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Concrete creep and shrinkage effect in adhesive anchors subjected to sustained loads

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ABSTRACT

The safe design of fastening systems requires an accurate understanding of all time-dependent phenomena that may lead to damage or even failure during its service life of typically 50 years. Generally, safety and serviceability requirements are ensured through rigorous experimental testing during the approval phase. In the case of time-dependent phenomena, or more specifically the behavior under sustained load, the common practice of directly testing all critical service conditions fails. The long-term response can only be approximated e.g. by short-term structural system tests that are extrapolated to the full life-time utilising empirical models as required by current guidelines. These are based on the assumption of uniformly distributed bond stress along the anchor, attribute all creep deformations to the adhesive mortar, neglect the concrete creep contribution, and assume a stationary creep process represented by a power-law. Generally, it can be assumed that reliable predictions of the time-dependent behavior of complex systems can only be obtained by models that are derived from a systematic investigation of all involved factors and their interaction. In this study, specifically the effect of concrete creep and shrinkage on the long-term behavior of adhesive anchor systems, based on extensive experimental data and numerical analyses, is investigated. A state-of-the-art computational framework is applied which can explicitly model the underlying physical and chemical mechanisms at early age and beyond. The well-established Lattice Discrete Particle Model (LDPM) describes the time-dependent mechanical response of the structure considering the local maturity of concrete, temperature, and moisture content. After calibration and validation of the numerical framework, structural deformations owing to concrete creep, bond stress redistributions over time, and the gradual development of damage at higher load levels are discussed.

1. Introduction

Structural engineering requires a combination of many different technologies. Particularly, the necessity of connecting different structural elements, the assemblage of precast elements, and the attachment of non-load bearing components, makes fastening technology a key technology in modern construction. Consequently, fastening systems play a crucial role concerning the performance and safety of many structural elements and structures. The potential failure of single anchors might cause tremendous structural system damage. Thus, meticulous design both in terms of safety and serviceability is required. The failure of anchor elements could lead to disastrous incidents, potentially associated with casualties and large direct and indirect economic damage. This became evident from one of the rare disasters, the Big Dig ceiling collapse, on July 10, 2006. A series of installation mistakes can be found among the reasons for the accident. Nevertheless, one of the main probable causes was the poor creep resistance of the chosen epoxy based adhesive anchor product [1]. This incident highlights the necessity of precise long-term performance predictions as a crucial element of safe anchor design.

Fastening systems, as other construction products, have to undergo rigorous testing in course of an approval process to ensure their compliance with the established short-term and long-term performance criteria. The necessary tests for the approval of anchors can be found e.g. in [2,3]. Fasteners can be categorized according to the load transfer mechanism in (1) mechanical anchors, where the load is transferred in terms of mechanical interlock or friction, and (2) adhesive anchors, where the load is transferred in terms of bond [4] through a chemical adhesion agent. Currently, the long-term performance under sustained load is verified for bonded anchors only through relatively short sustained load tests on anchors systems. These are performed at standard and slightly elevated temperatures. The aforementioned typically

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1000–2000 h long tests yield deformation time series that are then extrapolated to 50 years utilising a power-law [5,6]. The performance criterion is formulated in terms of a displacement limit that is derived from short-term tests until failure [2,5]. In the last years, researchers have looked more closely into the long-term performance of adhesive anchors arriving at recommendations for testing and large sustained load reduction factors [7]. In parallel, a systematic review of the power-law extrapolation technique revealed possibilities to improve its robustness as discussed in [8,9] without need for further testing. Nevertheless, a clear understanding of the critical mechanisms that are necessary to safely extrapolate to unobserved configurations or situations is still missing.

In mechanical anchor systems long-term deformations under sustained load originate in the viscoelasticity of concrete. Adhesive anchors exhibit additional long-term deformations due to the viscoelastic nature of the bonding agents, i.e. the organic or inorganic adhesives also termed mortars. In current practice, only the latter contribution is considered and experimentally evaluated under the assumption of a constant bond stress distribution along the anchor threaded rod. This assumption follows from the so called uniform bond model that is used to design adhesive anchors at ultimate tensile capacity. When the embedment depth h_{ef} and the anchor diameter d have a ratio $4 \leqslant \frac{h_{ef}}{d} \leqslant 20$, and a maximum diameter $d_{max} = 50$ mm, the pull out strength of a single anchor N can be expressed as:

$$N = \tau \pi d h_{ef} \tag{1}$$

assuming that the bond strength τ is reached at all positions along the anchor length (uniform bond model).

An in-depth understanding of the long-term behavior of the aforementioned structural systems requires clear insights into the critical (damage) mechanisms and deterioration processes affecting the involved materials in course of time. Anchor systems are comprised of different materials, e.g. steel, concrete, adhesive mortars. Thus, a systematic approach requires the individual study of all mechanisms that occur in each material in course of time under loading and at various environmental conditions including, but not limited to, creep, shrinkage, thermal strains, and aging. Then, an application of the acquired understanding to the entire structural system should provide the required knowledge to predict and assess a structure's long-term performance.

Concerning the 50 year performance prediction of adhesive anchors under sustained load accurate results, especially under higher load levels, can only be expected if the chosen model accounts for (a) the visco-elastic response of both materials, (b) their aging nature, (c) a realistic stress distribution along the anchor, and (d) correct damage mechanics. The current approach based solely on the global response in structural system tests can only provide limited insights. The power-law extrapolation method was originally developed for the response of non-aging polymer materials. Therefore, it can not be expected to fully represent the complex response of structures such as bonded anchors installed in concrete [8,9]. Recently, a more refined approach was proposed by Kränkel et al. [10] using a rheological model to describe the viscoelastic response of adhesive anchor systems. This model is directly calibrated based on experimental data obtained in a number of different structural anchor tests. In spite of the achieved improved prediction quality in time, this model can not separate the deformation contributions of concrete creep, creep of the adhesive, or damage in either of the two materials. Furthermore, since an anchor installed in concrete is modeled in its entirety as a single structural component the actual bond stress distribution along the anchor and it's potential evolution in time are not accessible. Thus, only limited insights into the underlying mechanisms can be obtained.

Finite or discrete element analysis accounting explicitly for all relevant aspects (items a–d) and mechanisms can provide the required insights. However, the development, calibration and application of such more physically based approaches is also more challenging. For heterogeneous materials like concrete this requires the understanding of the main chemical and physical mechanisms that occur on lower scales – moisture transport and hydration – as they determine the evolving (aging) material properties, and drive creep and shrinkage. Similarly, the curing and aging kinetics of adhesive mortars have to be understood as they determine the visco-elastic response and damage mechanics of the adhesive layer.

The presented study investigates the influence of concrete creep (and shrinkage) on the long-term performance of bonded anchor systems based on numerical simulations calibrated to a large experimental dataset. In order to isolate concrete creep effects the mortar viscoelasticity is neglected on purpose in the numerical work. The computational framework couples different models in order to capture the physical and chemical phenomena governing concrete [11]. In particular, the Hygro-Thermo-Chemical model (HTC) [12,13] is used to solve the coupled hydration, moisture transport, and heat transfer problems. Furthermore, as introduced by Bažant [14,15] strain additivity can be assumed between creep strains, hygral strains, and thermal strains. The former can be modelled in a rate-type form based on the Micro-Prestress Solidification theory (MPS). The formulation also considers the changes of the material due to ongoing hydration. The mechanical response and damage are represented by a discrete concrete model, the well-established Lattice-Discrete-Particle-Model (LDPM) [16,17]. The used modeling framework is able to capture the apparent stress-dependence (non-linearity) of concrete creep due to damage. However, it is not able to accurately predict tertiary creep failure in its present form. An extension of the framework to include rate-dependent softening based on activation energy as proposed e.g. by Bazant and co-workers [18,19] would remove this limitation. This extension is necessary to study the creep effects on the bearing capacity. Although an important topic, this is not the focus of the present paper. Instead, this investigation aims at a quantification of the secondary concrete creep contribution to structural system deformations for which the current implementation suffices.

The investigation of the concrete creep and shrinkage effects on bonded anchor systems requires a number of different experiments on the material and structural scale. These also serve for the model calibration and validation. The subsequent sections present data on two concretes (termed concrete A and B) including full mechanical characterisations in terms of modulus, strength and fracture parameters at the ages of 3 and 28 days, respectively. Additionally, experimental data for the calibration of the multi-physics framework are presented. The experimental basis for multi-decade concrete simulations is introduced through the longest available creep time-series of concretes with similar composition that can be found in the literature [20,21].

Tests on adhesive anchors include (i) standard pull-out tests on slabs, both subjected to confined and unconfined conditions, (ii) sustained load tests in a controlled environment, again subjected to confined and unconfined conditions. The latter are accompanied by concrete creep and shrinkage tests. Representative for the multitude of products on the market, a typical vinyl-ester and a typical epoxy based adhesive mortar having approvals in the US and Europe are studied. For the purpose of this investigation, the properties of the adhesives are represented by purely elastic bond slip laws, abbreviated BL1 and BL2. The mortar viscoelasticity is intentionally neglected on the computational side in an attempt to isolate concrete effects.

2. Review of modeling framework

This paper uses a computational framework capturing most of the relevant physical and chemical phenomena of concrete in a coupled way. As a matter of fact, the chemical reactions of early age concrete (a), the moisture transport due to variable environmental conditions and self - desiccation (b), and the heat transfer related to different environmental conditions and to exothermic chemical reactions (c), are