A passing sustained load test is one for which the extrapolated displacement is less than the displacement defined as loss of adhesion for the anchor.

With this approach it is verified that the system does not fail under a sustained load of approximately 1.6 times of the design load.

This approach is based on two assumptions: first, that the Findley extrapolation to 50 years (438,000 hours) from data derives over a period of 1008 hours is conservative; and second, that the displacement at loss of adhesion as derived from short-term tests in accordance with Figure 3 represents a conservative estimate of the failure displacement. There has recently been a general discussion regarding how accurate and conservative these assumptions are and subsequently how safe the adhesive anchors that are loaded according to the corresponding approvals and evaluation reports generated from these tests actually are in practice. In order to gain more knowledge on the real safety level of the evaluated adhesive anchor systems, an extensive test program has been undertaken.

DESCRIPTION OF TEST PROGRAM

All tests were performed with one adhesive injection system which consists of a vinyl ester resin with additional cementitious content. The system holds an Evaluation Service Report (ESR) from the ICC Evaluation Service which is based on acceptance criteria contained in AC308 [AC308]. Since the test program was intended to evaluate the safety level associated with the assessment system, all test results are presented as a function of the characteristic bond stress value for long-term sustained loading as given in the ESR, whereby AC308 dictates that the anchor design strength for sustained tension loading be taken as 75% of the characteristic design value based in part on sustained load testing.

Sustained load tests were performed at five different load levels. The tests were continued well beyond the time limits established in current assessment requirements. All tests with the exception of those conducted at the highest sustained load level were performed in a partly unconfined loading setup. The high-load tests were conducted in a fully confined test rig. All test results were converted to unconfined loading using an assumed ratio of unconfined to confined of 0.75 in order to be able to make a correct comparison to the approval values. The tests were performed at the standard (room) temperature of 20°C (68°F). The test results are summarized in Table 1:

Sustained load level in relation to characteristic long-term bond strength in the evaluation report $\tau_{test} / \tau_{k,uncr,lt}$	**Sustained load level in relation to the design long-term bond strength in the evaluation report** $\tau_{test} / \tau_{d,uncr,lt}$	**Duration of sustained load testing** (hours/days)	**Number of replicates** (n)
1.05	1.61	12900/538	3
1.12	1.72	21000/875	3
1.30	2.00	12900/538	2
1.54	2.36	7100/296	3
1.75	2.69	7100/296*	3

*1 failure occurred at 3200 hours/133 days

Table 1 – Sustained Load Tests

EVALUATION OF FAILURE CRITERIA OF CURRENT APPROVAL SYSTEM

As discussed previously, in order to determine the theoretical failure associated with sustained loading the displacement at loss of adhesion must be derived from short-term reference tests. For the tested adhesive anchor system at the tested diameter and embedment depth, the displacement at loss of adhesion was established as δ_{adh} = 0.39 mm. The average displacement at ultimate load was δ_{ult} = 0.62 mm.

Figure 4 shows the time-displacement plots for the sustained load tests. The plots represent the average of all tests performed at each load level with the exception of the plots for loading at 1.75 times the rated long-term bond strength which represent single tests. The displacement at loss of adhesion and at ultimate load are shown as well. The tests are ongoing. At the time of this writing, no failures have occurred in tests up to a loading level of 1.54 times the characteristic long-term approval bond stress. All curves have stabilized and the anchors show only negligible further displacement after several thousand hours of testing despite having reached the displacement level corresponding to loss of adhesion. In the tests with bond stress levels of 1.54 times rated, the displacements now exceed the displacement at peak load by approximately 30% and the anchors show no evidence of impending failure. One anchor failed when tested at a the load level corresponding to 1.74 times the characteristic long-term rated bond stress. The displacement at failure was 1.1 mm, which is approximately 2.8 times higher than the displacement at loss of adhesion and 1.8 times higher than the displacement at peak load. Two other anchors tested at this load level have not failed at the time of this writing and show only negligible displacements after approximately 4000 hours of loading.

For these tests, the displacement at loss of adhesion as a failure criterion is quite conservative (by a factor of 2.8). Also the displacement at peak load as a failure criterion would be conservative (by a factor 1.8).

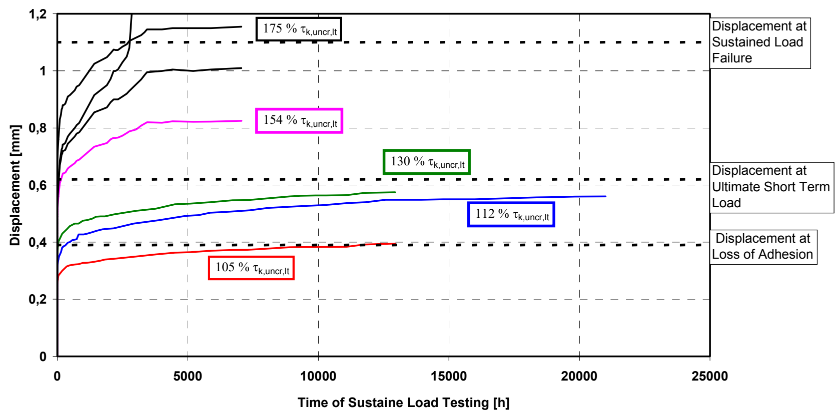

Figure 4 – Displacement Behavior for Sustained Load Tests

EVALUATION OF TIME OF TESTING OF CURRENT APPROVAL SYSTEM

The minimum required duration of testing according to AC308 [AC 308] is 1008 hours. In the test program described here, sustained load tests up to 21000 hours were performed. In order to show the effect of testing duration, the Findley approximation is shown in Figure 5 for one test. The red curve is extrapolated from displacements measured between 0 and 1008 hours, whereas the blue curve is derived from test results up to 21000 hours. The Findley approximation from 1008 hours of measured displacements is shown in detail in Figure 1. Comparing the two curves in Figure 5 it can be seen that the extrapolation based on the shorter test duration overestimates the displacements quite significantly.

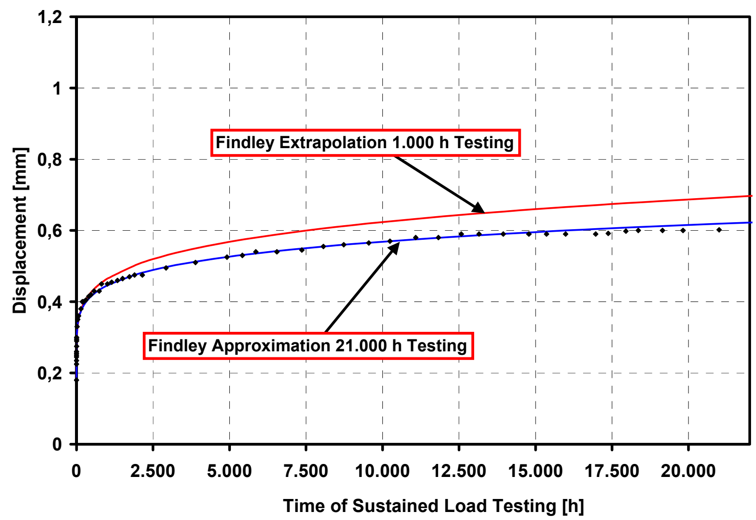

Figure 5 – Findley Extrapolations for Varying Test Durations

Extrapolating both curves to the relevant 50 years (438000 hours) as shown in Figure 6 shows that for this test series the extrapolation based on the shorter test duration as permitted in AC308 (1008 hours) yields approximately 20% higher displacements at 50 years than if the extrapolation is taken from measured displacements up to 21000 hours.

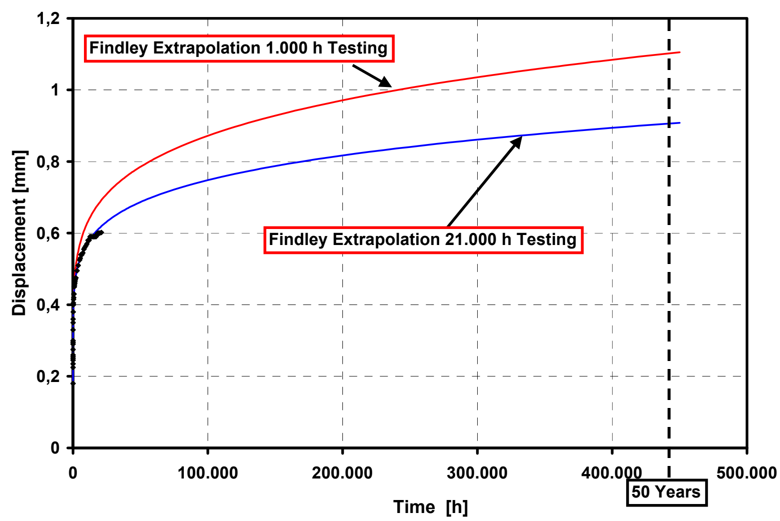

Figure 6 – Findley Extrapolations to 50 Years for Varying Test Durations

EVALUATION OF THE SAFETY RESERVES IN THE TESTING AND EVALUATION APPROACH

Based on the measured displacement behavior in the sustained load tests, extrapolation using the Findley Creep Law can be performed as described above. By extrapolation to a defined displacement, the theoretical duration to failure under applied sustained tension load can be derived.

As a first step, this extrapolation was performed using all available data from the sustained load tests, which includes testing from 7000 to 21000 hours. The required minimum test duration according to AC308 is 42 days (1008 hours). The theoretical failure was evaluated for each loading level for three different displacement criteria levels: Displacement at loss of adhesion (0.38 mm), displacement at peak load (0.62 mm), and the measured displacement corresponding to sustained load failure (1.1 mm). The results are presented in Figure 7 using a logarithmic time scale. For better evaluation of the data, the results for each failure criteria are represented with a logarithmic trend line.

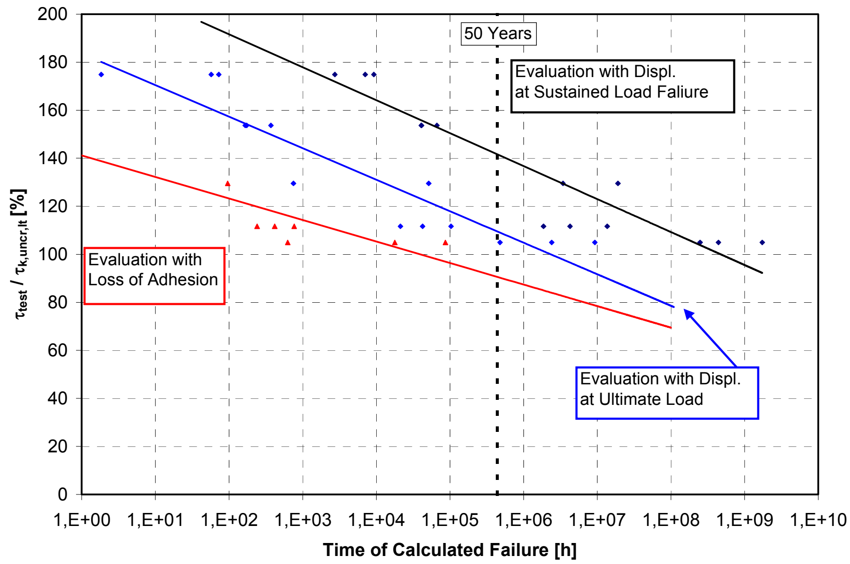

Figure 7 –Evaluation of Tests for Time to Failure

To evaluate the safety level of the current U.S. assessment procedure (AC308) the reduced test duration requirement must be taken into account. To evaluate the difference between sustained load testing up to 1008 hours and longer-term testing, the extrapolation was repeated with test results from the first 1008 hours only. The results are presented in Figure 8 as dashed lines. It can be seen that for each failure displacement assumption, there is a significant difference in the predicted sustained load time to failure for a given load level. The theoretical time to failure at the characteristic long-term bond stress level decreases for the evaluation using the loss of adhesion criterion from 45 to 2.3 years, for the evaluation using displacement at failure load from 262 to 84 years, and for the evaluation using the displacement at sustained load failure from 54000 to 11500 years.

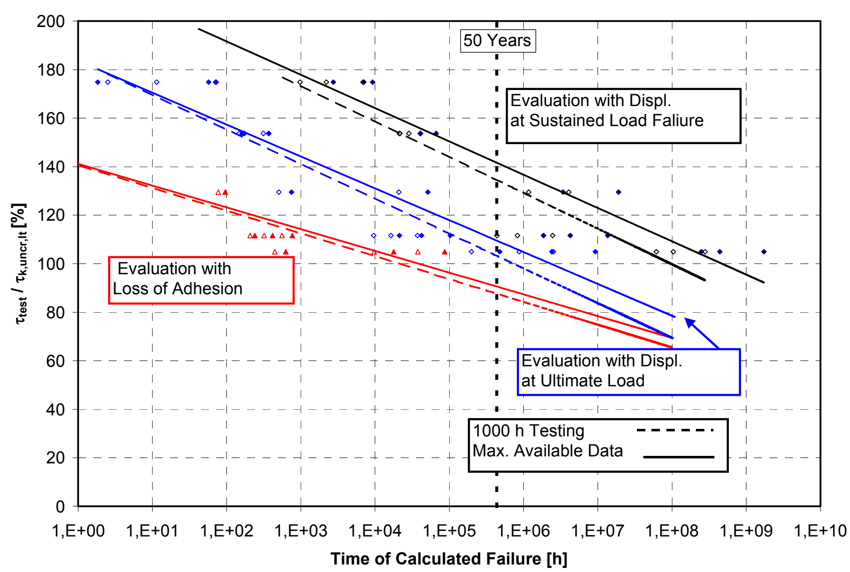

Figure 8 – Time to Failure Evaluation of Performed Tests - Comparison of Assessment Procedures

In order to evaluate the safety margin inherent in the current assessment approach, the extrapolation using data from the first 1008 hours of testing is combined with the assumption of failure at the loss of adhesion displacement (red line). This is compared with the same extrapolation taking the displacement at peak load as the failure criterion (blue line). Finally, both of these predictions are compared with the results derived from extrapolating using all available data points and taking the displacement at sustained load failure as established for higher load levels (see Figure 4) as the failure criteria (black line). The time to failure lines derived from the extrapolated test results are shown in Figures 9 and 10, whereby the red line represents the current assessment procedure in AC 308 (42 days, loss of adhesion). For the tested system, the displacement at peak load could be justified as the failure criterion since the failure in the tests occurred typically between the threaded rod and the adhesive where no loss of adhesion can occur. This evaluation is shown in the graph with the blue data points and trend line. Assuming that the anchor is continuously loaded with 100% of the characteristic load given in the ESR, an average time to failure based on the current testing and evaluation approach would be 2.3 years. Using the displacement at peak load assumption, the time to failure increases to 84 years. For the same system, the time to failure based on the extended sustained load testing and the measured sustained load failure displacement indicates an average failure time of 54000 years.

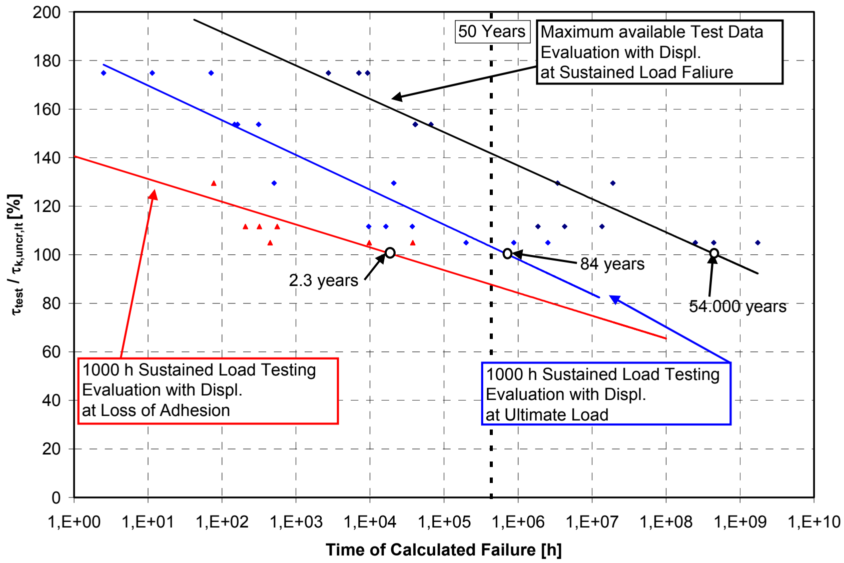

Figure 9 – Time to Failure Evaluation of Tests – Comparison of Evaluated Failure Time at Characteristic Load for Sustained Load Applications

Verifying the additional safety margin within the assessment procedure, the theoretical resistance corresponding to a 50-year sustained load duration can be evaluated. The results are shown in Figure 10. If the criteria uses data from only 1008 hours testing and the loss of adhesion failure criteria, a resistance of 88% of the reference value is derived. As shown, this contrasts with 142% of the reference value when all available data are used and the specific displacement at sustained load failure is taken as failure criterion.

The sustained load tests according to AC308 are conducted with 55% of the ultimate short-term mean resistance. Taking the results of the assessment for this test series, this corresponds to 0.55 x 1.42/0.88 = 0.89 or 89% of the ultimate short-term resistance.

If the displacement at peak load (short-term loading) is used as the failure criterion, a 55% test load level corresponds to 0.55 x 1.42/1.03 = 0.76 or 76% of the ultimate short-term resistance.

This evaluation shows that there is a substantial safety margin within the testing and evaluation concept of AC308. The required reduction factor of 0.75 to be taken on short-term resistance in AC308 is conservative and no reduction of this factor is indicated based on the performed tests and evaluation. Furthermore it may be considered whether this factor could be increased for suitable products based on testing.

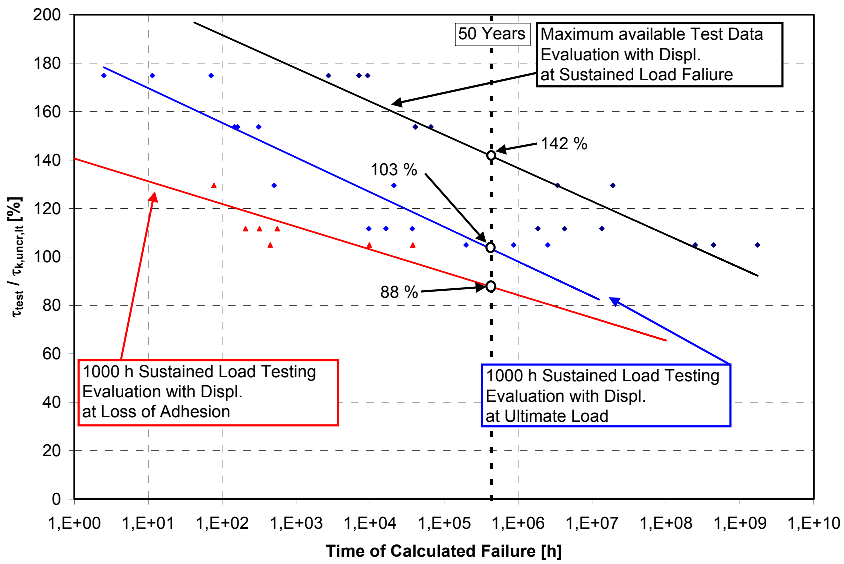

Figure 10 – Time to Failure Evaluation of Performed Tests – Comparison of evaluated Resistance assuming a Failure at 50 years Loading

COMPARISON OF EVALUATION REPORT VALUES TO LONGTERM TESTING AND EVALUATION

All evaluations were performed based on an average time to failure curve. To evaluate the resistances stated in the ICC-ES evaluation report for applications with sustained loads, the characteristic time to failure curve must be used. Based on the average time to failure curve, valid for the maximum available data of the sustained load tests and the displacement at sustained load failure as failure criteria (black curve in figures above), and the scatter of the single tests, a characteristic time to failure curve is established. The characteristic time to failure curve is shown in Figure 11 as a dashed line.

Evaluating the characteristic time to failure curve at different load levels, the theoretical time to failure at the specific load level can be determined. If the specific system is loaded to a level corresponding to the characteristic bond stress for sustained loading (75% of the short-term value) specified in the ESR, the theoretical time to failure is 950 years. At the design load level the theoretical time to failure increases astronomically (to 1.4 million years) and at the allowable load level the theoretical time to failure is essentially infinity. Clearly, these derived failure times indicate a large safety margin against long-term bond failure for adhesive anchor systems evaluated under AC308 [AC 308].

The characteristic resistance at 50 years (438,000 h) is 114% of the characteristic bond strength for sustained loading (75% of the short-term value) specified in the ESR. This corresponds to a reduction factor for sustained loads of 0.86.

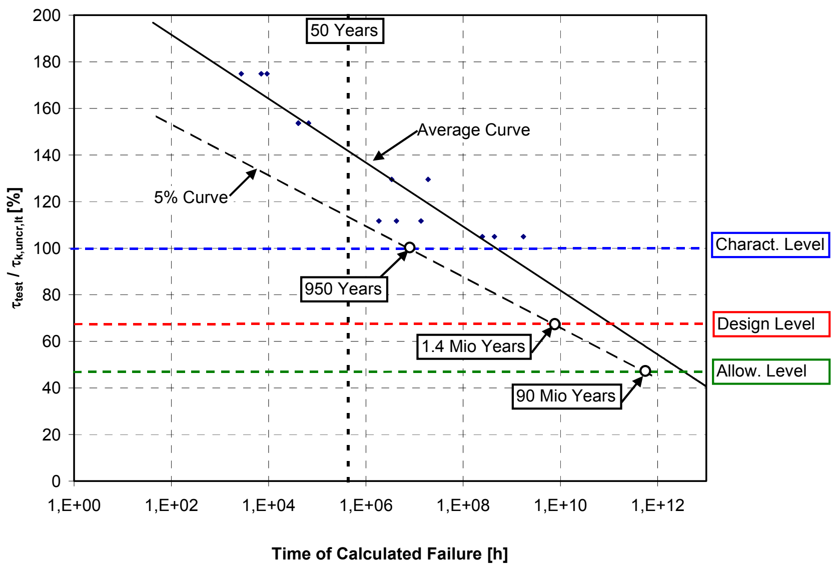

Figure 11 – Time to Failure Evaluation of Performed Tests – Average and Characteristic Curve in Comparison with Characteristic, Design and Allowable Load Levels from Evaluation Report

SUMMARY

The current testing and evaluation concept requires a minimum of 1008 hours of sustained load be applied. The measured displacements are extrapolated to 50 years (438000 hours) for the standard temperature case. The derived displacement must be less than the displacement corresponding to loss of adhesion as derived from monotonic tension tests.

To evaluate the safety margins within this assessment procedure, sustained load tests at several load levels with a duration of up to 21000 hours have been performed. The tests are ongoing.

Evaluation of the test results to date show the following results:

- Extrapolation of displacements using the Findley Creep Law and data derived from a test duration of 1008 hours is conservative compared to the displacements predicted with data from a longer test duration.
- The assumption of failure at a displacement corresponding to loss of adhesion is very conservative. The tested anchors showed failure displacements of approximately 2.8 times of the displacement at loss of adhesion in sustained load tests.
- It can be concluded, that sustained load testing at 55% of the ultimate mean short-term resistance using the current evaluation concept corresponds to sustained loading at 86 to 89 % of the mean ultimate value.
- Based on the tests, the characteristic time to failure curve was established for the tested system. Assessment for the specified resistances corresponding to sustained loads in the ICC-ES ESR for the system using the time-to-failure curve indicates astronomically long times to failure.

These results show, that for the tested system at room temperature, a significant safety margin is associated with the current testing and evaluation concept of the current U.S. acceptance criteria for sustained loading. Extension of these conclusions to elevated temperature conditions and to other types of adhesive anchor systems requires additional study.

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EFFECT OF ENVIRONMENTAL EXPOSURE ON THE CREEP BEHAVIOR OF ADHESIVE ANCHORS

by Adham M. El Menoufy, Khaled A. Soudki, Ahmed K. El Sayed, and Hannah Schell

Synopsis: This paper describes an experimental investigation on the long-term creep behavior of adhesive anchors under sustained tensile loads in combination with different environmental exposures. The experimental program comprises of 36 pull-out test specimens. The specimens consist of a cylindrical shape concrete block of 300 mm (12 inch) in diameter and 200mm (8 inch) in depth, with 15M (No. 5) deformed steel bars post-installed to an embedment depth of six times the bar diameter or 125mm (5 inch). Three types of adhesives were used: Type A - Fast setting two component methyl methacrylate adhesive, Type B - Fast setting two part epoxy adhesive and Type C - Standard set two part epoxy adhesive. The study is divided into four phases. Phase I consists of static pullout tests to determine the yield strength (f_y) and the maximum capacity of each anchor system. Phase II consists of sustained load tests under load levels of 40%f_y at normal laboratory conditions. Phases III and IV are sustained load tests under load levels of 40%f_y with moisture exposure and freeze/thaw cycling, respectively. All sustained load tests lasted for a period of at least 90 days. The results of the static pullout testing showed that specimens with epoxy based adhesive exhibited stronger bond strength, forcing the anchor to fail by rupture prior to bond failure. As for the sustained load test results, specimens with standard set epoxy based adhesive showed insignificant creep displacement under room conditions, however, when exposed to moisture noticeable creep displacements were recorded. Specimens with both fast setting epoxy and methyl methacrylate based adhesives showed higher creep displacements under environmental exposure versus those kept at room temperature.

Keywords: creep; adhesive; anchors; sustained load; epoxy.