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Creep behaviour of tension loaded adhesive anchors in noncracked low strength concrete

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Abstract. Post-installed anchorages or reinforcements using bonding adhesives are invariably used in the present day construction industry. Although, various attempts to develop a generalized theory for design and analyses of adhesive anchorages have been made, the actual anchorage behaviour is still considered to be dependent on the adhesive product in use. The creep behaviour of adhesive anchors were investigated again intensively after several failure were observed. Several research experiments in this regard are performed by different researchers to establish a new procedure of failure accounting the creep effects of adhesive anchors. This work discusses the results of an experimental program undertaken at the University of Stuttgart, for establishing the time-to-failure behaviour under sustained loads for two different adhesive anchor products. The complete test program included reference pull out tests to evaluate the ultimate capacities. Sustained load tests were performed for the load levels corresponding to 85%, 75% 65% and 55% of the ultimate capacity observed in the reference tests. The test program also included sustained loading tests at different temperature conditions like ambient temperature (23°C) and moderately high temperature (43°C). A comparison of the creep behaviour for standard and sub-standard installation condition was also included in the test program to see the effect of a reduced installation cleaning process. In this paper, the results for standard installation with ambient temperature of 23°C are used to demonstrate the sustained load effects in the framework of time-to-failure behaviour. The possibility of arriving at a safe load level which can be sustained throughout the design lifetime of 50 years is discussed using the time-to-failure curves.

1. Introduction

The utilization of post-installed fasteners and reinforcements using bonding adhesives has gained considerable popularity in the reinforced concrete (RC) construction industry. Various aspects related to analysis and design of post installed adhesive/bonded anchors have been covered in [1, 2]. In spite of the attempts to develop a general theory for design and analysis of post installed adhesive anchors in concrete, the actual behaviour is typically considered as product dependant. In this context, based on the mandatory assessment procedures [3, 4], each adhesive anchor system has to be qualified for use.

The creep behaviour of adhesive anchors came under the limelight of research following the 2006-Boston Tunnel Accident [5-7], where partial collapse of the tunnel ceiling took place because of the creep failure of the employed adhesive anchors. The incident raised several questions related to behaviour of adhesive anchors under sustained loads, and called for reliable evaluation procedures that could ensure the necessary durability of the adhesive anchor systems. Experimental investigations are

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reported by different researchers [8-10] in this regard, with an objective to establish a procedure accounting the creep effects of adhesive anchors. Analytical studies investigating the creep behaviour of adhesive anchors [11, 12] have also been reported.

2. Current state-of-the-art consideration of creep of adhesive anchors

In the US, ACI 318 [1] provides the procedure for design of adhesive anchors, and the design values required therein are obtained using the evaluation and testing procedures provided by ACI 355.4 [3]. In Europe, EN-1992-4 [2] deals with the design of adhesive anchors using the parameter values obtained through evaluation and test procedures prescribed in EAD 330499 [4]. The procedure adopted for evaluation of a safe load level that could be sustained throughout the service life is essentially same in both US and Europe. Both codes [3, 4] propose independent expressions for a level of safe load N_{sust} . Under the calculated sustained load, displacement-time curves are evaluated through the prescribed test procedures. An extrapolation of the displacement is done as a power function of the time, in order to evaluate the projected displacement at the end of service life (typically 50 years). The assessment criteria for safely sustaining the loads is the condition that the projected displacement should be lesser than the limiting displacement at loss of adhesion evaluated using the reference tests. If the assessment criteria is not satisfied, the level of N_{sust} is reduced by a factor α_{sust} and the test procedure is repeated until a safe load level satisfying the displacement criteria is obtained. It is noted here that the sustained load behaviour is product-dependent and each adhesive anchor product is evaluated independently.

3. Research motivation and objectives

The current process described above, is iterative in nature. The minimum duration of sustaining the load is set at 42 days (1000h) by ACI 355-4 [3]. EAD 330499[4] sets the requirement to 90 days (a little over 2000h). Hence, the number of iterations, typically multiplies the time required for obtaining the results. Furthermore, higher the number of iterations, higher is the testing cost. As a consequence, the levels of sustained loads are deliberately reduced during testing in a way to arrive at a level satisfying the assessment criteria in a minimum number of iterations. This off course could introduce an additional conservative factor into the design, the value of which is unknown (since the highest possible level of load which satisfies the assessment criteria is not known).

In the present study, the sustained load behaviour is observed in the framework of the time to failure curves. To this end, an experimental program undertaken at the University of Stuttgart in order to study the behaviour of two different adhesive anchor products (one epoxy based adhesive and other vinyl based adhesive) subjected to sustained loads is briefly described, and its findings are discussed. The parameters varied in the experimental investigation were ambient temperature and quality of installation. In this paper, the tests at ambient temperature with standard installation are discussed for both the products. The objective of the experiment program was to establish the time-to-failure curves governing the creep behaviour of the two adhesive anchor systems. Using the time-to-failure curves, attempts are made in this paper to arrive at a safe level of load which can be reliably be sustained throughout the service life of 50 years.

4. Test program and results

This paper discusses the results for the two adhesive anchor products (epoxy and vinyl type), for ambient temperature of 23°C and standard installation as per the manufacturer's instruction. The program included short term tests (confined tension) for evaluation of the ultimate capacity N_u (See table 1). Sustained load tests were performed for level of sustained load corresponding to 85%, 75% and 65% of the average ultimate load N_u from the short term tests. If failure of specimen was observed for the sustained load test with lowest load (65%) in the duration of 3000h, the tests at a further lower load level of 55% were conducted. Otherwise, the tests at 55% were not done.

The geometry of specimen used for all the tests shown in table 1 is shown in figure 1. The specimen was provided with a steel cylinder in order to achieve the essential confinement from the side to avoid any concrete type failure and ensure bond as the governing failure mode. The schematic arrangement for the test set-up for the short term load tests is also shown in figure 1. The top surface of the specimen was also confined using a steel plate in the test set-up.

Temperature	Test Type	No. Test Epoxy (nomenclature)	No. Test Vinyl (nomenclature)
23°C	Short Term	5 (E-T23-REF-1to5)	5 (V-T23-REF-1to5)
	Sustained at 85%	3 (E-T23-85-1to3)	3 (V-T23-85-1to3)
	Sustained at 75%	3 (E-T23-75-1to3)	3 (V-T23-75-1to3)
	Sustained at 65%	3 (E-T23-65-1to3)	3 (V-T23-65-1to3)
	Sustained at 55%	3* (E-T23-55-1to3)	3* (V-T23-55-1to3)

Table 1. Details of test program	with standard	installation	at 23°C.
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* Performed only when failure was observed at level of 65% of ultimate capacity



Geometry of the Specimen

Schematic Test Set-up for Short Term Tests

Figure 1. Geometry of specimen, and test set up for short term load.



Figure 2. Short term conned tension test results for the epoxy and vinyl type anchor products.

The load displacement curves obtained from the short term tests are shown in figure 2. The epoxy based adhesive anchor system was found to have mean ultimate capacity of 97,15kN (variation of 3,0%) and the displacement at ultimate (ultimate displacement) of 1,162mm (variation of 4,8%). The displacement at loss of adhesion was evaluated as per the provisional guidelines [3, 4] to be 0,71mm (variation of 29,6%). The vinyl based adhesive anchor system was found to have a mean ultimate capacity of 67,13 kN (variation of 3.7%) and the ultimate displacement of 0,770 mm (variation of 2,4%). The displacement at loss of adhesion was evaluated as per the provisional guidelines [3, 4] to be 0,65mm (variation of 16,6%). It is noted here that for both the adhesive anchor products tested in this work, the scatter in the value of displacement at loss of adhesion is much higher than that in case of ultimate displacement (displacement at ultimate load).

			Time to
Туре	Nomenclature	Status	failure
			[h]
	E-T23-85-1	Failed	0,07
	E-T23-85-2	Failed	0,06
	E-T23-85-3	Failed	0,10
	E-T23-75-1	Failed	0,26
	E-T23-75-2	Failed	0,93
Fnovu	E-T23-75-3	Failed	0,29
Ероху	E-T23-65-1	Failed	214,55
	E-T23-65-2	Failed	17,64
	E-T23-65-3	Failed	126,07
	E-T23-55-1	Unloaded	3000,00
	E-T23-55-2	Unloaded	3000,00
	E-T23-55-3	Unloaded	3000,00

Specimen Centering Fixture Plate #3 Plate #3 Displacement Transducer Connecting Fixture Tie rod Central Shaft of springs Plate #2 Compressible steel springs Plate #1 Fixture to center Tie rod Plate #0 Reference horizontal plate

 Table 2. Time-to-failure data obtained from tests.

Туре	Nomenclature	Status	Time to failure
Vinyl	V-T23-85-1	Failed	[h]
	V-T23-85-2	Failed	0,14
	V-T23-85-3	Failed	6,62
	V-T23-75-1	Failed	125,22
	V-T23-75-2	Failed	0,34
	V-T23-75-3	Failed	46,24
	V-T23-65-1	Unloaded	3000,00
	V-T23-65-2	Unloaded	3000,00
	V-T23-65-3	Unloaded	3000,00

The load levels corresponding to 85%, 75% and 65% of the evaluated average ultimate load for the respective anchor system (epoxy/vinyl) was calculated, and used for sustained load tests. The test set-up used for sustained load tests is shown in figure 3. The sustained load of different levels was applied using compressed springs. This test set-up was developed at Institute of Construction Materials, University of Stuttgart, and the related details are documented in [9]. The set-up again simulated confined tension state for the adhesive anchor. The displacement at the tip of the anchor was monitored continuously using a potentiometer. The minimum duration of sustaining the load was set to 3000h. Cases with higher percentage (85% and 75% of Nu) of ultimate load were expected to fail. The intention of the test process was to note the time to failure as a function of the percentage of ultimate load. This required that for the lowest force level, the specimens should not fail in the test duration. For specimens which did not fail till 3000h the time to failure was noted as 3000+. The obtained time to failure data for the epoxy and the vinyl based adhesive anchor systems is shown in table 2. For the epoxy based anchor, all the specimens loaded to 65% of the ultimate load failed. Hence, sustained load tests at 55% of the ultimate load were performed to attain the load level at which the specimens did not fail in the sustained load duration of 3000h.

5. Discussion of results

The objective of the test program was to investigate the sustained load behaviour of adhesive anchor systems in the framework of time-to-failure behaviour. It can be seen clearly from table 2, that the time-to-failure is inversely proportional to the load sustained. In visualizing the time to failure behaviour over a period of 3000h for different level of sustained loads, the points of time to failure are plotted against the percentage of ultimate load for the epoxy and the vinyl systems in figure 4. For the lowest level of load, in which no failure was observed in the test duration of 3000h, the time-to-failure is conservatively assumed to be 3000h, although the actual time to failure is higher and not known. To the plotted points, a power function relating the long term load level N_{μ} to the corresponding time to

failure T of the form $N_{lt} = A \times T^{\alpha}$ is fitted, where A and α are constants determined based on the data points. With this exercise, it is possible to arrive at an average level of load for both the anchors, having time to failure equal to 438000 hrs (50 years). This load level as evaluated for the epoxy based adhesive anchor system is 46,4% and that for the vinyl based adhesive anchor system is 58,6%. It is noted here that since the time-to-failure for the lowest sustained load level in the test program was conservatively assumed to be 3000h, the fitted curve and hence the values of load level having time to failure of 50 years are also on the conservative side.



Figure 4. Time-to-failure behaviour as observed from sustained load tests.

Thus the process of testing described in this work offers an opportunity to arrive at the highest level of load at which failure does not occur till a duration of 50 years of service life. This work presents an overall approach in terms of mean level of loads. For design applications it is essential to express the time-to-failure variation in terms of the characteristic values, by treating the test data statistically. The procedure offers the possibility of an alternate assessment criteria in terms of the time to failure behaviour for sustained load behaviour of adhesive anchors.

The average level of load obtained using the described procedure does not necessarily satisfy the criteria prescribed by the provisional guidelines which is in terms of the critical displacements corresponding to loss of adhesion. This is because the time-to-failure behaviour described so far, does not account for the displacement behaviour. In order to consider the displacement behaviour the time to attain certain level of displacement can be expressed as a function of the load sustained. The displacement corresponding to ultimate load (ultimate displacement) and the displacement corresponding to loss of adhesion evaluated from the short term tests are used here as the reference displacement levels. Since continuous displacement measurement is performed in the sustained load tests, it is possible to determine the time at which the displacement reaches the limiting displacement at loss of adhesion and the time to ultimate displacement is plotted against the sustained load level (expressed in terms of percentage of ultimate) in figure 5 for the epoxy type adhesive anchor system. Here again, a power function relating the long term load level N_{μ} to the corresponding time to loss of

adhesion T of the form $N_{lt} = A \times T^{\alpha}$ is fitted for each curve, where A and α are constants determined based on the data points. Using the fitted expression the load level corresponding to the time to loss of adhesion of 43800 hrs (50 years) is extrapolated to be 41% of the average ultimate load. In a similar way, the load level corresponding to the 50 years' time to reach the ultimate displacement is estimated to be 43% of the average ultimate load. Through this procedure, it can be stated that the criteria of displacement at loss of adhesion is likely to be met at about 40% of the ultimate capacity for the epoxy anchor product tested in this work. Thus, the presented test procedure also offers an estimate of the load level which corresponds to N_{sust} .



Figure 5. Time-to-displacement curves for epoxy based adhesive.

The scatter in the displacement values at loss of adhesion is much higher than that in case of displacement values at ultimate load. Hence, having the displacement at ultimate load as governing criteria appears to be more reasonable. It is noted here that, in comparison to the iterative process required by the current provisional guidelines, the presented process is relatively less time consuming, and is capable of providing an estimate for the highest possible load level that can satisfy the critical displacement criteria.

6. Conclusions

The approach of assessment of sustained load behaviour of adhesive anchors in the current provisional guidelines is based on an iterative procedure to arrive at a level of load which can be sustained in a way that the displacement extrapolated from the resulting displacement-time graph is below the displacement at loss of adhesion from the reference short term tests. The tests are time consuming, and with each iteration, the time to obtain the results is multiplied. In order to optimize the evaluation procedure, the tests are deliberately performed at lower levels of sustained loads, so that the assessment criteria is satisfied in, as less number of iterations, as possible.

The present paper discussed the evaluation of sustained load behaviour from an alternate perspective of time to failure curves. The test procedure was aimed at obtaining the time to failure as a function of the level of sustained load. The test matrix is extended, if needed, in a way that, for the lowest level of sustained load, no failure is observed during the sustained load duration of 3000h. Using the time-to failure data as a function of the sustained load level, the process to arrive at a level of load with time to failure equal to the service life was obtained. This level of load corresponds to the one at which failure under sustained load is not expected till the end of service life.

The test set up offered continuous measurement of the displacement data. This made it possible to evaluate the time at which each specimen reached the displacement at loss of adhesion as well as the ultimate displacement. The resulting time-to-displacement curves were extrapolated to evaluate a level of load at which the time to reach loss of adhesion and ultimate displacement was equal to the service life. In this way, an estimate of the level of load which could satisfy the assessment criteria is obtained. Since in the test observation, the scatter in values of displacement at loss of adhesion is significantly higher in comparison to that in case of displacement at ultimate capacity, it appears more reasonable to express the assessment criteria in terms of ultimate displacements.

It is noted here, that the paper is aimed at demonstrating an alternate perspective for evaluation of sustained load behaviour of adhesive anchors. The results presented are preliminary and limited in nature. It is essential to consider additional parameters, and further develop the evaluation process that is introduced here.

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