Using of the Design Assisted by Testing Method in case of the Experimental Verification of the Load-Carrying Capacity of Expansion Anchors

Michal Štrba and Marcela Karmazínová

***Abstract*—**In this paper they are described the information about an evaluation of the test results in case of an experimental research which was focused on a selected type of the steel mechanical fasteners to concrete under a tension loading. Generally, problems of an anchoring it is one of the most important parts of a design and realization in civil engineering from the basic building constructions to the bridges or high-rise buildings. In this event they are used especially two systems of steel fasteners. At first they are so called cast-in-place members (mostly the usual anchor bolts) and secondly, they are used post-installed anchors, which can be the expansion or the bonded ones, where both of them have their own advantages, disadvantages, their specific characteristics as well as the actual behaviour under different loading. However, this paper is oriented only to the verification of mean and design values of load-carrying capacity of the steel post-installed mechanical expansion anchors to concrete subjected to a monotonic and repeated tension loading.

***Keywords*—**Design assisted by testing, effective anchorage depth, experimental verification, modes of failure, post-installed expansion anchor.

I. Introduction

THEY are used the steel post-installed anchors very often this days as one of the several main possibilities for the anchoring of building structures or other types of load-bearing structures in civil engineering especially because of their fast and easy installation.

Mentioned anchors can be divided into two basic groups. First, they are used bonded anchors (for example the chemical ones), which are specific because of their available and uniform loading transfer, but then as disadvantages can be taken the dependence on the weather and temperature conditions together with the waiting phase (i.e. with a curing time before an anchor can be fully loaded). In fact, the bonded anchors have a very similar actual behaviour under loading to the cast-in-place fasteners, despite they are post-installed. Secondly, they are the mechanical anchors (for example the expansion ones, which were used for the loading tests, Fig. 1), which are very often used mainly because their immediate introduction of loading and total independence from weather conditions during an installation.

Fig. 1 type of the steel mechanical post-installed expansion anchors which have been selected for the loading tests

They have been realized on the authors' workplace several series of the loading tests of described fasteners (expansion ones), where these experiments were mainly focused on the actual behaviour and on a load-carrying capacity determination of these members under a tension loading (which is one of the elementary possibilities of using of these members in practice, see Fig. 2).

They were performed loading tests with both, static as well as cyclic tension force. The reason why the repeated forces had been used was to find the values of the load-carrying capacity also in case of a cyclic loading, because described mechanical expansion fasteners are often used in conditions, where it can occur very easily the repeated load (for example a wind load, an anchoring of heavy machinery and a vehicle load, etc.), whereas in general, they are usually known only the static values of a tension load-carrying capacity (from the design

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M. Štrba, AdMaS Research Centre, Faculty of Civil Engineering at the Brno University of Technology, Veveří St. 331/95, 602 00, Brno, the Czech Republic, (corresponding author to provide phone: 420-54114-7305; e-mail: strba.m@fce.vutbr.cz).

M. Karmazínová, AdMaS Research Centre, Faculty of Civil Engineering, Brno University of Technology, Veveří St. 331/95, 602 00, Brno, the Czech Republic, (phone: 420-54114-7310; e-mail: karmazinova.m@fce.vutbr.cz).

manuals of the anchor producers). On the other hand, the values in case of the cyclic loading are very rarely available. Hence, it is efficient to find the suitable material and geometric parameters and their relations so that both materials, steel and concrete, can be utilized and used as comparably as possible.

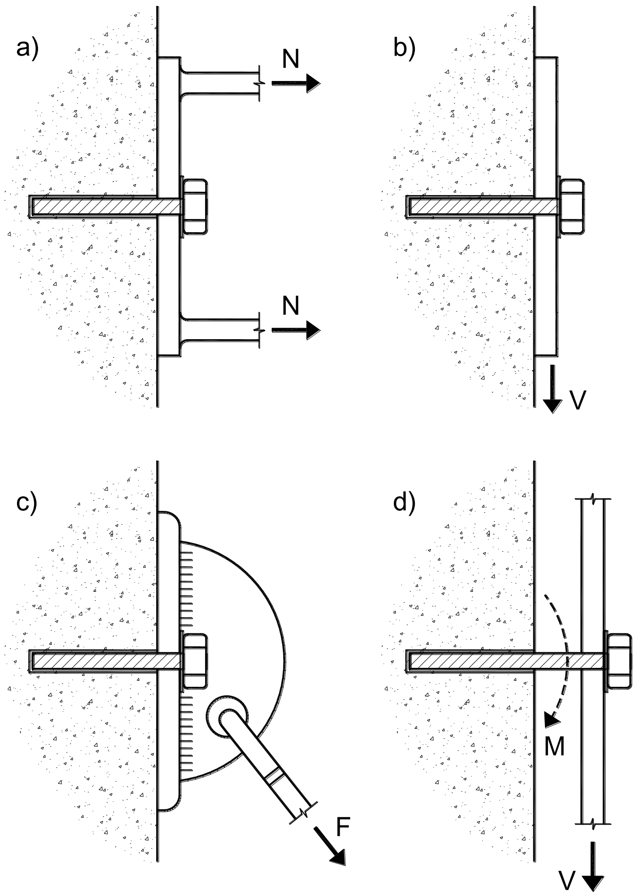

Fig. 2 illustration of some basic modes of loading; a) tension, b) shear, c) tension and shear, d) shear and bending moment

II. Modes of Failure of Expansion Anchors

In case of tension loading they are two most frequent mechanisms of failure. The first of them is a failure of steel (so-called "steel-bolt failure", see Fig. 3 left) and the second one is a failure of concrete (so-called "concrete-cone failure", see Fig. 3 right and Fig. 4) [1] [2].

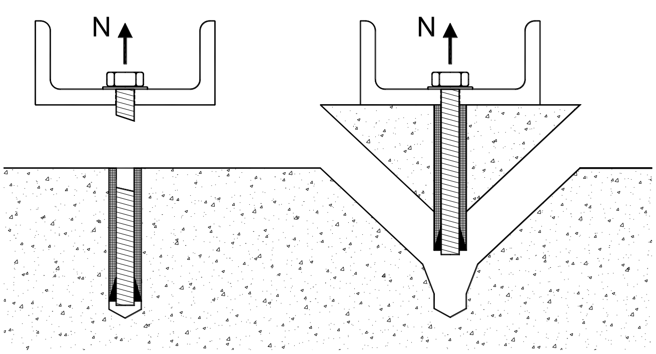

Fig. 3 steel-bolt failure (left) and concrete-cone failure (right)

It has to be mentioned, that this type of anchors are not very suitable if they are installed near to the edge of concrete member or if they are placed in group with small spacing between or among themselves. In such a case the load-carrying capacity has to be reduced, see [2].

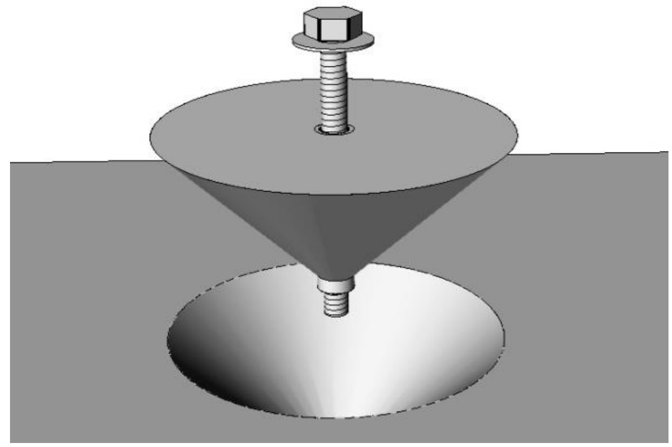

Fig. 4 illustration of the concrete-cone failure

They exist also other types of failures (for example it can be a partial pull-out of the anchor together with a small surface concrete-cone failure, a total pull-out of the anchor or even a stripped thread of the steel bolt). But all of these cases are not common and they usually occur just because of wrong procedure of a fastener installation and their number can be taken as insignificant (for the test evaluation).

III. Load-Carrying Capacity Determination

For a determination of the load-carrying capacity in the event of static tension loading they are important material and geometric characteristics of selected expansion anchors as well as of the used concrete. Then, the capacity can be determined for both main modes of failure.

A. Steel-bolt failure

In case of steel-bolt failure the static load-carrying capacity N_s is generally based on a simple formula of a tension capacity of a steel bolt, which is given as a multiplication of a tensile stress area of the anchor bolt A_s and the ultimate tensile strength of a steel f_{ub}, see [1] and [3]:

$$N_s = k_s \cdot A_s \cdot f_{ub}\,, \tag{1}$$

where the additional coefficient k_s represents a reduction factor respecting statistic uncertainties during the installation of the anchor or of the used material characteristics variables. The value of the coefficient k_s is very near to 1.0.

Based on previous experiences and providing known high reliability of steel [1] [4], the mean value of load-carrying capacity can be taken as:

$$N_{s,m} = 1.0 \cdot A_s \cdot f_{ub}\,. \tag{2}$$

As an example of the equation (2) they are in the graph on the Fig. 5 shown the curves of mean values of the load-carrying capacity for the bolt grades 4.6 to 10.9, i.e. for the ultimate tensile strength f_{ub} 400 to 1000 MPa (the example is made only for bolt diameters M8 to M12, but the curves can be used for bigger bolts, too).

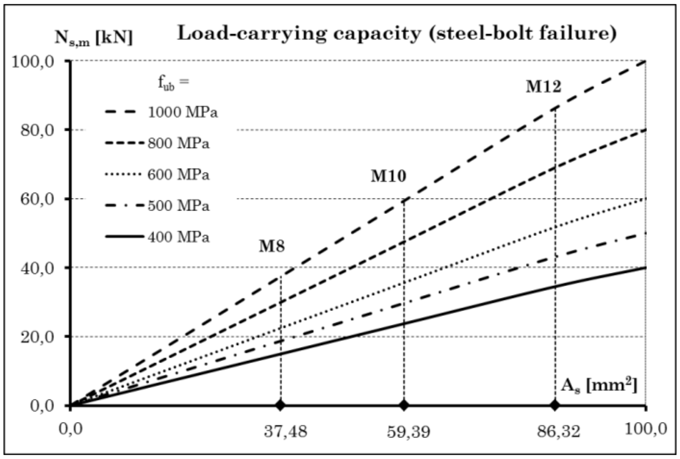

Fig. 5 load-carrying capacity in case of the steel-bolt failure

B. Concrete-cone failure

As mentioned above, the second of the two most frequent modes of failure is a concrete-cone failure, which in principle can occur due to the exceeded ultimate tension capacity of concrete. This ultimate capacity N_u can be generally taken as the multiplication of the effective area of concrete A_c and concrete tensile strength f_{ct} (usually recalculated and replaced in the formulas by the values of the compressive cylindrical strength f_c or the compressive cube strength f_{cube}), which can be written as:

$$N_u = A_c \cdot f_{ct} \,. \tag{3}$$

They are several methods for a determination of this load-carrying capacity. The two most often used ones are the Concrete-Capacity-Method [5] and Concrete-Cone method [6]. In both these methods there is one other very important parameter (except the strength of concrete), which is so-called effective anchorage depth h_{ef}.

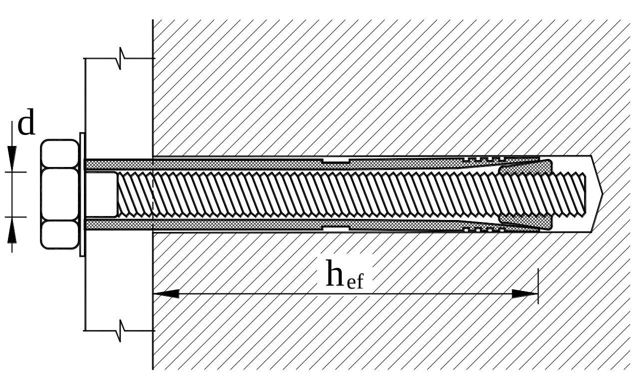

Fig. 6 illustration of the effective anchorage depth h_{ef} definition

In fact, the effective depth is the total length of an anchor sleeve between the surface of concrete member and the expansion cone of the anchor (see Fig. 6, where the value *d* is a diameter of the anchor bolt).

It is obvious that the size of the effective anchorage depth directly influences the tensile resistance in case of concrete-cone failure; i.e. the longer the effective depth is, the bigger the concrete area is. This principle is very similar to the failure in the event of cast-in anchorage bolts.

The difference between both forenamed methods is in the geometric shape, which is taken as the idealized failed form of concrete member (or specimen).

In case of Concrete-Cone Method the idealized failed form is a cone with the base of radius r_k. Then, the effective area of concrete A_c equals the cone base area (see Fig. 7):

$$A_c = \pi \cdot r_k^2 = \pi \cdot h_{ef}^2 \tag{4}$$

and the value of ultimate load-carrying capacity N_{u1} is shown in the formula:

$$N_{u1} = k_c \cdot \pi \cdot h_{ef}^2 \cdot f_{ct} \,, \tag{5}$$

where the k_c value is (analogous to the k_s value in case of steel-bolt failure) a reduction factor respecting statistic uncertainties as well as the conditions during an installation. Then, the final formula of the mean value of load-carrying capacity according [5]–[8] is written as:

$$N_{u1,m} = 0.84 \cdot \pi \cdot h_{ef}^2 \cdot f_{cube150}^{0,5} \,. \tag{6}$$

where the value $f_{cube150}$ is a concrete compressive cube strength (with concreting tested on cubes 15 cm × 15 cm × 15 cm).

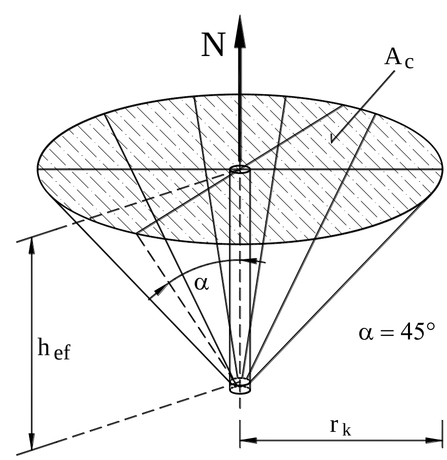

Fig. 7 idealized failed form of concrete specimen in case of the Concrete-Cone Method (the anchorage depth equals the radius of the cone base)

On the other hand, in case of Concrete-Capacity Method the failed form of concrete member is simplified even more and it is a pyramid with square base (see Fig. 8). Then, the effective tensile area of concrete A_c is given by the base area of this pyramid:

$$A_c = a^2 = h_{ef}^2 \tag{7}$$

and the equation of the ultimate load-carrying capacity of the expansion anchor according this method N_{u2} is written:

$$N_{u2} = k_c \cdot h_{ef}^2 \cdot f_{ct}, \tag{8}$$

where the coefficient k_c has the same meaning as in the formula (5) and its value can be more specified for selected type of the fastener on the basis of performed loading tests (providing a sufficient number of tests).

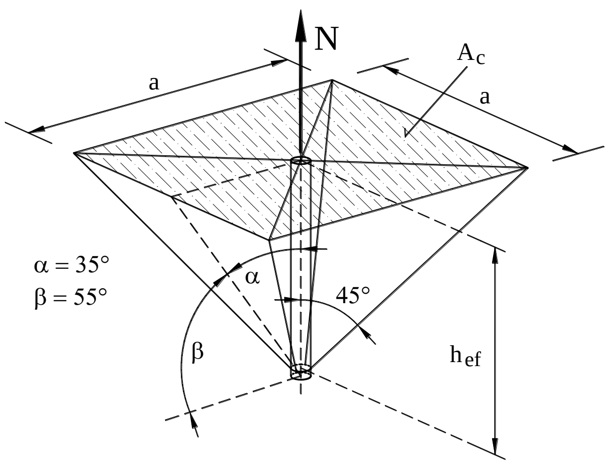

Fig. 8 idealized failed form of concrete specimen in case of the Concrete-Capacity Method

Next, based on the previous experiences with the results, it is in the Concrete-Capacity Method also usually taken the modified value of the anchorage depth (reducing h_{ef}^{2} into $h_{ef}^{1.5}$) and the final formula of the mean value of load-carrying capacity is:

$$N_{u2,m} = 13.2 \cdot h_{ef}^{1,5} \cdot f_{cube150}^{0,5}. \tag{9}$$

Except the mentioned Concrete-Cone Method and Concrete-Capacity Method, there is for example so called Theoretical Method [9], which uses a size effect for the evaluation of the test results. But, this method hasn't been used in this described experimental evaluation.

C. *Cyclic tension loading*

Generally, in the event of cyclic (repeated) tension loading the rules of the determination of the load-carrying capacities (for steel-bolt failure or concrete-cone failure) are not described. However, they can be related to the values of the static load-carrying capacities (for both appropriate modes of failure) by the help of the loading tests with using of the cyclic tension force. It means that they can be taken as the relations of the loading amplitudes of the used tension forces ΔN_{test} (between the maxim force $N_{max,test}$ and minimum force $N_{min,test}$) to the values of described static load-carrying capacities in dependence on a total number of loading cycles n_{cycl} at the moment of the failure, where:

$$\Delta N_{test} = N_{\max,test} - N_{\min,test}. \tag{10}$$

Providing that all the mentioned values are recorded during the experiments, the basic formula of these relations can be written as:

$$\Delta N_{test} = (k \cdot \log n_{cycl} + q) \cdot N_{stat}, \tag{11}$$

where the values k and q are the parameters of the fatigue curve, the N_{stat} is a static load-carrying capacity, i.e. either it is the value $N_{s,m}$ according to (2) or the value $N_{u1,m}$ according to (6), respectively $N_{u2,m}$ according to (9). Then, the equation (11) can be modified for all the mean values of the loading amplitudes into three next formulas:

$$\Delta N_{s,m} = (k_s \cdot \log n_{cycl} + q_s) \cdot N_{s,m}, \tag{12}$$

$$\Delta N_{u1,m} = (k_{c1} \cdot \log n_{cycl} + q_{c1}) \cdot N_{u1,m}, \tag{13}$$

$$\Delta N_{u2,m} = (k_{c2} \cdot \log n_{cycl} + q_{c2}) \cdot N_{u2,m}, \tag{14}$$

where (analogously as above) the value "1" in the index means that it belongs to the Concrete-Cone Method and the value "2" in the index means that it belongs to the Concrete-Capacity Method (the same marking is used in all next equations).

IV. Loading Tests Realization

They were performed loading tests of expansion anchors to concrete with the tension force on a few series of specimens (including the pilot series). For the experiments they were selected some specific parameters of the anchors as well as of the concrete members, see below.

A. *Loading tests equipment*

In case of the realization of all loading tests it was used an appropriate load equipment which consisted of a hydraulic cylinder fixed to the main steel loading frame and connected to an operating device. Then the strain gauge load cell (being a part of the hydraulic cylinder) was used for the tension force measurement and finally, for the displacement measuring (in case of some tests) they were used position sensors. All parts together were connected to the measuring center controlled by software.

The illustration of the equipment is shown on Fig. 9, where the meaning of used numbers is as follows: 1 – load cell, 2 – position sensor, 3 – hydraulic cylinder, 4 – control equipment, 5 – measuring center, 6 – computer software.

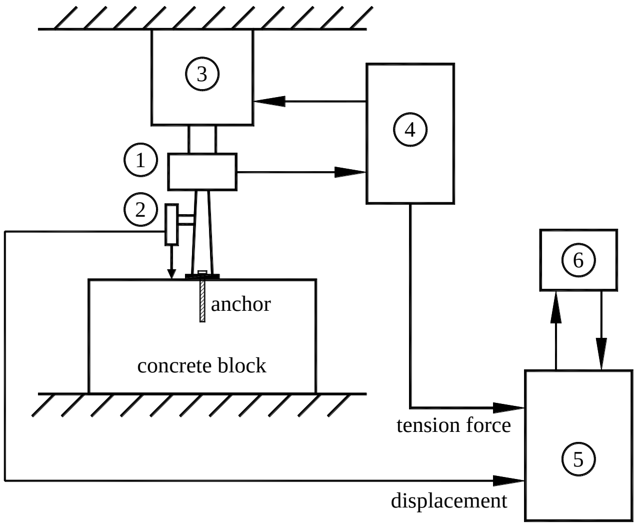

Fig. 9 scheme of the used loading test equipment

In fact, they were used two different loading machines during the experiments. One of them was used only for static loading tests and the second one was used for static and cyclic loading tests. But they both have the same scheme as shown in Fig. 9 so that this fact doesn't have any influence on test results evaluation. The illustration of loading tests arrangement is shown in Fig. 10 and Fig. 11.

Fig. 10 illustration of the test arrangement (the steel loading frame)

Fig. 11 illustration of the test arrangement (cylinder and loading cell)

B. Steel expansion anchors to concrete used for the tests

For all the experiments they have been used standard steel mechanical expansion anchors of marks KOTE and Fisher (with steel bolts, sleeves and expansion cones; see Fig. 1 and Fig. 12), which have to be installed using specified controlled torque depending on the diameter of an anchor bolt d and on the steel grade of the bolt, i.e. of an ultimate strength f_{ub}. The selected bolt diameters have been chosen as 8, 10, 12 and 16 mm, while the strength f_{ub} was 800 MPa in all cases (i.e. the chosen bolt grade was 8.8). The effective anchorage depths h_{ef} have been chosen with various values from 30 to 85 mm.

Fig. 12 steel mechanical expansion anchors used for the loading tests

C. Concrete specimens (blocks) used for the tests

They have been used two different types of concrete specimens for the loading tests. First, they have been selected concrete blocks with smaller dimensions 500 mm × 400 mm × 250 mm, which were used only in case of static tension forces. Next, the concrete blocks with bigger dimensions 600 mm × 500 mm × 350 mm (Fig. 13) were used first of all for the tests with using of cyclic loading, but also (only some of them) in case of static tension forces, see [4], [10] and [11].

The compressive cube strength $f_{cube150}$ of the specimens has been chosen as various values from 4.0 MPa to 70.0 MPa (static loading tests) respectively from 20.0 MPa to 48.0 MPa (cyclic loading tests).

Fig. 13 concrete specimens used for the experiments

D. Realization of cyclic tension loading

In case of cyclic loading they were chosen various series of loading amplitudes ΔN for each selected combination of the anchorage parameters (i.e. in the event of different diameters of anchor bolts, effective anchorage depths and compressive cube strengths of concrete). These values of ΔN have been created by the hydraulic arrangement described in first part of this chapter (Fig. 9 to Fig. 11) with the controlled force. Before beginning of each loading test they were set two values (minimal and maximal tension force) and then it was used a criterion for an ending of the test by the limit of maximal value of deflection (which was 50 mm). The frequency of all loading amplitudes was chosen 5 Hz. Some more detailed information about the initial phase of described cyclic tests as well as about the process of loading itself can be found in [12] [13] and [14], where the same equipment for the cyclic tests was used in case of selected details of newly developed temporary truss footbridge.

V. Results of the Loading Tests

They were performed 158 loading tests with using of a static tension force, where the achieved failure mode was either steel-bolt failure (in 31 cases) or concrete-cone failure (in 127 cases). In the event of using cyclic tension force they were performed 261 tests (including 40 pilot ones), where they occurred steel-bolt failures in 163 cases and concrete-cone failures in 98 cases (Table 1). Total number of tests was 419.

Table 1 total numbers of performed loading tests

Static loading tests	Cyclic loading tests	Mode of failure
31	163	Steel-bolt failure
127	98	Concrete-cone failure
158	261	Total number of tests

Some examples of the failed specimens in case of concrete-cone failure are shown in Fig. 14 and Fig. 15.

Fig. 14 failed specimen (concrete-cone failure)

Fig. 15 failed specimen (concrete-cone failure)

They were also a few results with other modes of failure, but they occurred mostly because of a bad installation of the anchor or because of the incorrect setup of the loading test. These results haven't been taken to the final evaluation.

A. Results of static loading tests – steel-bolt failure

On the basis of the 31 loading tests [11], the value of the coefficient k_s has been determined as 1.024 and the mean value of load-carrying capacity can be taken as:

$$N_{s,m} = 1.024 \cdot A_s \cdot f_{ub} \, . \tag{15}$$

Then, by the help of a procedure of a design assisted by testing, which is based on a probabilistic evaluation and can be found in Eurocode [15], it have been determined the design value of load-carrying capacity in case of steel-bolt failure as:

$$N_{s,d} = 0.713 \cdot N_{s,m} \, . \tag{16}$$

B. Results of static loading tests – concrete-cone failure

In this case, based on 127 test results, where the concrete-cone failure occurred, the mean values of the load-carrying capacities (according to two methods described above) have been calculated and the equations (6) respectively (9) have been verified [16] into:

$$N_{u1,m} = 0.67 \cdot \pi \cdot h_{ef}^2 \cdot f_{cube150}^{0,5} \, , \tag{17}$$

$$N_{u2,m} = 15.6 \cdot h_{ef}^{1,5} \cdot f_{cube150}^{0,5} \, . \tag{18}$$

Analogously, using the method of design assisted by testing, they were derived the design values of load-carrying capacity in case of concrete-cone failure as:

$$N_{c1,d} = 0.388 \cdot N_{c1,m} \, , \tag{19}$$

$$N_{c2,d} = 0.446 \cdot N_{c2,m} \, . \tag{20}$$

C. Results of cyclic loading tests – steel-bolt failure

On the basis of 163 results, where the steel-bolt failure occurred during loading tests with using of a cyclic tension force, it has been verified the mean value $\Delta N_{s,m}$ of the tension loading amplitude as:

$$\Delta N_{s,m} = (-0.089 \cdot \log n_{cycl} + 0.821) \cdot N_{s,m}, \tag{21}$$

where n_{cycl} is the number of cycles in the moment of failure and the numeric value is a derived parameter of fatigue curve.

Then, by the help of the mentioned method for design assisted by testing given by Eurocode [15], it has been derived also the design value of load-carrying capacity as follows:

$$\Delta N_{s,d} = 0.555 \cdot \Delta N_{s,m}. \tag{22}$$

D. Results of cyclic loading tests – concrete-cone failure

They have been performed 98 loading tests (including 26 pilot tests) with cyclic tension forces where the achieved failure was the concrete-cone failure [16]–[l8].

Next, they have been verified the mean values of the tension loading amplitudes depending on the static values of load-carrying capacity according to the utilized methods mentioned above:

$$\Delta N_{u1,m} = (-0.0416 \cdot \log n_{cycl} + 0.8932) \cdot N_{u1,m}, \tag{23}$$

$$\Delta N_{u2,m} = (-0.0395 \cdot \log n_{cycl} + 0.9048) \cdot N_{u2,m}, \tag{24}$$

where n_{cycl} and the numeric values have the same meaning as in the equation (21).

And finally, according to the probabilistic method for design assisted by testing the design values $\Delta N_{u1,d}$ and $\Delta N_{u2,d}$ of load-carrying capacities has been determined as follows:

$$\Delta N_{u1,d} = 0.521 \cdot \Delta N_{u1,m}, \tag{25}$$

$$\Delta N_{u2,d} = 0.535 \cdot \Delta N_{u2,m}. \tag{26}$$

VI. Conclusion

They have been performed altogether 419 loading tests of the selected type of expansion anchors to concrete with using of (static and cyclic) tension force, where the result was the steel-bolt failure or concrete-cone failure.

The design values in case of static tension force can be taken as 70 % of the mean value of load-carrying capacity in case of steel-bolt failure and as around 40 % of the mean value of load-carrying capacity in case of concrete-cone failure (depending on chosen evaluating method; either Concrete-Cone Method or Concrete-Capacity Method).

Then, the design values of loading amplitudes of load-carrying capacity in case of the cyclic tension force have been derived as approximately 50 % of mean values (for selected number of cycles, which, in practice, can be usually chosen as 2×10^6 cycles).

All the obtained formulas of design values in case of steel-bolt failure and concrete-cone failure can be subsequently compared and used together to get an efficient design of all anchorage parameters; it means to determine suitable relations between effective anchorage depths, diameters of bolt, strength of steel and concrete so that the probability for both failure modes would be the same.

However, the described formulas of design load-carrying capacities cannot be generalized yet, because although they are based on relatively big number of tests, they still have been obtained in case of various configurations of anchorage parameters. Hence, it would be appropriate to perform other loading tests for the selected configuration of anchorage parameters to get bigger number of results for the same parameters and then try to verify the design formulas more accurately.

Acknowledgment

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