Anchorage of corroded reinforcement – from advanced models to practical applications

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Abstract

When reinforcement in concrete corrodes, splitting stresses around corroded bars may lead to cover cracking and even cover spalling, affecting the anchorage. The aim of this paper is to give an overview on both advanced and practical models for anchorage capacity of corroded reinforcement which have been developed at Chalmers, and to show how these models can be applied in the assessment of existing bridges. The application of the practical model is exemplified in assessment of two bridges built in the 1960s. The bridges exhibit systematic damage in the form of spalled concrete on the bottom side of the main beams at cast joints where large amounts of reinforcement are spliced. The anchorage length needed to anchor the yield force was calculated from the bond-slip response, using the one-dimensional bond-slip differential equation. The model proved to be easy to use in practical design work. Furthermore, the bridges could be shown to have sufficient capacity, and costly strengthening could be avoided. This work clearly demonstrates the potential to certify sufficient load-carrying capacity of corroded reinforced concrete structures through improved models.

Keywords: Keywords: Anchorage, Corrosion, Bond-slip, Concrete, Reinforcement

1. Introduction

Infrastructures represent a large capital investment in all developed countries. To establish sustainable development, it is of great importance that the investments result in safe structures with predictable performance. Despite significant advances in construction design and practice, corrosion in reinforced concrete (RC) structures is still a leading cause of deterioration worldwide. This situation has led to a growing demand for better assessment of existing concrete structures and has revealed a need for an improved understanding of the structural effects of corrosion.

Corrosion of the steel reinforcement has two major effects: 1) reduction of the effective rebar area, and 2) change of bond properties between the reinforcement and the concrete, which is the topic of this paper. This has been studied by many researchers; for a state-of-the-art report see [1]. Advanced three-dimension Nonlinear Finite Element (3D NLFE) analysis has proven to be capable of describing the behaviour of reinforced concrete in a comprehensive way provided that appropriate constitutive models have been adopted. Furthermore, the effect of corrosion on the load-carrying capacity and the structural performance of existing structures can be more realistically predicted; such models have been developed at Chalmers, see e.g. [2-5]. Although 3D NLFE analyses allow for a more accurate description of the deterioration and enable a better understanding of the structural effects at the material and structural levels, they are numerically expensive and thus incomprehensible for full-scale practical applications. Thus, there is also a need for simple model predicting the bond-slip behaviour for corroded bars, as the one presented by Lundgren *et al.* [6] and further validated in Zandi *et al.* [5]. The aim of the present study is to give an overview on both advanced and practical models for anchorage capacity of corroded reinforcement which have been developed at Chalmers, and to show how these models can be applied in assessment of existing bridges.

2. Advanced NLFE models

The volume expansion of corrosion products locally may lead to cover cracking/spalling and steel-concrete bond deterioration, and globally may result in a decrease in the load-carrying capacity and a change in the structural performance of concrete structures. These effects has been simulated in 3D NLFE analysis using a deterioration model previously developed by Lundgren [2-3], and thereafter extended by Zandi [4-5]. Major milestones throughout the development phase of the model, shown in Figure 1, include: (a) development of bond and corrosion models and validation with several experiments [2-3], (b) extending the model accounting for the flow of rust throughout cracks and experimental validation [4], and (c) developing a new computation scheme enabling the simulation of cover spalling for high corrosion attacks [5].

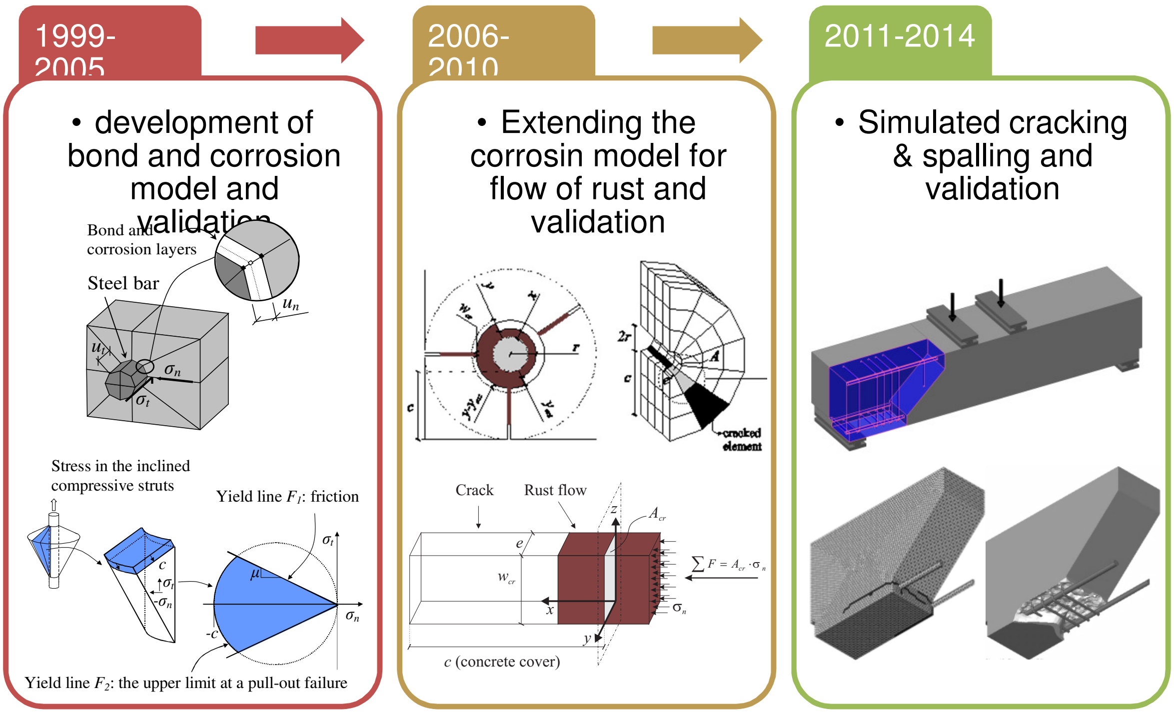

Figure 1. Overview of the earlier developments of deterioration model including major milestones.

3. A simplified model for practical application

A simplified **1D** model for the **A**ssessment of anchorage in corroded **R**einforced **C**oncrete structures; referred to as **1D-ARC** model in this paper, has been established at Chalmers [6]. Major milestones throughout the development phase of the model are shown in Figure 2. The 1D-ARC model was originally formulated based on the analytical bond-slip model in Model

Code 1990 [7] combined with a parametric study using 3D NLFE analyses and several experiments [6]. The model was later verified by results from test specimens with natural corrosion [8]. Moreover, the model was recently validated by 3D NLFE analyses and experiments for high corrosion attacks leading to cover spalling [5]. This model was even applied in practice in a pilot study including two bridges, thereby demonstrating its excellent potential for practical use; this is further discussed in section 4. Moreover, the 1D-ARC model has recently been adopted by fib-SAG7 – Modelling of structural performance of existing structures – to be included in the planned Model Code for the assessment of existing structures. This demonstrates that the model has been internationally recognized which can be considered as a major milestone in the development of the model.

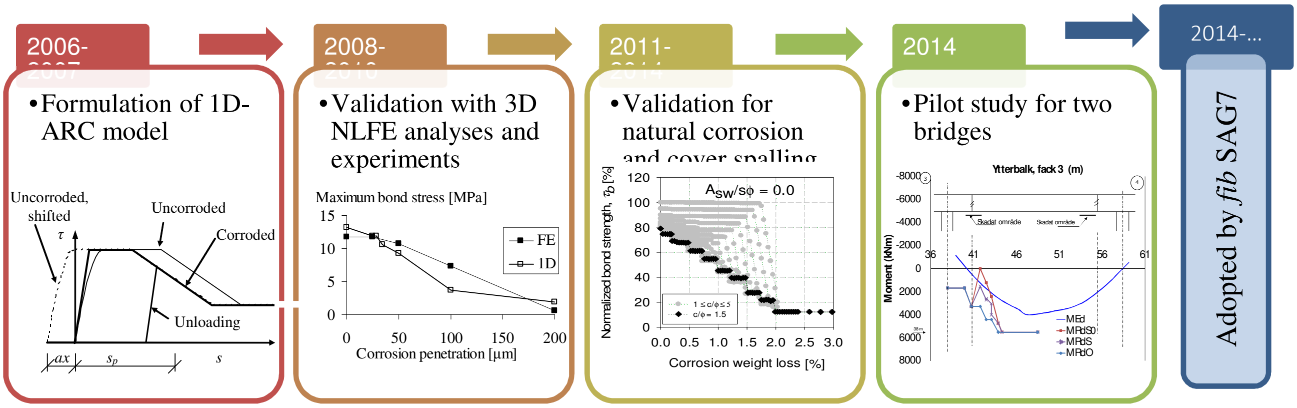

Figure 2. *Overview of the earlier developments of the 1D-ARC model including major millstones.*

4. Application of the 1D-ARC model in assessment of two bridges

The methodology is exemplified in assessment of two bridges, “Blommenbergsviadukten” and “Gröndalsviadukten”, bridges in Stockholm built in the 1960s. The bridges were built in phases; the first phase consisted of columns, cross beam, and a part of the superstructure, see Figure 3. Thereby, a cast joint was placed at each main beam on either side of each row of columns. This led to that large amounts of reinforcement were spliced at each cast joint; see Figure 3. Today, the bridges exhibit systematic damage in the form of spalled concrete on the bottom side of the main beams at these cast joints; an example is shown in Figure 3. At the assessment of the bridges, sufficient capacity could be shown if the structure was assumed to be undamaged. Considering the visible damages, this was however considered to be an unrealistic assumption. As the documented damages are located close to points where the bending moment is zero, it was first examined whether a simplified assumption that the bond strength was zero in the damaged areas would be enough; however, this conservative assumption resulted in insufficient capacity. Accordingly, a more detailed investigation on the anchorage in the damaged sections was needed. Thus, the model by Lundgren et al. [6] was applied. The bond versus slip was obtained first, and the anchorage length was calculated by numerical solving the basic 1D bond-slip differential equation along a bar.

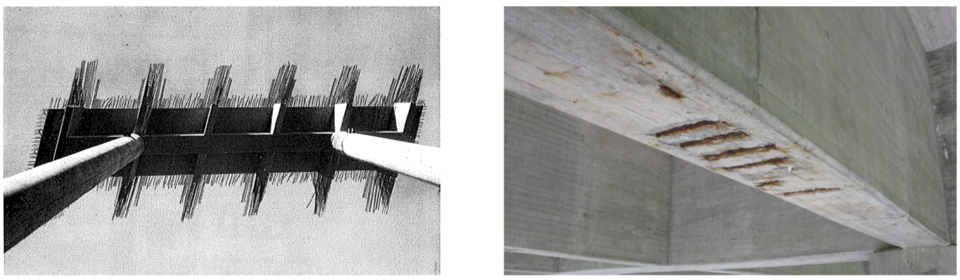

Figure 3. Left: Photo from the time of construction, showing the large amount of reinforcement spliced at the cast joints. Right: Example of a damage with spalled cover at a cast joint at the bridge today.

5. Conclusions and outlook

Models for anchorage capacity of corroded reinforcement, developed at Chalmers, were briefly reviewed. The 1D-ARC model was validated for anchorage in RC structures with cover cracking and spalling. The validation was conducted through a comparison to 3D FE analysis and experiments. Thereby, sufficient knowledge and models exist to calculate the anchorage capacity in concrete structures damaged by reinforcement corrosion. The model proved to be very useful in practical engineering work. Application to two bridges showed its potential to demonstrate sufficient load-carrying capacity, and thereby avoiding costly strengthening. The economical saving is around 27 million SEK for the two studied bridges only. For the bridges in question, a more detailed damage mapping will be performed, focusing on details that showed to be critical in this evaluation.

A problem in the assessment of existing structures is to evaluate the current corrosion penetration. Measurement methods for the corrosion rate exist; however as the corrosion rate typically varies over time, and as the measurements must be combined with assumptions about how long time the corrosion has progressed, the resulting corrosion penetrations become very uncertain. In an ongoing research project, the real corrosion penetration will be measured in a relatively large number of specimens, and the results will be correlated with the visible damages in the form of crack pattern and crack widths. In this way, we hope to develop methods to link visible damages to the effect on load-carrying capacity.

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