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Prediction of the creep behaviour of bonded anchors until failure – A rheological approach

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HIGHLIGHTS

- A modified Burgers model was developed to predict creep of bonded anchors.
- The model takes nonlinear viscoelastic behaviour and material degradation into account.
- The model input parameters were experimentally determined on bonded anchors.
- The model enables the prediction of creep failure as well as the time-to-failure.

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ABSTRACT

This contribution presents a model which accurately describes the nonlinear viscoelastic deformation behaviour of bonded anchors under sustained load. The model consists of rheological elastic, plastic and viscous components which possess nonlinear material properties. Nonlinearities depending on the applied stress level, the duration of the load period and material degradation processes are included for this purpose. The values of the input parameters for the rheological components can be experimentally determined by three series of tests on bonded anchors. The model enables the prediction of primary, secondary and tertiary creep until failure as well as time-to-failure. It is therefore suitable for service-life prediction.

1. Introduction

Bonded anchors possess viscoelastic material behaviour. When subjected to short-term stress, the anchors respond in a stiff manner. Under sustained loading conditions, time-dependent deformation occurs, i.e. creep. Both, short-term and long-term deformations of bonded anchors are inherently nonlinear, which means that deformation behaviour depends on applied stress as well as age and degradation of the adhesive material. This has to be taken into account when considering service life. Since the fatal collapse of a suspended ceiling section in the Interstate 90 Connector Tunnel in Boston, Massachusetts on July 10th 2006, it is well known that an insufficient consideration of this non-linear creep deformation can lead to unexpected failure under sustained stress. In this case an epoxy anchor adhesive which was susceptible to creep and which therefore would not have been approved for this application, was used. Furthermore the failed anchors showed an improper or deficient installation. Both facts caused the collapse of the suspended ceiling section, NTSB [14]. Nevertheless, standards for testing the creep of bonded anchors exist for more than 20 years, i.e. ASTM E1512, which has been first established in 1993. The accident has provoked extensive research work on creep and creep failure of bonded anchors.

Current standards use a pass/fail approach to assess the ability of bonded anchors to withstand sustained loading conditions, Cook et al. [6,7]. Thus creep tests are carried out on bonded anchors under different conditions. The conditions vary from the given standard with regard to load level, duration and temperature (ambient/elevated) of the test. The measured displacements of the bonded anchors with time are extrapolated by fitting a creep function. The creep function may be a logarithmic function, as in ASTM E1512. [3] and AC58 [1], a power function (Findley Power

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Law) as proposed in ACI355.4 [2] and ETAG 001-5 [11] or a third degree polynomial as used by Ocel et al. [15]. To fulfil acceptance criteria for adequate creep resistance, the extrapolated displacement of the bonded anchors has to fall below a critical displacement which is determined in a static tension test (pull out test).

The approach described above has crucial disadvantages. Firstly, the value of the projected anchor displacement at the point in time which is used for the pass/fail evaluation depends on the creep function chosen, Cook et al. [6,7] and Davis [8]. In a 27-year creep study on bonded anchors, Eligehausen and Silva [10] pointed out significant differences between the projected creep displacements using a logarithmic and a power regression function as well as differences between the predicted and the measured creep displacement. Secondly, the pass/fail approach cannot predict the time-to-failure of bonded anchors under sustained load in dependence of external (e.g. load level or temperature) and internal conditions (e.g. anchor dimensions or type of adhesive). However, knowledge of the time-to-failure is essential for a more accurate estimation of the performance of bonded anchors in practice.

To solve this limitation Cook at al. [6] introduced the stress versus time-to-failure method. Therefore, a series of tests at varying sustained stress levels have to be performed and the time-to-failure recorded to create a time-to-failure chart in dependence of the applied stress, Cook [6,7] and Davis [8]. This method permits a service life prediction for bonded anchors based on extensive testing of the anchor systems under assessment. Disadvantageous for this method is the either required long duration of testing to create the time-to-failure chart or the necessity of a long-term extrapolation to get information for the whole service life.

In this contribution the service life of bonded anchors is determined by a rheological model. This model considers the nonlinear viscoelastic behaviour including the material degradation effects at high stresses as well as effects of the present temperature (ambient/elevated). Consideration of these product-specific effects enables the model to precisely predict primary and secondary as well as tertiary creep of the bonded anchors, Fig. 1. The advantage of this rheological approach is the predictability of both the bonded anchors displacement at any particular point in time and the time-to-failure, which is assumed to correspond by the beginning of tertiary creep. The predictability of this effective deformation behaviour of the anchors until failure at sustained loading conditions is an enhancement compared to the pass/fail approach of the current standards, where conservative service life estimation is given.

2. Rheological model for non-linear creep of bonded anchors

Linear viscoelastic material behaviour is usually described by the well-known Burgers model. The model consists of two parts in series connection: a Maxwell element (spring and dashpot in series connection) and a Kelvin/Voigt element (spring and dashpot in parallel connection), Fig. 2.

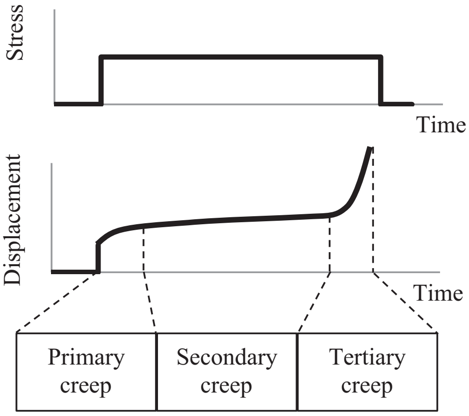

Fig. 1. Three stages of creep.

The time-dependent strain $\varepsilon(t)$ for the Burgers model at constant stress τ is given by Eq. (1).

$$\varepsilon(t) = \frac{\tau}{E_1} + \frac{\tau}{\eta_1} t + \frac{\tau}{E_2}\left[1 - \exp\left(-\frac{E_2}{\eta_2} t\right)\right] \tag{1}$$

Here, E_1 and E_2 are the Young's moduli of the spring elements and η_1 and η_2 the coefficients of viscosity of the dashpot elements. The first two terms of Eq. (1) represent instantaneous elastic strain and viscos flow of the Maxwell element. The last term represents the delayed elastic deformation of the Kelvin/Voigt element.

Since the anchors possess nonlinear viscoelastic material behaviour, the Burgers model was modified. Therefore, the Young's moduli of the spring elements and the coefficients of viscosity of the dashpot elements of the model follow nonlinear laws. Additionally, plastic deformations have to be considered.

The modification of the model implies three aspects, nonlinearities depending on (a) the applied stress level, (b) the duration of the load period and (c) the material degradation processes.

2.1. Nonlinear stress dependency

Under short term loading the total deformation of bonded anchors consists of elastic as well as plastic components, Eq. (2).

$$\varepsilon = \varepsilon_{el} + \varepsilon_{pl} \tag{2}$$

To take the plastic components into account, the Hookean springs were transformed into elastic–plastic deformation elements with a deformation modulus E_p. To consider the nonlinearity of the elastic and plastic components the deformation modulus is described by a stress dependent function, Eq. (3).

$$E_{p1} = E_{p2} = E_p(\tau) \tag{3}$$

The elastic deformation component ε_{el} is due to movements of macromolecular structure of the polymer used as adhesive. Under tensile loading, the polymer molecules deviate from their energetically advantageous location and stretch out instantaneously, Hellerich et al. [13]. This causes an increasing distance of the atoms and the distortion of the valence angles in the macromolecules of the polymer, Ehrenstein [9]. Upon unloading, the molecules slide back in their initial position. The process is thus reversible, Hellerich et al. [13].

In contrast the plastic deformation component ε_{pl} is a result of short-term material degradation processes such as micro cracking in the polymeric adhesive (cohesive capacity) and initiating loss of adhesion at the interfaces anchor rod/adhesive or adhesive/concrete (adhesive capacity). It is therefore irreversible.

At low stresses the plastic component is negligible. As the stress increases plastic deformation raises significantly. In the range of stresses, relevant for practical application, the elastic deformations are roughly proportional to the applied stress, whereas the plastic deformations increase slightly disproportionate. At stress levels close to the load bearing capacity a strong disproportionate increase of irreversible plastic component of the total anchor deformation occurs.

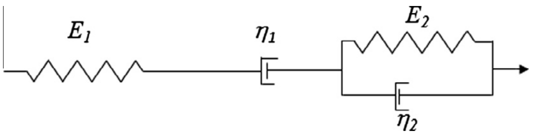

Fig. 2. Burgers model for viscoelastic behaviour.