Steel-to-Concrete Anchorage System Reliability Verified Based on Failure Probability Evaluated Using Test Results

Marcela Karmazínová

***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.

***Keywords*—**Reliability, failure probability, steel, concrete, anchorage, test results, expansion anchors, resistance, tensile loading, shear loading, experimental verification, load-carrying capacity, characteristic, design, experiments, statistical evaluation.

I. 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.

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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).

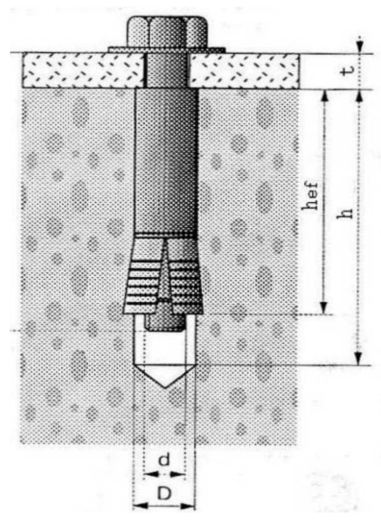


Fig. 1 typical composition of torque-controlled expansion anchor

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 with respect to the random variability of input quantities and number of tests realized are presented.

II. Experimental Research Programme – Basic Information

During several last years in our testing laboratory the loading tests of torque-controlled expansion anchors to concrete produced in our country have been conducted. Together 368 specimens under static loading actions as well as under dynamic loading actions have been tested so far. Among all tests, 277 specimens under static and also dynamic tensile loading (see e.g. [7], [8], [9], [10], [11], [12]) and 91 specimens under static shear loading have been tested.

For the test specimens under shear loading the expansion torque-controlled anchors (see Fig. 1) with the parameters as follows have been used: For the anchor bolts the steel grade of 8.8 with nominal ultimate tensile strength of f_{ub} = 800 MPa, and diameters of d = 10, 12 and 16 mm have been used. The external diameters of anchor sleeve were D = 14, 18 and 24 mm. Concrete cube strength f_{cc} of the specimen bodies was in the range from 19 to 37 MPa and the effective anchor embedment depth h_{ef} was in the range from 50 to 80 mm.

III. Experimental Verification and Results – Resistance Mean values

A. *Expansion Anchors Subjected to Static Tensile Force*

Depending on basic parameters of fastening arrangement different types of failure mode can be established. For the behaviour of anchor under tensile loading the embedment depth h_{ef} and concrete strength f_{cc} together with the bolt dimensions d, D and its strength f_{ub} are decisive, especially.

a)

b)

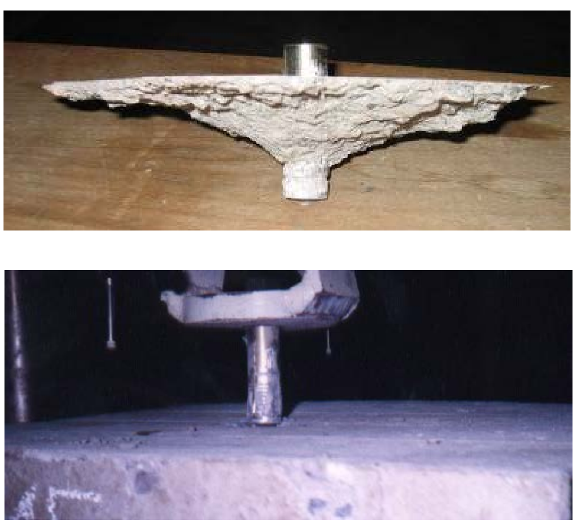


Fig. 2 tensile loading – illustration of actual concrete failure modes: a) concrete-cone failure, b) anchor pull-out

Depending on embedment depth, either steel failure or concrete fracture can occur. Steel failure by yielding and fracture of the anchor bolt is characteristic for the deep embedment and relatively low steel strength. Concrete failure is usually characterized by one of following possible modes: concrete-cone failure (see Fig. 2a), if the anchor distance from the edge is large, or anchor pull-out (see Fig. 2b).

Because steel bolt failure and its corresponding load-carrying capacity are known in general, the solution was concentrated to concrete failure, mainly. For the large edge distance, concrete-cone failure occurred in 86 cases. Basic parameters significantly influencing resulting resistance were: the anchorage depth in the range from 50 to 80 mm and concrete cube strength in the range from 20 to 70 MPa.

For the primary evaluation of the test results the basic calculation models according to published results (see [1], [2], [3]) have been used. For the subsequent analysis directed towards the determination of characteristic and design values of the anchor resistance the methods covered by the normative documents (for detail see [25]) for the design assisted by testing can be used.

a) ACI-method

b) ψ-method

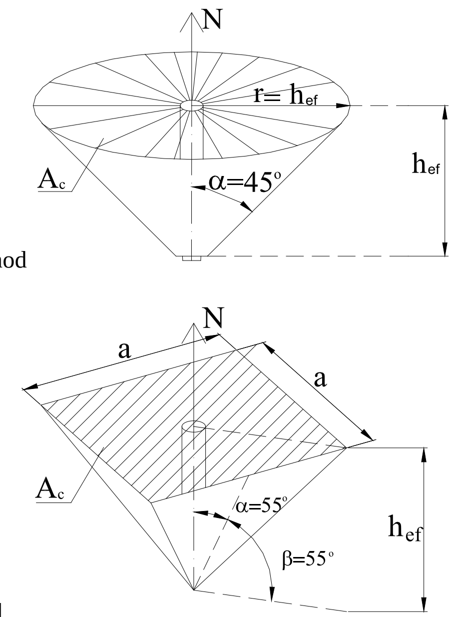


Fig. 3 tensile loading – concrete-cone failure: principles of calculating methods

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 resistance have been determined (for more see [15] - [17]) by the regression analysis used for the comparison of test and theoretical results.

Based on “Concrete-Cone Method” (see [1], [3]) the tensile resistance can be expressed by the general basic format of

$$N_u = A_c \cdot f_{ct} \,, \tag{1}$$

where A_c is projected area of the cone and f_{ct} is concrete tensile strength. Then, according to the “45-Degree Cone Method”, that means, for example, “ACI-method” considering 45˚ lateral failure cone (see Fig. 3a), and for the embedment depth h_{ef} and tensile strength expressed by the cube strength as $f_{ct} = k \cdot f_{cc}^{0.5}$, it can be written

$$N_u = k_{ACI} \cdot \pi \cdot h_{ef}^2 \cdot f_{cc}^{0.5}, \qquad (2)$$

where k_{ACI} is units dependent. For “ACI-method” the format (2) comes to the format of (see [11], [12])

$$N_u = 0.86 \cdot \pi \cdot h_{ef}^2 \cdot f_{cc}^{0.5} \qquad (3)$$

or $N_u = 2.7 \cdot h_{ef}^2 \cdot f_{cc}^{0.5}$. (4)

Based on Concrete Capacity Design Method (see [1], [3]), that means “ψ-method” (see Fig. 3b), for example, the corresponding general expression can be presented in the basic form of

$$N_u = k_\psi \cdot h_{ef}^{1.5} \cdot f_{cc}^{0.5}, \qquad (5)$$

where the factor k_ψ is usually derived from the test results using the regression analysis ($k_\psi \approx 13$ to 15 according to [1], [3], for example), so that for “ψ-method” the format (5) comes to the format of

$$N_u = 13.5 \cdot h_{ef}^{1.5} \cdot f_{cc}^{0.5} \qquad (6)$$

The mean value of the load-carrying capacity considered according to “ACI-method” and verified evaluating test results can be given as

$$N_{um} = 0.74 \cdot \pi \cdot h_{ef}^2 \cdot f_{cc}^{0.5}, \qquad (7)$$

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

The mean value of load-carrying capacity taken according to “ψ-method” and evaluated using the test results can be given by the equation of

$$N_{um} = 16.8 \cdot h_{ef}^{1.5} \cdot f_{cc}^{0.5} \quad \text{[N]}. \qquad (8)$$

B. Expansion Anchors Subjected to Static Shear Force

Also in the case of shear loading, depending on basic parameters of fastening arrangement different modes can occur. For the behaviour of anchor under shear force the edge distance e and concrete strength f_{cc} together with the bolt dimensions d, D and its strength f_{ub} are decisive, especially. Also the embedment depth h_{ef} can influence the fastening load-carrying capacity.

Depending on the edge distance and embedment depth, either steel failure or concrete fracture can occur. Steel failure by yielding and fracture of the anchor bolt is characteristic for deep embedment, low steel strength and large edge distance. Concrete failure is characterized by one of the possible modes: lateral concrete-cone failure (see Fig. 4a) for the anchors closed to edge, and concrete spalling (see Fig. 4b) or concrete crushing (see Fig. 4c), respectively, for the large distance from the edge. The failure by concrete spalling can occur for deeper embedment, concrete crushing may occur if the anchorage embedment depth is small ($h_{ef} \leq 4D$ to $6D$).

Within this information the results covering the set of lateral concrete-cone failure occurring in the case of 43 tests, are presented. Additionally in 58 cases the other failure modes occurred (bolt failure, concrete spalling, concrete crushing).

a) 

b) 

c) 

Fig. 4 shear loading – illustration of actual concrete failure modes:
a) lateral concrete-cone failure,
b) concrete spalling, c) concrete crushing

For the primary evaluation of the test results the basic calculation models according to published results (see [1], [2], [3]) have been used. For the subsequent analysis oriented to the determination of characteristic and design values of anchor resistance the method according to the normative documents (see [25]) for the design assisted by testing can be used.

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. 4a) occurred in 43 cases. Basic parameters significantly 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.

The load-carrying capacities mean values have been determined [2], [3], similarly as in II.A section, using two main calculating methods.

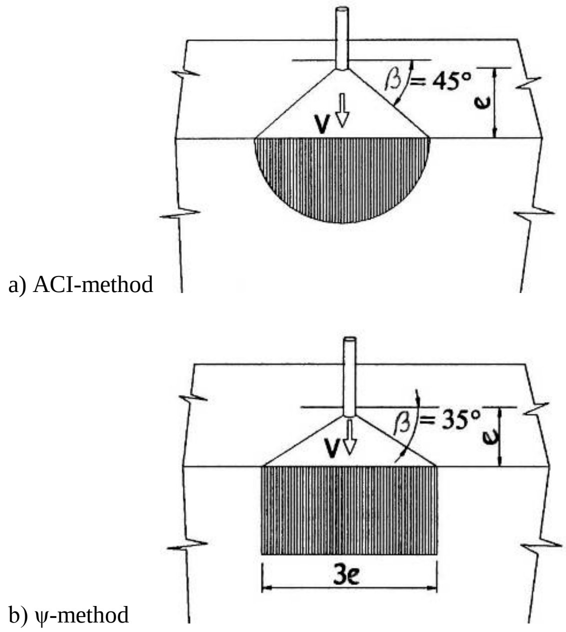


Fig. 5 shear loading – lateral concrete-cone failure: principles of calculating methods

Based on Concrete-Cone Method (see [1], [3]) the shear breakout capacity can be expressed by the general format of

$$V_u = A_c \cdot f_{ct}\,, \tag{9}$$

where A_c is projected area of the lateral cone and f_{ct} is the concrete tensile strength. According to the "45-Degree Cone Method", that means, for example, "ACI-method" considering 45˚ lateral failure cone (see Fig. 5a), and for the edge distance of e and the tensile strength expressed by the cube strength as $f_{ct} = k \cdot f_{cc}^{0.5}$, it can be written

$$V_u = k_{ACI} \cdot \frac{\pi \cdot e^2}{2} \cdot f_{cc}^{0,5}\,, \tag{10}$$

where k_{ACI} is units dependent. For "ACI-Method" the format of (10) comes to the format of (see [11], [12])

$$V_u = 0.137 \cdot \pi \cdot e^2 \cdot f_{cc}^{0.5} \tag{11}$$

or $V_u = 0.43 \cdot e^2 \cdot f_{cc}^{0.5}$. (12)

Based on Concrete Capacity Design Method (CC Method – see [1], [3]), that means, for example, "ψ-method", the corresponding general expression can be presented in the basic form of

$$V_u = k_\psi \cdot e^{1.5} \cdot f_{cc}^{0.5}\,, \tag{13}$$

where the factor k_ψ is usually derived from the test results using the regression analysis (e.g. $k_\psi \approx 5$ to 6 according to [1], [3]), that the format of (13) comes to the format of

$$V_u = 4.68 \cdot e^{1.5} \cdot f_{cc}^{0.5}. \tag{14}$$

The mean value of the load-carrying capacity considered according to "ACI-method" and verified evaluating test results can be given as

$$V_{um} = 0.24 \cdot \pi \cdot e^2 \cdot f_{cc}^{0.5}\,, \tag{15}$$

where e is the edge distance (see Fig. 5) and f_{cc} is concrete cube strength.

The mean value of load-carrying capacity taken according to "ψ-method" and evaluated using test results can be given by the equation of

$$V_{um} = 7.3 \cdot e^{1.5} \cdot f_{cc}^{0.5} \quad \text{[N]}. \tag{16}$$

IV. Statistical Analysis – resistance Characteristic and Design Values

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 [13], [15], [16], [17]).

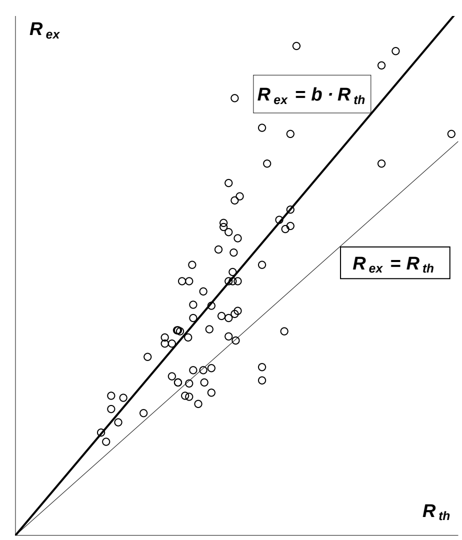


Fig. 6 "$R_{ex} – R_{th}$" diagram

For the following determination of characteristic and design values R_k, R_d of the resistance (in this case the load-carrying capacities N and V) the statistical parameters of the ratios of experimental and mean values of the resistance have been obtained using the statistical analysis. To determine the characteristic and design resistances, for the test results elaboration the standard procedure following the principles of the design assisted by testing (for more see [12]) has been applied (similarly as e.g. in [13], [15], [16]). This procedure is based on the comparison of the experimental resistances R_{ex} obtained from the loading tests and the theoretical resistances R_{th} obtained from the calculation according to the theoretical resistance model; it is derived from the statistic evaluation of the probabilistic resistance model R in the form of

$$R = b \cdot R_{th} \cdot \delta \,, \tag{17}$$

where b is the reduction factor (see Fig. 6) and the error term δ is coming from the differences of experimental and theoretical resistance values

$$\delta_i = \frac{R_{ex,i}}{b \cdot R_{th,i}} . \tag{18}$$

Then, characteristic and design resistances are given in the formats of

$$\begin{aligned} R_k &= b \cdot g_{Rth}(m_{Xj}) \cdot \exp(-k_\infty \cdot \alpha_{Rth} \cdot v_{Rth} - \\ &- k_n \cdot \alpha_\delta \cdot v_\delta - 0.5 \cdot v_R^2) \end{aligned} , \tag{19}$$

$$\begin{aligned} R_k &= b \cdot g_{Rth}(m_{Xj}) \cdot \exp(-k_{d,\infty} \cdot \alpha_{Rth} \cdot v_{Rth} - \\ &- k_{d,n} \cdot \alpha_\delta \cdot v_\delta - 0.5 \cdot v_R^2) \end{aligned} , \tag{20}$$

where the expression $b \cdot g_{Rth}$ (m_{Xj}) = m_R is the mean resistance value (with the mean values of the input random variables X_j), coefficients of the predicting method k_∞, k_n, $k_{d,\infty}$, $k_{d,n}$ are depending on the tests number (see [13]) and α_{Rth}, α_δ are the weighting factors according to following formulas

$$\alpha_{Rth} \cong \frac{v_{Rth}}{v_R} , \tag{21}$$

$$\alpha_\delta \cong \frac{v_\delta}{v_R} . \tag{22}$$

For the calculation of characteristic and design resistance values it is necessary to know the variation coefficients v_{Xj} of the input random variables X_j, which are usually known from the earlier experiences, and the variation coefficient v_R of the resistance R. The variation coefficient v_R follows from the variation coefficients v_{Xj} and 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 the experimental and theoretical values.

A. Expansion Anchors Subjected to Static Tensile Force

For the calculation of anchor system resistance by two methods described in II.A, statistical parameters (i.e. mean value, standard deviation and variation coefficient) of the ratio of experimental values to theoretical values calculated according to formulas (7) and (8) are viewed in Table 1 and graphically expressed in Fig. 7, respectively. These statistical parameters can show the significant differences between actual experimental values and mean values of the resistance.

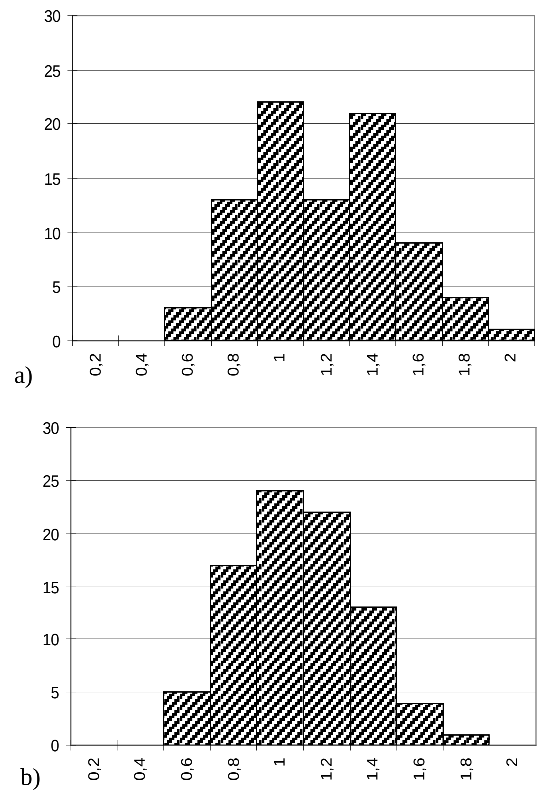


Fig. 7 tensile loading – histogram of $N_{u,ex}$ / N_{um} ratios:
a) mean value N_{um} according to (7);
b) mean value N_{um} according to (8)

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 (7)	1.086	0.302	0.278
N_{um} accord. to (8)	0.990	0.246	0.248

Formulas (7) and (8) 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_{uk} and N_{ud} have been obtained as:

for the mean value according to (7)

$$N_{uk} = 0.38 \cdot \pi \cdot h_{ef}^2 \cdot f_{cc}^{0.5}, \tag{23}$$

$$N_{ud} = 0.24 \cdot \pi \cdot h_{ef}^2 \cdot f_{cc}^{0.5}, \tag{24}$$

for the mean value according to (8)

$$N_{uk} = 10.2 \cdot h_{ef}^{1.5} \cdot f_{cc}^{0.5}, \tag{25}$$

$$N_{ud} = 6.7 \cdot h_{ef}^{1.5} \cdot f_{cc}^{0.5}. \tag{26}$$

B. Expansion Anchors Subjected to Static Shear Force

For methods mentioned in II.B statistical parameters of the ratio of experimental to theoretical values calculated according to (15) or (16) are seen in Table 2 and in Fig. 8.

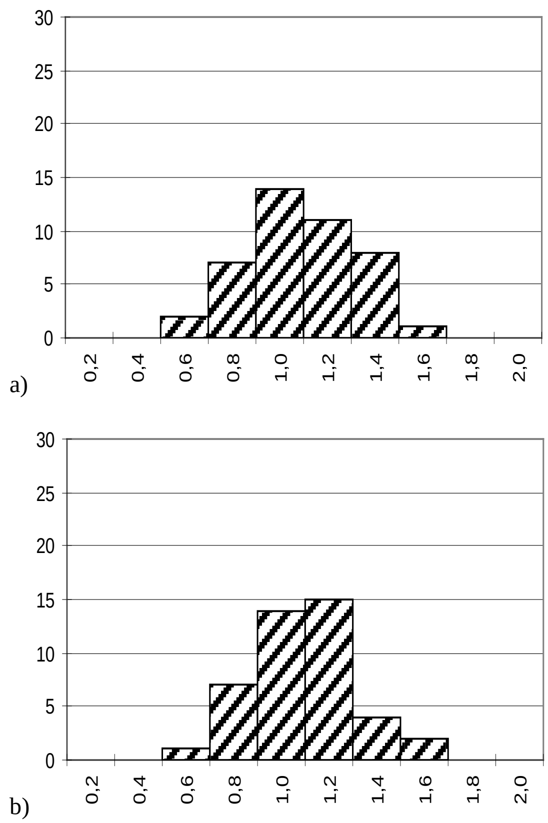


Fig. 8 shear loading – histogram of $V_{u,ex}$ / V_{um} ratios:
a) mean value V_{um} according to (3);
b) mean value V_{um} according to (4)

Formulas according to (15) and (16) 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_{uk} and V_{ud} can be given as:

for the mean value according to (15)

$$V_{uk} = 0.11 \cdot \pi \cdot e^2 \cdot f_{cc}^{0.5}, \tag{27}$$

$$V_{ud} = 0.065 \cdot \pi \cdot e^2 \cdot f_{cc}^{0.5}, \tag{28}$$

for the mean value according to (16)

$$V_{uk} = 4.41 \cdot e^{1.5} \cdot f_{cc}^{0.5}, \tag{29}$$

$$V_{ud} = 2.87 \cdot e^{1.5} \cdot f_{cc}^{0.5}. \tag{30}$$

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 (15)	1.140	0.265	0.232
V_{um} accord. to (16)	1.001	0.201	0.201

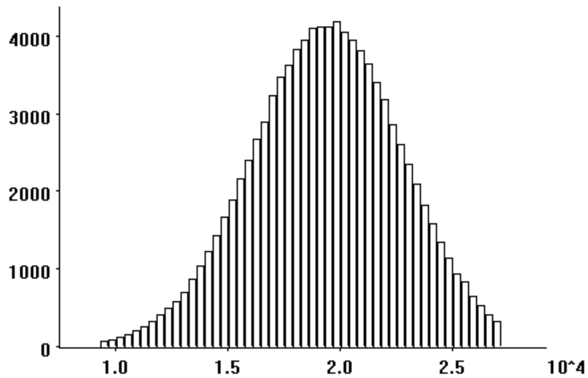
V. Probabilistic Analysis – Failure Probability and Structural Reliability

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, and, in the case of shear for various combinations of edge distance e and concrete cube strength f_{cc}.

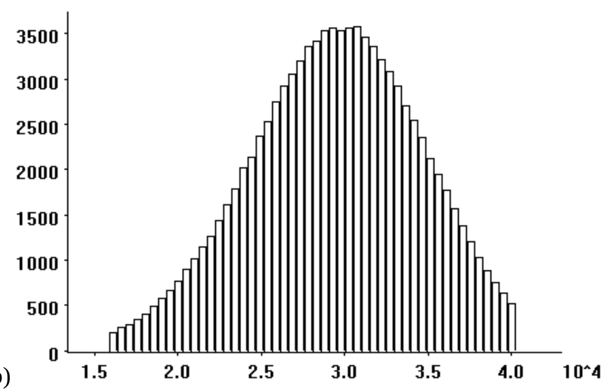
For each equation expressing the design resistance, i.e. for (24), (26) in the case of tensile loading and for (28), (30) in the case of shear loading, in common 150 runs with $1 \cdot 10^5$ simulation steps, which is in total $1.5 \cdot 10^7$ simulations, have been performed. For all variables the normal distribution has been considered, variation coefficient values have been taken as mentioned above (see paragraphs IV.A, IV.B). 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. [4], [14], [18], [19], [20], [21],) can characterize the reached reliability level and its recommended value for the reliability class RC2 (with 50 years reference period – for more see [25]), which is ordinarily considered for the structure of usual civil engineering construction, is β = 3.8 with corresponding failure probability of about $7 \cdot 10^{-5}$.

A. 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 (24) or (26). Some examples of histograms obtained by the simulation are in Fig. 9. Table 3 shows: though the expression (24) gives the lower failure probability than expression (26), the expression (24) is too conservative.



a)



b)

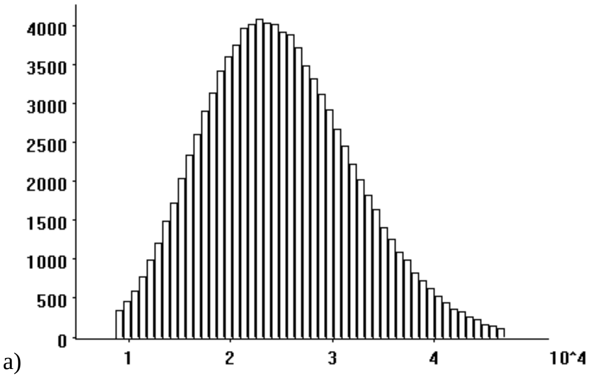
Fig. 9 tensile loading – examples of MC-simulation of N: a) N_{ud} according to (18), b) N_{ud} according to (20)

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

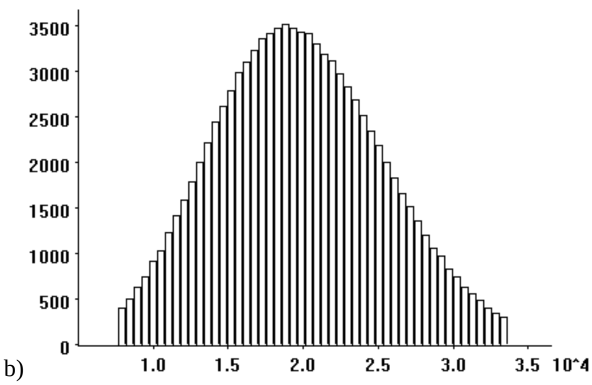
Probabilistic analysis	MC	FORM	
	failure probability P_f		reliability index β
N_{ud} accord. to (24)	3.8E-6	4.0E-6	4.46
N_{ud} accord. to (26)	1.2E-5	1.4E-5	4.19

B. 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 (28) or (30). Illustration of histograms obtained by the simulation is in Fig. 10. Similarly as above, Table 4 shows: the expression (28) gives the lower failure probability than the expression (30), but the expression (28) is more conservative.



a)



b)

Fig. 10 Shear loading – examples of MC-simulation of V: a) V_{ud} according to (22), b) V_{ud} according to (24)

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

Probabilistic analysis	MC	FORM	
	failure probability P_f		reliability index β
V_d accord. to (28)	8E-6	2.7E-6	4.55
V_d accord. to (30)	6E-5	2.9E-5	4.02

VI. Conclusions

For expansion anchors subjected to both loading actions, that means tension or shear, the expressions (24) and (28) with the powers of h_{ef} or e equal to 2 give higher reliability and safety than the equations (26) and (30) with the powers of h_{ef} or e equal to 1.5. However, the expressions (24) and (28) are too conservative in comparison with the equations (26) and (30), for which the failure probability are just enough accurate from the viewpoint of necessary reliability and economy design. Based on this information, the following particular conclusions can be deducted for anchors subjected to tensile force and to shear force, separately.

A. Expansion Anchors Subjected to Static Tensile Force

- For the practical calculation of the load-carrying capacity of steel expansion anchors to concrete subjected to tensile force the expression in the form of $N_{ud} = 6.7 \cdot h_{ef}^{1.5} \cdot f_{cc}^{0.5}$ can be taken as the suitable formula for the design resistance.
- The expression in the format of $N_{uk} = 10.2 \cdot h_{ef}^{1.5} \cdot f_{cc}^{0.5}$ can be taken as the suitable formula for the characteristic resistance.
- The design resistance is 39.9 % of the mean value of the resistance obtained from the test results using statistical and probabilistic evaluation, and the characteristic value is 60.7 % of the mean value.
- Then, the partial safety factor for the material is given as $\gamma_{M,N} = N_{ud} / N_{uk} = 1.52$. This value derived from the test results is less than the values of safety factors mentioned in the producers' documents, for example, which are usually given from 2.5 to 3.0 approximately.

B. Expansion Anchors Subjected to Static Tensile Force

- For the practical calculation of the load-carrying capacity of steel expansion anchors to concrete subjected to shear force the expression in the form of $V_{ud} = 2.87 \cdot e^{1.5} \cdot f_{cc}^{0.5}$ can be taken as the suitable formula for the design resistance.
- The expression in the format of $V_{uk} = 4.41 \cdot e^{1.5} \cdot f_{cc}^{0.5}$ can be taken as the suitable formula for the characteristic resistance.
- The design resistance is 39.3 % of the mean value of the resistance obtained by statistical and probabilistic evaluating test results and the characteristic value is 60.4 % of the mean value.
- The partial safety factor for the material is calculated as $\gamma_{M,V} = V_{ud} / V_{uk} = 1.54$. Also this value obtained from the tests is less than the values of safety factors mentioned in the producers' documents, which are usually given from 2.5 to 3.0.

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