Design of Concrete Structures, 2000, EU - Brite EuRam III.

Fang, C., Lundgren, K., Chen, L. and Zhu, C. (2004) 'Corrosion influence on bond in reinforced concrete', Cement and Concrete Research. Department of Civil Engineering, Shanghai Jiaotong University, Shanghai 200240, China: Elsevier Ltd, 34(11), pp. 2159–2167.

Fischer, C. and Ozbolt, J. (2012) 'Influence of bar diameter and concrete cover on bond degradation due to corrosion', Bond in Concrete 2012, pp. 445–451.

Ghandehari, M., Zulli, M. and Shah, S. P. (2000) 'Influence of corrosion on bond degradation in reinforced concrete', in Proceedings EM2000, Fourteenth Engineering Mechanics Conference. Austin, Texas: ASCE, pp. 1–15.

Horrigmoe, G., Saether, I., Antonsen, R. and Arntsen, B. (2007) Sustainable Bridges. Laboratory investigations of steel bar corrosion in concrete - background document SB3.10.

Law, D. W., Tang, D., Molyneaux, T. K. C. and Gravina, R. (2011) 'Impact of crack width on bond: confined and unconfined rebar', Materials and Structures, 44(7), pp. 1287–1296.

Lee, H. S., Noguchi, T. and Tomosawa, F. (2002) 'Evaluation of the bond properties between concrete and reinforcement as a function of the degree of reinforcement corrosion', Cement and Concrete Research, 32(8), pp. 1313–1318.

Lin, H. and Zhao, Y. (2016) 'Effects of confinements on the bond strength between concrete and corroded steel bars', Construction and Building Materials. Elsevier Ltd, 118, pp. 127–138. Available at: http://dx.doi.org/10.1016/j.conbuildmat.2016.05.040.

Lundgren, K., P. Kettil, K. Zandi Hanjari, H. Schlune, and A. Soto San Roman, Analytical model for the bond-slip behaviour of corroded ribbed reinforcement. Structure and Infrastructure Engineering, 2012. 8(2): p. 157-169.

Lundgren, K., Nilsson, U., Ronnebrant, R., Maglica, A. (2014): Bärighetsutredning av betongbroar med rostande armering. Bygg & Teknik, 2014:7.

Mangat, P. S. and Elgarf, M. S. (1999) 'Bond characteristics of corroding reinforcement in concrete beams', Materials and Structures, 32(2), pp. 89–97.

Ng, S., Craig, B. C. and Soudki, K. A. (2002) 'Effects of FRP wrapping on the bond strength of corroded steel reinforcing bars', in 2nd Material Speciality Conference of the Canadian Society for Civil Engineers. Montreal, Canada, pp. 1–9.

Nilsson, U. and K. Lundgren, Blommenbergsviadukten, 2-2033-1. Kompletterande bärighetsutredning med avseende på kontroll av kapacitet i gjutfogar baserat på beräkningsmodell utvecklad av Chalmers tekniska högskola, 2014a, Ramböll Sverige AB

Nilsson, U. and K. Lundgren, Gröndalsviadukten, 2-2034-1. Kompletterande bärighetsutredning med avseende på kontroll av kapacitet i gjutfogar baserat på beräkningsmodell utvecklad av Chalmers tekniska högskola, 2014b, Ramböll Sverige

Perez, I. F., Tahershamsi, M., Marí, A. R., Bairán, J., Lundgren, K., Zandi, K., Plos, M., 1D and 3D analysis of anchorage in naturally corroded specimens, Proceedings of the 10th fib International PhD Symposium in Civil Engineering, Université Laval, 21 – 23 July 2014, Québec, Canada p. 547-552.

Rodriduez, J., Ortega, L. M. and Casal, J. (1994) 'Corrosion of reinforcing bars and service life of reinforced concrete structures: corrosion and bond deterioration', in International conference 'Concrete across borders'. Odense, Denmark, pp. 315–326.

Rodriguez, J., Ortega, L. M. and Garcia, A. M. (1994) 'Assessment of structural elements with corroded reinforcement', in International Conference on Corrosion and Protection of Steel in Concrete. Sheffield, UK, pp. 171–185.

Rodriguez, J., Ortega, L. M., Casal, J. and Diez, J. M. (1996) 'Corrosion of reinforcement and service life of concrete structures', in 7th International Conference on Durability of Building Materials and Components. Stockholm, Sweden.

Roman ASS. Bond Behavior of Corroded Reinforcement Bars - FE modelling and parameter study. Chalmers University of Technology, 2006.

Schlune H. Bond of corroded reinforcement - Analytical description of the bond-slip response. Chalmers University of Technology, 2006.

Shima, H. (2001) 'Local bond stress–slip relationship of corroded steel bars embedded in concrete', in Banthia, N., Sakai, K., and Gjørv, O. E. (eds) Third International Conference on Concrete Under Sever Conditions. Vancouver, Canada, pp. 454–462.

Stanish, K., R.D., H. and Pantazopoulou (1999) 'Corrosion effects on bond strength in reinforced concrete', ACI Structural Journal, 96(6), pp. 915–921.

Wang, X., Nguyen, M., Stewart, M. G., Syme, M., Leitch, A., Analysis of Climate Change Impacts on the Deterioration of Concrete Infrastructure – Synthesis Report, 2010, CSIRO, Canberra.

Zandi, K., K. Lundgren, M. Plos, and D. Coronelli, Three-dimensional modelling of structural effects of corroding steel reinforcement in concrete. Str. and Infrastr. Eng., 2013. 9(7): p. 702-718.

Zandi, K. (2015) Corrosion-Induced Cover Spalling and Anchorage Capacity, Structure and Infrastructure Engineering (1573-2479). Vol. 11 (2015), 12, p. 1547-1564.

Zandi Hanjari, K. and Coronelli, D. (2010) Anchorage Capacity of Corroded Reinforcement: Eccentric Pull-out Tests. Gothenburg, Sweden, Report 2010:6.