Micro-to-macro mechanical modeling of corrosion-induced cracking

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Corrosion of reinforcement bars in concrete plays a significant role in determining a structure's durability and serviceability lifetime [1]. Chemical species (Fe2+, OH–) diffuse through the pore space of cementitious material and undergo various chemical reactions, which lead to the formation of corrosion products (Fe(OH)2, Fe(OH)3) within the pore space. Over time, these precipitates grow and exert pressure on the solid phase, which leads to fracture initiation and, ultimately, to the deterioration of a structure. In concrete, pore sizes range from nanometers to micrometers with a random spatial distribution. This stochastic nature is expected to influence the ionic diffusion in the pore network and the development of stresses in the matrix. Furthermore, the three mechanisms involved: ionic diffusion, chemical reactions and stress development, are strongly influenced by each other, and their interplay is thus crucial to fracture initiation.

Despite its importance, corrosion-induced cracking has mostly been studied with phenomenological models, which are calibrated for specific systems but cannot be easily generalized. Here, we propose a first-principle-based and thermodynamically-consistent micro-to-macro modeling approach for corrosion-induced cracking. Our model explicitly includes all relevant mechanisms, which are the release of ferrous ions at the steel-concrete interface, the diffusion of the products through the pores, the chemical reactions leading to the formation of rust (ferrous/ferric precipitates) [2], the stress build-up due to the pore-filling process, and finally the stress-induced damage of concrete when the material strength is exceeded. The pressure exerted on the pore walls due to a growing precipitate is quantified through the crystallization theory [3]. Our approach links the micro-mechanical processes (ionic diffusion, chemical reactions and stress development) with the macro-scale load-bearing capacity of the material and structure, and can be applied to any corrosion-susceptible system. Finally, we examine various properties of this complex heterogeneous system by analyzing the influence of the porous structure (porosity, pore size distribution) on the corrosion-induced cracking process and the overall material performance.

References

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