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Membrane behavior in RC slabs subjected to simulated reinforcement corrosion

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ABSTRACT

Deterioration due to corrosion has been a growing concern in the last decades since it compromises the serviceability of structures and results in a decrease of the structural safety. Apart from deterioration, also the awareness of the importance of structural robustness has increased due to several failures with progressive collapse. The activation of membrane action in reinforced concrete slabs can significantly increase the structural robustness by providing an alternate load path. A validated numerical model for the tensile membrane behavior of reinforced concrete slabs is used to investigate the influence of (simulated) corrosion effects on this membrane behavior. A two-step analysis is adopted: first a cross-section analysis is performed, followed by an analysis of the structural member. It was observed that even for small corrosion levels, there was a significant influence on the ultimate bearing capacity of the slab. Finally, also the influence of different corrosion locations was investigated.

1. Introduction

In the last decades, deterioration of existing structures has been a growing concern as this plays a crucial role in the asset management of our aging patrimony. Deterioration due to corrosion of the reinforcement in reinforced concrete structures has been of particular concern. The associated reduction of the cross-section directly results in a decrease of the structural safety. Furthermore, cracking, possible loss of the concrete section and loss of bond might compromise the serviceability of the structure and the stresses building up due to the formation of corrosion products can decrease the bearing capacity and lead to spalling.

Another topic of particular interest is the assessment of structural robustness. Due to tragic events such as the partial collapse of the Ronan Point building, research into structural robustness increased significantly. The apartment tower lacked alternate load paths to redistribute forces in the event of a partial collapse. Hence, one way to increase structural robustness is to provide such alternate load paths. Such an alternate load path can be offered by the activation of membrane action effects in reinforced concrete beams or slabs.

Both the topics of deterioration and structural robustness are combined in this contribution: the influence of corrosion on the membrane behavior of a reinforced concrete slab is investigated.

In the following sections, a brief introduction to membrane action in reinforced concrete members and the process of reinforcement corrosion is given. Next, a framework for a Finite Element analysis of reinforced concrete elements subjected to corrosion is described. Finally, this framework is illustrated through a reinforced concrete slab example subjected to large deformations.

The results of this research are of particular importance in the development of a framework for the assessment of structural robustness of deteriorating structures.

2. Membrane action effects in reinforced concrete elements

The design of reinforced concrete beams and slabs is traditionally based on small deformation theories in which the resistance for bending and shear of these elements is the main design criterion. When an accidental situation occurs, e.g. the loss of a column or wall, large deformations are expected and the bending behavior is shifted towards membrane behavior. This shift results in the development of an alternate load path, allowing to transfer the loads to (remaining) supports. The activation of membrane action can significantly increase the load-carrying capacity of concrete elements that have sufficient horizontal restraints [1–6].

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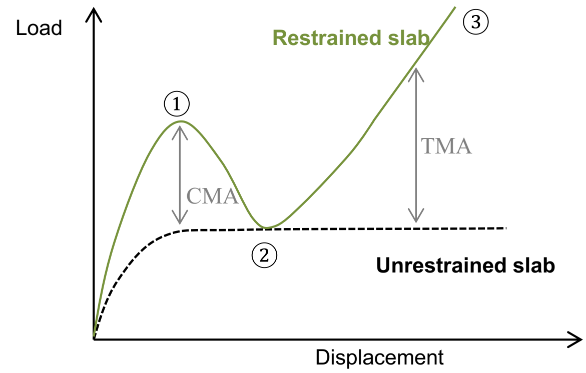

Fig. 1. Load–displacement behavior of restrained and unrestrained RC slabs.

Fig. 1 shows the typical load–displacement behavior of both unrestrained and restrained reinforced concrete beams or slabs.

In case no horizontal restraint is present, the element will deflect under the applied load until a yielding plateau is established and failure occurs either due to concrete crushing or rupture of the reinforcement.

When the element is restrained against horizontal movements, e.g. by neighboring elements, compressive membrane action (CMA) is activated at small deflections due to the restrained outward movement along the edges. This may offer a much higher bearing capacity than predicted by Johansen's yield line theory, especially in case of elements with a small slenderness.

After the maximum flexural capacity is achieved in point 1, the load–displacement graph shows a rapid decrease of the supported load with further increasing deflection as a result of the reduction of compressive membrane forces. Then, near point 2, membrane forces reach the stage where they change from compressive to tensile forces. If possible, the element's boundary restraints start to resist inward movements of the edges. Cracks extend over almost the full thickness and the steel reinforcement acts as a tensile net that enables additional load-carrying capacity under increasing deflections: tensile membrane action (TMA) is activated. The load increases for a second time until the rupture of the reinforcement at point 3. It is obvious that in this last stage, the properties of the reinforcement have a major influence on the failure load.

It should be noted that failure can occur in the compressive membrane stage or in the tensile membrane stage, depending on the element's slenderness: the higher the slenderness, the more tensile membrane action is to be expected.

Research into membrane action traces back to the middle of the 20th century. Experimental research performed by e.g. Ockleston [7], Guice & Rhomberg [8], Park [9], Vecchio & Tang [10], Wood [11] provided experimental evidence of the beneficial influence of compressive membrane action. Soon, several researchers developed analytical models to describe this phenomenon. Such models can be found e.g. in [9,10].

Experimental investigations into (restrained) slabs subjected to very large deflections demonstrated that a collapse load was significantly higher than the peak load due to compressive membrane action. Most of these test, however, included only small-scale or medium-scale specimens with a small thickness [8,9,12]. Experiments with respect to tensile membrane behavior on large-scale specimens were performed by Gouverneur [5].

The occurrence of tensile membrane action in the center and compressive membrane action at the edges of the slab was shown to be the load-carrying mechanism in case of horizontally unrestrained two-way slabs subjected to very large deformations [13–15].

In case of robustness quantification, the quantification of the (residual) capacity of the alternative load path established by the development of compressive or tensile membrane action becomes of crucial importance.

3. Corrosion

A common deterioration mechanism in reinforced concrete is corrosion of the reinforcement steel. As indicated in Rodriguez et al. [16], corrosion affects both the concrete and the reinforcement. As such, deterioration occurs at different levels:

- The cross-section of the reinforcement is reduced;
- The mechanical properties of the reinforcement are reduced;
- Expansion of corrosion products results in cracking and spalling of the concrete cover;
- The bond between the steel and surrounded concrete is reduced.

Because of these phenomena, the safety of concrete structures subjected to reinforcement corrosion is reduced. According to the Model Code for Service Life Design [17], the process of corrosion can be divided roughly into two time periods: the initiation period and the propagation period. In the first phase, the reinforcement becomes depassivated, due to the ingress of chlorides or due to carbonation. During the second phase, the reinforcement itself is affected: the net cross-section is reduced and corrosion products start to accumulate, resulting in a volumetric expansion of the bars. Both the initiation and propagation phase are governed by different stochastic parameters and can be described by mathematical models. In this contribution, only the propagation phase will be considered.

3.1. Influence on the cross-section

The propagation phase can be characterized by the corrosion current density i_{corr} (i.e. the current per unit area). Due to the complex nature of reinforcement corrosion, different types of models have been developed to describe this parameter. On the one hand side, there are empirical models that do not take into account the actual processes and mechanisms that occur. On the other hand, there are also models that focus on the electrical resistivity or oxygen diffusion resistance of concrete. Some of these models use additional correction factors to take into account other influences such as macro-cell action. Finally, several authors have used numerical models to simulate the corrosion process. There is no generally accepted model to mathematically describe the corrosion rate.

An example of an empirical model, is the model according to Vu & Stewart [18] and Stewart & Suo [19]. They state that the corrosion rate is determined by Eq. (1):

$$i_{corr}(t_p) = i_{corr}(0) \cdot 0.85 t_p^{-0.29} \tag{1}$$

where $i_{corr}(t_p)$ [μA/cm^2] is the corrosion rate at time t_p, t_p [years] is the time since corrosion initiation and $i_{corr}(0)$ [μA/cm^2] is the corrosion rate at the start of the corrosion propagation. The latter is calculated from:

$$i_{corr}(0) = \frac{2.7(1 - W/C)^{-1.64}}{a} \tag{2}$$

where W/C [–] is the water cement ratio and a [cm] is the concrete cover. Hence the corrosion rate only depends on the concrete composition through the water cement ratio and on structural properties through the concrete cover. It follows from Eq. (1) that the corrosion rate decreases in time, which is due to the formation of