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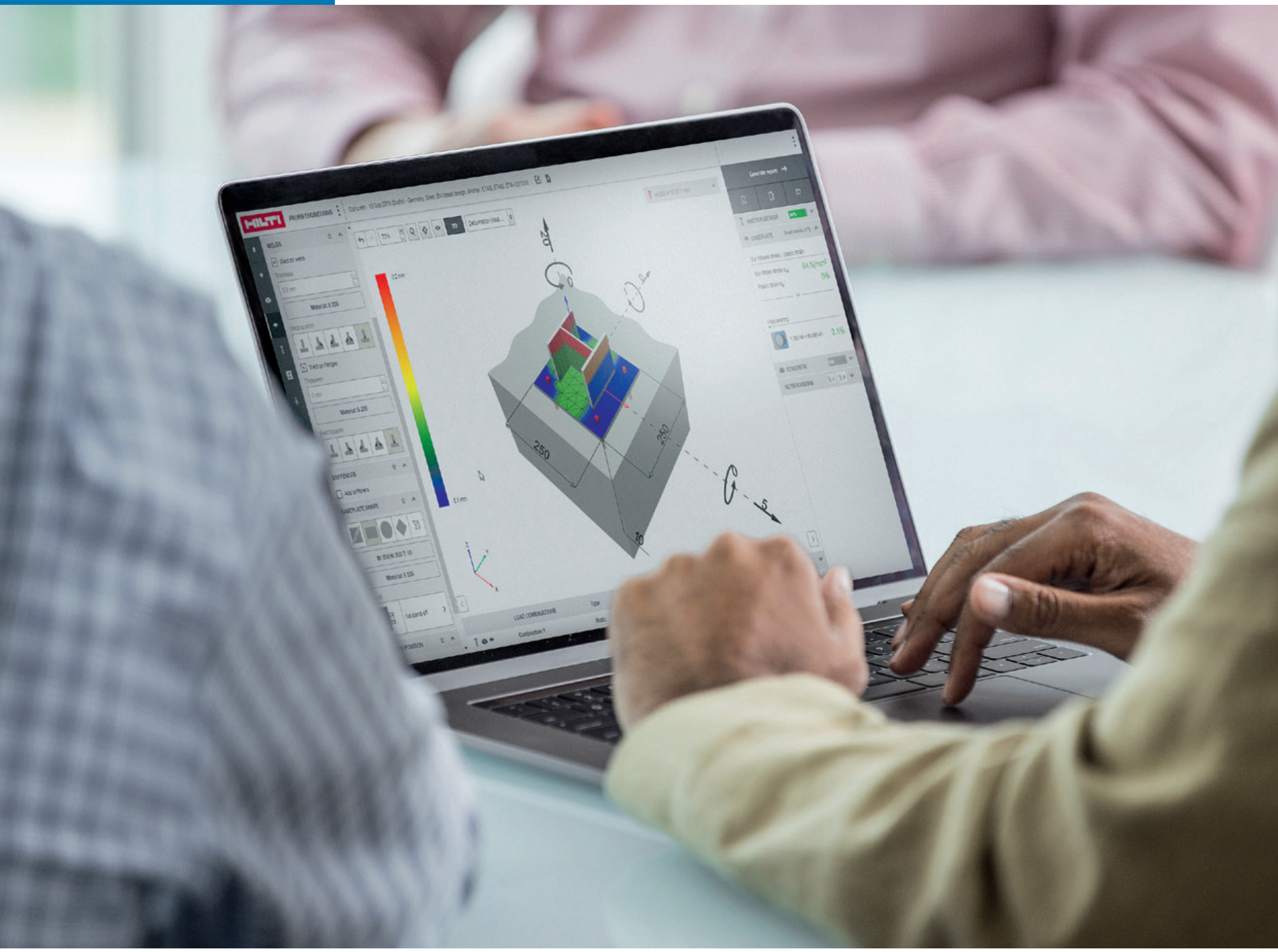

Comprehensive base plate and anchor design based on realistic behavior – new design software based on realistic assumptions

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Comprehensive base plate and anchor design based on realistic behavior – new design software based on realistic assumptions

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A key criterion when applying the relevant design regulations for fixtures anchored in concrete is the assumption of a rigid base plate if the load of the fixtures has been determined by elastic theory. However, no clear rules are in place as to when a base plate should be deemed sufficiently rigid. As a consequence, the necessary validation of this assumption at the end of the design process is generally omitted or involves highly complex manual calculations. In the following article we will examine this topic in detail. Current design regulations for fixtures will be closely analyzed in combination with flexible, i.e. not infinitely rigid, base plates. We will also highlight the potential consequences of assuming a supposedly rigid base plate. Finally, we will demonstrate ways in which an entire base point, including profile, welds, stiffeners, base plate, anchors and concrete, can be modelled. This enables the complete design of the base point as well as its optimization according to different parameters, in line with the component-based FE method. An important aspect of this approach is that all assumptions made for the design of the individual components of the complete joint do not contradict one another. To this end, further research and development work was required in some cases.

Keywords: base plate design, anchor design, fixture design

Wirklichkeitsnahe und vollständige Bemessung von Ankerplatten einschließlich der Befestigungsmittel – neue Bemessungssoftware auf Basis wirklichkeitsnaher Annahmen. *Eine wesentliche Voraussetzung für die Anwendung der geltenden Bemessungsvorschriften für Befestigungsmittel, die in Beton verankert werden, ist die Annahme einer biegesteifen Ankerplatte, wenn die Beanspruchung der Befestigungsmittel nach der Elastizitätstheorie bestimmt wird. Jedoch gibt es hierzu keine klaren Regelungen, ab wann eine Ankerplatte als ausreichend biegesteif anzusehen ist. Die notwendige Überprüfung dieser Annahme am Ende einer Bemessung erfolgt demzufolge in aller Regel nicht bzw. durch sehr aufwendige Berechnungen von Hand. In diesem Artikel wird die Thematik umfassend beleuchtet. Es werden die aktuellen Bemessungsvorschriften für Befestigungsmittel in Kombination mit flexiblen, d. h. nicht unendlich biegesteifen Ankerplatten näher betrachtet. Darüber hinaus werden Konsequenzen aufgezeigt, die bei einer als vermeintlich biegesteif angenommenen Ankerplatte entstehen können. Schließlich werden Lösungswege aufgezeigt, wie der komplette Fußpunkt einschließlich Profil, Schweißnähte, Steifen, Ankerplatte, Dübel und Beton gesamthaft modelliert werden kann. In der Folge kann der Fußpunkt vollständig bemessen und über unterschiedliche Parameter optimiert werden. Die Autoren bedienen sich dabei der komponentenbasierten FE-Methode. Wichtig ist, dass alle getroffenen Annahmen für die Bemessung der einzelnen Komponenten der vollständigen Verbindung sich nicht widersprechen dürfen. Hierzu war zum Teil weitere Forschungs- und Entwicklungsarbeit erforderlich.*

Stichworte: *Ankerplatte; starre Ankerplatte; Fußplatte; Dübelbemessung; Schweißnahtbemessung; Steifen*

1 General

The design of base plates and their fixtures anchored in concrete is important for planners and users. Modern fixtures allow concrete structures to carry heavy loads, and these safety-relevant joints must be designed with precision. Furthermore, the planning engineer is liable to the building owner for economic construction, i.e. to design the structure according to methods that allow the best possible use of the fixtures [1].

According to European standards [2,3], the serviceability limit state and ultimate limit state must be observed, taking into account design actions and design resistances ($E_d \leq C_d$ and $E_d \leq R_d$.).

1.1 Anchor load distribution

The forces acting on the anchor can be generally determined on the basis of Eurocode 2, Part 4 [4] according to elastic theory or with reference to FprCEN/TR 17081 [5] according to plastic theory.

A key assumption when calculating the tensile forces in the fixtures of a group according to elastic theory is that the base plate remains plane (flat) under the influence of the internal forces [4], generally referred to as a “sufficiently rigid base plate.” The distribution of forces in a fixture group subjected to a bending moment with a rigid base plate is shown schematically in Figure 1 while it is assumed that the stiffness of the anchors in a group are identical and directly proportional to the area of the stressed cross section and the modulus of elasticity of the steel (E_s= 210,000 N/mm^2). Furthermore, it is assumed that a triangular concrete compressive stress state forms at the outer end below the base plate (Figure 1). The stiffness of the concrete is characterized by the elastic modulus or simplistically with E_c= 30,000 N/mm^2 [4]. Furthermore, in the part of the fixture subjected to compression, anchors do not act in either tension or compression, unless they are configured for a stand-off installation.

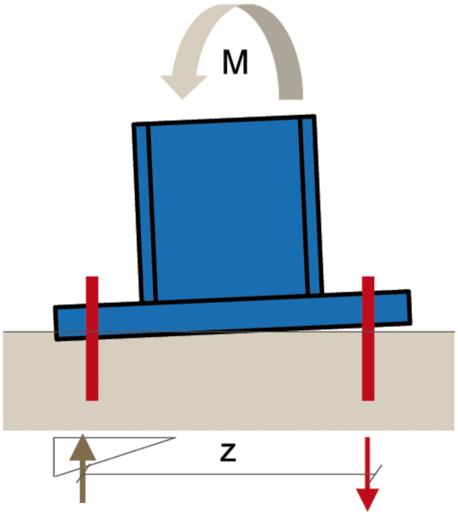


Fig. 1. Distribution of forces in an anchor group subjected to bending moment
Bild 1. Verteilung der Kräfte bei einer durch Biegemoment beanspruchten Befestigungsgruppe

A simple variant of the non-linear calculation is the plasticity theory, which can be considered suitable for the verification of the ultimate limit state for anchoring in concrete if the conditions of FprCEN/TR 17081 [5] are taken into account [4]. Only the equilibrium conditions are fulfilled; the compatibility conditions are neglected. The plasticity theory assumes that the fixtures have sufficient ductility under tensile and shear loads [5]. This condition only applies to steel failure, ductile steel, small hole clearance and fixtures with a constant cross-section over the anchorage depth (e.g. threaded rods) [5]. If the fixture does not have a constant cross-section, additional material-specific and geometric requirements must be considered. These requirements are not observed by all anchoring systems on the market. FprCEN/TR 17081 [5] takes into account both rigid and flexible base plate behavior. In the case of a rigid base plate, it is assumed that concrete compressive stresses are distributed triangularly from the outer end of the base plate, whereby the base plate must be thick enough to ensure that it does not yield at the edge of the attached member. In the case of a flexible base plate, it can be simply assumed that the compression reaction is located at either the edge or centroid of the compression element of the attached member [6]. These assumptions are on the safe side, especially for relatively small attachments compared to the size of the base plate. In general, [5] is limited to the application under tensile load and/or lateral load with uniaxial bending.

1.2 Resistance of fixtures

The calculation or verification of the resistance is only possible if a distinction is made in the design both according to load direction (tensile load, shear load, combined tensile [shear]load) and according to failure modes [1]. In 1995, the CEB (Comité Euro-International du Beton) published a design method [7] which meets these requirements. Known as the concrete capacity (CC) method, it is part of the currently valid ETAG 001 [8] and EOTA TR029 [9] and is also be included in Eurocode 2 as Part 4 [4].

The basic assumption of the CC-method is that the anchor forces on the concrete surface are calculated from the forces and moments acting on the base plate, assuming a linear material behavior of concrete and anchor (elasticity theory), and that the base plate remains plane [1, 4]. The requirement for a sufficiently rigid base plate with respect to the design resistance is explicitly included in the scope and implicitly from the factor used in the CC method to take into account of the influence of the eccentricity of the resulting tensile load on the failure load of groups ($\psi_{ec,N}$).

According to the CC method, the failure load of the group is calculated according to [10] for uneven loads, e.g. bending moments acting on the base plate or eccentric tensile loads. If the resultant tensile force R is applied directly in line with the anchor and the projection of the fixture is neglected, then the failure load of the group corresponds to the value of a single anchor, regardless of the spacing (Figure 2c). If the resultant tensile force is applied at any other position within the group (Figure 2b) then the failure load of the group may be assumed to follow a hyperbolic progression between the extreme cases a and c. This is taken into account in the CC method with the $\psi_{ec,N}$ factor.

In [1] it is explicitly pointed out that the equation for the factor $\psi_{ec,N}$ does not apply if a flexible base plate is used or if the distribution of the load acting on the base plate on the individual fixtures is not calculated according to the elasticity theory.

If the resistance side is carried out according to the plasticity theory [5], numerous restrictions apply. In addition to the ductility requirement for the fixtures, the calculation ensures that steel failure occurs before the characteristic resistance for pull-out/pull-through, concrete cone failure, splitting and concrete edge failure is achieved. In practice, this can be achieved by selecting a sufficiently large anchorage length. For this reason, this usually requires larger edge distances in order to guarantee a concrete cone failure. It may not be possible to find a fixture solution in narrow concrete members.

1.3 What is meant by "sufficiently rigid"?

If the forces acting on the fixtures are determined by the elasticity theory and if the fixtures are to be verified in ac-

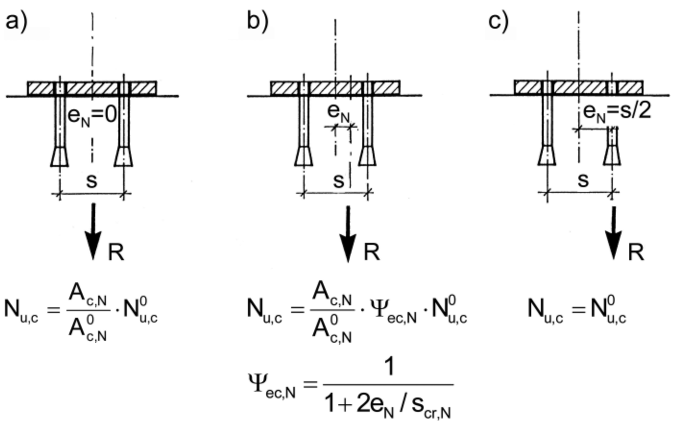


Fig. 2. Accounting the eccentricity of the external load in the CC-Method [1]
Bild 2. Berücksichtigung der Exzentrizität der äußeren Last beim CC-Verfahren [1]

cordance with current regulations [1,4,8,9], the base plate must be sufficiently rigid. It is the authors' opinion that there is no uniform and clearly binding statement as to how this should be achieved.

- In order to ensure sufficient base plate rigidity, [11] suggests limiting the stresses in the base plate. According to Figure 3, bending stresses in the base plate should be averaged over a range of 2*t+s (t = base thickness, s = profile web thickness) in front of the attachment. If the mean bending stress in the steel plate is less than the yield point, it can be assumed that the base plate is sufficiently rigid [11].
- Numerical [12] and experimentally obtained results [13,14,15] indicate that the stress criterion [11] is not universally valid and can potentially lead to significantly higher anchor loads than calculated according to the elasticity theory.
- In [16], a statement is made regarding "sufficient rigidity" using the ratio of distance from edge of profile to the edge of the baseplate related to base plate thickness. This is presumably intended to prevent any prying forces.
- Eurocode 2, Part 4 [4] indicates that the deformation of the base plate should be negligible compared to the axial displacements of the anchor. If this requirement is not met, the deformation of the base plate must be taken into account.
- According to the latest research [15], sufficient rigidity or the thickness of the base plate should be determined according to two criteria: a stress criterion and a deformation criterion. This is achieved with the stress limitation according to [11]. Furthermore, the elastic deflection of the base plate under design internal forces must be limited, taking into account anchor displacement. [15] indicates that the deformation under tensile actions essentially depends on the anchor rigidity of the anchor system used.

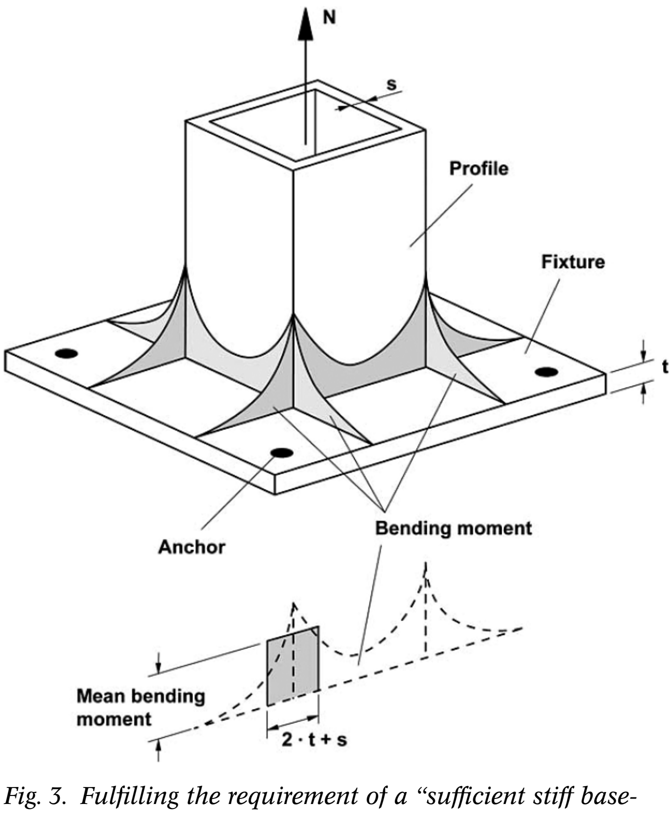


Fig. 3. Fulfilling the requirement of a "sufficient stiff baseplate" by limiting the bending stress, s = web-thickness of profile, t = thickness of plate [11]
Bild 3. Einhaltung der „Biegestarren Ankerplatten"-Definition durch Begrenzung der Biegespannung, s = Profilstegdicke, t = Ankerplattendicke [11]

2 Theory vs. reality or ideal rigid vs. flexible and related consequences

2.1 Base plate thicknesses in practice

The assumption that the base plate does not deform under applied loading actions determined on the basis of the elasticity theory is not always guaranteed for base plate thicknesses in standard practice. As already discussed, one of the assumptions for a rigid base plate is that the resulting concrete compressive force acts on the outer end of the base plate and thus results in the inner lever arm z (Figure 4a above).

If, however, in contrast to the assumption, a flexible base plate is used, this leads to a reduction in the lever arm of the internal forces and thus to higher loads on the fixture, depending on the rigidity. In extreme cases, a plastic hinge is likely to form in the base plate at the edge of the profile (Figure 4a below), whereby the resulting concrete compressive force will move towards the edge of the profile. If substantial deformation occurs as a result of a plastic hinge forming in the base plate on the tension side of the connection, the plate corners can become compressed against the concrete, inducing additional prying forces which, in turn, lead to an increase in the tensile force in the anchors. These prying forces can also occur with larger base plate protrusions, flexible base plates and predominantly tensile loads (Figure 4b). The load-distributing effect of the base plate is prevented by the considerable deformation of the loaded base plate, which can lead to significant overloading and premature failure of a anchor within a group (Figure 4c).

2.2 Base plate thicknesses in practice

Figure 5 shows design examples of a base plate in practice. In this case, the anchor loads were calculated by the responsible engineer using market-leading manufacturer software and assuming a rigid base plate. Subsequently, the anchor loads of the identical base plate were calculated by the responsible structural engineer under realistic assumptions using non-linear methods. If both results are compared, there are clear differences with regard to the maximum anchor tensile load of the individual anchor in a group of up to 50 %. This indicates that the base plate used is not sufficiently rigid. Why this behavior was not taken into account in the original design will be explained in more detail in the following section.

3 A new approach

3.1 Current procedure

Today, computer programs are normally used to design fixtures with anchors. As a rule, the design software carries out the steps in Figure 6 based on the assumption of a rigid base plate – shown in simplified form.

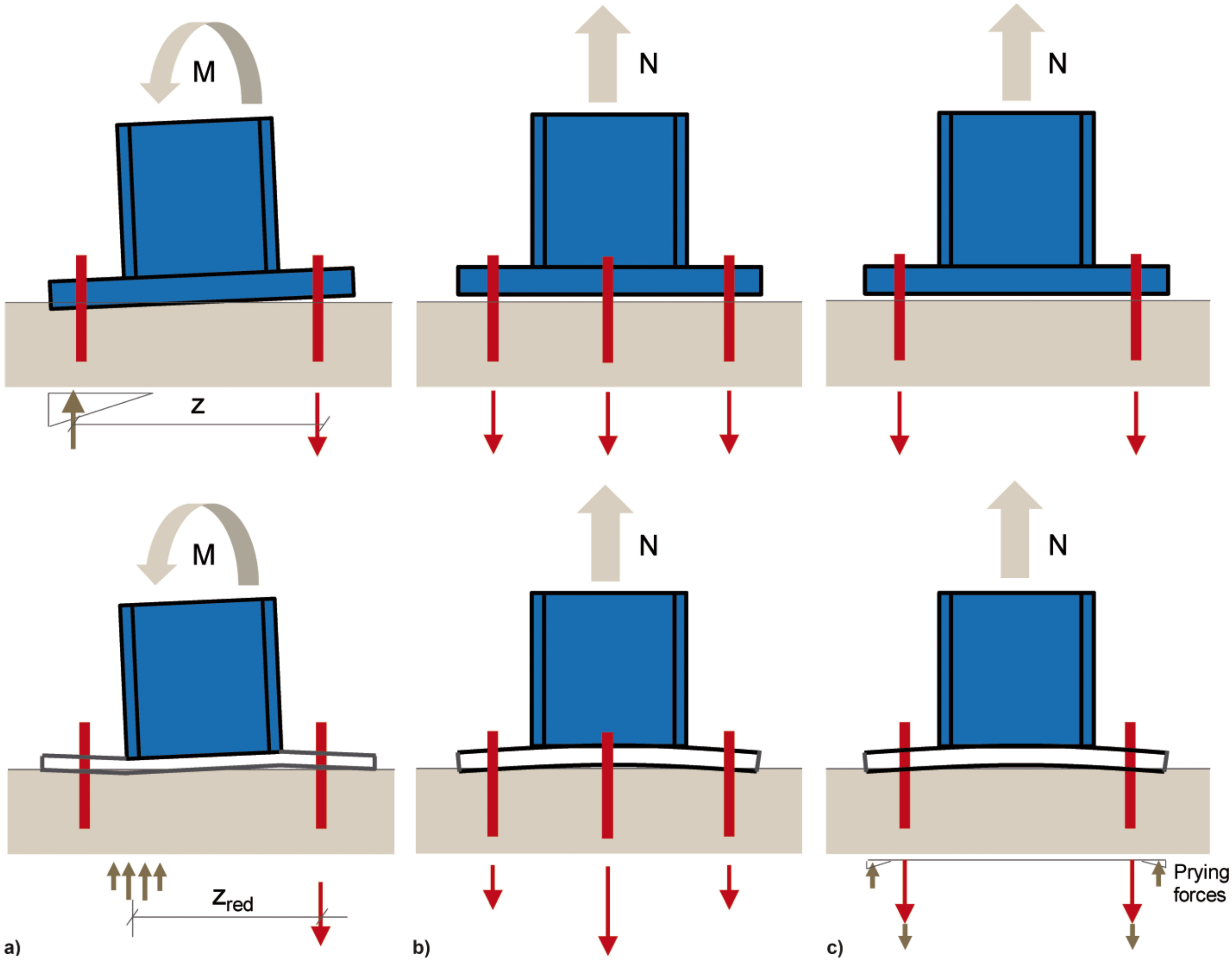


Fig. 4. Increase of anchor forces (action) associated with a flexible baseplate: a) reduction of inner lever arm, b) prying forces, c) limited equal load distribution
Bild 4. Vergrößerung der Ankerlasten (Einwirkung) in den Befestigungselementen bei biegeweicher Ankerplatte: a) Reduzierung des inneren Hebelarms, b) Abstützkräfte, c) eingeschränkte Lastverteilung

As a first step, the concrete compressive forces below the base plate with triangular distribution of the concrete compressive stress and the tensile forces on the fixtures are determined according to the elasticity theory, assuming a rigid base plate (Figure 6, step 1). If the mean bending stress in the steel plate is less than the applied stress criterion, it is assumed that the base plate is sufficiently rigid (based on the concept of [11]). The determination of the bending stress in the base plate can be clearly illustrated by a single-span or multi-span beam, in which the profile is used as a support and the concrete compressive force and anchor loads as external loads (Figure 4, step 2). These stresses are used to calculate the required plate thickness.

The last and ultimately necessary step in checking whether the actual base plate behaves rigidly under the loads is not yet possible or only with the aid of special software based on non-linear FE analyses. It is therefore the engineer's responsibility to verify the not clearly defined base plate rigidity.

Furthermore, necessary assumptions such as the anchor stiffness, which according to [15] can have a significant influence on the anchor loads, must be estimated, as these are not yet available.

The use of displacement values based on the specifications in the corresponding ETA of a fixture is not sufficient and can also lead to incorrect anchor loads.

3.2 Component-based finite element method (CBFEM)

In order to be able to assess the actual rigidity of the base plate and its fixtures, but also the welds and attachment, it is necessary to make realistic assumptions about the load-deformation behavior of the individual components and thus take equilibrium and compatibility conditions into account. In the future, this will be possible with the Hilti PROFIS Engineering Suite/base plate module [17] on the basis of the component-based finite element model (CBFEM) analysis. It combines the component method commonly used in steel construction with a powerful finite element calculation and provides precise verification of all components of a joint. Specifically, the base point is divided into individual components, which are described by realistic assumptions about the load-deformation behavior or stress-strain curves. This in turn allows the overall system to be described by the realistic assumptions and the force distribution. In the above software, the components

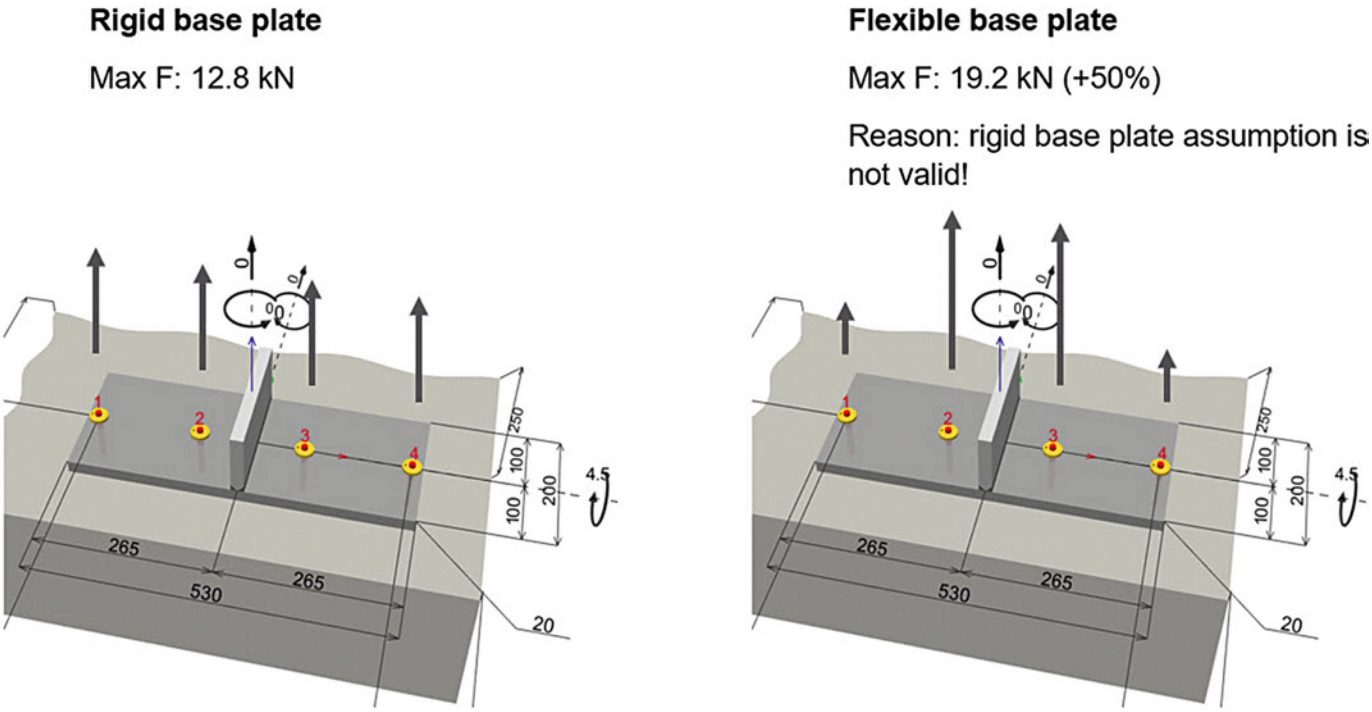


Fig. 5. Difference of calculated anchor loads based of the theory of elasticity compared to the anchor forces calculated with the help of finite element method
Bild 5. Unterschied der berechneten Ankerlasten nach Elastizitätstheorie im Vergleich zu den tatsächlichen Ankerlasten mithilfe nichtlinearer Methoden

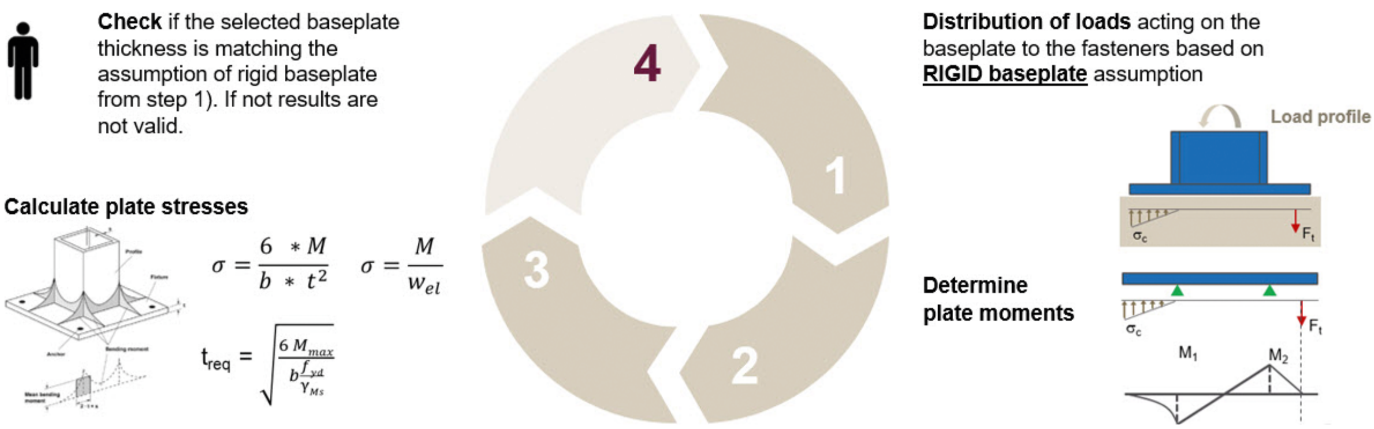


Fig. 6. Realized (steps 1 to 3) and necessary design steps (steps 1 to 4) to ensure a sufficient stiffness as required in EC 2, part 4 [4]
Bild 6. Durchgeführte (Schritte 1 bis 3) und notwendige Bemessungsschritte (Schritte 1 bis 4) zur Gewährleistung einer ausreichend starren Ankerplatte nach EC 2, Teil 4 [4]

considered for the entire base point (Figure 7) are the profile, the stiffeners, if any, the base plate, the welds, the fixture and the concrete.

The base plate, the welded-on profile and the stiffeners around the welds are described taking into account the material properties according to EN 1993-1-1 [3] or EN 1993-1-5 [18], modeled according to the FE method and provided with an elastic-plastic (welds) or elastic-plastic, linear hardening material law (profile, stiffeners and base plate). The concrete response is formulated on the basis of the concrete properties according to EN 1992-1-1 [2], whereby the spring stiffness of the concrete is based on the Winkler-Pasternak model. The load-deformation behavior of the anchors, which has a significant influence on the level of the support forces, was determined in a research project at Hilti taking into account prestress, material of the anchor and coefficient of friction. It has been shown that the anchor rigidities obtained in some cases deviate significantly from the values in the corresponding approval documents. This can be explained by the fact that the displacement values of the anchor published in the corresponding documents/evaluations were determined under a different philosophy (maximum displacement values) than is required for determining the rigidity of the fixture for the design of the base plate (minimum displacement values).

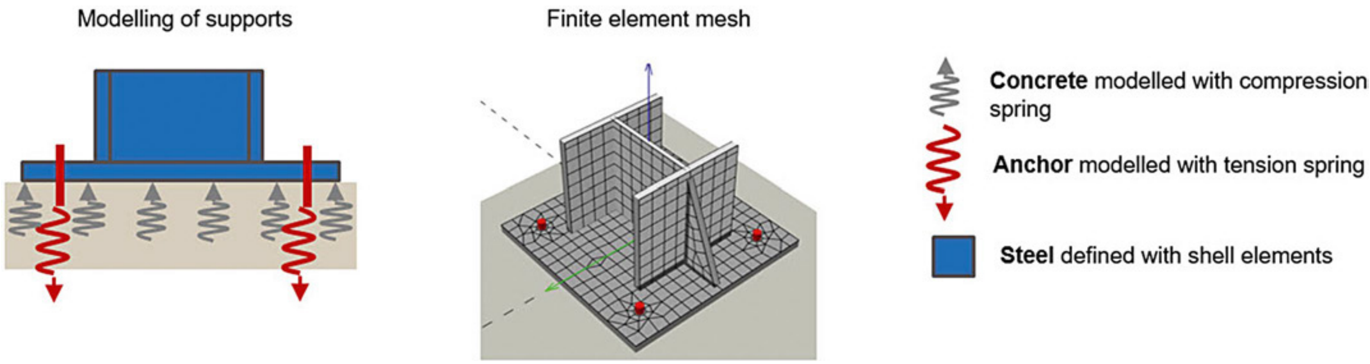
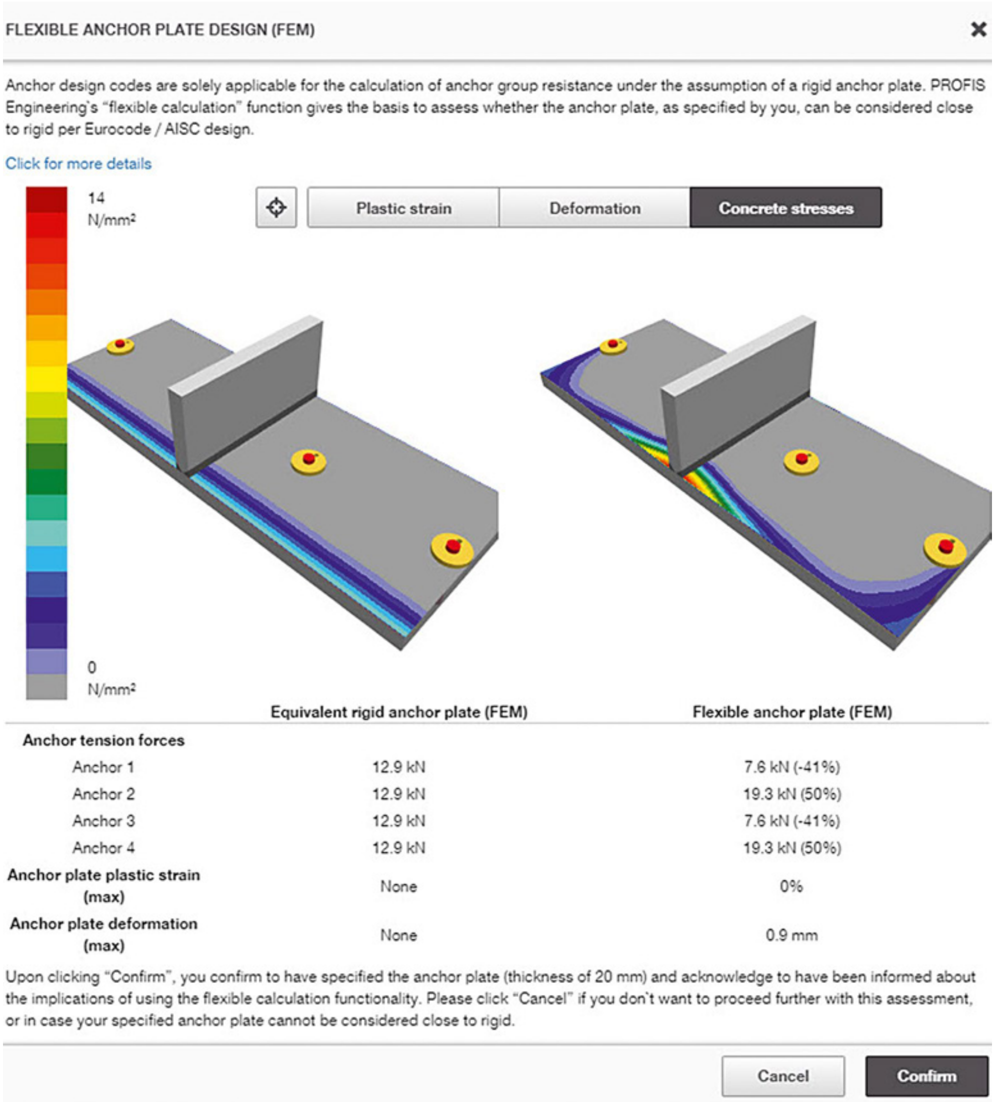


Fig. 7. Components taken into account by the Hilti PROFIS engineering baseplate module [17]
Bild 7. Berücksichtigte Komponenten des Hilti PROFIS Engineering Ankerplatten Moduls [17]



	Equivalent rigid anchor plate (FEM)	Flexible anchor plate (FEM)
Anchor tension forces		
Anchor 1	12.9 kN	7.6 kN (-41%)
Anchor 2	12.9 kN	19.3 kN (50%)
Anchor 3	12.9 kN	7.6 kN (-41%)
Anchor 4	12.9 kN	19.3 kN (50%)
Anchor plate plastic strain (max)	None	0%
Anchor plate deformation (max)	None	0.9 mm

Fig. 8. Comparison of loads on anchors, calculated according to method I (stiff baseplate) and method II (realistic assumption, flexible baseplate)
Bild 8. Gegenüberstellung der Ankerlasten berechnet nach Verfahren I (biegesteife Ankerplatte) und Verfahren II (wirklichkeitsnahe, flexible Ankerplatte)

3.3 Is the base plate approximately rigid? How to check

Whereas no check of the actual base plate rigidity was previously carried out, this is now performed at the end of the calculation process with the aid of the above-mentioned Hilti PROFIS Engineering software [17]. The anchor loads calculated according to the elasticity theory (method I) are compared with the anchor loads taking account of equilibrium and compatibility conditions on the basis of realistic assumptions of the load-displacement be-

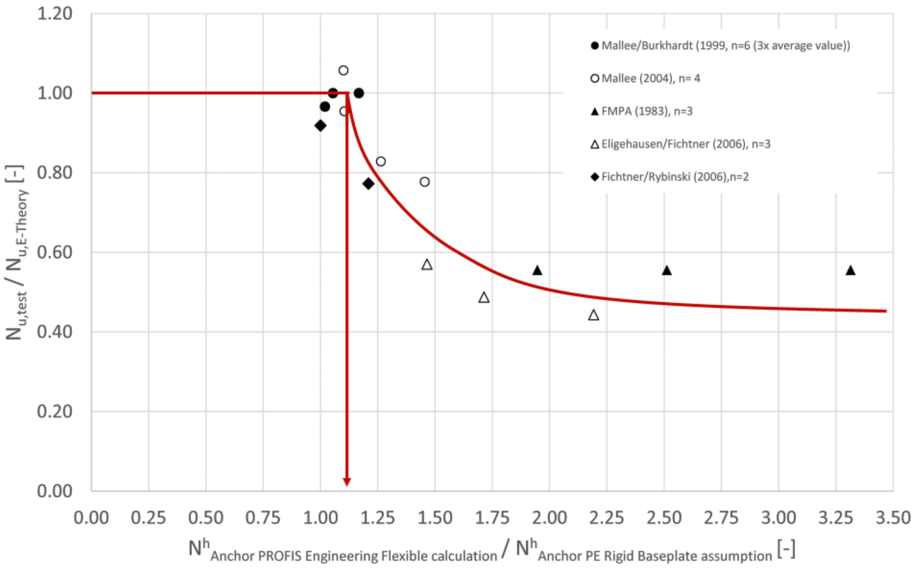


Fig. 9. Increase of anchor forces (action) associated with a flexible baseplate: a) reduction of inner lever arm, b) prying forces, c) limited equal load distribution
Bild 9. Quotient aus gemessener und rechnersicher Bruchlast nach der Elastizitätstheorie von Gruppenbefestigungen als Funktion des höchstbelasteten Dübels unter Berücksichtigung wirklichkeitsnaher Annahmen zum höchstbelasteten Dübel nach E-Theorie (starre Ankerplatte)

havior and the stress-strain curves of the individual components (method II), and assuming a rigid base plate (Figure 8). By comparing the anchor loads of both methods, the gap between theory (rigid base plate) and practice within a software can be determined.

To determine the influence of an increased anchor load on the total failure load of the fixture group, test values were recalculated using the Hilti design software in conjunction with the Hilti base plate module [17].

Figure 9 shows experimentally determined mean failure loads of anchor groups ($N_{u,test}$) [11,13,14,15] related to the calculated failure load taking into account the elasticity theory ($N_{u,\ E\text{-theory}}$) as a function of highest loaded anchor of the group based on non-linear assumptions [17] related to the calculated value of the most loaded anchor, determined on the basis of the elasticity theory [17]). These tests take into account anchor groups with four and nine anchors under uniaxial and biaxial bending in non-cracked concrete. In the tests, cast-in headed studs and post-installed anchors were used. The plate thicknesses used were those calculated using the stress criterion of [11] but also deliberately lower plate thicknesses were tested. Figure 9 was chosen in order to estimate to what extent a deviation of the most heavily loaded anchor of a group from the calculation according to the elasticity theory affects the overall group's load capacity. On the basis of the available test values, it can be seen that with a deviation of the anchor loads of the most loaded anchor of a group of approx. 10 % – between rigid and realistic baseplate assumptions – the mean failure load of the group fixture corresponds to the mean group failure load calculated according to the elasticity theory. This means that in the case of approx. 10 % deviation in the anchor loads between the rigid plate and the flexible plate, no negative influence on the load bearing capacity could be observed in the tests.

The comparison of the rigid and the realistic base plate in combination with the above investigations should help the planning engineer to make an assessment of the existing base plate thickness that does not contradict the applicable guidelines.

4 According to the calculation, my base plate is far from rigid! What can I do?

If the difference between the determined anchor loads according to method I (elasticity theory) and method II (realistic assumptions) is significant, the base plate used is flexible. In this case, the user can resort to various measures, which can also be calculated with the software or the base plate module [17], in order to arrive at the valid assumptions of procedure I. These include increasing the size of the welded profile to reduce bending in the plate, reducing the base plate protrusions to minimize prying forces, increasing the thickness of the base plate, or using stiffeners/web plates. Using a less stiff anchor system can also reduce anchor loads. A further approach is to ensure that steel failure occurs before the characteristic resistance for pull-out, concrete cone failure or splitting (concrete-related failure modes) is achieved. As a rule, this can be achieved by selecting a sufficient anchorage length.

5 Summary and outlook

This article comprehensively examined the challenge of realistically assuming all boundary conditions for base plate design. The current design regulations for fixtures were closely analyzed in combination with flexible – i.e. not infinitely rigid – base plates. We also highlighted the potential consequences of an incorrect assumption of a rigid base plate. Finally, we demonstrated ways in which an entire connection, including profile, welds, stiffeners, base plate, anchors and concrete, can be modelled, designed and optimized in one step. To this end, further research and development work was required in some cases.

Hilti is thus continuing along the path it has taken and established in the market to develop software for planners and customers in the form of the PROFIS Engineering Suite, which – integrated into its workflow and software environment – not only provides security but also significantly increases transparency. It also significantly increases efficiency in base plate design. Our goal is for our planners to calculate support reactions and for the Hilti software to take care of the complete and verifiable verification of the base point. Further ideas for additional features are already in the planning stage.

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PROFIS ENGINEERING SUITE

New approach for the anchor design

With the innovative PROFIS Engineering Suite Hilti offers a user-friendly design software for fastenings in concrete and masonry. Furthermore, applications like a complete handrail design as well as the comprehensive baseplate design with all relevant verifications in ULS and SLS are integrated.

The new web-based Software with an individual customizable user interface provides always the latest state of the art – even without annoying but safety relevant updates – and offers a complete workflow integration for your structural design and execution, incl. documentation. Further highlights:

- Interface to Dlubal RStab / RFEM and Excel
- Export option to CAD and BIM Software like Tekla

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