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Bonded Anchor in Concrete under Sustained Load

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ABSTRACT

The use of bonded anchors in engineering practice is continuously increasing. However, due to the complexity of the load-transfer mechanism and use of new chemical adhesives, their safety under sustained load is still not clear and it is the topic of intensive research. In the present paper the results of a 3D finite element parametric study for a single bonded anchor loaded under sustained tensile load are presented and discussed. The numerical model is first calibrated based on the experimental tests and subsequently the parametric study is carried out. The influence of geometry, fracture properties and creep of concrete and chemical adhesive (epoxy) on the behavior of anchors under sustained load is investigated. The results of the study show that fracture of concrete and its interaction with creep of concrete has dominant influence on the resistance and behavior of anchors under sustained load. Moreover, the behavior of bonded anchors under sustained load is more sensitive if the ratio between the strength of chemical adhesive and concrete increases. It is shown that the most critical situation is the use of high quality polymer in a low quality concrete. With this respect further experimental and numerical studies are needed.

INTRODUCTION

Bonded anchors transfer the load from metallic anchor or rod into a concrete member over the chemical adhesive (e.g. epoxy). Their behavior is dependent on embedment depth, concrete properties, properties of steel used for the threaded rods, properties of chemical adhesive (strength and stiffness) and boundary conditions1,2,3. Similar to mechanical anchors, design of bonded anchors is based on the Concrete Cone capacity method1,4,5. However, with respect to the sustained load there are two important differences between mechanical and bonded anchors: (i) Time deformation of mechanical anchors (headed stud, post-installed undercut or expansion anchors) is due only to the contribution of concrete. In bonded anchors, instead, time deformation comes from the contribution of concrete and chemical adhesive.

Therefore, it is not surprising that the behavior of bonded anchors under sustain load is more sensitive than the behavior of mechanical anchors. (ii) Mechanical anchors transfer the load from the anchor into the concrete as a point load relatively deep into a concrete member. However, bonded anchors transfer the load over the chemical adhesion through the entire anchor length. From the fracture mechanics point of view, failure mechanism of mechanical anchors belongs into the category of the so called negative geometries, i.e. with the increase of the crack length, stress intensity factor at the crack tip decreases. Therefore, when at constant load the crack length increases, for instance due to creep of concrete, resistance is not decreasing. However, in bonded anchors there is a redistribution of stresses between concrete and chemical adhesive over the entire embedment depth, which generally leads to decrease of anchor resistance under sustained load.

Due to the above mentioned differences between mechanical and bonded anchors, the design of bonded anchors with respect to the sustained load is more demanding than the design of mechanical anchors. It is still not clear how the effect of creep of concrete6 and chemical adhesive7 should be accounted for in order to design save and economical fastenings. The main aim of the present study is to investigate, in the qualitative sense, the factors that are responsible for the failure of bonded anchors under sustained load

Constitutive law and FEdiscretization

Numerical simulation is performed using 3D finite element (FE) code MASA9. The constitutive law for concrete is the micro plane model with relaxed kinematic constraint10. Polymer (epoxy) is modeled by the recently proposed microplane model for metallic kind of materials11, assuming to be friction insensitive. Principally, creep of concrete and polymer is simulated based on the linear rate- type creep law (generalized Maxwell chain model) with eight age dependent units12. It is coupled into a series with the microplane model . In this way the total strain is decomposed into elastic, damage (microplane) and creep component..

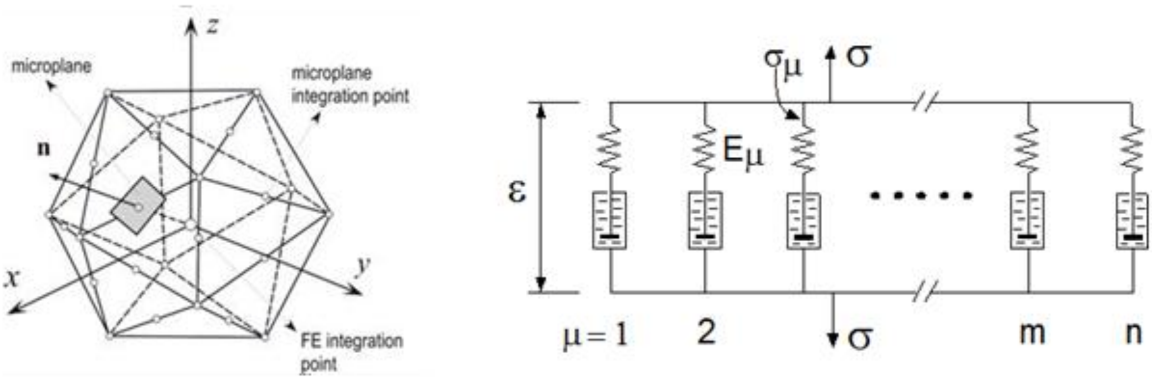

Fig. 1: Serial coupling of microplane model (left) and generalized Maxwell chain model (right)

Creep strain from the Maxwell chain model is assumed to be linear proportional to stress. For concrete and polymer this is approximately valid if the stress level compared to strength is relatively low. However, at higher stress levels there is the interaction between non-elastic strains (creep) and damage, which leads to progressive creep deformations, i.e. non-linear creep (creep-fracture interaction). To account for non-linear creep, here is proposed relatively simple approach.

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$$\varepsilon_{creep} = f(\sigma)\, \varepsilon_{creep,linear} \qquad (1a)$$

$$f(\sigma) = 1.0 \qquad \text{for} \qquad \sigma_{vM} \leq \alpha f_{c,R} \qquad (1b)$$

$$f(\sigma) = 1.0+50\left(\frac{\sigma_{vM}-\alpha f_{c,R}}{(1-\alpha) f_{c,R}}\right)^2 \qquad \text{for} \qquad \alpha f_{c,R} < \sigma_{vM} \leq f_{c,R} \qquad (1c)$$

With $f_{c,R} = f_c\,(0.80-(3\sigma_V/5f_c))$ (1d)

where σ_{vM} = von Mises stress, σ_V = volumetric stress, f_c = uniaxial compressive strength, $f_{c,R}$ = uniaxial confined compressive strength and α = proportionality limit.

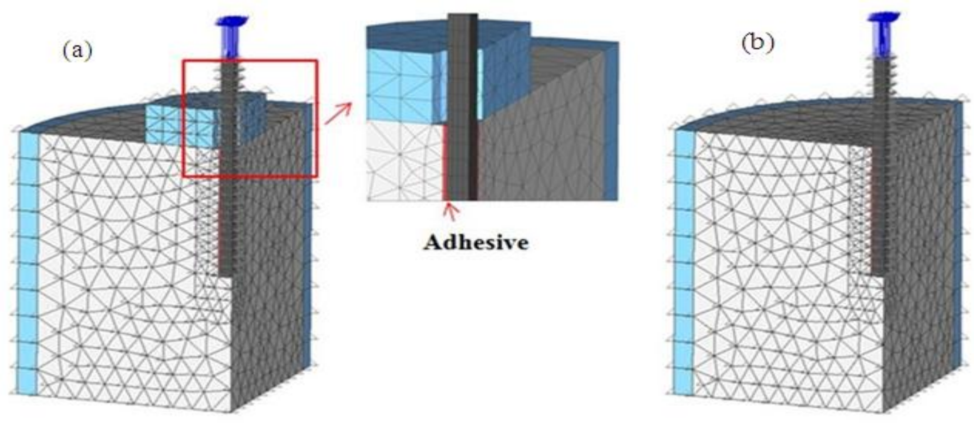

Fig. 2: 3D FE discretization hef/d = 6: (a) confined specimen and (b) unconfined specimen.

The typical FE discretization of the experimentally tested geometry is shown in Fig. a. The discretization is performed using 3D eight (polymer, anchor and external steel cylinder) and four nodes finite elements (concrete and supporting steel plate). Figure b shows the model in which the internal steel plate is removed and supports are imposed at the top of the external steel cylinder (unconfined specimen). The load is applied at the top of the anchor, either through displacement control (instantaneous loading) or by load control (sustained load). To assure results independent of the element size the regularization based on the simple crack band method is employed13

PARAMETRICSTUDIES

After the calibration of the numerical model a parametric study are performed. In the first part of the study the material properties for concrete and polymer are kept constant and only embedment depth is varied: hef/d = 4, 6 and 8. The analysis is performed for confined and unconfined conditions and the level of sustained load is varied from 30% to 85% of the short term resistance.

The typical load-displacement curves for short term loading are shown in Fig. 3. By reducing the sustained load level from 85% to 30%, the time to failure gradually increases and under a certain load level (strength under sustained load) no failure occurs. Similar results are obtained for all configurations and for both confined and unconfined specimens. However, the limit on the sustain strength is higher for unconfined specimen, i.e. 50% for confined and 65% for unconfined specimen. The reason is due to the fact that for confined specimen the load transfer from the anchor into concrete is localized along the anchor length and von Mises stresses are approximately constant. Consequently, no redistribution of shear stresses over the anchor length is possible.

In unconfined specimen, instead, the distribution of von Mises stresses over the anchor length is not uniform (see Fig. 9b). Therefore, due to the creep of concrete and polymer, the redistribution of stresses is possible with the consequence that the strength under sustained load is higher, i.e. 65% of short term loading resistance instead of 50% in case of confined anchor. The influence on the sustained strength in unconfined specimen is stronger especially for higher load levels. The reason is due to the fact that for smaller embedment depth the possibility for redistribution of stresses due to creep-fracture interaction is lower than in case when the embedment depth is larger.

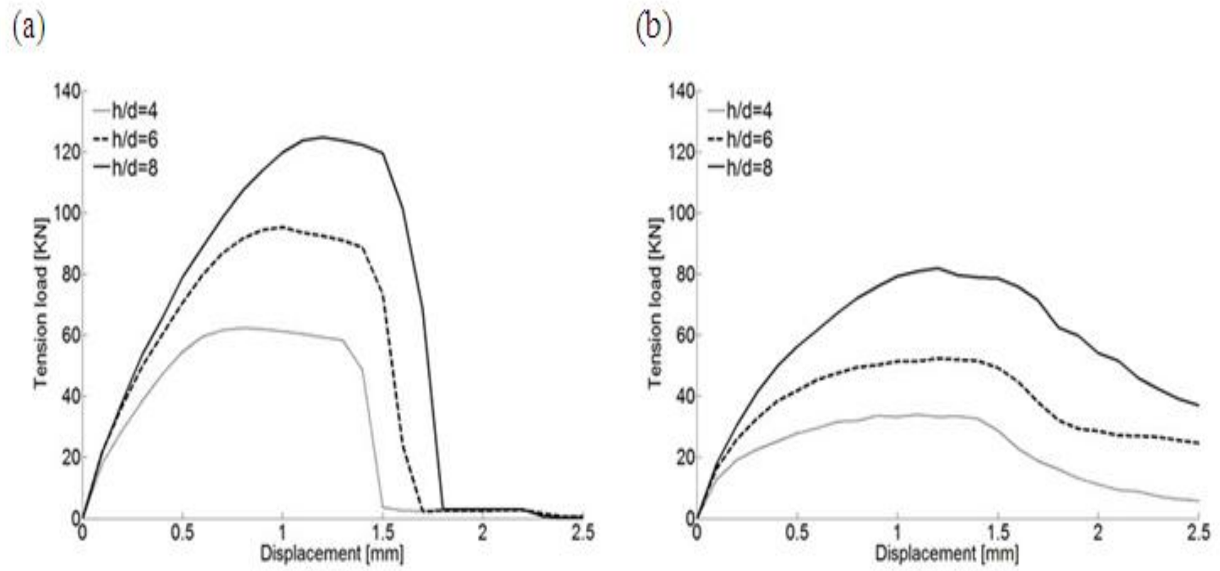

Fig. 3: Load-displacement curves for different embedment depth: (a) confined and (b)unconfined specimen

The typical distribution of damage in concrete in terms of maximum principal strains, which corresponds to the crack width of approximately 0.25 mm, is for sustained load level of 65% and hef/d = 8 shown in Fig. for confined and unconfined specimens. Because of the non-elastic deformations due to creep of concrete and polymer there is an increase of concrete damage in time, which finally leads to failure. This is the case for both, confined and unconfined specimens. However, in the confined specimen damage is localized in the concrete elements along the embedment depth with the stresses level that is almost constant over the entire length (see Fig. 4).

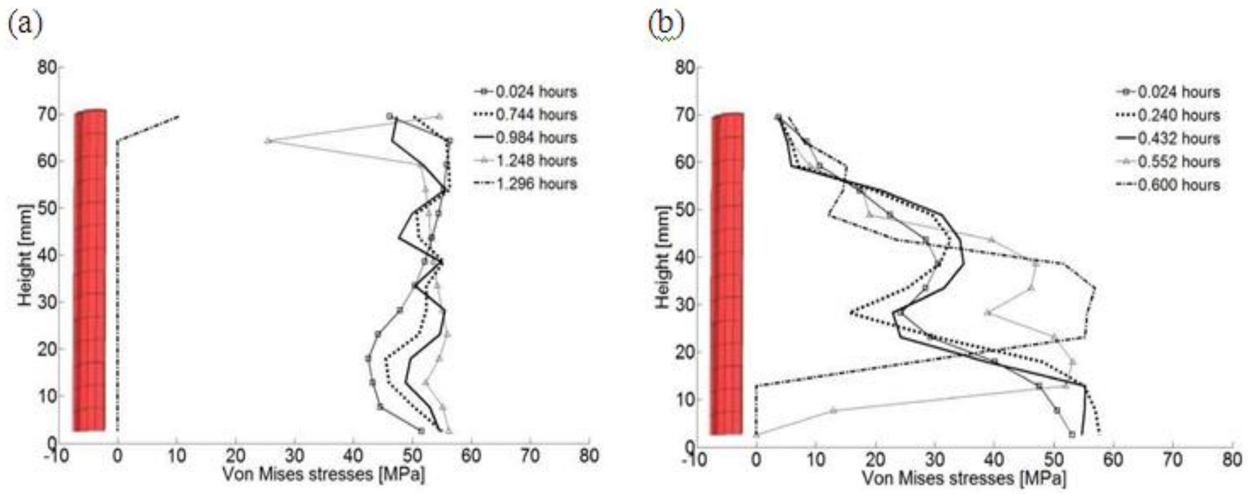

Fig. 4: Distribution of von Mises stresses in the polymer over the embedment depth for hef/d = 6 and sustained load level 85%: (a) confined and (b) unconfined

The failure of confined anchor is due to the pull-out. In unconfined specimen maximum damage is observed at the bottom of the anchor. Due to creep it propagates in time along the anchor depth and inclined cracks (concrete cone) forms with the final failure mode that is a combination of the pull-out and concrete-cone failure. Consequently, in contrary to the confined anchor, for unconfined anchor the redistribution of stresses along the anchor depth is possible, which explains why the sustain strength is higher. As can be seen from Fig. 9b, due to the redistribution of stresses, the peak stress is moving from the bottom of the anchor into direction of concrete surface. The maximum von Mises stress in polymer in both cases is approximately the same, however, for unconfined anchor it is located only at the bottom of the anchor whereas for confined anchor maximum stress is distributed over the entire anchor length.

Tab. 1 Uniaxial compressive and tensile strength varied in the analysis

Case	Concrete		Polymer
	Uniaxial Compressive strength (MPa)	Tensile strength (MPa)	Compressive & tensile strength (MPa)
Case 0 (Experimental test)	26.0	2.60	60.0
Case 1	50.0	5.00	60.0
Case 2	50.0	5.00	30.0
Cass 3	26.0	2.60	30.0

From the above numerical results, it is obvious that creep of concrete and polymer significantly influence the sustained resistance of chemical anchors. However, it is not clear whether creep of concrete, polymer or both is responsible for relatively strong degradation of resistance under sustained load. To investigate this, the parametric study for the case hef/d = 6 and sustained load of 85% and 65% is carried out. In the study the following cases are investigated: (1) creep of both, concrete and polymer, is considered; (2) only creep of polymer; (3) only creep of concrete and (4) creep of both materials but concrete is assumed to be linear elastic.

The results are plotted in Fig. 5 in terms of displacement history curves. They clearly indicate that in most cases the interaction between creep of concrete and non-linear behavior of concrete (damage and cracking) is responsible for strong reduction of the strength under sustained load. Only in case of relatively high sustained load (85%) and unconfined anchor the influence of creep of concrete and polymer is practically the same and almost independent of damage in concrete.

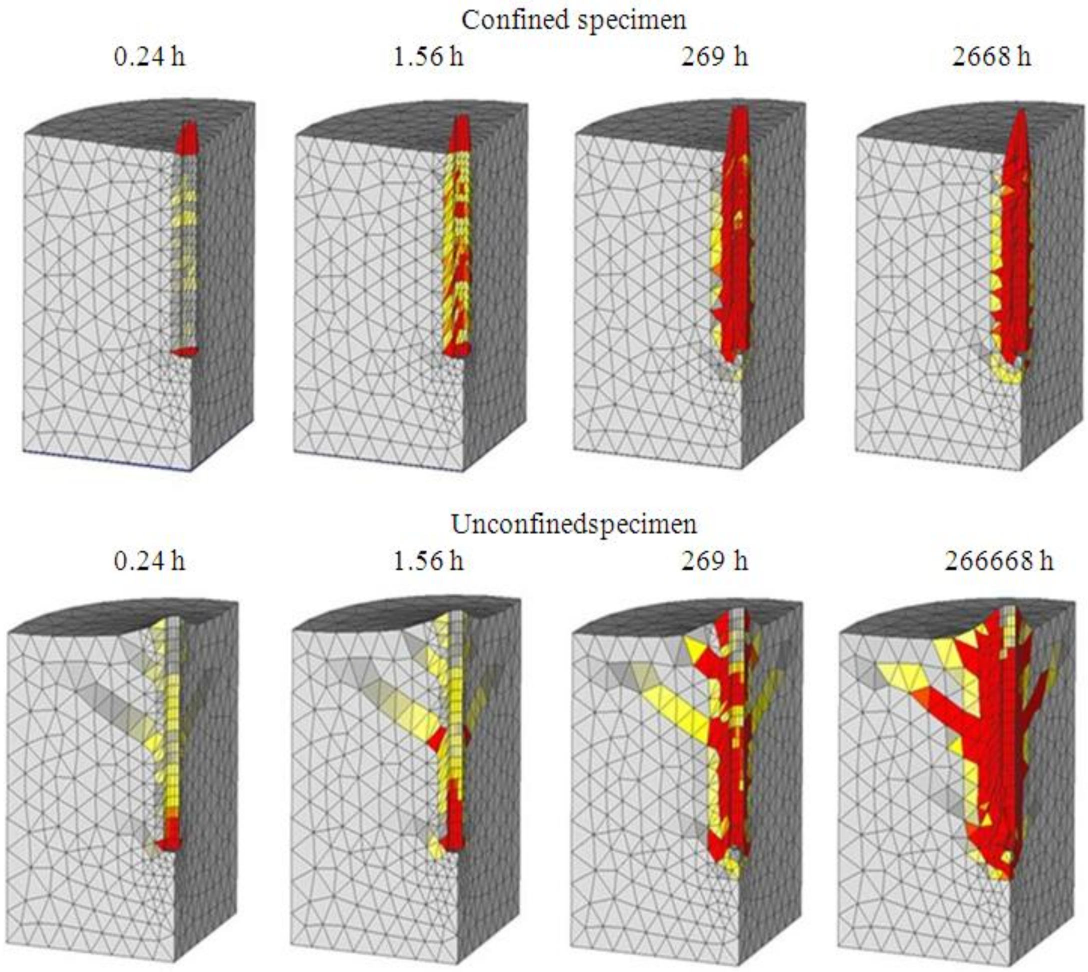

Fig. 5: Development of damage with time (hef/d = 8, 65% of sustain load), confined (top) and unconfined (bottom) (red zone corresponds to crack width of 0.25 or greater)

In further parametric study the influence of material properties (uniaxial compressive and tensile strength) on the resistance of anchors under sustained load is investigated. The material properties for the analyzed cases are summarized in Tab. 2. Note that all other properties are the same as specified in Tab. 1. The analysis is carried out for hef/d = 6 (confined and unconfined anchors).

The short-term load-displacement curves for all cases, as summarized in Tab. 2, are plotted in Fig. 12. As expected, with increasing strength of concrete and polymer the anchor resistance increases. For the confined specimen the resistance is directly proportional to the strength of polymer and concrete has almost no influence.

CONCLUSIONS

In the present study the influence of creep of concrete and polymer of chemical anchors is numerically investigated. Based on the results of numerical study the following can be concluded. (1) The employed numerical model, which is calibrated based on the experimental tests, is able to realistically replicate the response of anchors for instantaneous and sustained load; (2) It is demonstrated that the behavior and resistance of anchors under sustained load is mainly controlled by creep of concrete that interacts with damage; (3) For confined anchors no redistribution of shear stresses over the anchor length is possible. However, in case of unconfined anchors such redistribution is possible with the consequence that for relatively high load level the time to failure increases.

Moreover, the sustained strength for unconfined anchors is higher; (4) For unconfined anchors time to failure decreases with decrease of embedment depth. Confined anchors are less sensitive on the embedment depth due to the fact that the stress distribution over the anchor length is almost constant; (5) The most critical situation for bonded anchors occurs when the strength of polymer is much higher than that of concrete. In such cases stresses and damage of concrete is relatively high, which cause significant creep induced damage of concrete (non-linear creep) and leads to strong reduction of resistance; (6) Further experimental and numerical studies are needed in order to investigate the influence of material properties, geometry and environmental conditions on the resistance of bonded anchors under sustained load.

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