Verification of steel-to-concrete anchorage system reliability based on failure probability evaluation using test results

MARCELA KARMAZÍNOVÁ and JINDRICH MELCHER
Faculty of Civil Engineering
Brno University of Technology
Veveří St. 331/95, 602 00 Brno
CZECH REPUBLIC
karmazinova.m@fce.vutbr.cz, melcher.j@fce.vutbr.cz, http://www.fce.vutbr.cz

Abstract: - The paper deals with the problems of load-carrying capacity of the particular type of anchorage systems and the topic discussed in the paper is oriented to the post-installed steel anchors to concrete. Some information about the statistic and probabilistic evaluation of the test results for expansion anchors subjected to tensile force and shear force are presented in the paper. Within the framework of the large experimental research programme realized in authors' workplace in the last period, steel expansion anchors to concrete under tensile and shear loading have been tested. A large number of the experimental results – the values of load-carrying capacities namely – has been obtained from these loading tests. Then these test data have been evaluated by the methods of the design based on test results. Using the procedure for the evaluation of the design resistance, characteristic and design values of the resistance have been calculated for particular loading types (tension, shear). For these calculations, the necessary statistical uncertainties influencing the resistance uncertainty (variability of material and geometrical properties mainly) have been taken into account.

Key-Words: - Reliability, failure probability, steel, concrete, anchorage, evaluation, test results, expansion anchors, resistance, tensile loading, shear loading, experimental verification, load-carrying capacity, resistance, characteristic, design, design assisted by testing.

1 Introduction

The efficiency and accurate placement together with the modern easy technologies and techniques are the main advantages of post-installed fastening systems. For fastening to concrete in the new constructions as well as in repair works steel expansion anchors can be very suitable. The behaviour of these anchoring systems can be rather complicated considering the influence of concentrated loads, their various and different directions and, especially, the failure mode depending on the load transfer from anchor body into concrete base. Thus experimental verification together with statistical and probabilistic analysis of appropriate test results should be an authority for the theoretical modelling and practical design of the fastening systems.

In the paper the brief information on the main results (failure mechanism and adequate resistance) of the loading tests of steel expansion anchors under tensile loading is presented.

During recent decade, in our workplace, the research oriented to the anchorage to concrete is developed. As one of the parts of this research the large experimental programme of steel expansion anchors to concrete has been realized in authors' testing laboratory. Within the framework of the realized experimental programme the expansion anchors under tensile static and dynamic loading and under shear static loading have been tested. Tests were focused on the experimental verification of the actual behaviour of the investigated anchor elements – so called torque-controlled expansion anchors (see Fig. 1).

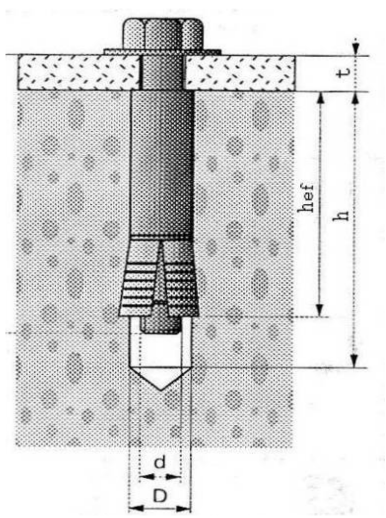


Fig. 1 Typical composition of torque-controlled expansion anchor

Strain mechanisms during loading processes and failure mechanisms with the corresponding load-carrying capacities have been monitored, especially. As follows, partial results of the design resistance of steel expansion anchors to concrete loaded by static tensile force or static shear force, obtained from the experimental verification and the statistical and probabilistic analysis, are presented.

2 Experimental verification and results – resistance mean values

From 343 tests of expansion anchors to concrete under static loading, both by tensile force (239 tests) and by shear force (104 tests), the typical failure mechanisms and corresponding values of load-carrying capacities have been obtained as the bases for the anchor resistance determination.

2.1 Expansion anchors subjected to static tensile force

The failure of anchors subjected to tensile force can occur both by steel and concrete failure. Because steel bolt failure and its corresponding load-carrying capacity are known in general, the solution was concentrated to concrete failure, mainly. For anchor large distance from the edge, concrete-cone failure (see Fig. 2) occurred in 86 cases. Basic parameters significantly influencing resulting resistance were: the anchorage depth was in the range from 50 to 80 mm, concrete cube strength was from 20 to 70 MPa.

Fig. 2 Tensile loading – concrete-cone failure: illustration of the actual failure

Based on two basic methods most often used for the determination of concrete-cone failure resistance – i.e. “Concrete-Cone Method” and “Concrete-Capacity Method” (see e.g. [1], [2], [3]) – the mean values of the load-carrying capacity have been determined (for more see e.g. [4], [6], [11]) by the regression analysis used for the comparison of test and theoretical results.

For so called “ACI-method” (see Fig. 3a) based on Concrete-Cone Method, the mean value of load-carrying capacity using test results can be given as

$$N_{um} = 0.74 \cdot \pi \cdot h_{ef}^{2} \cdot f_{cc}^{0.5}, \qquad (1)$$

where h_{ef} is the effective anchorage depth (see Figs. 1 and 3) and f_{cc} is concrete cube strength.

For so-called “ψ-method” (see Fig. 3b) based on Concrete-Capacity Method, the mean value of the load-carrying capacity using the test results can be given by the equation of

$$N_{um} = 16.8 \cdot h_{ef}^{1.5} \cdot f_{cc}^{0.5} \quad \text{[N]}. \qquad (2)$$

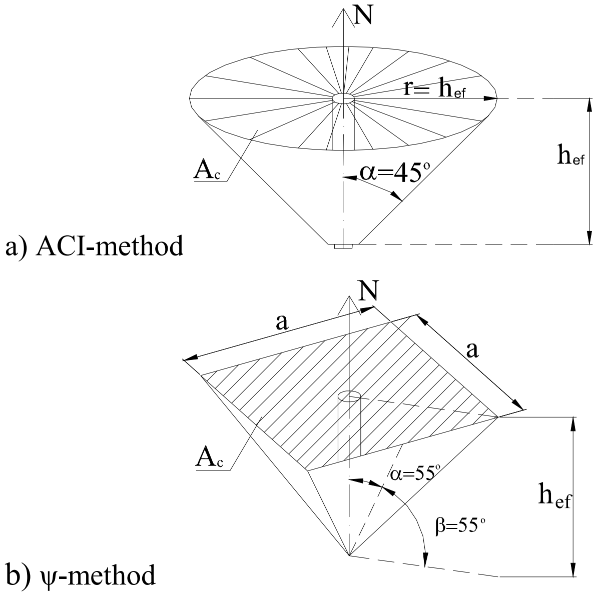


Fig. 3 Tensile loading – concrete-cone failure: principles of calculating methods

2.2 Expansion anchors subjected to static shear force

Also in the case of anchors under shear loading, both steel failure and concrete failure can occur. Here the solution was also directed to the concrete failure only. For anchors closed to the edge, lateral concrete-cone failure (Fig. 4) occurred in 43 cases. Basic parameters influencing the resistance were: the edge distance was in the range from 60 to 95 mm, concrete cube strength was from 19 to 37 MPa.

Fig. 4 Shear loading – lateral concrete-cone failure: illustration of the actual failure

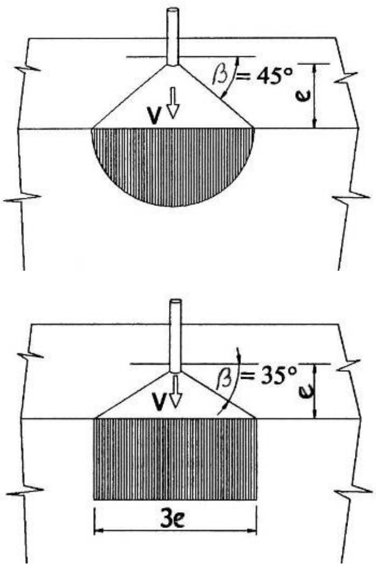
The load-carrying capacity mean values have been determined [2], [3], similarly as in 2.1, using two main calculating methods.

For "ACI – method" (see Fig. 5a) the mean value of load-carrying capacity derived from test results can be given by the formula of

$$V_{um} = 0.24 \cdot \pi \cdot e^2 \cdot f_{cc}^{0.5}, \qquad (3)$$

where e is the edge distance (see Fig. 4a) and f_{cc} is the cube concrete strength. For "ψ – method" (see Fig. 5b) the mean value of load-carrying capacity from test results can be given by the expression of

$$V_{um} = 7.3 \cdot e^{1.5} \cdot f_{cc}^{0.5} \quad \text{[N]}. \qquad (4)$$



a) ACI-method

b) ψ-method

Fig. 5 Shear loading – lateral concrete-cone failure: principles of calculating methods

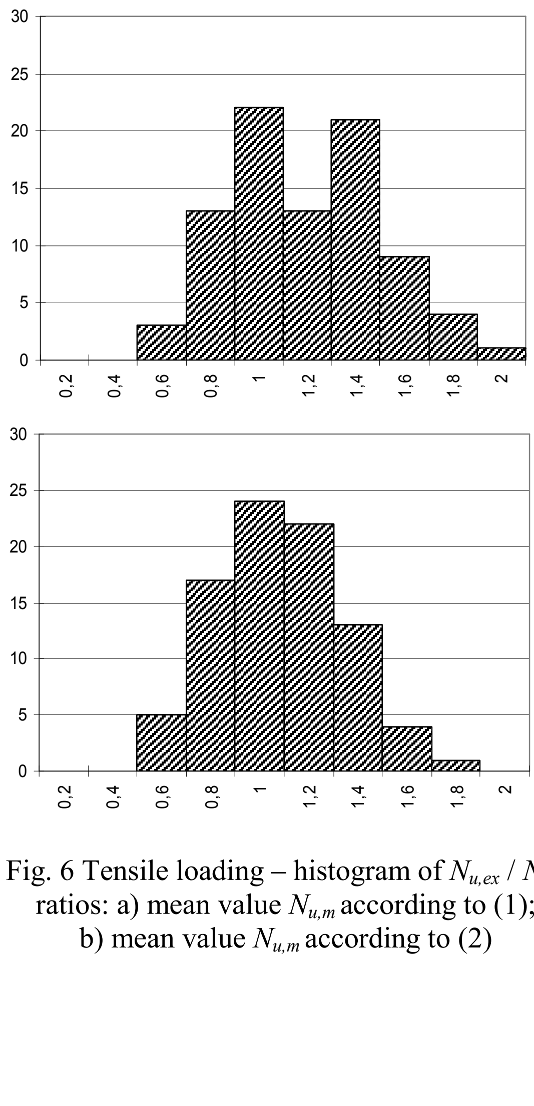
3 Statistical analysis – characteristic and design resistance

Using statistical analysis statistic parameters of the ratios of resistance experimental to mean values have been obtained. To determine characteristic and design resistances using the test results elaboration, the philosophy of the design assisted by testing have been applied (as e.g. in [2], [3]). The methodology is in principle based on the comparison of experimental resistances R_{ex} obtained from the tests and theoretical resistances R_{th} calculated according to the suitable theoretical resistance model. Then the characteristic and design resistances are derived using the statistic evaluation of the probabilistic resistance model R in the form of $R = b \cdot R_{th} \cdot \delta$. This method, known as so-called "standard procedure", is in detail described in [13] (here not more analyzed).

For the practical application of this procedure it is necessary to know variation coefficients v_{Xj} of input random variables X_j and variation coefficient v_R of the resistance R. The variation coefficient v_R follows from the variation coefficients v_{Xj} and from variation coefficients v_{Rth} of the resistance model function and v_δ of the error term. The variation coefficient v_{Rth} may be calculated as the variation of the resistance function and it is depending on this function mathematical form. The uncertainties in the resistance model are taken into account by the differences of experimental and theoretical values.

3.1 Expansion anchors subjected to static tensile force

For the calculation of anchor system resistance by two methods described in 2.1, statistical parameters (i.e. mean value, standard deviation and variation coefficient) of the ratio of experimental values to theoretical values calculated according to formulas (1) and (2) are viewed in Tab. 1 and in Fig. 6 graphically expressed, respectively. These statistical parameters can show the significant differences between actual experimental values and mean values of the resistance.



a)

b)

Fig. 6 Tensile loading – histogram of $N_{u,ex}$ / N_{um} ratios: a) mean value $N_{u,m}$ according to (1); b) mean value $N_{u,m}$ according to (2)

Table 1 Statistical parameters of $N_{u,ex}$ / N_{um} ratios

Statistical analysis	mean value m	standard deviation s	variation coefficient v
N_{um} accord. to (1)	1.086	0.302	0.278
N_{um} accord. to (2)	0.990	0.246	0.248

Formulas (1) and (2) are generally useful for the determination of the resistance for anchors subjected to tensile force. Using the standard procedure for characteristic and design resistances and considering the usual values of the variation coefficients of input random variables (h_{ef} and f_{cc}) v_{hef} = 0.03, v_{fcc} = 0.2, characteristic and design resistances N_k and N_d have been obtained as:

for the mean value according to (1)

$$N_k = 0.38 \cdot \pi \cdot h_{ef}^2 \cdot f_{cc}^{0.5}, \tag{5}$$

$$N_d = 0.24 \cdot \pi \cdot h_{ef}^2 \cdot f_{cc}^{0.5}, \tag{6}$$

for the mean value according to (2)

$$N_k = 10.2 \cdot h_{ef}^{1.5} \cdot f_{cc}^{0.5}, \tag{7}$$

$$N_d = 6.7 \cdot h_{ef}^{1.5} \cdot f_{cc}^{0.5}. \tag{8}$$

3.2 Expansion anchors subjected to static shear force

For methods mentioned in 2.2 statistical parameters of the ratio of experimental to theoretical values calculated according to (3) or (4) are seen in Tab. 2 and in Fig. 7.

Formulas according to (3) and (4) are generally useful for the load-carrying capacity determination for the anchors under shear loading. Using the standard procedure and considering the values of the variation coefficients of input random variables (e and f_{cc}) v_e = 0.1, v_{fcc} = 0.2, characteristic and design resistances V_k and V_d can be given as:

for the mean value according to (3)

$$V_k = 0.11 \cdot \pi \cdot e^2 \cdot f_{cc}^{0.5}, \tag{9}$$

$$V_d = 0.065 \cdot \pi \cdot e^2 \cdot f_{cc}^{0.5}, \tag{10}$$

for the mean value according to (4)

$$V_k = 4.41 \cdot e^{1.5} \cdot f_{cc}^{0.5}, \tag{11}$$

$$V_d = 2.87 \cdot e^{1.5} \cdot f_{cc}^{0.5}. \tag{12}$$

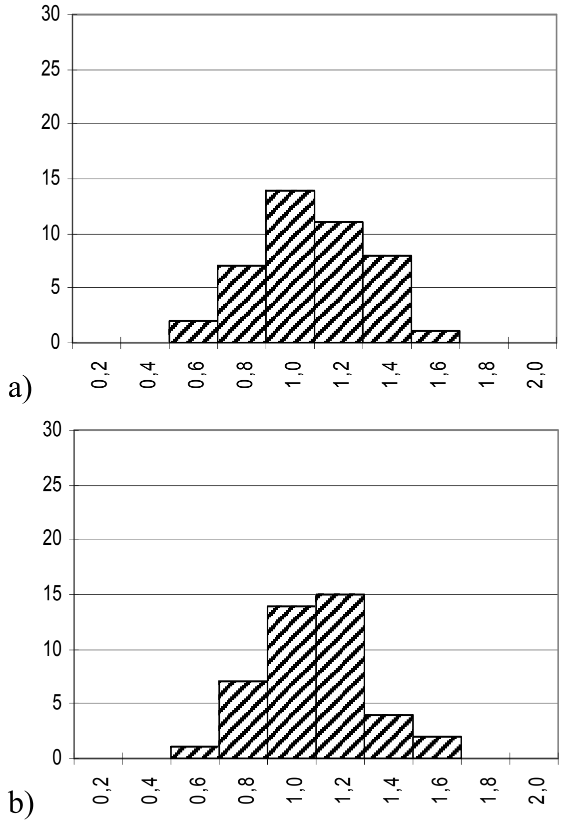


Fig. 7 Shear loading – histogram of $V_{u,ex}$ / V_{um} ratios:
a) mean value $V_{u,m}$ according to (3);
b) mean value $V_{u,m}$ according to (4)

Table 2 Statistical parameters of $V_{u,ex}$ / V_{um} ratios

Statistical analysis	mean value m	standard deviation s	variation coefficient v
V_{um} accord. to (3)	1.140	0.265	0.232
V_{um} accord. to (4)	1.001	0.201	0.201

4 Probabilistic analysis – failure probability and reliability

To evaluate the most suitable expression for the design resistance calculation, the failure probability of the investigated anchoring system can be used for the verification of the reached level of reliability. Using Monte Carlo simulation and FORM method (for comparison), failure probabilities have been calculated for the design resistances for tensile and shear force which have been derived always for two basic calculating methods as seen above. The failure probability by MC simulation has been calculated for various particular values of input variables, that means various combinations of anchorage depth h_{ef} and concrete cube strength f_{cc} in the case of tension,

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and, in the case of shear for various combinations of edge distance e and concrete cube strength f_{cc}. For each equation expressing the design resistance, i.e. for (6), (8) in the case of tensile loading and for (10), (12) in the case of shear loading, in common 150 runs with $1 \cdot 10^5$ simulation steps, which is in total $1.5 \cdot 10^7$ simulations, have been performed. For all variables the normal distribution has been considered, variation coefficient values have been taken as mentioned above (see paragraphs 3.1, 3.2). For FORM calculation the same parameters have been used. Here in addition, the reliability index β corresponding to the obtained failure probability has been calculated. The reliability index (see e.g. [13]) can characterize the reached reliability level and its recommended value for the reliability class RC2 (with 50 years reference period – for more see [13]), which is ordinarily considered for the structure of usual civil engineering construction, is β = 3.8 with corresponding failure probability of about $7 \cdot 10^{-5}$.

4.1 Expansion anchors subjected to static tensile force

For the load-carrying capacity of expansion anchors subjected to tensile force the design values can be given by the equations (6) or (8). Some examples of histograms obtained by the simulation are in Fig. 8. Tab. 3 shows: although the expression (6) gives the lower failure probability than the expression (8), the expression (6) is too conservative.

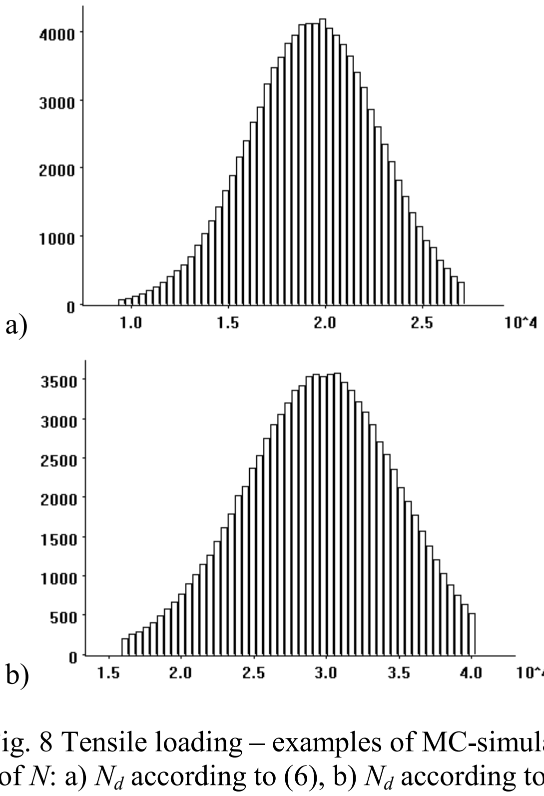

Fig. 8 Tensile loading – examples of MC-simulation of N: a) N_d according to (6), b) N_d according to (8)

Table 3 Failure probability and reliability index – expansion anchors subjected to tensile force

Probabilistic analysis	MC	FORM	
	failure probability P_f		reliabil. index β
N_d accord. to (6)	3.8E-6	4.0E-6	4.46
N_d accord. to (8)	1.2E-5	1.4E-5	4.19

4.2 Expansion anchors subjected to static shear force

For the load-carrying capacity of expansion anchors in shear the design values are given by the equations (10) or (12). Illustration of histograms obtained by the simulation is in Fig. 8. Similarly as above, Tab. 4 shows: the expression (10) gives the lower failure probability than the expression (12), but the expression (10) is more conservative.

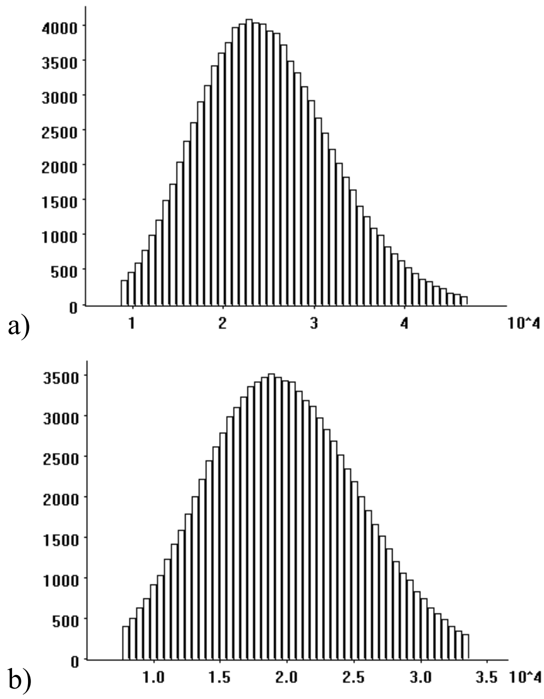

Fig. 9 Shear loading – examples of MC-simulation of V: a) V_d according to (10), b) V_d according to (12)

Table 4 Failure probability and reliability index – expansion anchors subjected to shear force

Probabilistic analysis	MC	FORM	
	failure probability P_f		reliabil. index β
V_d accord. to (10)	8.0E-6	2.7E-6	4.55
V_d accord. to (12)	6.0E-5	2.9E-5	4.02

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5 Conclusions

For expansion anchors subjected to both loading actions, that means tension or shear, the expressions (6) and (10) with the powers of h_{ef} or e equal to 2 give higher reliability and safety than the equations (8) and (12) with the powers of h_{ef} or e equal to 1.5. However, the expressions (6) and (10) are too conservative in comparison with the equations (8) and (12), for which the failure probability are just enough accurate from the viewpoint of necessary reliability and of the economy design. Then, the expressions (8) and (12) can be taken as the suitable formulas for the practical calculation of the design resistance of steel expansion anchors to concrete subjected to tensile or shear force.

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