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DEPENDENCE OF ULTIMATE BOND STRESS ON BONDED ANCHOR CARRYING CAPACITY

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ABSTRACT

This article describes an analysis of bonded anchors exposed to a tensile load. The results of the experiments performed give a global view of the influence of particular design parameters on the bearing capacity of anchor joints. An anchor's behaviour during its service life is affected by many parameters, such as the material characteristics of steel bolts, the characteristics of the base material (usually concrete), the bonding material's characteristics (glue or mortar), the installation process and the placing of the anchor, the influence of the concrete reinforcement, the tightening moment, the load type, etc. The experiments described in this paper are focused on problems with bond stress quality.

KEY WORDS

- *bonded anchor*
- *bearing Capacity*
- *tensile load*
- *bond stress*
- *experiments*
- *numerical Modelling*

BEARING CAPACITY OF BONDED ANCHORS

The failure of an anchoring joint under a tensile load can occur in several ways. The first failure occurs when the tensile capacity of a steel anchor bolt is depleted. This type of failure depends on the material of the steel bolt and is typical of smaller anchors installed in high strength concrete. The second type of failure involves the extraction of the anchor bolt from the concrete, which occurs when the bond stress at the area of contact between the bolt and the glue or the glue and the concrete is exceeded. This type of failure is typical of larger anchor bolts installed in high-strength concrete. In all other events concrete failure occurs in the form of the extraction of a concrete cone.

Unfortunately, the boundary between failure types is not definite and depends on many parameters. Experiments conducted up to now show that under typical conditions, when no steel failure occurs, the anchor loses its bearing capacity through a combination of bond failure and concrete failure.

The bond between the anchor bolt and the basic material, which is usually concrete, can be provided by some mortar mixtures based on different binder types or, more often, by glue based on some kind of resin. The diameter of the drilled opening is also chosen, depending on the type of glue. The thickness of the bonding layer for anchor bolts with a typical diameter is from 1 to 2 mm for glues, and it can be greater for mortar compounds.

Depending on the mechanical properties of a specific glue type, contact failure arises either at the interface between a steel bolt and the glue or at the interface between the glue and the concrete. Failures in the area of the contact between glue and concrete are more frequent for currently used glues. The dependence of the final bearing capacity under a tensile load on bond quality is usually described by the ultimate value of the bond stress on a given contact surface.

Relations describing the ultimate bearing capacity of a bonded anchor under a tensile load can be found in professional publications. The mean value of the bearing capacity under tensile load N_u [N] for failure depending on the anchoring depth can be expressed according to (Eligehausen, Mallé, Rehm, 1984) as (1) [1]. They conducted a set of experiments with M8 to M30 anchors, which

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were anchored by mortar based on unsaturated polyester resin. The compressive concrete strength in these experiments was within an interval of 15 – 40 MPa.

$$N_u = 0.85 \, . \, h_{ef}^2 \, . \sqrt{f_{cc,200}} \, , \tag{1}$$

Where h_{ef} is the anchoring depth [mm],

$f_{cc,200}$ – the mean value of the concrete's compressive cubic strength assessed on specimens 200mm in length [MPa].

According to these experiments, relation (1) is valid for anchors installed at an anchoring depth equal to nine multiples of the diameter of the anchor bolt. This anchoring depth is usual and is also predetermined by anchor producers.

For anchoring depths lower than nine multiples of an anchor's bolt diameter the influence of the concrete's characteristics is much more evident. The recommended anchoring depth of 9d is determined by the quality of currently used glues, by the strength of the commonly used C20/25 concrete and by the material characteristics of the steel bolt. This depth represents the boundary between concrete failure and steel bolt failure. For lesser anchoring depths the concrete's strength and the bond quality exercise a decisive influence on bearing capacity. For greater anchoring depths it is the ultimate strength of the anchor bolt's steel that is decisive.

An implementation of bond stress in contact areas into the relation for bearing capacity depending on anchoring depth was published by (Cook, 1993) [2]. There, relation (1) is valid for the bearing capacity of anchors installed shallower than h_c [mm] according to relation (2). For deeper installed anchors it is necessary to use relation (3).

$$h_c = \frac{\tau_u \, . \, \pi \, . \, d}{1.8 \, . \sqrt{f_c}} \, , \tag{2}$$

Where τ_u is the ultimate tangential stress on the contact area between steel and glue [MPa],

f_c – the cubic compressive concrete strength [MPa]

d – the anchor bolt diameter [mm],

$$N_u = 0.85 \, . \, h_c^2 \sqrt{f_{cc,200}} + \pi \, . \, d \left(h_{ef} - h_c \right) . \, \tau_u \, , \tag{3}$$

When the anchor fulfils the specifications $d \leq 50$ mm, the contact surface is $\pi \, . \, h_{ef} \, . \, d \leq 50\,000$ mm^2 and is installed at an anchoring depth interval of $4.5 \leq h_{ef} / d \leq 20$, then according to (Cook, Kunz, Fuchs, 1998) [3], relation (4) is sufficiently accurate for the bearing capacity under a tensile load.

$$N_u = \pi \, . \, d \, . \, h_{ef} \, . \, \tau_u \, , \tag{4}$$

The value of the ultimate bond stress in the contact area for these types of anchors is, according to these authors, in an interval of 10 to 20 MPa. As they also say the value of a bond stress only minimally depends on the compressive strength of concrete, it is possible to consider that it is independent. Due to the smoother surfaces of holes drilled in high-strength concrete the bond stress can even be a little bit smaller than for ordinary concrete.

All these relations are compared with the results of experiments performed at the Department of Metal and Timber Structures of the Brno University of Technology. There is also another relation deduced by the authors from this research, which brings about both a simplification and a refinement.

INFLUENCE OF BOND QUALITY ON BEARING CAPACITY

The quality of the connection between a steel bolt and glue, and especially between the glue and the concrete, has a great effect on the final bearing capacity of a bonded anchor.

Because the value of the ultimate bond stress is important, it is necessary to pay attention to all of the events which can influence it. One of the main parameters influencing the final bearing capacity value is the cleaning procedure for drilled holes.

The standard cleaning method, as is usually specified by anchor producers, is to blow air through the hole, then to remove the dust from the surface of the hole with a steel brush, and finally to blow air through a second time. The influence of the cleaning method described by authors [Eligehausen, Meszaros 1998] [4] is detailed in Fig 1. There is a difference in the bearing capacities of anchors installed in cleaned holes and non-leaded holes in the top picture. In these tests M12 anchors installed 110 mm deep in concrete with a mean compressive strength value of 25 MPa were tested.

In the graph in Fig. 1 the influence of the cleaning methods is indicated for three different glue types. From this graph we can state that the most important part of the cleaning process is brushing, i.e. the removal of dust particles from the surface of the hole. The air blowing itself only has a small effect on the final bond quality, but is necessary for providing the right hole dimensions.

Another parameter influencing bond quality is the drilling method. The drilling method significantly influences the smoothness of the hole's surface and is chosen according to concrete strength and anchor diameter. The most usual method for anchors with a diameter of d < 50mm is impact drilling with a diamond drill. This drilling procedure provides a sufficiently rough hole surface

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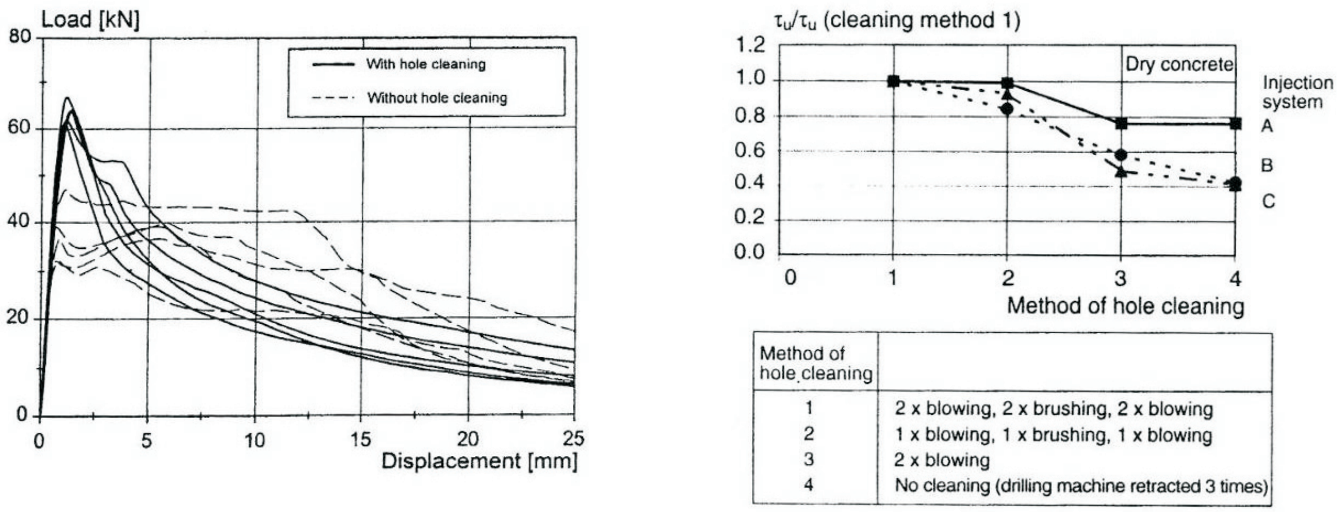

Method of hole cleaning	
1	2 x blowing, 2 x brushing, 2 x blowing
2	1 x blowing, 1 x brushing, 1 x blowing
3	2 x blowing
4	No cleaning (drilling machine retracted 3 times)

Fig. 1 *Influence of drilled hole cleaning procedure (Eligehasuen, Meszaros 1996).*

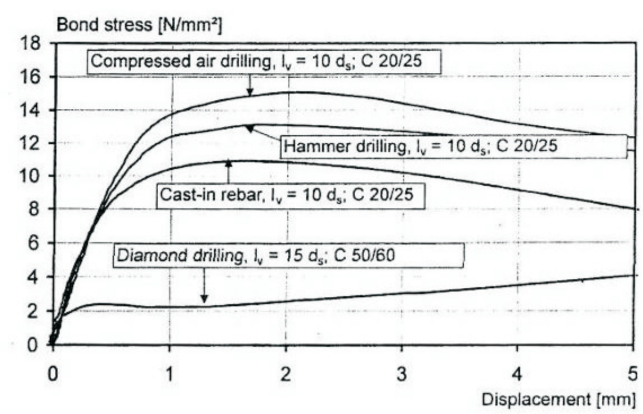

Fig. 2 *Influence of drilling method (Spieth, Eligehausen, 2002).*

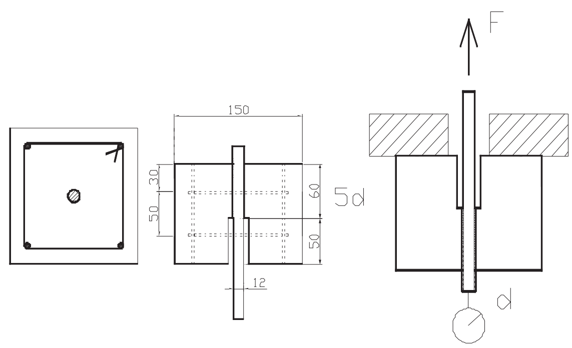

Fig. 3 *Experiment scheme.*

to ensure a high-quality connection between the concrete and the glue. The dependence of the bond stress on the drilling procedure is shown in Fig. 2 [Spieth, Eligehausen, 2002] [5].

EXPERIMENTAL VERIFICATION OF ULTIMATE BOND STRESS ON CONNECTION GLUE – CONCRETE

The experiments described below were performed according to standard [6] for the assessment of the mechanical lock of reinforcement bars and concrete. Bond stress is defined as a tangential stress along a reinforcement bar. It is a quotient of an applied tensile force and the contact area which is given by the anchoring depth and by the bar diameter (in this case by the diameter of the drilled hole). The experiment scheme is in Fig. 3.

In the first experiment set we tested M12 (metric screw thread) anchors bonded by vinyl urethane resin compared to embedded bars. The concrete used in these tests had a mean compressive cubic strength value of 43MPa. This value was verified on six specimens. The concrete characteristics corresponded with class C35/42 concrete according to EC2. The results of the first set of experiments are shown in Fig. 4; they are also published in [7]. Specimens from two producers with glues based on vinyl urethane resin are marked as VU. For the purpose of comparing the results we also performed three tests with embedded steel screws. These results are marked as EB.

In the next experiment set we tested the same anchor type bonded

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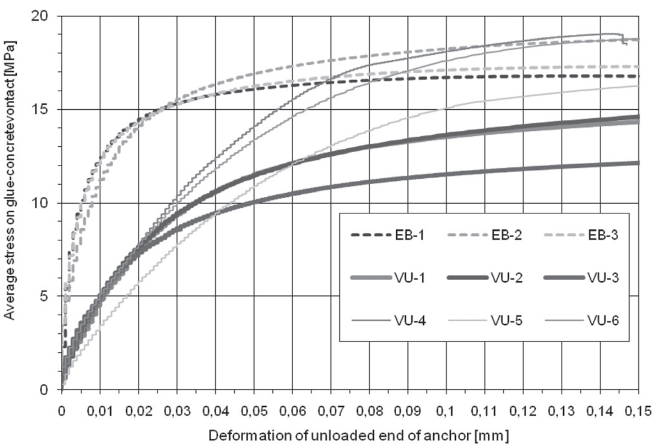

Fig. 4 *Results of bond stress tests,* $f_{cm,cube}$ *= 43.0 MPa*
VU – Vinyl-urethane resin, EB – Embedded screws.

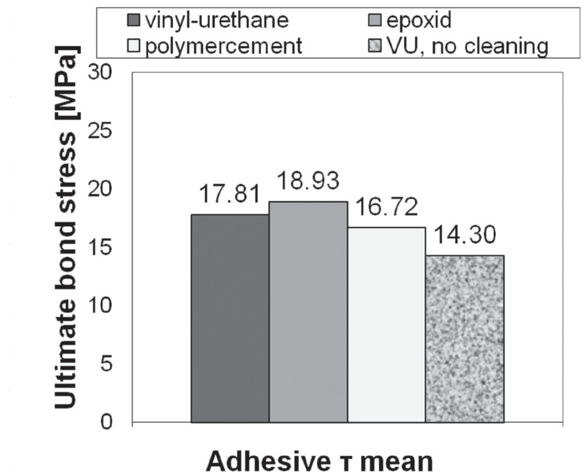

Fig. 6 *Mean values of ultimate bond stress.*

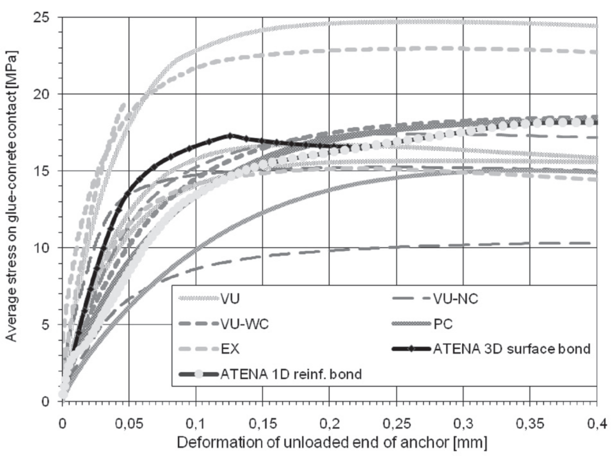

Fig. 5 *Results with* $f_{cm,cube}$ *= 28.5 MPa*
VU-Vinyl urethane resin, EX-Epoxy resin, PC-Polymer cement compound, VU-N-Vinyl urethane resin with non – cleaned holes, VU-W- Water cleaned hole.

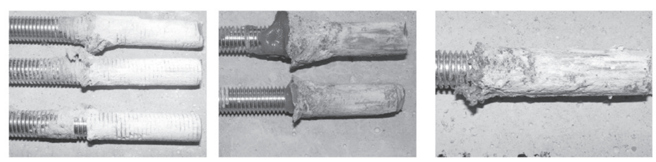

Fig. 7. *Bond failure - Polymer cement compound, Epoxy resin, Vinyl urethane resin.*

by glues based on vinyl urethane resin, epoxy resin and a polymer cement compound. In this second test set the mean concrete compressive strength value was 28.5 MPa, which corresponded with class C20/25 concrete.

In these experiments we also tested different cleaning procedures.

Fig. 5 features the results of experiments with different glue types. Specimens with glue based on vinyl urethane resin are marked as VU (VU-N for non-cleaned holes, VU-W for water cleaning); specimens with glue based on epoxy resin are marked as EX; and those with polymer cement compound are marked as PC. This graph also contains the results obtained from a numerical model created with Athena 3D software. The mean ultimate bond stress values for all of the glue types are summarised in Fig. 6.

The failure for each specimen type is in Fig.7. For specimens with polymer cement glue, the failure occurred at the area of contact between a steel bolt and the glue. It is obvious that this is a failure occurring due to the glue reaching its shear strength. The other two glues always failed at the bond at the area of contact between the glue and the concrete. With unaided vision it is impossible to determine how much bond failure is influenced by concrete characteristics and how much by glue characteristics.

NUMERICAL MODEL

The numerical model in Fig. 8 was created with ATENA software using 3D contact elements. The bond between the glue and the concrete is defined by normal and tangential stiffness. For a description of bond behaviour there are two stiffnesses in each defined direction. The first is a stiffness valid before reaching the

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ultimate stress value for the connection, and the second is valid after exceeding this boundary value. For normal stiffness the boundary value of the stress is defined by the value of the bond's tensile strength (in this case it is the mean value of the concrete's tensile strength). For tangential stiffness the boundary value is defined by the ultimate value of bond stress and the friction coefficient. For our model we used the mean value of the ultimate bond stress from the experiments and a friction coefficient of 0.2. The tangential and normal stiffness before reaching the boundary value, of the stress were modelled by the value 1.0x105 MN/m^3. After exceeding the boundary stress value we used a stiffness of 1.0 MN/m^3. To ensure the solution's stability the stiffness after the bond failure should not be zero.

The contact model is described in detail in [8]. For concrete modelling we used a 3D nonlinear cementitious model. This concrete model is able to represent the nonlinear behaviour of concrete, including tensile and compressive softening. Crack formation and propagation is solved using nonlinear fracture mechanics. This concrete model uses the crack band model for the behaviour of cracked concrete. The glue is modelled as a linear elastic material with an elasticity modulus of 47GPa, which was experimentally verified [9].

For one anchor installed in concrete it is possible to use axial symmetry and solve it as a planar problem. This can be done by ATENA with the same material model characteristics.

It is also possible to model a bonded anchor as an embedded bar via 1D Beam elements using special elements for the mechanical bond between the reinforcement bar and concrete. We also used a model with 3d surface contact elements for the study of the influence of the ultimate bond stress on the final bearing capacity of a single anchor. The results of this study are in Fig. 9. There we modelled a single M12/110 anchor. We only changed the boundary value of the tangential stress (ultimate bond stress τ_u) in the connection model of the interface between the glue and the concrete (on the horizontal axis). The corresponding value of the ultimate bearing capacity is on the vertical axis. In this graph two sets of models are displayed. In the first the glue is modelled only as a linear elastic material while in the second it is modelled as a bilinear material with an elastic and flat plastic line of the work diagram. The peak value of this bilinear diagram was 10 MPa [9].

COMPARISON OF RESULTS

All of the experimental and numerical results are summarised and compared to the published relations (1), (2), (3), (4) in Fig. 10. The experimental results in this graph were obtained from several sets of specimens. The mean value of the concrete's compressive cubic strength was in a range from 18.9 to 46.2 MPa

(According to Fig. 9, it is an area where the concrete has a great influence on the bearing capacity under tensile load). Therefore, these results have been normalised for class C20/25 concrete (for the mean value of compressive cubic strength) as:

$$\overline{f_c} = \sqrt{\frac{29}{f_c}}$$

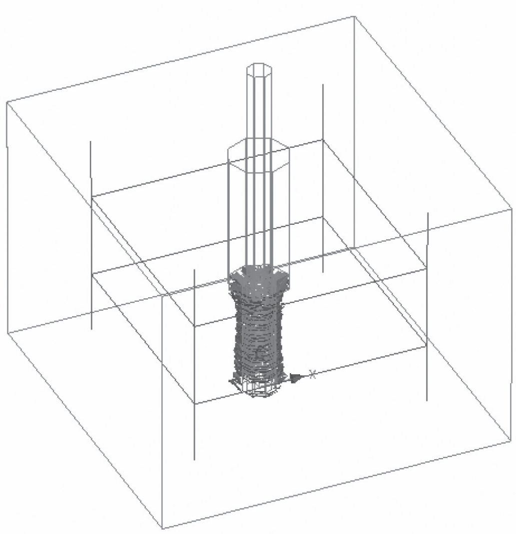

Fig. 8 *Atena 3d surface model.*

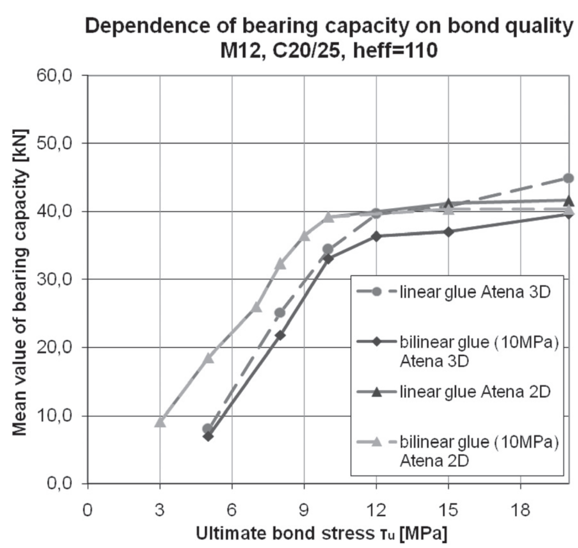

Fig. 9 *Atena connection material study.*

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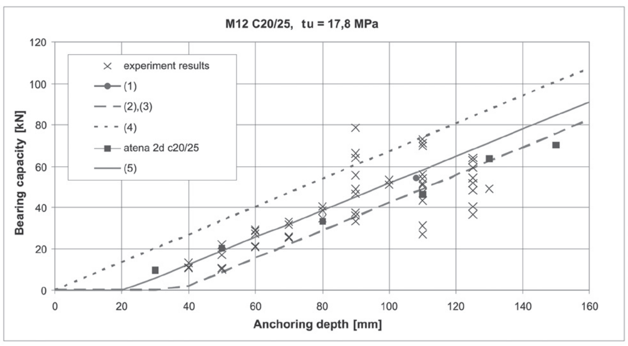

Fig. 10 *Comparison of experimental results and relations.*

From Fig. 10 we can say that relation (4) is inaccurate especially for very low anchoring depths. This is caused by the presumption that anchor failure is determined only by ultimate bond stress and is not affected by concrete characteristics. According to the results of the bond quality experiments, we can declare that the relation for full contact failure (4) is valid only for the high strength concrete class. The results of relations (2) and (3) in their combination are undervalued for the lower anchoring depths. Relation (1) includes the influence of the anchoring depth on the anchor bolt diameter (the anchor diameter is 1/9 of the anchoring depth). Therefore, the comparison for this relation can only be made for one anchoring depth and one anchor bolt diameter. For the M12 anchor it is an anchoring depth of 108 mm.

CREATION OF A NEW RELATION

In bond quality tests the stress distribution along the anchor bolt is due to the almost uniformly distributed specimen configuration. This stress distribution is in contradiction with the real stress distribution when the top surface around the anchor is unloaded: Fig. 11.

If we want to use the value of the ultimate bond stress from the experiments in the relation for bearing capacity, we have to implement the real distribution. For this we can use a comparison of the stress distribution areas. Thereafter, we can say that the effective anchoring depth can be expressed as:

$$h_{ef} = \left(h - 1.5 \,.\, d_0\right)$$

Cracks corresponding with the real stress distribution along the anchor bolt are shown in Fig. 16. This crack distribution was obtained from a numerical model with 3D Surface contact elements.

$$N_u = \pi \,.\, d_0 \,.\, \left(h - 1.5 \,.\, d_0\right) . \tau_u \,.\, \alpha \quad [\mathrm{N}];\ \alpha = \min\left[\left(\frac{f_{c,cube}}{40}\right)^{\frac{1}{2}};1\right] \qquad (5)$$

$$N_u = \pi \,.\, d_0 \,.\, \left(h - 1{,}5 \,.\, d_0\right) . \tau_u \quad [\mathrm{N}] \qquad (6)$$

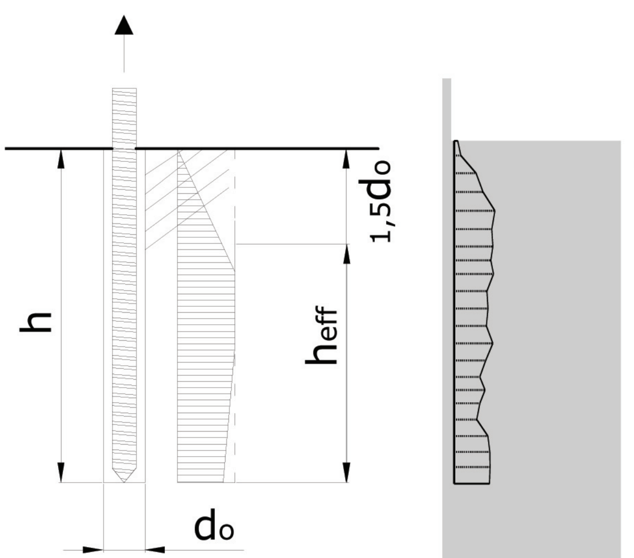

Fig. 11 *Bond stress distribution.*

Fig. 12 *Cracks in Atena 3D.*

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CONCLUSION

Both the experimental results and the numerical model results confirmed that the relation for full contact failure along the anchor bolts is not accurate for anchors used in concrete with a mean compressive strength value lower than 40 MPa. In this case the influence of concrete characteristics is crucial. For more accurate results it is also useful to implement the real bond stress distribution in the relation for bearing capacity.

Considering these facts we can express a more accurate relation for the mean value of bearing capacity for a bonded anchor under tensile load as (5), where the full contact failure is given by (6). The influence of concrete characteristics in this relation is summarised in Fig. 13.

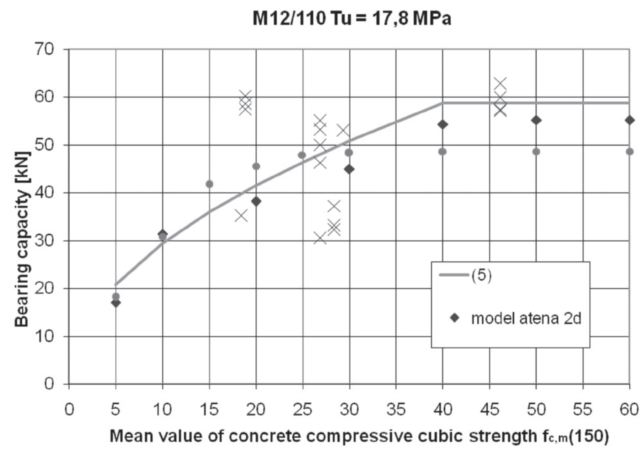

Fig. 13 *Comparison of results for different concrete strengths.*

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