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AN EFFICIENT REVIEW GUIDELINE FOR ANCHOR DESIGN

Jan Attinger[1], Tadeusz Szczesiak[2], Yves Mondet[3], Peter Rangelow[4], Matthias Stadler[5], Christian Schneeberger[6]

[1] Project Engineer, Section of Seismic Engineering, Basler & Hofmann AG, Zürich, Switzerland (jan.attinger@baslerhofmann.ch)
[2] Dr., Section of Structural Engineering, Swiss Federal Nuclear Safety Inspectorate ENSI, Brugg, Switzerland
[3] Head of the Section of Seismic Engineering, Basler & Hofmann AG, Zurich, Switzerland
[4] Dr., Senior Expert, Section of Seismic Engineering, Basler & Hofmann AG, Zurich, Switzerland
[5] Structural Engineer, Stangenberg und Partner GmbH, Bochum, Germany
[6] Deputy Head of Section of Structural Engineering, Swiss Federal Nuclear Safety Inspectorate ENSI, Brugg, Switzerland

ABSTRACT

The rigid baseplate assumption as outlined in EN 1992-4:2018 is not conservative for slender plate geometries. This observation the authors often encountered in their regulatory review practice of anchorage design for cable support structures and pipelines in nuclear facilities. As an alternative to the rigid baseplate design assumption, Finite Element (FE) calculations of the anchorage components considering realistic plate flexibility became increasingly popular in the last years. However, the FE based design approach is sensitive to some key analysis assumptions (e.g. fastener stiffness), requires additional product characteristics from the manufacturer and lacks important design guidance and regulation. To address these challenges and rationalise the review procedure, the authors developed a review guideline that proposes practical verification methods for anchor designs and addresses key technical aspects for the assessment of post-installed mechanical fasteners. Additionally, a case study based on the FE design approach demonstrates the significant influence of the assumed anchor stiffness on the design anchor forces, which may vary by a factor 2.

INTRODUCTION

In nuclear power plants (NPPs), many safety relevant components are anchored to the concrete structure by post-installed mechanical fasteners. Usually, plant operators in Switzerland and other European countries design their fastenings in accordance with the Eurocode EN 1992-4:2018 and rely on the therein proposed rigid baseplate assumption. Amongst others, Li (2017) has shown that assuming a rigid baseplate in the calculation of the anchor forces of a non-rigid (flexible) baseplate is not conservative, even when the deformation of the baseplate remains elastic, because the effective reduction of the inner lever arm and potentially arising prying forces may not be adequately considered.

The Swiss Federal Nuclear Safety Inspectorate (ENSI) and its experts (Basler & Hofmann and Stangenberg & Partner) are repeatedly facing the challenge of reviewing a large number of anchor designs that assume rigid baseplates, even though the baseplates cannot be a priori considered as sufficiently stiff. To address the issue, a major anchor manufacturer launched a new design software that calculates anchor forces with the Component-based Finite Element Method (CBFEM). A comparison of the design anchor forces calculated with the previous (rigid baseplate) and new (CBFEM) software versions of the manufacturer revealed an increase up to two times for rather typical anchor designs. In the authors' opinion, while the rigid baseplate assumption is not conservative in many cases, the FEM based approach of the manufacturer seems to be overestimating the anchor forces due to over-conservative assumptions, e.g. the anchor stiffness. Hence, because of the key challenges: a) lack of guidance on establishing the engineering model and its FE implementation; b) ambiguity of the requirements for the rigid baseplate assumption in normative documents; c) demanding projects that require a large number of anchor designs to be assessed in short time and d) lack of transparency of design software provided by the manufacturer, the authors decided to create a practical guideline to facilitate the review process.

With the presented review guideline herein (note that the guideline is intended for the reviewer and not the project engineer), the authors define the procedure and the key technical aspects to be considered in the assessment of post-installed mechanical fasteners subjected to static and seismic loading. Namely, it provides a flowchart that assigns each anchorage design to an adequate verification approach. Moreover, the guideline addresses the aforementioned challenges by proposing requirements for the rigid baseplate assumption, reasonable parameters for the stiffness of the fasteners and a verification procedure using the FE approach.

REVIEW GUIDELINE AND VERIFICATION CATEGORIES

The subject of the review guideline are anchorages with mechanical post-installed fasteners that generally consist of a steel section (profile) welded to a rectangular baseplate (see Figure 1).

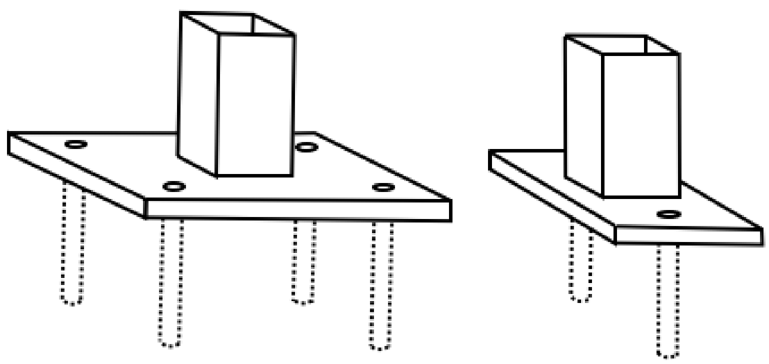
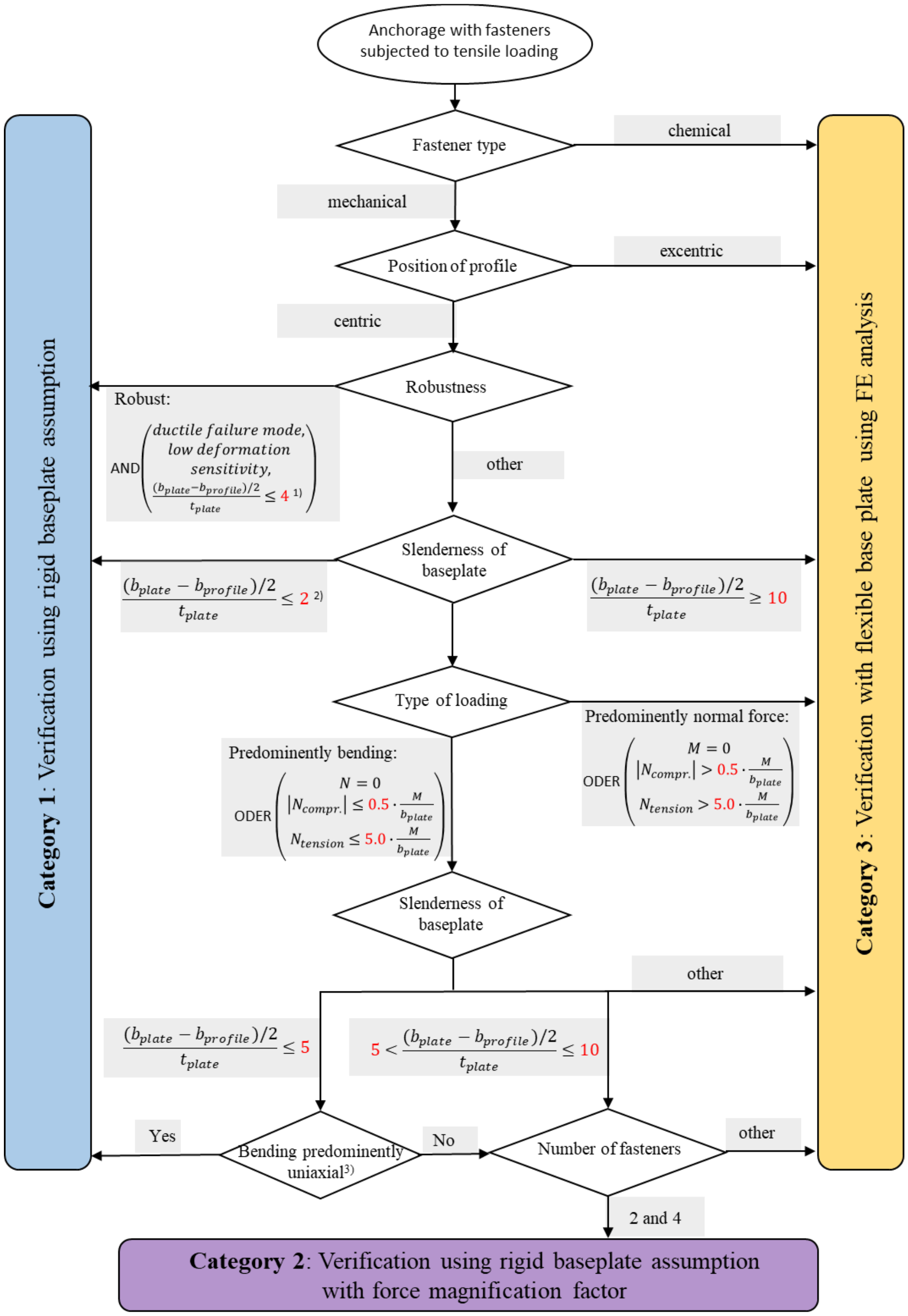


Figure 1. Typical anchorage design for pipelines and cable support structures.

Using the flowchart in Figure 2 each anchor design is assigned to one of three verification categories. Under certain relatively restrictive criteria regarding geometry and type of loading, the verification calculation can be carried out using the rigid baseplate assumption (category 1). For frequently occurring plate geometries that cannot be considered sufficiently rigid in bending, the authors propose a simplified check based on the rigid baseplate assumption with a tensile force amplification factor (category 2). For all other cases, a FE based verification calculation considering flexible baseplates and fasteners should be carried out (category 3).



1) Slenderness criterion according to TVA (1984)
2) Slenderness criterion according to NRC (1979)
3) Bending is considered predominantly uniaxial, if the smaller moment in one principal direction is not greater than 20% of the moment in the other principal direction.

Comments:

- The verification procedure of category 3 can always be applied
- b_{plate}, $b_{profile}$: For predominantly uniaxial bending the profile and baseplate dimensions are to be taken in the direction of the inner lever arm. Otherwise, the less favourable dimensions are to be taken
- For biaxial bending, M corresponds to the larger bending moment in absolute values

Figure 2. Flowchart for determination of the verification category of the anchor design intended for the review procedure

Anchorage designs belonging to Verification Category 1

To perform a verification assuming a rigid baseplate, the deformation of the plate must be negligible compared to the axial deformation of the fastener, i.e. the plate must be sufficiently stiff, see also clause 6.2.1 (2) in EN 1992-4:2018. To check this so-called "deformation criterion", there are some approaches in the literature. Fichtner (2011) suggests the deformation criterion is fulfilled (i.e. valid rigid baseplate assumption) for anchorages with centrically connected profiles under uniaxial bending if the plate width is no larger than twice the profile width ($b_{plate}/b_{profile} \leq 2$). The US NRC considers the rigid plate assumption justified if the "slenderness ratio" of cantilever length $x = (b_{plate} - b_{profile})/2$ to plate thickness t_{plate} does not exceed $x/t \leq 2$. In the civil construction guideline TVA DS-C1.7.1, an anchor plate is regarded to be sufficiently rigid if the criterion $x/t \leq 4$ is met. Based on the aforementioned documents, the authors consider the flexibility (i.e. slenderness) of the baseplate taking into account two additional relevant aspects (robustness and type of loading) and define three criteria for the validity of the assumption of a rigid baseplate:

a) $x/t \leq 2$
b) $x/t \leq 4$ and the anchorage design is robust (i.e. ductile failure mode; low deformation sensitivity)
c) $x/t \leq 5$ and the anchorage is mainly subjected to unidirectional bending

The criteria a) to c) are implemented in the flowchart shown in Figure 2.

Due to the borehole windows (to prevent reinforcement damage) and small profile dimensions of cable support structures and pipelines in nuclear facilities, the anchorage designs often do not meet the criteria for verification category 1. The authors intendedly did not include more elaborate deformation criteria as proposed by Fichtner (2011), Hofmann (2021) and Fitz et al. (2018), because they require further calculations and do not solely rely on geometric parameters.

Anchorage designs belonging to Verification Category 2

The analyses of achorage designs of cable support structures and pipelines have shown that the slenderness ratio x/t is usually between five and ten ($5 \leq x/t \leq 10$) and biaxial bending predominates for seismic loading. Hence, a majority of anchor designs do not fall into category 1 (rigid baseplates). To deal with the relatively slender anchorage designs that are often encountered, a procedure is proposed that follows the simple calculation method for rigid baseplates, but empirically takes into account the magnification of tensile forces due to the deformation of the baseplate and the fasteners. Comparative calculations for 57 anchorage designs of cable support structures have shown an increase up to 80% of the anchorage design force based on the assumptions of a rigid baseplate (category 1) vs. flexible baseplate (category 3). Furthermore, this increase strongly depends on the anchorage type (2 or 4 fasteners).

Because reliable correlations between the anchorage key parameters and the increase in anchorage tensile force (e.g. baseplate slenderness x/t and tensile force in fastener) could not be found, it is proposed to apply a tensile force magnification factor solely based on the anchorage layout (two or four fasteners). For rectangular baseplates with two fasteners, an increases by about 20% of the tensile force was observed in the above-mentioned sample of cable support structures. For rectangular baseplates with four fasteners, the tensile force magnifies by about 50%.

For seismic design, the utilization factor for the fastener is calculated by $\beta_{N,V} = \beta_N + \beta_V = N_{Ed}/N_{Rd,i,eq} + V_{Ed}/V_{Rd,i,eq}$, hence a linear interaction between shear and normal loading is assumed (see EN 1992-4:2018, appendix C.5). When the utilisation factor β_N is determined using the rigid baseplate assumption, the design verification of the anchorage simplifies to $1.2 \cdot \beta_N + \beta_V \leq 1.0$ for two fasteners and $1.5 \cdot \beta_N + \beta_V \leq 1.0$ for four fasteners, respectively. In case of a static loading, the same procedure can be applied considering the corresponding superposition rule. A flowchart of the verification procedure for category 2 is illustrated in Figure 3.

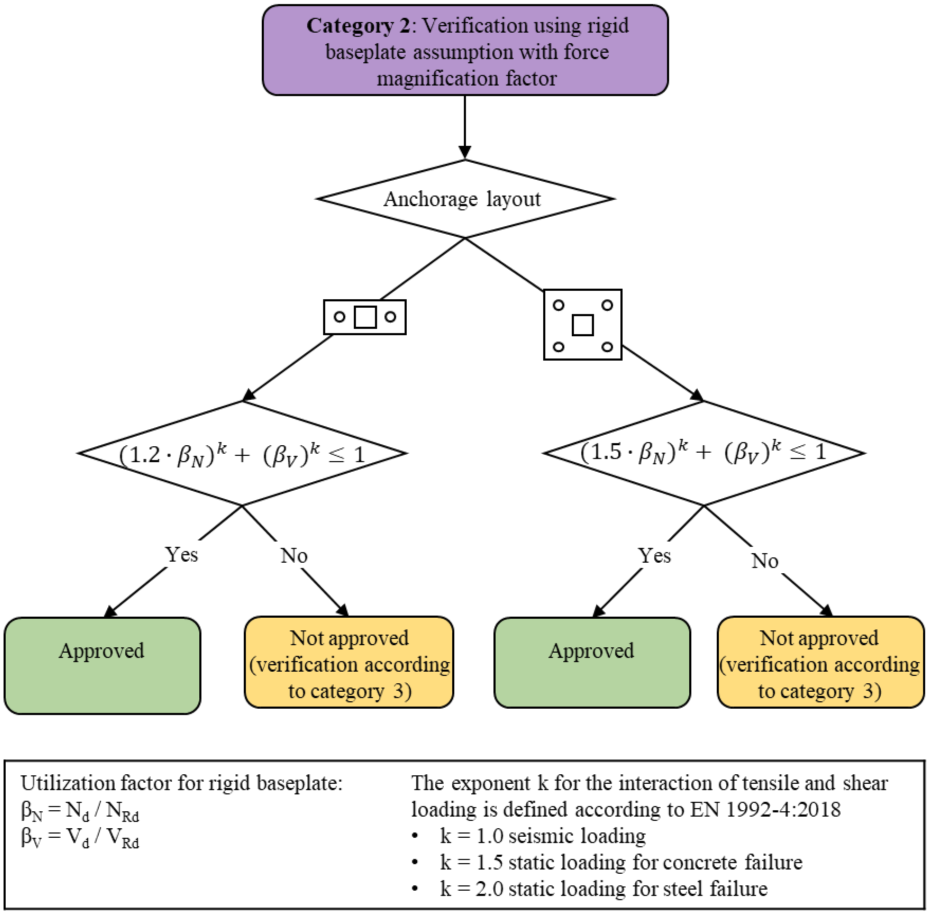


Figure 3. Review verification procedure for anchor designs in category 2

Anchorage designs belonging to Verification Category 3

A FE based verification calculation taking into account the deformation of the baseplate and the fasteners can be applied in any case, and is required if an anchorage design does not pass the criteria for category 1 or 2. In the following, the authors first provide some guidance for FE modelling of the anchorage using a simple approach and subsequently discuss the applicability of the capacity models in EN 1992-4:2018 for flexible baseplates (i.e. insufficiently stiff).

The tensile forces of the fasteners can be calculated with an own model using a FE software of choice or with a verified design software suitable for the corresponding design situation (e.g. seismic loading). The baseplate can be modelled with shell elements, which are supported by tension springs representing the fasteners and by compression springs for the concrete contact surface. The concrete stiffness can be estimated using the empirical formula given by Li (2019) $C_C=15 \cdot f_c$ [N/mm^3], where f_c is the compressive strength of the concrete. It was found that variations of the concrete spring stiffness do not significantly influence the forces in the fasteners. Therefore, more sophisticated concrete stiffness models are not required. For the axial stiffness of the fasteners (expansion and undercut types), the formula $C_A=\varphi \cdot (E_s \cdot A_s)/h_{ef}$ (Li (2017)) with a coefficient $\varphi = 0.4$ can be applied, where E_s stands for the Young's modulus of steel, A_s for the effective cross section area of the fastener and h_{ef} for the effective anchorage depth.

The stiffness of the fastener can be reduced if a ductile failure mode (e.g. pull-out in the case of expansion anchors) becomes decisive and a brittle failure mode (e.g. concrete breakout) can be excluded.

Any axial slip of the fastener due to cyclic tensile forces during an earthquake is difficult to quantify and generally does not need to be considered. Concerning the distribution of the shear force on the individual anchors, the provisions of EN 1992-4:2018, clause 6.2.2 apply and the influence of an existing or non-existing annular gap filling shall be taken into account.

With respect to the anchor's capacity, the provisions of EN 1992-4:2018 should be applied to both static and seismic actions. For the calculation of the group capacity of the fasteners with respect to concrete failure according to EN 1992-4:2018, in particular for the correction factor $\psi_{ec,N}$ included therein, a linear distribution of the fastener's tensile force is assumed. According to the software specifications of *Dr. Li Anchor Profi*, a linear distribution can be assumed if a plane can be fitted through the displacements of the fasteners in tension with a deviation of less than 5% between each displacement point and the plane. An anchorage fulfils this criterion automatically, if three or less fasteners are in tension. For anchorages with four or more fasteners in tension the criterion is usually not fulfilled due to the bending deformation of the baseplate. In such cases, a supplementary verification must be performed on the highest loaded fastener (see also Li (2019)) because the assumption underlying the group capacity formula is not fulfilled.

REVIEW SITUATION

The number of anchorages to be reviewed by the regulator can vary greatly depending on the project. For a small batch up to 5 anchorages, it may be effective to apply category 3 verification method for all anchorages. For a medium batch up to 20 anchorages, the systematic approach according to the flowchart in Figure 2 is recommended, especially since the utilization ratios β_N and β_V for the verification category 1 and 2 can usually be taken from the printouts of the designer's calculation. In case of a large batch (more than 20 anchorages, usually around 100), a spreadsheet with an implementation of the flowchart can automate the verification to a large extent. Furthermore, in the case of a large batch, it may be expedient to check only a representative random sample of the anchorages.

In addition to the aforementioned anchor force capacity verifications, the reviewer should always evaluate whether displacements of the anchorage need to be restricted due to deformation sensitivity of the anchored structure and to the assumed static boundary conditions, see also EN 1992-4:2018, Annex C.6.

INFLUENCE OF ANCHOR STIFFNESS

When calculating the anchor forces using an FE-model with tension-only springs for the anchors, the assumed spring stiffness is a decisive parameter, as reported by Fitz et al. (2018) and confirmed by analyses of the authors (see Figure 4). However, it is not straightforward to estimate the equivalent spring stiffness, as it depends on several factors such as: a) the elastic steel elongation of the fastener; b) the concrete deformations at the force transmission zone and c) slip and prestressing conditions. In the following the authors list three approaches to define an equivalent spring stiffness to represent a fastener in the FE-analysis:

- **Approach according to Dr. Li Anchor Profi**: In this software, the anchor stiffness is estimated based on a semi-empirical approach ($C_A = \varphi \cdot E_s \cdot A_s / h_{ef}$.) According to the software's recommendation, the empirical coefficient φ ranges from 0.3 to 0.5 for mechanical fasteners. If the coefficient is set to 1.0, the spring stiffness C_A corresponds to the stiffness of the steel shaft of the fastener alone.

- **Approach according to Hilti Profis Engineering**: In this software, the applied anchor stiffness is not transparent to the user. According to Fitz et al. (2018), the values for the anchor stiffness were determined in an internal research project under the philosophy of minimum displacement or maximum equivalent stiffness, respectively. In particular, uncracked concrete with no slip at the steel-concrete interface and anchors in prestressed conditions were considered.

- **Approach using the fastener's approval documents:** In the approval documents of the fastener, measured displacement values δ_N for a certain load level N are declared. The declared displacements correspond to the maximum displacement measured in a test series, in which the anchors are approximately loaded to 70% of their design resistance (see EAD 330232-00-0601). Therefore, the equivalent stiffness defined by N/δ_N is expected to be lower than the effective average stiffness, and can be calculated for cracked and uncracked concrete as well as for short and long-term loading, since values for all conditions are reported in the approval documents.

In the case study shown in Figure 4, the tensile forces N for an anchorage under a uniaxial bending is plotted against the anchor stiffness C_A. The graph shows an increase of the anchor force with increasing spring stiffness, as the inner lever arm gets smaller and prying forces develop from a certain stiffness onward (marked with a grey dot). The dashed lines labelled with numbers from one to five represent different approaches for calculating the anchor stiffness. Calculating the anchor spring stiffness based on the displacement and force values reported in the approval document for cracked and uncracked concrete results in a relatively low stiffness (see dashed lines 1 and 2). A slightly higher stiffness and thus anchor force is obtained by the approach of Dr. Li Anchor Profis with the empirical coefficient φ set to 0.4 (see dashed line 3). Setting the coefficient φ to 1.0 and therefore only account for the flexibility of the steel shaft leads to a yet higher force (see dashed line 4). When accounting for pretensioning the effective stiffness of the anchor can be several orders of magnitude higher than the stiffness of the steel shaft alone. Although the exact value of the stiffness used in Hilti Profis Engineering for the expansion anchor of the case study is not known, based on the software's anchor force it can be assumed to be around $1 \cdot 10^8$ kN/m (dashed line 5).

The forces determined by FE-analyses for the different anchor stiffness values range from around 5 to almost 11 kN in the presented case study. When the anchor force is computed under the rigid baseplate assumption, a value of 5.1 kN is obtained, which roughly corresponds to the FE result with an anchor stiffness according to line 1. Note that the force magnification factor of 1.2 mentioned in Figure 2 can be roughly back calculated in the graph, since 1.2·5.1 kN = 6.1 kN approximately corresponds to the force obtain by the FE-analysis with an anchor stiffness of $C_A = 0.4 \cdot E \cdot A_s / h_{ef}$ (dashed line 3).

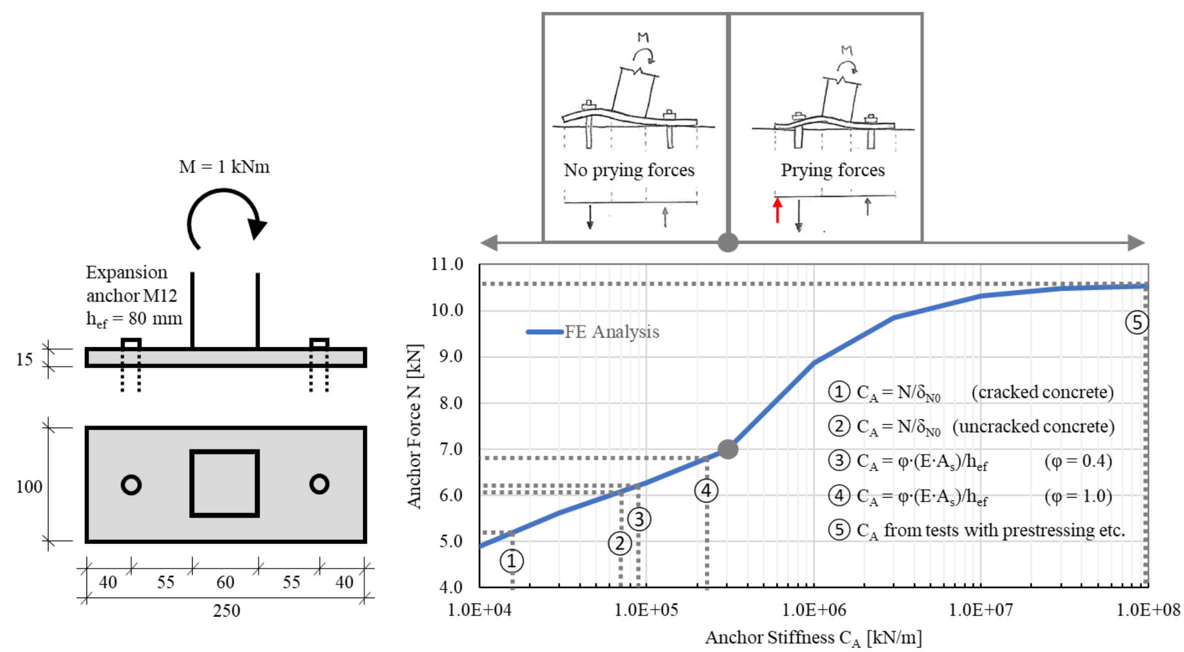


Figure 4. Case study on influence of anchor stiffness on anchor force

The authors consider the approach represented by the dashed line 3 simple and appropriate for the design verification. The consideration of pretensioning (line 5) is complex and seems to be over-conservative especially under seismic action, as creep effects and slip deformations might reduce or eliminate the preload. The approach using the maximum displacement and force values of the approval document (line 1 and 2) might underestimate the design force, as the average stiffness of the fastener is expected to be higher. It should be noted that for other anchor types, the discrepancy between the different approaches can be significantly smaller.

CONCLUSIONS

The outlined review guideline helps to rationalise the assessment of anchor designs and covers some key technical aspects that current normative documents are lacking specification. Using the review procedure presented herein, only a small number of anchorage designs require FE analysis for assessment in a design review process by the regulator. Thus, the review process becomes more efficient and can be largely automated when implemented in a spreadsheet. Furthermore, the review guideline is instructive for the user, as it depicts decisive anchorage characteristics and their impact on the structural safety. In addition, the thresholds in the flowcharts (Figure 2 and 3) can easily be recalibrated to improve accuracy when new data is collected.

The case study on the influence of the anchor stiffness (decisive model parameter) on the design anchor force illustrates the challenges of FE-based calculations. Different approaches for the anchor stiffness estimation lead to substantially different tensile forces in the anchors.

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