The influence of material and geometric parameters on the design of steel mechanical anchors to concrete under tension loading

Michal Štrba, Marcela Karmazínová and Veronika Václavíková

***Abstract*—** This paper deals with some problems in case of the effective and efficient design of post-installed steel mechanical expansion anchors to concrete which are subjected to the tension loading using either static or cyclic loading force. Also the influence of some selected parameters and characteristics in case of the load-carrying capacity determination and of the actual behaviour of these fastening members is discussed.

All the presented information and results are mostly based on the previous theoretical and experimental research realized in last years on the authors' workplace and oriented to a verification of these steel anchors to concrete using the effect of the mechanical interaction of both component materials (steel and concrete).

Within the framework of mentioned research programme a large number of loading tests were performed for various loading cases and all the results were subsequently elaborated to get values of load-carrying capacity corresponding different failure mechanisms of these fasteners depending on the used material and geometric parameters as well as on the type of loading. They were also realized some additional loading tests for the verification of actual material properties of the selected members (especially in case of strength characteristics). All the data and test results obtained from the performed experiments were evaluated using statistic and probabilistic approaches to get the characteristic and design values of load-carrying capacity. Therefore, this article provides some additional information about the general principle of mentioned members for fastening as well as it complements some author's previous publications in this field.

***Keywords*—**Design parameters, expansion anchors, failure modes, load-carrying capacity, loading tests, tension force.

I. Introduction

THEY exist many types of fastening systems, where in case of an application to concrete many kinds of them have widespread use. However, two main groups of these members can be distinguished.

As the first group they can be taken some older and more traditional members, so-called "cast-in-place" fasteners, which have to be always used before the concrete is poured into the formwork. On the contrary, the second group contains the newer approach, where we can find so-called "post-installed" members, which are placed in the concrete after its hardening.

Currently, members from the second group are used slightly more often, especially because of their easier installation, which can obviously cause a faster building process in general and give an advantage in case of serious requirements for an efficient design and fast construction. Compared to the cast-in-place systems, another reason for more frequent application of post-installed fasteners can be also their higher accuracy (which goes in cast-in-place systems together with more complicated assembly procedure and higher need for accuracy checks).

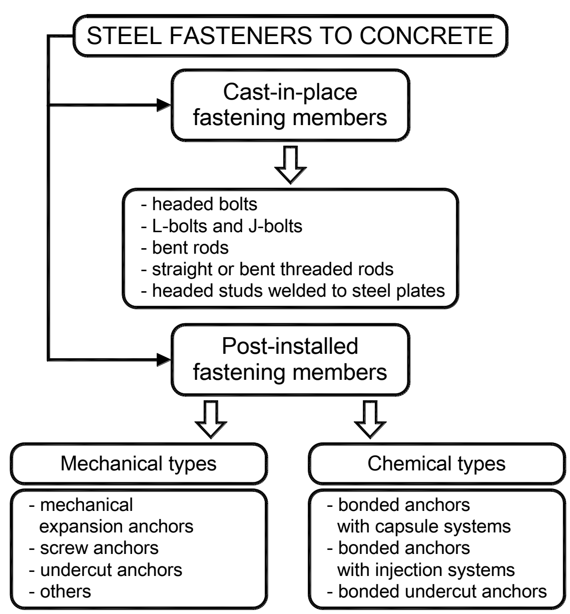

Fig. 1 the types of fastening methods to concrete

An overview of most common types of the steel fasteners to concrete represented two mentioned groups is shown

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on Fig. 1, where also the post-installed members are divided into two groups according their specific technology (i.e. mechanical and chemical types).

Both named systems have their own specific design and geometric arrangement and their type of loading depends mostly on their particular use in construction [1].

The main aim of the research was to obtain information and experiences about the actual behaviour and to get the values of a load-carrying capacity in case of the post-installed mechanical anchors subjected to tension loading.

Although this paper is focused mainly on the post-installed members, they are on Fig. 2 for better illustration shown also some examples of the mentioned cast-in-place fastening members with a description. For more examples see e.g. [2].

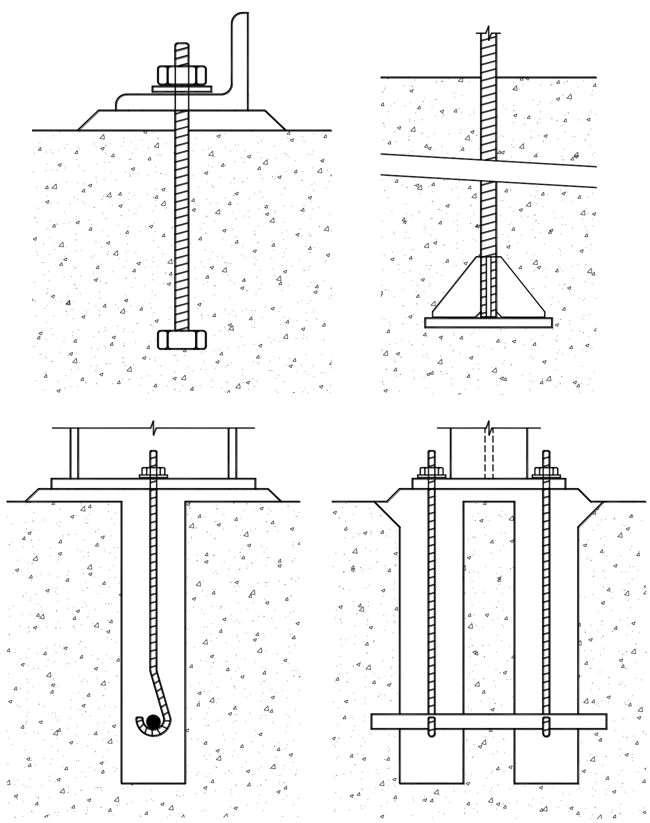


Fig. 2 some examples of cast-in-place steel fasteners to concrete (top left – the headed bolt; top right – the threaded rod welded to the steel plate; bottom – bent threaded rods combined with concrete reinforcement)

II. Post-installed fastening members

In the field of post-installed anchorage members they can be found various types of them, where also the possibilities of their use are very wide (primarily in the civil and bridge engineering).

Generally, two main types of them can be mentioned, according their basic principle. Firstly they are the bonded anchors and then the mechanical anchors. The bonded ones (chemical types) are slightly more preferred because of their more available and uniform transferring of tension forces.

On the contrary, the mechanical ones are very useful, too. Mostly because their fast and easy installation (no additional binding material is needed, immediate loading transfer after installation and no dependency on weather conditions, unlike the chemical types). However these fasteners can be used for different kinds of loading (shear, tension, bending moment, etc.), from now, the attention will be paid only to the mechanical members to concrete used for tension forces.

A. Types of post-installed mechanical fastening members

In case of these fasteners the transfer of a tension force occurs only between the fastener itself and the base concrete material. Many types of these members exist. For example the screw anchors, where the diameter of the drilled hole d_h is slightly smaller than the diameter of the anchor d_0 so that the thread pitches can cut into the concrete surface inside the hole, see Fig. 3. In fact, this type of mechanical anchor has very similar principle of load transfer to the bonded type (i.e. it has more uniform force distribution along its length).

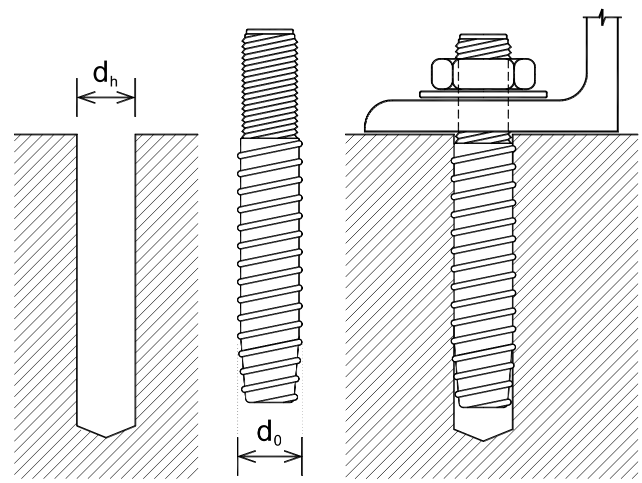


Fig. 3 illustration of the screw anchor

As another example they can be taken so-called undercut anchors, whose principle is shown on Fig. 4. In fact, for these members the special drilling equipment has to be used (see step 2 on Fig. 4) to make an undercut into a cylindrical hole.

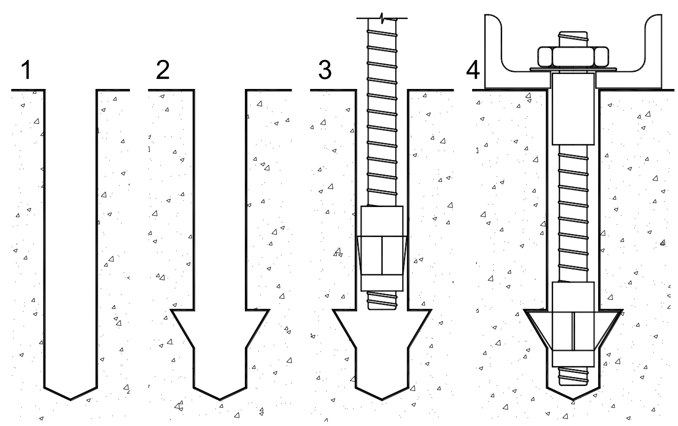


Fig. 4 illustration of the undercut anchor

B. Mechanical expansion anchors to concrete

However, in practice, the mostly used type of steel post-installed mechanical anchor to concrete is an expansion anchor with controlled torque, which usually consist of a steel bolt used together with the expansion sleeve and with the threaded cone (see Fig. 5).

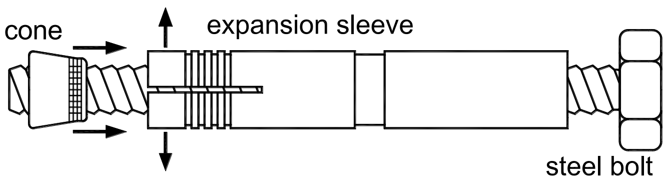


Fig. 5 mechanical expansion anchor to concrete

By using of a controlled torque on a bolt head the cone moves into a sleeve which opens towards the concrete surface and the expansion forces occur. This principle together with the principle of the loading transfer is shown on Fig. 6, where it is also added the comparison with the uniform loading transfer of a typical bonded anchor.

Note: it exist also another type of expansion anchor, which has controlled displacement, but it is not so commonly used.

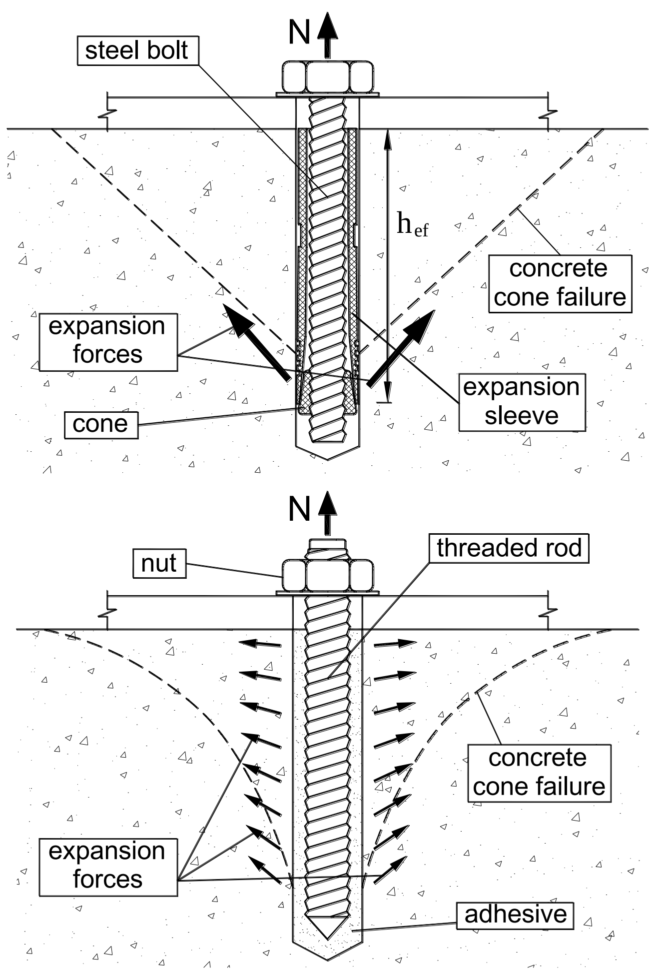


Fig. 6 the principle of loading transfer in case of the mechanical expansion anchor (top) and the bonded anchor (bottom)

III. Actual Behaviour under Tension Loading

Two most typical and frequent modes of failure exist in case of steel mechanical expansion anchors to concrete subjected to tension loading force. The first one is a failure of the steel bolt in its threaded part (it is so-called “steel-bolt failure”). In the second case the failure of concrete occurs, where the cone of concrete is being tear out from the concrete base (this failure mode is called “concrete-cone failure”), see Fig. 6 and Fig. 7.

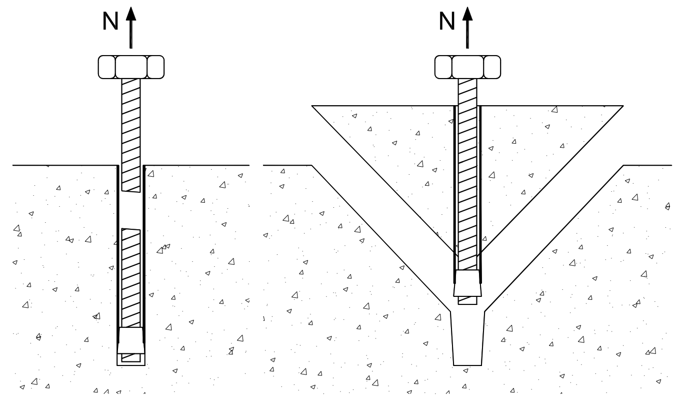


Fig. 7 illustration of modes of failure in case of steel mechanical expansion anchors to concrete under tension loading force; failure of steel bolt (left) and concrete-cone failure (right)

Except mentioned two modes they exist also another, less common cases, like e.g. the “pull-out failure”, where the whole anchor (including the expansion sleeve and the cone) is pulled-out from the concrete. At the same time it can be (but not always) damaged just small part of concrete on its surface immediately close to the anchor (it can occur, in fact, a small concrete-cone failure in this case, too). The second one, also not very common mode of failure is so-called “splitting failure”. For more details about the failure modes see [1].

IV. Load-Carrying Capacity in Case of the Tension Static Force

A. Failure of steel

Generally, in case of the steel failure the value of the ultimate load-carrying capacity of the mechanical expansion anchors N_s depends on the steel bolt tensile area A_s (it means on the diameter of the bolt d) and on the ultimate strength of steel f_{ub}. It can be taken as follows:

$$N_s = k_s \cdot A_s \cdot f_{ub}. \qquad (1)$$

The coefficient “k_s” in the formula (1) implies mostly the influences of selected statistic uncertainties (for example the variability of material characteristics and geometry as well as of the way and conditions of an assembly, etc.). Basically, this coefficient should reduce the load-carrying capacity.

However, due to some previous experiences and researches, the coefficient has usually its value very close to the value 1.0.

On the basis of 31 previously performed experiments with static tension loading force, the elementary formula (1) have been modified into the form of the mean value of the load-carrying capacity $N_{s,m}$ as follows:

$$N_{s,m} = 1.024 \cdot A_s \cdot f_{ub}. \tag{2}$$

For more specific details about the previously performed tests of the steel mechanical expansion anchors subjected to the static tension force see [3]–[5].

B. Failure of concrete

Next, in case of concrete-cone failure a few methods exist to determine the load-carrying capacity of expansion anchors under the tension loading force. Generally, this determination is based on the ultimate tensile capacity of concrete N_c, where the effective concrete area A_c and the concrete tensile strength f_{ct} are used together with possible use of an additional coefficient k_c, which can have (in principle) very similar meaning like the k_s factor in the formula (1).

$$N_c = k_c \cdot A_c \cdot f_{ct}. \tag{3}$$

All the methods vary according to the used geometric parameters of the anchors and according to the simplification of the shape of failed cone of concrete. This shape (or form) can be taken for example as a cone or as a pyramid. The effective tensile area of concrete changes according this simplification. In some methods the cylindrical strength of concrete is used, in another methods the cube strength is used, etc. However, in each method, the most important geometric parameter is so-called "effective length" of the anchor (or the "effective depth" of the anchor) h_{ef}. The geometric meaning of this value is shown on Fig. 6). Recently, the most frequent methods are so-called Concrete-Cone Method [6] and the Concrete-Capacity Method [7].

Based on 127 previously performed experiments with static tension loading forces, [3]–[5], the mean value of the load-carrying capacity according to the Concrete-Capacity Method can be taken as follows:

$$N_{c1,m} = 15.6 \cdot h_{ef}^{1.5} \cdot \sqrt{f_{cube150}}, \tag{4}$$

where the $f_{cube150}$ value is the compressive cube strength measured and tested on the concrete specimens with the dimensions 15 × 15 × 15 cm. Then, according to Concrete-Cone Method the mean value of the load-carrying capacity of the expansion anchor can be determined this way:

$$N_{c2,m} = 0.67 \cdot \pi \cdot h_{ef}^{2} \cdot \sqrt{f_{cube150}}. \tag{5}$$

For more principles in the event of the concrete cone failure and for more specific explanation of the load-carrying capacity determination in its case see [1] or [8]–[10].

C. Effective parameters in case of static tension force

On the basis of the determined formulas for the static load-carrying capacities in case of both failure modes it is possible to select the most efficient and effective anchorage parameters (the diameters of bolt, i.e. the tensile bolt areas, then the effective anchorage depths as well as the strengths of both used materials), so that the probability of the failure mode of both materials can be the same or at least very similar. Then, in such case, also the values of load-carrying capacity for the bolt failure and for the concrete cone failure could be the same.

Therefore, through the use of the mentioned equations for the mean values of load-carrying capacities (2) (4) (5) they can be derived the suitable relationships between all the parameters (geometrical and mechanical, see above), which have the influence to the resistance.

Consequently, according to the selected concrete failure method and based on the assumption, that the mean values of the load-carrying capacities of both failure modes should be equal, i.e.:

$$N_{s,m} = N_{c1,m}, \tag{6}$$

$$N_{s,m} = N_{c2,m}, \tag{7}$$

it can be written the equation for the anchorage parameters relationship in case of the Concrete-Capacity Method this way:

$$1.024 \cdot A_s \cdot f_{ub} = 15.6 \cdot h_{ef}^{1.5} \sqrt{f_{cube150}} \tag{8}$$

and in case of Concrete-Cone Method as follows:

$$1.024 \cdot A_s \cdot f_{ub} = 0.67 \cdot \pi \cdot h_{ef}^{2} \sqrt{f_{cube150}}. \tag{9}$$

Then, from the equations (8) and (9) they can be derived values of the corresponding effective tensile areas of the steel bolt as either:

$$A_s = \frac{15.6}{1.024} \cdot h_{ef}^{1.5} \frac{\sqrt{f_{cube150}}}{f_{ub}} = 15.234 \cdot h_{ef}^{1.5} \frac{\sqrt{f_{cube150}}}{f_{ub}}, \tag{10}$$

or:

$$A_s = \frac{0.67 \cdot \pi}{1.024} \cdot h_{ef}^{2} \frac{\sqrt{f_{cube150}}}{f_{ub}} = 2.056 \cdot h_{ef}^{2} \frac{\sqrt{f_{cube150}}}{f_{ub}}. \tag{11}$$

Next, in Table 1 and 2 the values of tensile steel bolt areas A_s according to the formulas (10) and (11) are written for some typical classes of concrete [11] and for one selected value of the ultimate strength of steel f_{ub} = 800 MPa, i.e. for steel bolt grade 8.8 [12].

Table 1 determination of the effective tensile bolt area A_s in case of Concrete-Capacity Method, i.e. according (10)

Effective anchorage depth	Concrete Class				
	C 16/20	C 20/25	C 25/30	C 30/37	C40/50
	Compressive cube strength $f_{ck,cone}$ [MPa]				
	20	25	30	37	50
h_{ef} [mm]	Tensile bolt area A_s [mm^2] for f_{ub} = 800 MPa				
60	39,58	44,25	48,47	53,83	62,58
70	49,88	55,76	61,08	67,84	78,86
80	60,94	68,13	74,63	82,88	96,35
90	72,71	81,29	89,05	98,90	114,97
100	85,16	95,21	104,30	115,83	134,65
110	98,25	109,85	120,33	133,63	155,35
120	111,95	125,16	137,11	152,26	177,00
130	126,23	141,13	154,60	171,69	199,58
140	141,07	157,72	172,77	191,87	223,05
150	156,45	174,92	191,61	212,80	247,37
160	172,35	192,70	211,09	234,43	272,51
170	188,76	211,04	231,18	256,74	298,46
180	205,66	229,93	251,88	279,73	325,18

Table 2 determination of the effective tensile bolt area A_s in case of Concrete-Cone Method, i.e. according (11)

Effective anchorage depth	Concrete Class				
	C 16/20	C 20/25	C 25/30	C 30/37	C40/50
	Compressive cube strength $f_{ck,cone}$ [MPa]				
	20	25	30	37	50
h_{ef} [mm]	Tensile bolt area A_s [mm^2] for f_{ub} = 800 MPa				
60	41,38	46,26	50,68	56,28	65,42
70	56,32	62,97	68,97	76,60	89,05
80	73,56	82,24	90,09	100,05	116,30
90	93,10	104,09	114,02	126,62	147,20
100	114,93	128,50	140,76	156,33	181,73
110	139,07	155,49	170,33	189,16	219,89
120	165,50	185,04	202,70	225,11	261,69
130	194,24	217,17	237,89	264,19	307,12
140	225,27	251,86	275,90	306,40	356,18
150	258,60	289,13	316,72	351,74	408,88
160	294,23	328,96	360,36	400,20	465,22
170	332,16	371,37	406,81	451,79	525,19
180	372,39	416,34	456,08	506,50	588,79

The graphic illustration of both derived relationships (10) and (11) for the determination of the steel bolt tensile area A_s according to Table 1 and 2 are shown on Fig. 8 and Fig. 9, where also the specific bolt diameters are selected and marked as M8, M10 and M12 adequately to their values of A_s.

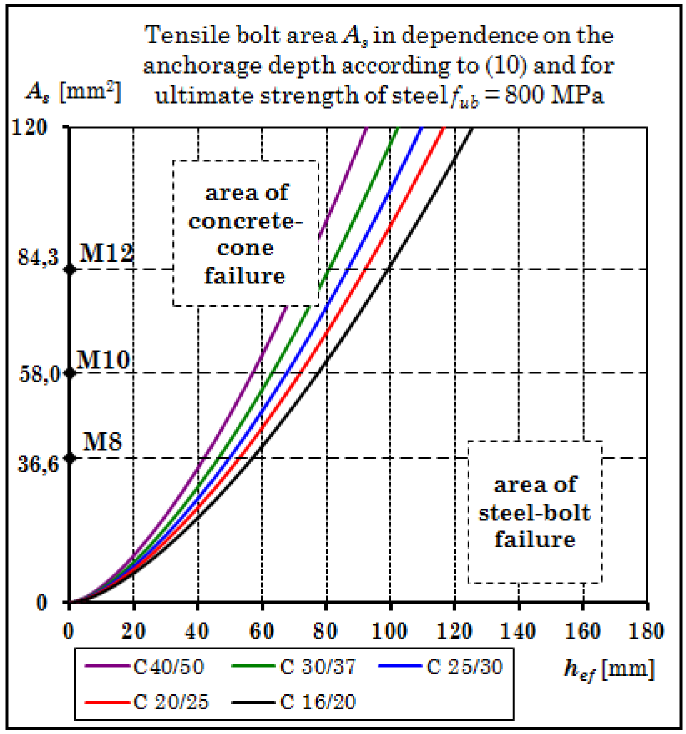


Fig. 8 relationships between the effective anchorage depth and tensile area of the steel bolt in case of Concrete-Capacity Method

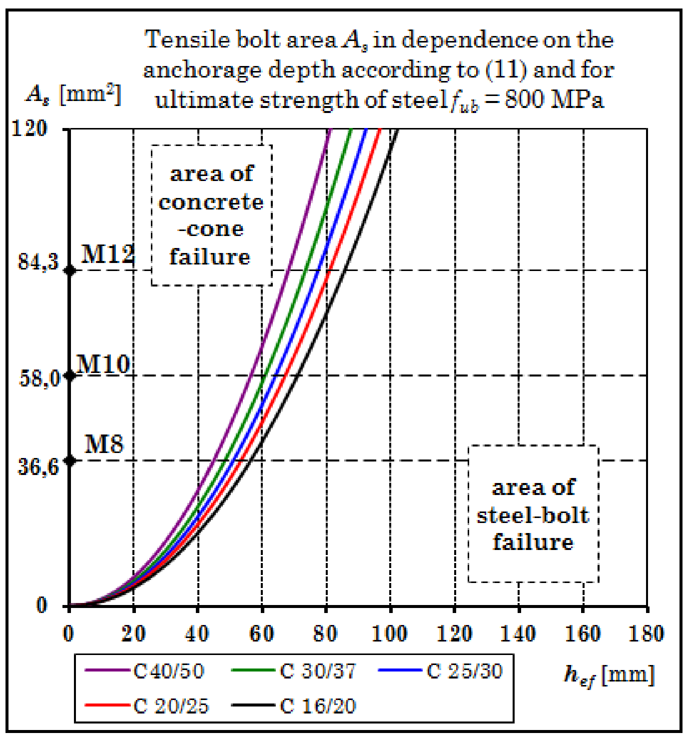


Fig. 9 relationships between the effective anchorage depth and tensile area of the steel bolt in case of Concrete-Cone Method

D. Design values of effective anchorage parameters

The derived relationships of the load-carrying capacities described above were also processed using the probabilistic evaluation of the test results, i.e. using the method of design assisted by testing given in Eurocode [13].

Note: for the testing the anchors KOTE and Fischer were used (see Fig. 10) with the bolt diameters M8, M10, M12 and M16 and with different ultimate strengths of steel as well as the concrete blocks with specific dimensions according the rules given in ETAG guideline [14] were used with different compressive strengths.

For the detailed information about the test arrangements and about the steel and concrete specimen specifications in case of the tests with static tension forces see [8] and [9].

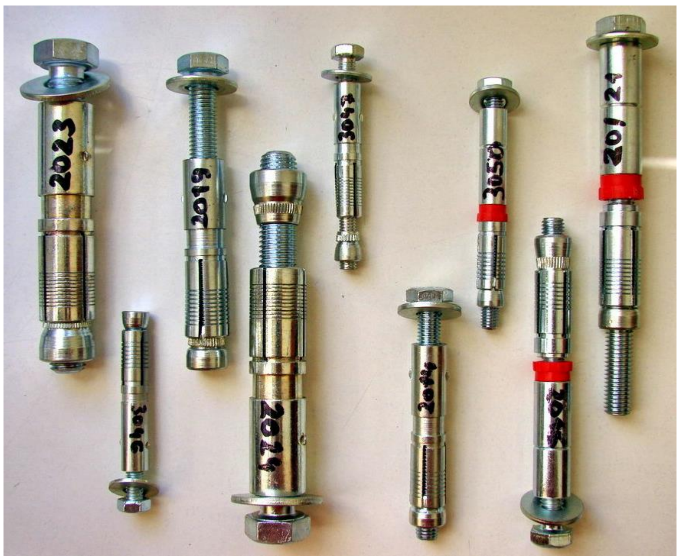


Fig. 10 examples of the steel mechanical expansion anchors to concrete used for the loading tests with tension forces

Some basic rules for the dimensions of specimens during loading tests as well as for the possibility of a displacement measuring according the ETAG [14] are shown on Fig. 11.

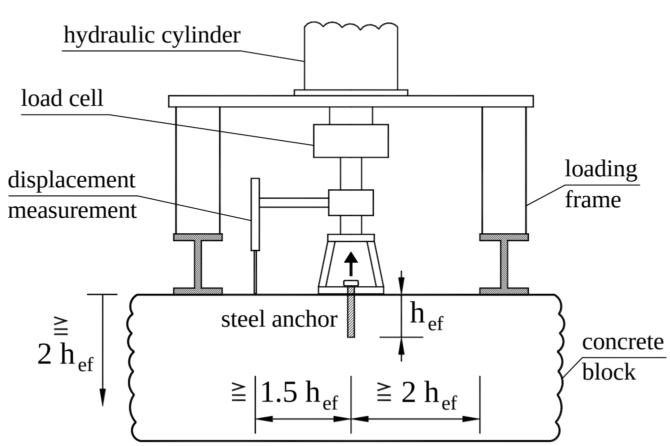


Fig. 11 geometric requirements for the loading tests (in dependence of the effective depth h_{ef} value)

Based on the probabilistic evaluation using Design assisted by testing the design values of the load-carrying capacities were determined sequentially, first for the steel-bolt failure as:

$$N_{s,d} = 0.713 \cdot N_{s,m} = 0.730 \cdot A_s \cdot f_{ub} \tag{12}$$

and then in case of the concrete-cone failure according to the Concrete-Capacity Method and to the Concrete-Cone Method as follows:

$$N_{c1,d} = 0.446 \cdot N_{c1,m} = 6.958 \cdot h_{ef}^{1.5} \cdot \sqrt{f_{cube150}}\,, \tag{13}$$

$$N_{c2,d} = 0.388 \cdot N_{c2,m} = 0.260 \cdot \pi \cdot h_{ef}^{2} \cdot \sqrt{f_{cube150}}\,. \tag{14}$$

Similarly as in case of the mean values – see the evaluation process in the formulas (6) to (11) – they could be also the effective tensile areas A_s of steel anchor bolt in their design values derived either for Concrete-Capacity Method as (15) and for Concrete-Cone Method as (16).

Next, also the illustration of the relationships (15) and (16) are shown in graphs on Fig. 12 and Fig. 13.

$$A_s = \frac{6.958}{0.730} \cdot h_{ef}^{1.5} \frac{\sqrt{f_{cube150}}}{f_{ub}} = 9.532 \cdot h_{ef}^{1.5} \frac{\sqrt{f_{cube150}}}{f_{ub}} \tag{15}$$

$$A_s = \frac{0.260 \cdot \pi}{0.730} \cdot h_{ef}^{2} \frac{\sqrt{f_{cube150}}}{f_{ub}} = 0.356 \cdot h_{ef}^{2} \frac{\sqrt{f_{cube150}}}{f_{ub}} \tag{16}$$

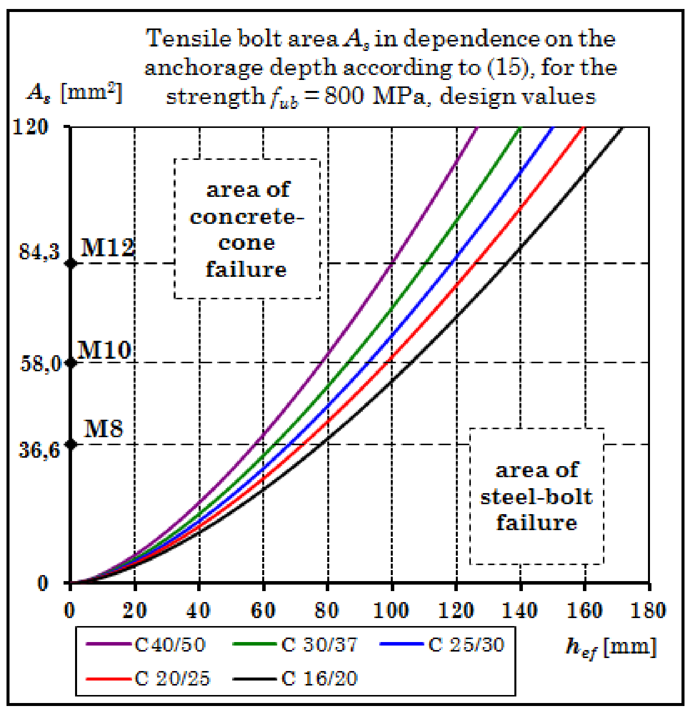


Fig. 12 relationships between A_s and h_{ef} for the design values according (15), i.e. according Concrete-Capacity Method

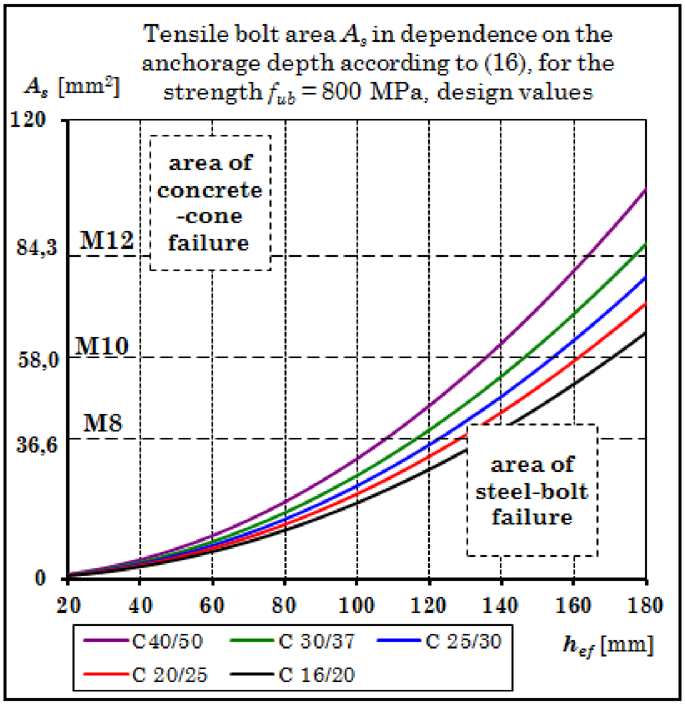


Fig. 13 relationships between A_s and h_{ef} for the design values according (16), i.e. according Concrete-Cone Method

E. Steel mechanical anchors under cyclic loading

Within the framework of described research in the field of steel mechanical expansion anchors to concrete also the loading tests with the use of cyclic tension forces were performed. The main reason for these experiments was that these fastening members could be often subjected to repeated loading. For example, in case of the wind load (where the anchors are used for the connections of bearing members or of the facade system elements) as well as in the field of the connections of heavy machinery anchored in the concrete foundations (e.g. pressing machines, production lines, etc.).

However, for this kind of loading, they are not defined any specific values (or formulas) for the load-carrying capacity. Therefore, one of the possible ways how to get these values can be to perform the loading tests of the selected anchors using cyclic tension forces with selected amplitudes ΔN between the maximum N_{max} and minimum N_{min} value:

$$\Delta N = N_{\max} - N_{\min} \tag{17}$$

and then to relate all the obtained results to the previously derived values of static load-carrying capacities N_{stat} in dependence on the final number of loading cycles n_{test} in the moment of the specimen failure (18).

Note: the two coefficients k and q in (18) represent the parameters of an expected fatigue curve in case of repeated loading.

$$\Delta N = (k \cdot \log n_{test} + q) \cdot N_{stat} \tag{18}$$

Subsequently, they were performed altogether 261 loading tests using cyclic tension forces within 6 regular series of specimens and one pilot series, where various selected values of amplitudes ΔN together with various combinations of the mechanical and geometric parameters were used (see below). The frequency for all test was selected as 5 Hz.

The mechanical anchors with the ultimate strength of steel f_{ub} of 800 MPa (i.e. bolt grade 8.8) and with the bolt diameter from 8 to 16 mm were used. Then, for the concrete blocks (specimens) the concrete of the compressive cube strength from 20.0 to 48.0 MPa was used. The effective depth h_{ef} was chosen from 30 to 85 mm.

For the testing with the repeated tension force the equipment with the hydraulic cylinder type AG 400-100 (by INOVA Prague) together with the load cell U5/500 (by HBM) was used, see Fig. 14. This equipment and the procedure were similarly used also in case of the research of the structural details of temporary steel footbridge, see [15]–[17].

Fig. 14 illustration of the loading test of the steel mechanical anchors with the cyclic tension force

During these tests also the influence of the displacement of the anchor on the test results was recorded, because the total displacement may shorten the effective depth of the anchor h_{ef}, especially in the starting phase of cyclic loading, when the loading force starts to increase. This effect was partially included in the evaluation process of the test results, see [18].

As an example of the results of the described loading tests with the cyclic tension force it is a graph on Fig. 15, where it is shown the relationship between the number of cycles n_{test} and the loading amplitude ΔN in case of all results, where the steel-bolt failure occurred. Therefore, in case of the steel failure the final formula of the relation between the design value of loading amplitude $\Delta N_{s,d}$ and the static resistance in dependence of the total number of cycles was derived using the Design assisted by testing method as follows:

$$\Delta N_{s,d} = 0.530 \cdot (-0.266 \cdot \log n_{test} + 1.608) \cdot N_{s,m} = \\ = 0.568 \cdot (-0.266 \cdot \log n_{test} + 1.608) \cdot A_s \cdot f_{ub} \quad . \tag{19}$$

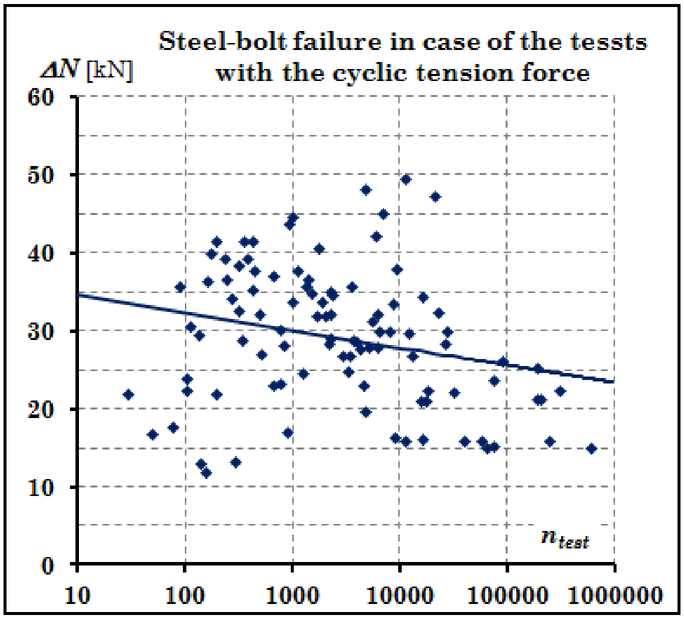


Fig. 15 cyclic test results in case of steel-bolt failure

Similarly, in case of concrete failure they were determined two formulas of the design values of loading amplitudes, i.e. $\Delta N_{c1,d}$ corresponding the Concrete-Capacity Method as (20) and $\Delta N_{c2,d}$ corresponding the Concrete-Cone Method as (21).

$$\Delta N_{c1,d} = 0.535 \cdot (-0.040 \cdot \log n_{test} + 0.905) \cdot N_{c1,m} = \\ = 8.346 \cdot (-0.040 \cdot \log n_{test} + 0.905) \cdot h_{ef}^{1.5} \sqrt{f_{cube150}} \tag{20}$$

$$\Delta N_{c2,d} = 0.521 \cdot (-0.042 \cdot \log n_{test} + 0.893) \cdot N_{c2,m} = \\ = 0.349 \cdot (-0.042 \cdot \log n_{test} + 0.893) \cdot \pi \cdot h_{ef}^{2} \sqrt{f_{cube150}} \tag{21}$$

Finally, the resulting relationships were derived for the determination of an effective values of the tensile steel bolt area A_s of the anchor using the same procedure as in case of loading tests with static tension forces.

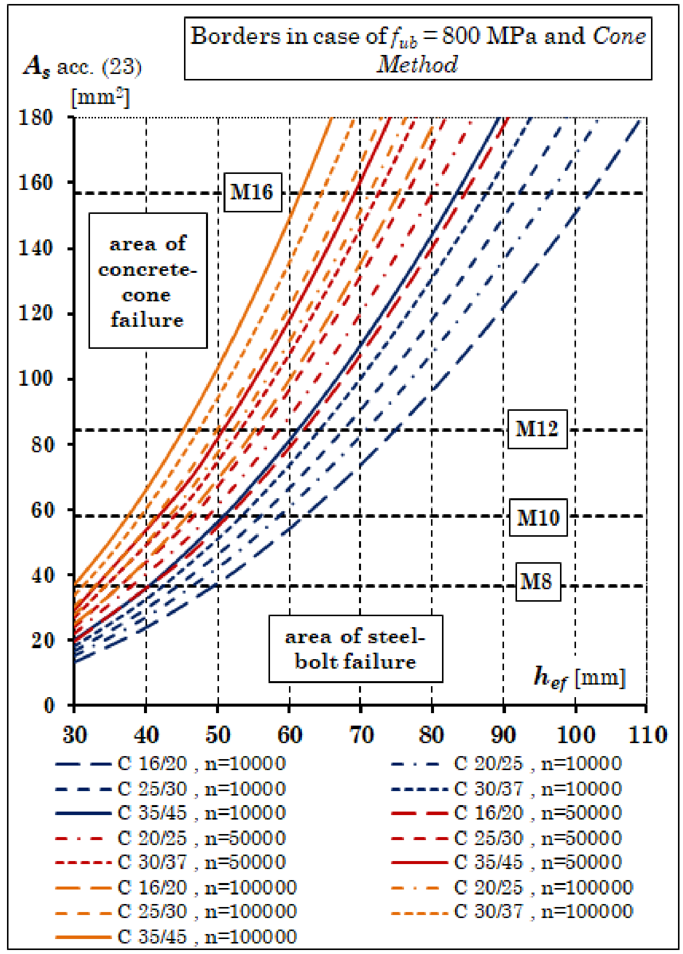
Firstly, the value in case of the Concrete-Capacity Method can be taken as:

$$A_s = \frac{15.38 \cdot (-0.04 \cdot \log n_{test} + 0.91) \cdot h_{ef}^{1.5} \sqrt{f_{cube150}}}{(-0.27 \cdot \log n_{test} + 1.61) \cdot f_{ub}} , \tag{22}$$

or in the field of the Concrete-Cone Method the relationship was determined as (23).

$$A_s = \frac{0.64 \cdot (-0.04 \cdot \log n_{test} + 0.89) \cdot \pi \cdot h_{ef}^{2} \sqrt{f_{cube150}}}{(-0.27 \cdot \log n_{test} + 1.61) \cdot f_{ub}} \tag{23}$$

On the last Fig. 16 they are shown the curves of the borders between the concrete-cone failure and the steel-bolt failure in case of cyclic tension loading, where the concrete failure have been taken according the Concrete-Cone method and the tensile area of the steel bolt was drown according to (23) for some selected classes of concrete together with selected numbers of cycle *n*. They were added, for better illustration, to this graph also all the used diameters of bolts (M8 to M16).



V. Conclusion

This article brings some comprehensive information about the loading tests which were performed within recent research projects on the author's workplace in case of steel mechanical anchorage members under tension loading.

The particular results (i.e. all the derived formulas and relationships presented above) clearly show the immediate influence of the geometric and material anchorage parameters (and their combinations) on the efficient and economic design of the steel mechanical expansion anchors to concrete in case of static and cyclic tension loading force.

From all the test results and from the derived formulas for the tensile area A_s in dependence to the effective anchorage length h_{ef} it is obvious, that the steel bolt fatigue in case of repeated loading can influence the load-carrying capacity much more than the characteristics of concrete.

Therefore, on the basis of the formulas (15) and (16) they can be chosen optimal design values of anchorage parameters in case of static tension force. By using of the last formulas (22) and (23) it can be made the economic and efficient design in case of cyclic tension loading.

Because, in general, they are not known the values of the load-carrying capacity in case of cyclic loading for described anchorage members (except some design values of selected developers), it can be useful this presented method, where they are firstly obtained the static (characteristic or design) values of the load-carrying capacity of these members and then they are compared with the cyclic values in dependence of the loading amplitudes and of the number of cycles to get the load-carrying capacity also in case of repeated loading.

However, all presented results were derived from the relatively small test number, so they may not be generalized. It is necessary to perform another tests with wider choice of all important parameters and characteristics, which have the direct influence on the design of selected post-installed anchorage members.

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