Severely Corroded Reinforced Concrete with Cover Cracking: Part 2. Anchorage Capacity

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Abstract. There is a growing need for reliable methods of assessing the load-carrying capacity and remaining service life of corroded structures. In an ongoing research by the authors, issues that have not been investigated in the methods and models available today to calculate the remaining load-carrying capacity of the corroded structures are identified. Two main issues; i.e. high amount of corrosion leading to cover spalling and the effect of corroding stirrups, were investigated in an experimental program. Pull-out tests were carried out on beam-end specimens with long embedment length to study the anchorage capacity of a corroded bar. The specimens were subjected to electrochemical corrosion process leading to different corrosion penetrations prior to mechanical loading. Details concerning electrochemical corrosion setup, corrosion-induced cracking and numerical modelling of a corroding bar are presented in a companion paper subtitled “Part 1. Crack initiation, crack propagation and cover delimitation”. Three types of specimens, with stirrups, without stirrups and with corroding stirrups, were subjected to pull-out test. The test results showed a significant influence of stirrups not only on corrosion-induced cracking but also on anchorage capacity and failure mode in the pull-out test. Finally, the corrosion and mechanical testing phases were simulated in a finite element model using the corrosion and bond models earlier developed by Lundgren [1,2]. The outcomes of the numerical modelling help to further understand the effect of high corrosion penetrations and presence of stirrups on failure modes observed in the experiments.

Introduction

When studying the anchorage of a ribbed bar in structural concrete members, the anchorage capacity is strongly influenced by the actual confinement conditions. In
In general, confinement is a result of the surrounding concrete, stirrups and transverse pressure [3]. The corrosion of reinforcement leads to volume expansion of the steel, which generates splitting stresses in the concrete influencing the bond between concrete and reinforcement. For a larger corrosion penetration, the splitting stresses may lead to cover cracking and, finally, spalling of the concrete cover. In the extreme case, when cover spalling occurs, the resisting mechanism in the cross section is altered and stirrups are the main factor providing confinement to the main reinforcement and resulting in residual anchorage capacity.

In earlier works within this field, several models of the corrosion and bond have been developed and implemented in the finite element. In the model by Lundgren [1, 2, 4], the splitting stresses are introduced and the bond stress depends not only on the slip but also on the normal stress between the reinforcement and the surrounding concrete. In addition the model is capable of taking into account the effects of the transverse pressure. However, the model is only calibrated for the effect of corrosion on the main reinforcement. To the authors’ knowledge, there exists no model taking into account the effect of corroded stirrups on cover cracking and cover spalling and to study the anchorage capacity after cover delamination. This is the main aim of the research carried out.

The detailed 3D bond and corrosion model, developed by Lundgren, was used to analyze test specimens with severe corrosion. The type of the specimen was similar to the ones tested by Magnusson [5], in which the specimens had a shape of a beam-end after inclined shear cracking. The details concerning the specimens, electrochemical corrosion and test set-up are presented in a companion paper subtitled “Part 1. Crack Initiation, Crack Propagation and Cover Delamination”.

The bond model is a frictional model and the corrosion model takes into account the effect of corrosion of main reinforcement and stirrups as the expansion of the corrosion products. The concrete was modelled using 3D solid elements with a constitutive model based on non-linear fracture mechanics using a rotating crack model based on total strain. Three-dimension solid elements with a constitutive model based on Von Mises yield criterion with associated flow and isotropic hardening were used to model the main reinforcement and stirrups. The results computed by the model were compared with the experiments.

### Experimental Setup

Pull-out tests were carried out on beam-end specimens with long embedment length to investigate the global bond behaviour of an anchored bar when the concrete cover has cracked and spalled off due to corrosion. In total, twenty two beam-end specimens were cast using a concrete grade of C30/37. The concrete was mixed in two batches, with and without 3% sodium chloride, and cast into beam-end moulds of which eleven specimens were made without sodium chloride and