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Four levels to assess anchorage capacity of corroded reinforcement in concrete

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ABSTRACT

Corrosion of reinforcement affects anchorage capacity. In this study, four levels of analyses were, for the first time, compared with each other and to tests of naturally corroded beams. In the most advanced approach, three-dimensional non-linear finite element (3D NLFE) analyses employing previously developed bond and corrosion models were carried out. These analyses agreed well with the experiments in terms of crack pattern and maximum load capacity. The next approach consisted of 3D NLFE analyses with a pre-defined bond-slip relation between concrete and reinforcement, resulting in reasonable agreement; however, the anchorage capacity was overestimated and the crack pattern deviated from the experiments. At the next level, the bond-slip relation was used together with a measured available anchorage length, and the anchorage capacity was obtained by numerically solving the one-dimensional differential equation; the results were reasonably close to the experiments. In the most simplified approach, a constant bond stress was assumed together with the available anchorage length measured, which underestimated the capacities. In conclusion, the more advanced analyses provide reliable information regarding the structural behaviour, while the two simplified methods are well suited for use in practice.

1. Introduction

The corrosion of steel reinforcement is one of the main deterioration issues in Reinforced Concrete (RC) structures. The study of corrosion effects is crucial for a better understanding of the structural behaviour of existing deteriorated concrete structures [1–3]. The corrosion process transforms parts of steel reinforcement into rust. This process leads to a reduction of the steel cross section affecting also its main mechanical properties [4–8]. However, the most severe effect of reinforcement corrosion is the volume increase of corrosion products causing splitting stresses along corroded reinforcement, which results in cracking and spalling, thus changing the bond properties between steel and concrete [9–13].

The bond mechanism is the transfer of stresses action between reinforcement and concrete, which makes it possible to anchor reinforcement in concrete. Bond action generates inclined forces, which radiate outwards in the concrete. The inclined stress is often divided into a longitudinal component, denoted the bond stress, and a radial component, denoted normal stress or splitting stress. The inclined forces are balanced by tensile ring stresses in the surrounding concrete, as explained by Tepfers [14]. If the tensile stress becomes larger than the tensile strength of the concrete, longitudinal splitting cracks will form in the concrete. This type of failure is called splitting failure. When the concrete surrounding to the reinforcement bar is well-confined, a pull-out failure characterised by shear cracking between the adjacent ribs is obtained; this is the upper limit of the bond strength. A common way to describe the bond behaviour is by relating the bond stress to the slip, that is, the relative difference in movement between the reinforcement bar and the concrete. However, as made clear above, the bond versus slip relationship is not a material parameter; it is closely related to the structure. Furthermore, as the bond depends on the structure's ability to carry splitting stresses, possible cracking or spalling due to corrosion will influence the bond to a large extent.

Many researchers have studied the effect of corrosion on bond deterioration. Several studies have investigated parameters which may influence bond and anchorage capacity of corroded structures; see [15–20]. These studies led to the development of different empirical, analytical and numerical models to assess the bond and anchorage behaviour of corroded reinforcement; see [21–27]. These models were developed based on different simplifying assumptions; thus, results with different levels of accuracy can

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be obtained using such models to assess the effect of corrosion on residual strength. However, it is rare to find comparisons between different models, especially on how capable models on different levels of detailing are compared to each other. The aim of this paper was to study and compare different methods to assess the anchorage capacity of naturally corroded RC structures. The assessment methods were based on four different levels of detailing and accuracy, ranging from advanced models suited for research to a simplified engineering approach suited for daily engineering work; see Fig. 1. Thereby, we can bring the knowledge gained from research into simplified models that can be of use in engineering practice.

The modelling approaches are organized from the most advanced to simplified ones as follows:

- Level IV: Using three-dimensional non-linear finite element (3D NLFE) analyses employing previously developed bond and corrosion models. This level of analysis is well suited to research purposes, describing and understanding the structural effects of corrosion.
- Level III: Using 3D NLFE analyses with a pre-defined one-dimensional (1D) bond-slip relation between concrete and reinforcement. This level of modelling cannot directly take into account the splitting effects of the reinforcement slip and the expansion of corrosion products; these effects are instead accounted for by modifying the 1D bond-slip relation given as input.
- Level II: Using a 1D bond-slip model and a given available anchorage length. The anchorage capacity was obtained by numerically solving the 1D differential equation along the available anchorage length.
- Level I: Using a simplified approach where the residual capacity of the bond-slip model is used together with a given available anchorage length. As the bond stresses are assumed to remain constant over the available anchorage length, the anchorage capacity can be directly calculated as in commonly used engineering approaches.

In general, existing models of bond for corroded reinforcement have been calibrated based on experimental investigations of artificially corroded specimens. However, there are reasons to believe that the deterioration caused by natural corrosion does not have the same effects on the structural behaviour as the deterioration caused by artificial corrosion [28], [29]. Thus, it is doubtful whether the results from these models can be reliably applied to structures in the field. Therefore, the results of the four different analysis methods were compared to the experiments of natural corrosion in Tahershamsi et al. [30] to study the accuracy of each assessment method.

2. Materials and experimental program

Tests on naturally corroded reinforced concrete beams were carried out in an earlier work by Tahershamsi et al. [30]. A condensed description of the tests is given in the following sections.

2.1. Test setup and specimen description

Specimens were taken from RC edge beams of a steel girder bridge with a concrete deck slab, Stallbacka Bridge in Sweden. During service life of the bridge, de-icing salt has been often applied on the bridge deck and thus chlorides from the de-icing salt had reached the steel bars in the concrete. For this reason, corrosion was considered to be the main cause of deterioration. Based on the damage patterns on the edge beams, the specimens were categorized into three different groups: Reference (R) specimens without any visible crack, Medium (M) damaged specimens with spalling cracks, and Highly (H) damaged specimens with spalling of the cover. Tests were carried out in two series. The analyses at Levels III and IV presented in this paper are focused on six of the thirteen tests in the second test series described in [30]. The six tests chosen for analyses are two Reference, two Medium, and two Highly damaged specimens. The analyses at Levels I and II were performed for all thirteen specimens in the second test series. The geometrical specifications of the specimens and test setup are shown in Fig. 2.

An indirectly supported four-point bending test configuration was used for the experiments. The test configuration was designed to secure an anchorage failure for beams with different degrees of corrosion damage in one common test setup [31]. More information about the test specimens and test setup are provided in [30,32].

2.2. Concrete properties

During the experimental work, cores of suspension holes were drilled out. The concrete compressive strength, f_c, was obtained by testing the cylindrical concrete samples for every beam specimen. More details regarding the compressive tests are available in [30]. The average compressive strength of the cores from each specimen was used for all analyses; see Table 1. The elastic modulus (E) used in the analyses, 24.0 GPa, was the average of the elastic modulus of three specimens evaluated in the first test series; for more details see [32]. The fracture energy was calculated from the compressive strength by means of the provisions given in *fib* Model Code 1990 [33]. The mechanical properties of concrete used in the analyses are provided in Table 1.

The tensile strength of concrete were not experimentally evaluated for each beam specimen, and thus had to be calculated from the compressive strength. However, the climatic data from a few

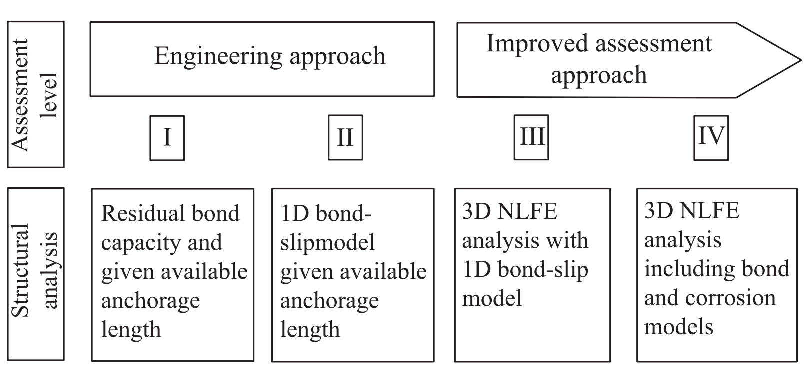

Fig. 1. Scheme for the four-level assessment approaches predicting the anchorage capacity of corroded reinforced concrete.