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DESIGN OF ANCHOR PLATES ACCORDING TO EN 1992-4:2019: A PRACTICE-ORIENTED VIEW

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ABSTRACT

The EN 1992-4:2019 (hereinafter referred to as EC2-4) currently applies to the design of anchor plates in Europe. This relatively new standard integrates the EOTA / TR / ETA / CEN-TS guidelines, which had existed in parallel for a long time, into one coherent and comprehensive standard. The introduction of this standard has made users more aware of certain topics, including the requirement for a rigid anchor plate.

In practice, an absolutely rigid anchor plate is often not achieved, especially with common dimensions. For the engineer, the question therefore arises as to whether the designed anchor plate is considered sufficiently rigid or not. The EC2-4 code does not provide any clear rules in this regard. Consequently, the only methods remaining for such cases are the use of a non-linear calculation with FEM, which provides a simulation of the plate bending under consideration of the supporting effects of the concrete face and the tensile loads in the anchors.

For a non-linear FEM calculation, the correct choice of input parameters, in particular anchor stiffness, is of crucial importance. In principle, the stiffer the anchor, the higher the anchor load and therefore the less favourable the verification. By choosing a comparatively high anchor stiffness, one is always on the conservative side (for the anchor force). There are, of course, justified reasons for choosing anchor stiffness as a “best estimate” value, e.g. economic considerations, as-built analysis, modifications in existing buildings where available installation space is limited. Publicly published information on anchor stiffness can be found in the technical assessments and in the relevant literature. However, the values listed there are not completely satisfactory and should be interpreted with caution, as, for example, the variation spread is not known or the number of tests is not sufficient for use in a statistical evaluation.

Anchor plates are standard for anchoring plant components in nuclear plants and facilities and it is essential that the designers have a correct and reliable design base. Standardised anchor plates with associated loads could be developed where no further detailed calculations in FEM are necessary to confirm the plate stiffness. Alternatively, stiffness values would have to be determined for the individual anchors, by the approval authorities in coordination with the other parties involved, which would then be used in the FEM calculations.

INTRODUCTION

EC2-4 is the new Eurocode which applies to the design of anchor plates in Europe. The European Technical Assessment (ETA) of anchors now only states product-specific characteristic values, and does not provide further design verifications or guidelines.

Compared to the former EOTA/TR, some parameters or equations have changed in EC2-4, but the main verification principles remain the same (steel failure, concrete cone failure, pull-out failure, combined failure, splitting failure). These changes in the standard verifications are not subject of this paper. For the interested reader, reference is made to the overview by fischerwerke (2020).

The main subject of this paper refers to section 6.2.1 a) – f) of EC2-4. In this chapter, a *"sufficiently stiff"* anchor plate is demanded to provide a linear strain distribution of each anchor. The requirement for a sufficiently stiff anchor plate is justified. It is well known that an anchor plate that is too thin could lead to higher forces in the anchors, and thus to an unsafe design. This particular issue has been known for some time and has already been analysed in recent years, see Mallée (1999) or Fichtner (2011), but the introduction of EC2-4 has made users more aware of the requirement for a sufficiently rigid anchor plate.

Unfortunately, EC2-4 does not specify a clear design verification when the design is to be considered "*sufficiently stiff*"; 6.2.1 e) gives some indications, e.g. if the anchor plate remains elastic ($\sigma_{Ed} < \sigma_{Rd}$) and the axial deformations of the anchors stay "*negligible*". If these conditions are not fulfilled, the elastic deformation of each anchor should be considered in the design. However, the code does not specify in more detail how these axial deformations etc. should be calculated. The following chapter describes how this design principle is dealt with in practice.

PRACTICAL APPROACHES TO DEAL WITH THE EFFECTS OF THE ANCHOR PLATE STIFFNESS IN THE DESIGN

In practice, the following three approaches are used to design an anchor plate:

A. A rigid anchor plate (linear – elastic behaviour)
B. A flexible anchor plate with anchors and idealized anchor stiffness (elastic springs)
C. A flexible anchor plate with *"realistic"* anchor stiffness

A. Rigid Anchor Plate

With the assumption of a rigid anchor plate, the design forces on each anchor could be calculated without the use of FEM. The equation of the distribution of the design anchor forces is included in the EC2-4, see Figure 1, and can be calculated in Excel or any other programmable software solution (Matlab, Mathcad).

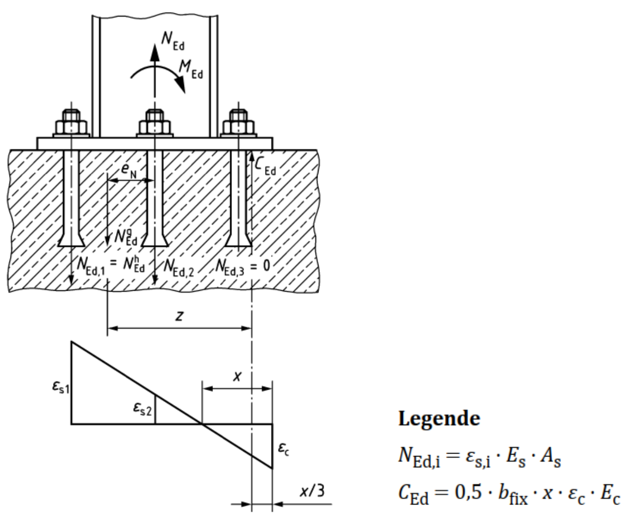

Figure 1. Analytical solution with a rigid anchor plate. Extract from EC2-4

Following this approach, it is not possible to make even a reliable statement about the deformation of the anchor, respectively of the internal forces. An anchor plate that is too thin could lead to higher forces in the anchors, as the plate bending reduces the size of the lever of the internal forces. In addition, support effects can occur with large acting normal force and large plate edge distance.

A rigid (*"infinitely stiff"*) anchor plate does not exist in reality and increasing the anchor plate thickness to avoid bending is not practical (see Figure 2). The use of stiffeners on anchor plates is not common, and leads to further design issues (space requirements, installing procedure, weldability and geometry layout) and costs. Therefore, a simple proof of a sufficiently stiff anchor plate cannot be provided with approach A.

The design engineer often relies on common thickness of anchor plates (15 mm, 20 mm) and argues with *"soft facts"* that the anchor plate is sufficiently stiff, for example with geometry ratios: plate thickness to anchor plate dimension, ratio of attached component to the anchor plate dimension, small distance of anchors to the plate edge, or experience from tests or literature.

Alternatively, the design engineer provides sufficient reserve in the design resistance to design load, as this approach could – in the case of high eccentric forces and small thickness – underestimate the design loads of individual anchors, see Mallée (1999). However, it is uncertain how large these load reserves are supposed to be. To conclude, approach A is unsatisfactory since no verifiable statement is made concerning the anchor plate stiffness.

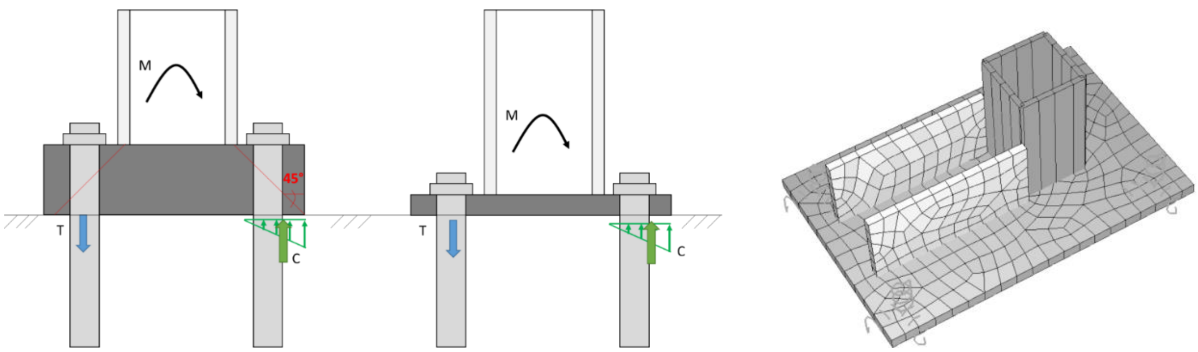

Figure 2. Left: Obviously sufficiently stiff anchor plate; Centre: Anchor plate with common dimensions, Right: Example of stiffened anchor plate in FEM

B. Flexible Anchor Plate with "Idealized" Anchor Stiffness

In this approach, the anchor plate is modelled in FEM (e.g. plate elements for the anchor plate, concrete bedding with contact elements, anchors with individual springs). Consequently, all the unfavourable effects of plate bending are reproduced and the anchor forces correctly calculated.

One main input is the spring stiffness representing the anchors. In a simple approach, the spring stiffness K_s is chosen according to the steel cross section and length of the anchors, and is based in principle on a common approach for headed studs, see Li (2017):

$$K_S = E_s * A_s / (h_{Ef} + t) \qquad (1)$$

where E_s is the E-modulus of steel [N/mm^2], h_{Ef} the effective anchorage depth [mm] and t the anchor plate thickness [mm].

This approach neglects the fact that post-installed anchors are – as a result of their mechanical fastening – less stiff than headed studs. In the most common case, the anchor stiffness is overestimated with eq. 1 and will attract higher loads, resulting in a conservative design for the anchor.

Unfortunately, the question of a sufficiently stiff anchor plate can only be answered inadequately here as well. Comparisons between the calculated maximum anchor force between approach A and B are not straightforward to interpret. A linear strain distribution will inevitably never be achieved. How much discrepancy between a rigid anchor plate and flexible anchor plate is acceptable for the design (up to 10% or 20%)? Such criterion must always be put into perspective, as with relatively small anchor forces, the absolute values can be irrelevantly small. Also, this is not only an economic issue. After all, a larger anchor nominal diameter requires larger spacing, higher distance to openings etc. and may lead to further design issues.

C. Flexible Anchor Plate with "Realistic" Anchor Stiffness

To take into account the quite complex verification equations as well as product-specific parameters makes it is almost necessary to use manufacturer-specific software products especially designed for anchor design. These software products could be based on the most realistic anchor stiffness, e.g. represented by non-linear stress-strain curves.

THE QUESTION OF CHOSING THE BEST REPRESENTING ANCHOR STIFFNESS

Anchor stiffness is a complex field, depends on various factors, whose influence can only be assessed experimentally and which have to be statistically evaluated, e.g.:

- anchor type,
- anchor manufacturer,
- nominal size of the anchor,
- anchorage depth,
- anchorage base (cracked / non-cracked concrete, concrete quality),
- spacing or group effects
- etc.

Although the anchors often have a non-linear stress-deformation behaviour (Figure 3), a linear idealization seems reasonable and sufficient for a calculations in an ultimate limit state (ULS) analysis. In ULS analysis, the real acting force is, based on the EC2-4 safety concept, usually less than half of the (characteristic) ultimate load capacity and the anchors do not reach their plastic behaviour.

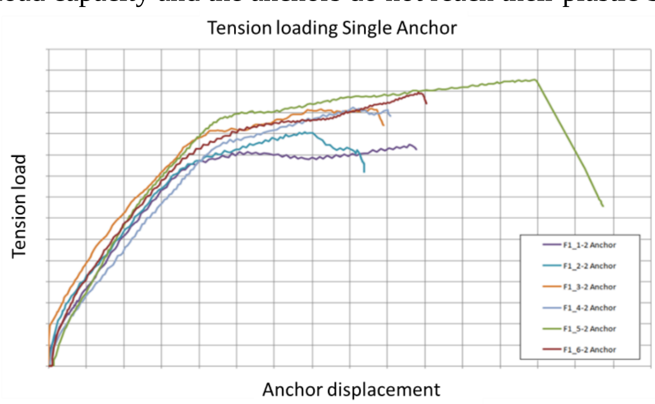

Figure 3. Example of a load displacement curve for an anchor under tensile load in non-cracked concrete. The colours represent different anchors with same specifications in the same test set-up.

European Technical Assessment (ETA)

For the standard design of anchor plates, the best knowledge base for an engineer is the product-specific documentation, e.g. the European Technical Assessment. The ETA provides corresponding tables of the deformation δ of anchors under a given load N_0 [kN], short-term δ_{N0} [kN] as well as long-term deformation $\delta_{N\infty}$, and is the basis to assess a linear-elastic anchor stiffness K_S with the equation:

$$K_s = N_0/\delta_{N0} \tag{2}$$

There is one drawback, however. The tables in the ETA are created to provide deformation for serviceability verifications, e.g. for cases in which deformation of anchors should be limited to a certain value. Therefore, the tabulated deformation values are on the upper side of the statistics, and the back-calculated stiffness is on the lower side. Hence, a less stiff anchor attracts less force and the acting forces are underestimated. Therefore, the stiffness values obtained from ETA tables are not completely suitable for ULS analysis. Nevertheless, the data points are real measured values and provide valuable insight into load-deformation behaviour of anchors.

As illustrated in Figure 4, the ETA values could sometimes lead to implausible stiffness values, e.g. a larger nominal diameter causes lower stiffness or the stiffness in cracked concrete is higher than in non-cracked concrete.

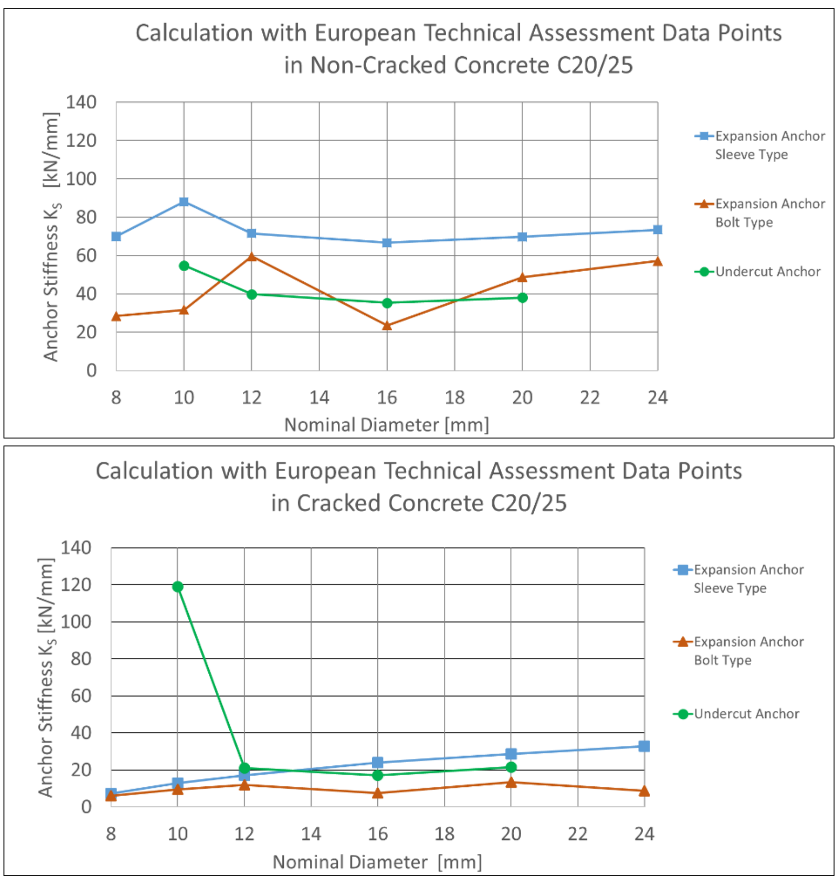

Figure 4. Distribution of anchor stiffness, based on calculation with values from ETA

ACI Standard 355.2

In ACI Standard 355.2 the axial stiffness of anchors in service load range β is defined with:

$$\beta = (N_{30\%} - N_{10\%}) / (\Delta_{30\%} - \Delta_{10\%}) \quad (3)$$

$N_{10\%,\,30\%}$: Mean load at 10%, respectively 30% of ultimate load measured in tension test [lb]
$\Delta_{10\%,\,30\%}$: Mean displacement measured at 10%, respectively 30% of ultimate load in tension test [in]

Based on such a *"characteristic"* (mean) stiffness value, a calculation in FEM could be executed in an appropriate way. The defined load area corresponds well to targeted scope (*"best-estimate value"*). Unfortunately, the stiffness β values are not available for most standard anchors in Europe. In addition, there is a risk that there are country-specific product deviations between the U.S. and Europe, or production cycles.

In general, the stated values with available ACI product datasheets (e.g. HILTI HDA or HSL-3-G) compare well to the calculation based on ETA values. Additionally, the product specification based on ACI 355.2 noted in a footnote for β is: *"Minimum axial stiffness values, maximum values may be 3 times larger (e.g. due to high-strength concrete)"*.

Experimental Results (Literature)

You find a large variety of anchor stiffnesses in literature (e.g. for parametric studies with FEM) or obtained from experiments. For a good overview, reference is made to Fichtner (2011) and Mahrenholtz (2012). It is well known that the anchor stiffness depends on the mechanical clamping (fastening). A mechanical expansion anchor is less stiff than a grouted anchor. Note that the anchors have sometimes almost an elasto-plastic behaviour. But only the first secant of the stiffness curve is relevant for our calculation, as with the partial safety concept, the anchor forces are always far less than their ultimate load capacity from trials. A load distribution on anchors with plasticity is currently not considered by EC2-4.

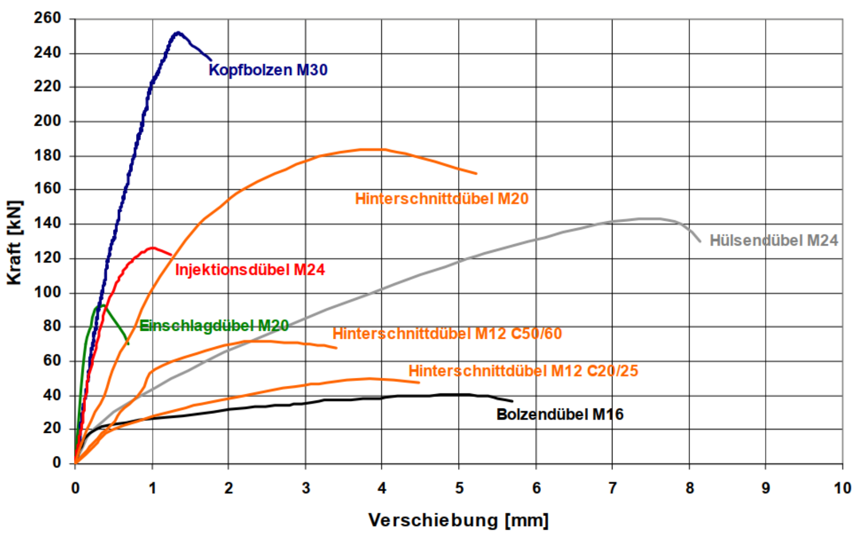

Figure 5. Load displacement curves. The colours represent different anchor types (blue: headed strut, red: bonded anchor, green: anchor nail, grey: sleeve expansion anchor, orange: undercut anchors, black: bolt-type expansion anchor. Extract from Fichtner (2011)

In practice, deriving the anchor stiffness on the basis of own literature research is not appropriate for design. From the documentations, the reader often has limited insight into the tests (anonymised product suppliers) and the amount of tests does not meet relevant statistical criteria or the used products are outdated. Being aware of this issue, Fichtner (2011) proposed to provide a medium anchor stiffness K_S, measured at $N = N_{50\%}$ (mean load at 50% of ultimate load measured in tension test), for cracked or non-cracked concrete, in its product specifications. Having access to the German laboratory that executed many tests for the products, he concluded that the appropriate stiffness K_S is approximately about two times the stiffness calculated from ETA specifications.

Fichtner (2011) in his extensive parametric calculations uses the values of k = 30 kN/mm, 90 kN/mm and 160 kN/mm to represent the full spectrum of all the anchor types (undercut, mechanical expansion anchors up to bonded anchors). For other authors and their assumptions regarding anchor stiffness, reference is made to Fichtner (2011).

Experimental Results (anchor manufacturer)

The anchor manufacturers have access to deep laboratory tests results, and according to their presentations, they are currently assessing or implementing the corresponding stiffness curves into their software products. They represent the anchors with linear elastic or non-linear load-displacements curves (Fritz, et. al (2019); fischerwerke (2021)). These derived curves are often not fully transparent or might not be published and be classified as industrial secret.

Semi-Empirical Formula (Literature)

Based on the experimental results and adapted from the semi-empirical stiffness calculation for headed studs, you can derive the following formula for anchor stiffness K_s:

$$K_S = E_s * A_s / (h_{Ef} / \varphi + t) \tag{4}$$

Here, E_s is the E-modulus of steel [N/mm^2], h_{Ef} the effective anchorage depth [mm] and t the anchor plate thickness [mm] as well as φ anchor stiffness factor [-].

The factor φ in eq. 4 can be chosen freely and is recommended by Dr. Li (2022) to choose between 0.3 – 0.5 in case of mechanical anchors. The higher the φ-factor, the more stiff the anchor. $\varphi = 1.0$ would approximately correspond to a headed stud, see Li (2017). A comparison between the semi-empirical formula and the ETA back calculation is provided in Figure 6. It shows generally a good match for $\varphi \approx 0.3$ for undercut and expansion anchors (sleeve types). Having in mind that the ETA is the lower bound of the stiffness, $\varphi = 0.5$ results in approximately double the ETA values for non-cracked concrete (undercut anchor and sleeve-type expansions anchors). For expansion anchors (bolt type), eq. 4 does not match really well, especially for higher diameters the anchor stiffness is overestimated. The semi-empirical formula as stated in eq. 4 is a simple yet determined approach, provides some flexibility and takes into account the main influencing factors and could be easily implemented in own FEM calculations.

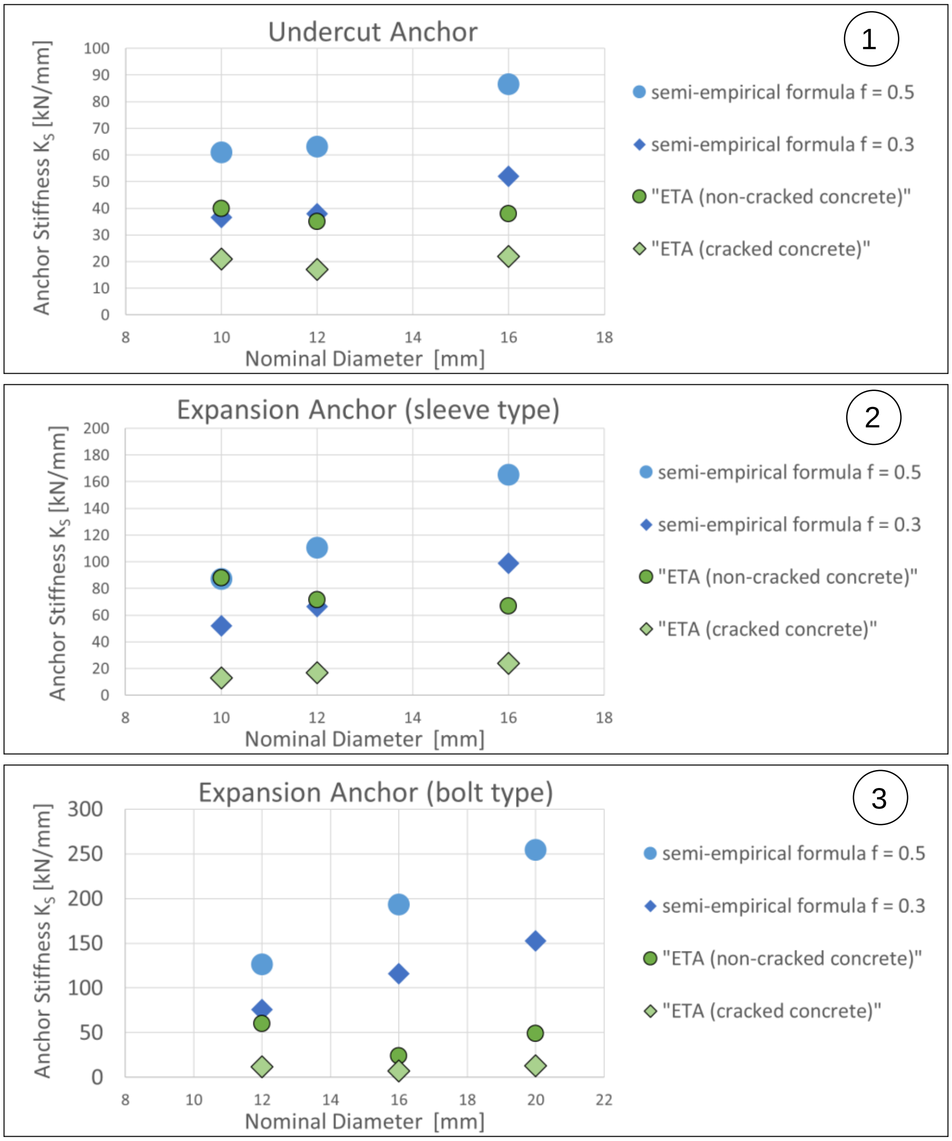

Figure 6. Comparison between semi-empirical formula and ETA values for an undercut anchor (1), expansion anchor (sleeve type) (2) and expansion anchor (bolt type) (3).

ASSESSMENT OF THE INFLUENCE OF THE FACTOR φ

A comparison between an anchor manufacturer software and an independent anchor design software which uses eq. 4 was conducted. The results are shown below in Figure 7 for an anchor plate thickness of 10 mm and 15 mm. The anchor plate dimension chosen was 300 mm x 300 mm with 4 expansion anchors (bolt type) M12, anchor spacing of 140 x 190. A bending of M_d = 5 kNm on the centric, quadratic profile 80/5 was applied.

The dashed line in Figure 7 represent the result obtained by the anchor manufacturer software (which does not have any anchor stiffness factor φ). By increasing factor φ the deviation gets larger. It can be seen that with the recommended value φ = 0.3 – 0.5, and in correspondence with Figure 6, the deviation between the two calculations stays below 10%. For small φ factors = 0.3 the anchor manufacturer software results in higher anchor loads, indicating that the anchor manufacturer expects a stiffer deformation behaviour than the semi-empirical formula. This statement is limited to the shown example and is not generally valid.

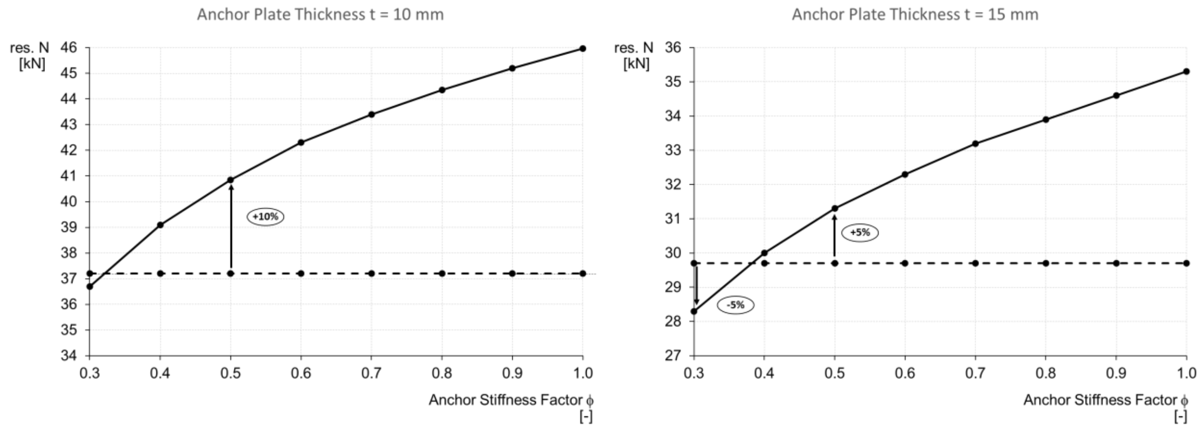

Figure 7. Effect of the anchor stiffness factor φ compared to results obtained by anchor manufacturer software

DISCUSSION

The current trend is to use anchor-specific FEM software for the anchor plate design, one driving force being that such software today is easily available and could run quickly on any modern computer. The new EC2-4 also pushes in this direction, as now in the code, a sufficient anchor stiffness is required or the additional load from anchor plate bending has to be considered. Without FEM calculation, such verification is always open to discussion and leads to design uncertainty.

In future, typical anchor plates with simple load combinations, which due to their parameters are not critical to plate bending, will be designed in FEM just to fulfil the requirement of the EC2-4. The approach of an assumed rigid anchor plate will disappear and would not be trusted anymore.

For the FEM calculation, one main input parameter is the anchor stiffness and this parameter has significant impact on the calculation results. Currently, the anchor stiffness for ULS calculation is neither specified in the code nor in the product specifications. In practice, different approaches will be used to determine this parameter. Some approaches may be more appropriate than others, and often, the designer will rely on anchor manufacturer software.

The anchor stiffness used for ULS calculation should be defined, either in the code, in the technical specification or some further guidelines, with the goal of standardization and uniform design. If this is not achieved, each engineer will use different approaches to define the anchor stiffness or absolutely rely on anchor manufacturer software solutions.

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