Numerical model of RC beam response to corrosion

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Abstract

The chloride-induced corrosion of reinforcement used to be represented by Tuutti's model with initiation and propagation phases. During the initiation phase chlorides penetrate the concrete cover and accumulate around reinforcement bars. The chloride concentration in concrete increases until it reaches a chloride threshold value, causing deterioration of the passive layer of reinforcement. Then the propagation phase begins. During the propagation phase steel has no natural anti-corrosion protection, a corrosion current flows and this induces the production of rust. A growing volume of corrosion products generates stresses in concrete, which leads to cracking, splitting, delamination and loss of strength. The mechanical response of RC elements to reinforcement corrosion has mostly been examined on the basis of a 2D cross-section analysis. However, with this approach it is not possible to represent both corrosion and static loading. In the paper a 3D finite element model of an RC beam with the two actions applied is presented. Rust is represented as an interface between steel and concrete, considering the volumetric expansion of rust.

Keywords: concrete, cracking, spalling, reinforcement corrosion, rust interface

1. Introduction

When the propagation phase of chloride corrosion begins rust is produced. In this phase concrete is damaged due to corrosion products expansion. The simulation of damage is aimed at the analysis of concrete cracking. The most popular model used for the analysis of the state of stress in the concrete surrounding a corroding reinforcement bar is a thick-walled cylinder model. This approach is limited to the consideration of one corroding rebar surrounded by a concrete cylinder with thickness equal to concrete cover. The model assumes that the cover fails with the first appearance of a crack on the surface. Using the thick-walled cylinder model it is not possible to simulate the pattern of possible failure of the whole element and the interactions caused by more than one corroding rebars are neglected.

It must be pointed out that apart from cracking of the concrete cover, another important modelling aspect is the incorporation of adhesive-frictional action at the interface of the corroding rebar and concrete. Cracking of the concrete cover implies the loss of confinement and a reduction in bond strength in the interfacial zone between the two materials. What is more, the soft layer created by corrosion products that accumulate on the bar surface can effectively reduce the friction component of the bond strength. In addition, the deterioration of the ribs of deformed bars causes a significant reduction of the interlocking forces between the ribs of the bars and the surrounding concrete keys. This deteriorates the primary mechanisms of bond between the deformed bars and concrete, and hence, the bond strength decreases significantly. On the other hand, when a rebar is slightly corroded the bond of steel and concrete improves. This is a consequence of the increase of friction and roughness of the steel surface. Further corrosion results in an abrupt reduction of concrete-steel bond.

2. Finite element model

To observe both cracking and bond reduction induced by corrosion and external loading a 3D model for a beam subjected to 3-point bending under displacement control and corrosion is analyzed. The model has been prepared in accordance with the experiment performed in [3]. The beam is 5 m long and the cross-section dimensions are 200 x 500 mm. The rust interface is initially 0.01 mm thick, however it is assumed that the thickness is a result of steel loss only. Thus, the steel bars diameters are 31.98 mm and 7.98 mm instead of 32 mm and 8 mm, for bottom and top reinforcements, respectively. The concrete cover is 20 mm. The rust interface properties have been obtained from a single rebar pullout test model, as discussed in [1]. No shear reinforcement is modelled.

The FE models have been built using Abaqus package. Since the analysis is performed as three-dimensional, the mesh is coarse and the beam analysis is performed for a quarter of a beam, since double symmetry holds. The mesh is composed of linear brick elements, representing concrete and steel, and 8-node cohesive elements representing the rust interface. The parts are connected using tie constraints. To overcome the mesh-dependency problem, the viscosity parameter is used as numerical stabilization measure. The preliminary results of the model have been presented in [2].

3. Constitutive models

In the presented analysis rust is introduced as an interface layer between solid elements. The material parameters are shown in Table 1. Steel is modelled as an elastic-plastic material with hardening. The concrete behavior is described using plasticity-based cracking model available in Abaqus [4]. In the damaged plasticity model, damage associated with concrete fracture leads to a reduction in the elastic stiffness, introduced by a scalar degradation variable. The evolution of the degradation variable is governed by a set of hardening variables and the effective stress, acting on the undamaged skeleton of the material. The damaged states are represented independently by increasing values of two hardening variables, which are referred to as equivalent plastic strains in tension (PEEQT) and in compression. The variables

Table 1: Material parameters

Interface parameters				Material parameters			
				Concrete		Steel	
Bond strength [MPa]	Bond stiffness [N/mm^3]	Separation [mm]	Corrosion -	Parameter	Value	Parameter	Value
300	1200	2.5	0%	E [MPa]	20 000	E [MPa]	200 000
300	3000	2.5	1%	ν [-]	0.2	ν [-]	0.3
50	700	2.5	4%	Stress at comp. peak f_c [MPa]	38.3	Yield stress σ_e [MPa]	350
17	30	0.4	6%	Strain at comp. peak ε_c [-]	0.2%	Tangent modulus E_T [MPa]	3 295
6	20	1.5	7%	Limit tens. stress f_t [MPa]	2		
4	5	1	8%				

also control the evolution of the yield surface and are related to the dissipated fracture energy. The plastic flow is governed by a nonassiociated flow rule.

Rust is modelled as an interface between steel and concrete, whose response is defined in terms of traction versus separation relation. The traction-separation model assumes initially linear elastic behavior followed by the initiation and evolution of degradation. The elastic behavior is written in terms of elasticity matrix that relates the nominal tractions to the nominal separations across the interface [4]. The maximum nominal stress criterion is used as the damage initiation criterion. After reaching the peak value a softening traction-separation relation is adopted. It is introduced by a damage variable which represents the overall damage in corrosion products and captures the combined effects of all active mechanisms.

4. Results and conclusions

The analysis considers three cases of uniformly distributed corrosion and deflection application. The corrosion level is understood as the loss of weight referred to the initial weight of rebar. In the first simulation the displacement changes from 0 to 50 mm and the corrosion level simultaneously increases linearly from 0% to 2%, 0% to 4% and 0% to 8%. In the second simulation the displacement changes from 0 to 50 mm and different corrosion levels are applied around top and bottom reinforcement. The last case considers different scenarios of load application. The corrosion and external loading are applied separately in different sequences: corrosion – displacement or displacement – corrosion.

In Fig. 1 the reduction of load-carrying capacity observed for the first simulation is presented. As corrosion and deflection increases, the total beam strength decreases, however it is not significant. For 8% corrosion the peak force decreases from 250 kN to 210 kN. Figure 2 presents the distribution of the equivalent plastic tensile strain (PEEQT) for the beam with 50 mm deflection and 8% corrosion applied simultaneously. The longitudinal corrosion-induced and vertical deflection-induced cracks can be noticed. For the beam loaded only with imposed deflection the maximum strains appear in the middle of the span, forming a vertical crack. As corrosion increases, the cross-section corners tend to spall off the beam. The vertical crack is translated away from the middle of the span, which can be an effect of combination of strains induced by high corrosion and deflection.

The analysis of the beam shows that the reduction of load-carrying capacity obtained due to corrosion is smaller than expected. However, severe damage to the cross-section due to corrosion process is of major importance when structural serviceability and durability is considered.

References

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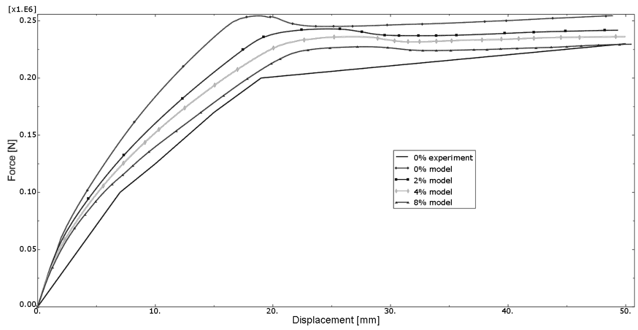

Figure 1: Total applied force vs. beam defection in the simulation of the increasing corrosion applied with forced deflection

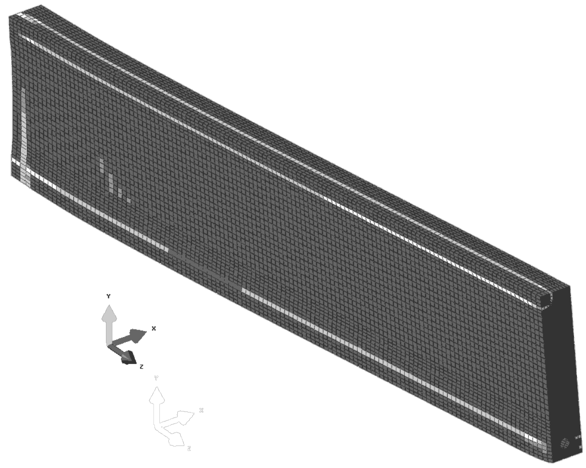

Figure 2: Final distribution of PEEQT parameter for beam with 50 mm deflection and 8% corrosion