Required Thickness of Flexurally Rigid Baseplate for Anchor Fastenings

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Abstract

The current design methods according to prEN1992-4 for multiple anchor fastenings with baseplates are based on the assumption that the baseplates are sufficiently rigid such that anchor tension forces are calculated using plane distribution method, as by analogy with beam bending where plane sections remain plane. But there is yet no provision on the level of stiffness required to achieve plane distribution of anchor tension forces. This can result in possible vulnerability in the practice of anchor design, because the baseplate may not be actually rigid enough to ensure plane distribution and there is no provision to check. The assumed rigid baseplate without checking its required stiffness may lead to the application of smaller anchor bolts and relatively thin (elastic) baseplates. This is unsafe since the real anchor tension forces on elastic baseplate can be much higher than those calculated with "plane distribution method".

In this paper, a method for identifying the required baseplate thickness to achieve the conditions of rigid baseplate assumption is presented and illustrated with sample calculations. A design method with elastic baseplate is proposed and discussed.

Key words: Anchorage design, rigid, elastic baseplate

1. Introduction

The design method for multiple anchor fastenings according to prEN1992-4 /1/ is based on the assumption that the anchor tension forces on baseplates are distributed linearly. In the practice, e.g. using most free anchorage design software products, the anchor tension forces are calculated by the plane distribution method, see Fig.1-1 c).

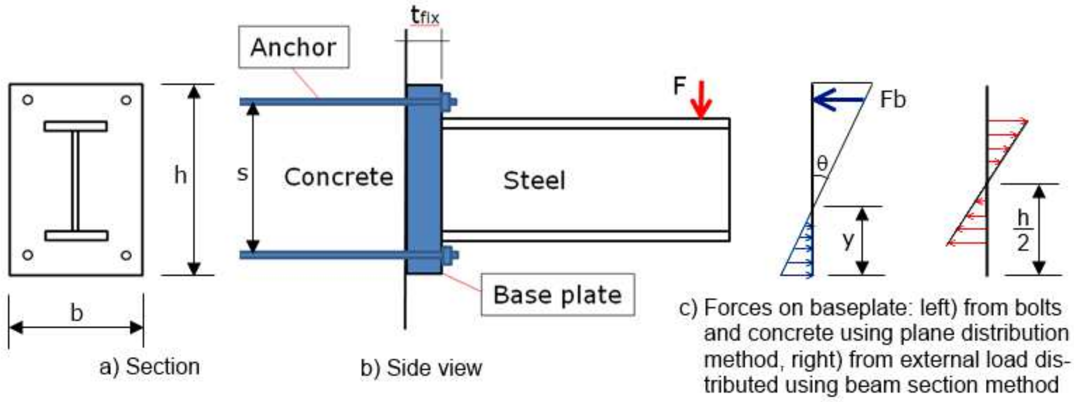


Fig. 1-1 Example of multiple anchor fastening with baseplate /4/

The forces from external loads are distributed onto the baseplate using the beam section method, see also Fig.1-1c). With the forces on the baseplate determined, stresses in the base plate are calculated through plate analysis, for example, using finite element analysis (FEA), assuming the baseplate is elastic. The baseplate thickness is then determined by the condition that under design actions the maximum stress in the baseplate does not exceed its design yield stress.
Tests conducted by university Stuttgart /2/ on models using thicknesses as obtained from the commonly used method described in the previous paragraph have shown much higher anchor tension forces than those assumed by the plane distribution method. This means that the current design method in the practice may underestimate the anchor tension forces and may be unsafe in many application cases.
In order to understand and solve this problem, there is a working party "required stiffness of baseplate" in the fib task group T2.9. In this paper, the research results of fib T2.9.8 conducted mainly by Dr. Li Anchor Profi GmbH on stiffness conditions for flexurally rigid baseplate and design method for elastic baseplate are presented.

2. Elastic baseplate model

2.1 Basic assumptions

For the elastic analysis of baseplate, e.g. shown schematically in Fig 2.1-1, the Kirchhoff plate theory /3/ is used with the baseplate being elastically bedded on concrete base. Bolts and concrete areas are represented by elastic springs.
In the analytical model, it is assumed that the following parameters are known and can be taken for the calculation.

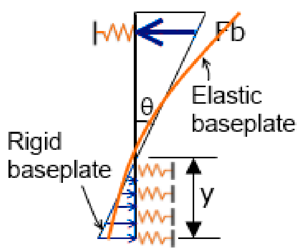


Fig. 2.1-1 Elastic baseplate model

- Baseplate thickness t_{fix} [mm] and E-modulus, e.g. 210,000 N/mm² for steel baseplate.
- Concrete bedding factor C_c [N/mm³] is derived from /5, 6/ with $15f_{c,cube}$, e.g. 375 N/mm³ for C20/25.
- Anchor stiffness or anchor spring constant C_A [kN/mm] at SLS may be determined by pullout tests with single anchors in uncracked concrete (fig. 2.1-2) /7/.

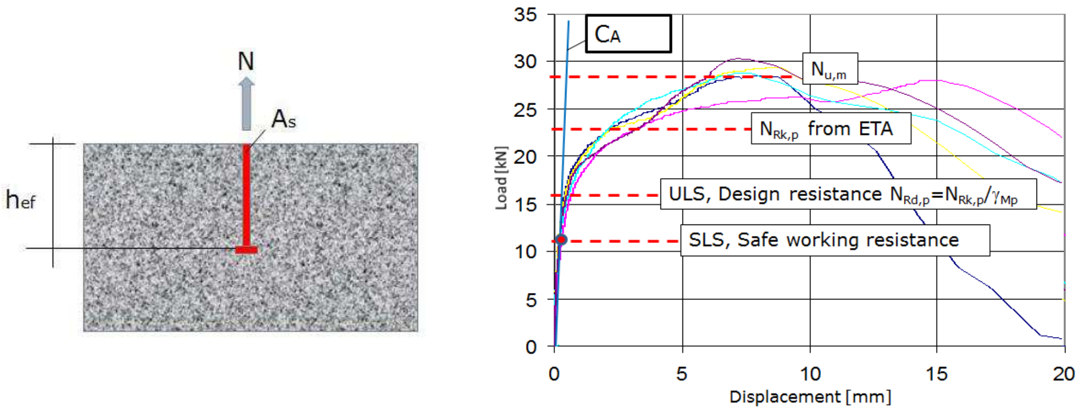


Fig. 2.1-2 Determination of anchor stiffness C_A by pullout tests /7/

- For headed studs with shaft cross section A_s, bearing area A_H and effective anchorage depth h_{ef} , the anchor spring constant may be expressed by

$$C_A = \frac{1}{\frac{h_{ef}}{E \cdot A_s} + \frac{1}{C_C \cdot A_H}}$$

- Profile is welded onto the baseplate so that the action forces from the profile may be calculated by beam section method rather conservatively, see Fig.1-1 c).

2.2 Numerical solution

A finite element program has been developed as part of a commercial anchorage design software /8/ to investigate the behavior of the elastic baseplate model. The process is iterative that from an initial spring setup, bolts in compression and concrete areas in tension are progressively eliminated, much like a beam on elastic foundation. Both rectangular and triangular elements are available in the FEA model so that baseplates of any shape can be analyzed. The influence of shear effect can also be investigated as an additional option. The commercial anchorage design software/8/ can also perform rigid baseplate analysis using the plane distribution method.

2.3 Verification of the elastic baseplate model by tests

In order to validate the proposed elastic baseplate model, models of 5 sets of tests from /2, 9/ were analyzed using the computer program /8/. In all tests, the thicknesses of baseplates are so chosen that their max. stress does not exceed the yield stress. Solutions were performed for both rigid and elastic baseplate method. The bonded anchor spring constants $C_A=EA_s/l$ ($l=t_{fix}+h_{ef}$) /10/ were used for the latter method.

Figures 2.3-1 to 2.3-3 show the dimensions of the tested multiple-anchor fastenings /2/ and the comparisons of calculated and tested results. For observing the current situation in the anchorage design practice using plane distribution method, the anchor tension forces calculated by this method are also plotted in the figures. It is evident that the elastic baseplate model provides very accurate anchor tension forces. The plane distribution method underestimates them dramatically in these 3 tests.

Figs. 2.3-4 and 2.3-5 show the test models of /9/ (t_{fix}=20mm) and the comparisons of calculated and tested results. An anchor spring constants of C_A= 39.8 kN/mm /9/ was used for the elastic baseplate analysis. It is again evident that the elastic baseplate analysis provides very accurate anchor tension forces.

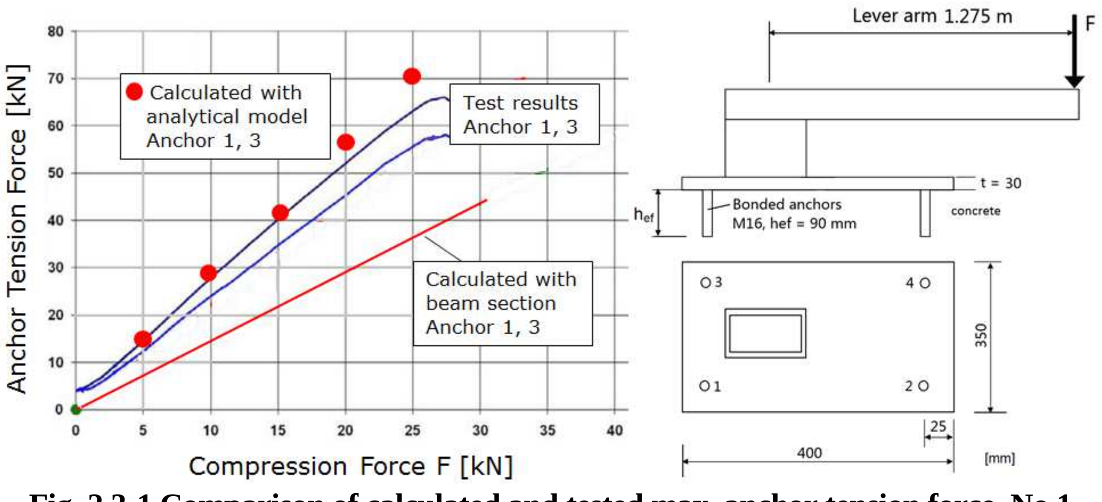


Fig. 2.3-1 Comparison of calculated and tested max. anchor tension force, No 1

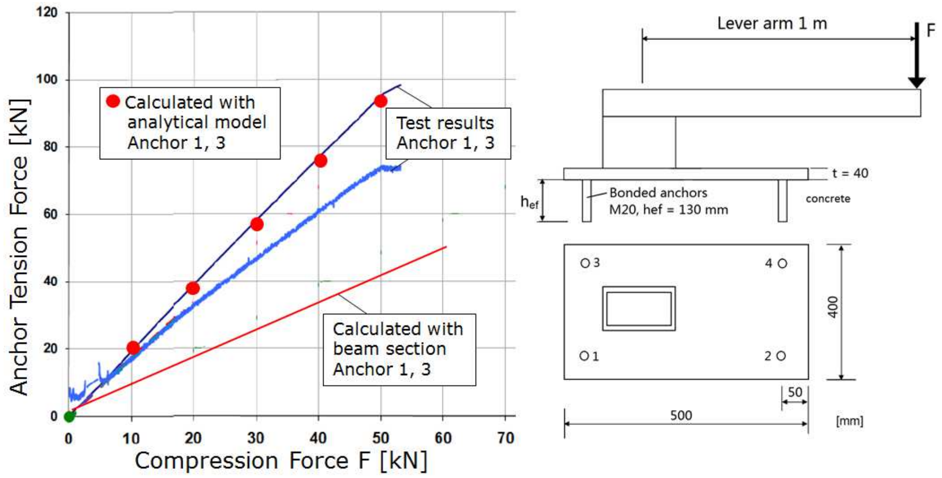


Fig. 2.3-2 Comparison of calculated and tested max. anchor tension force, No 2

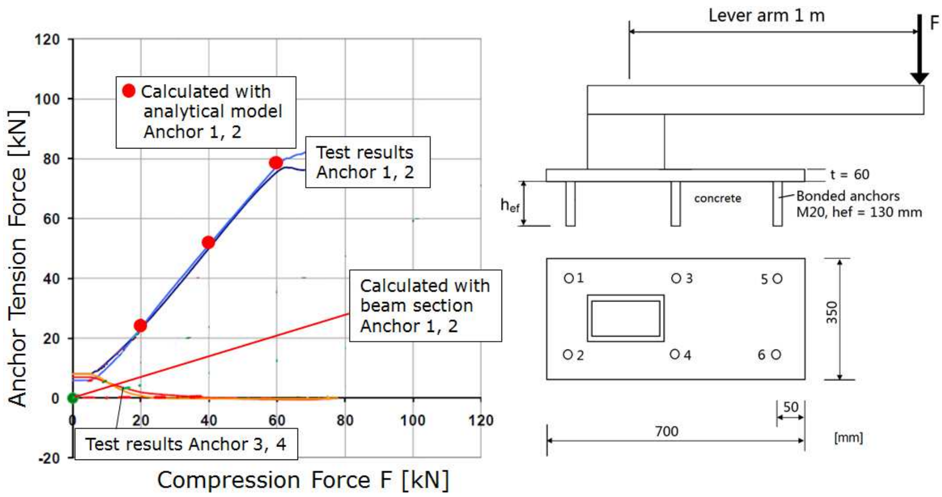


Fig. 2.3-3 Comparison of calculated and tested max. anchor tension force, No 3

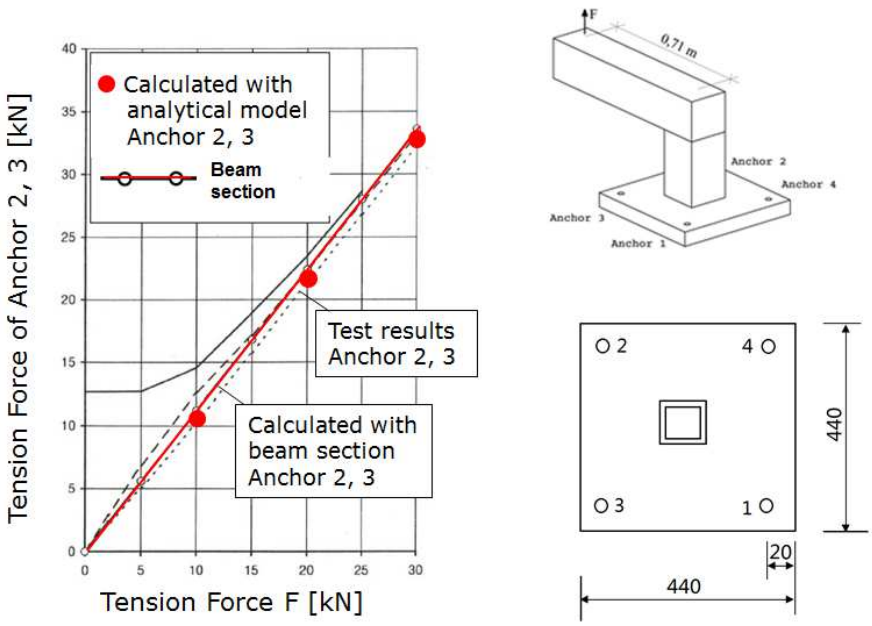


Fig. 2.3-4 Comparison of calculated and tested max. anchor tension force, No 4

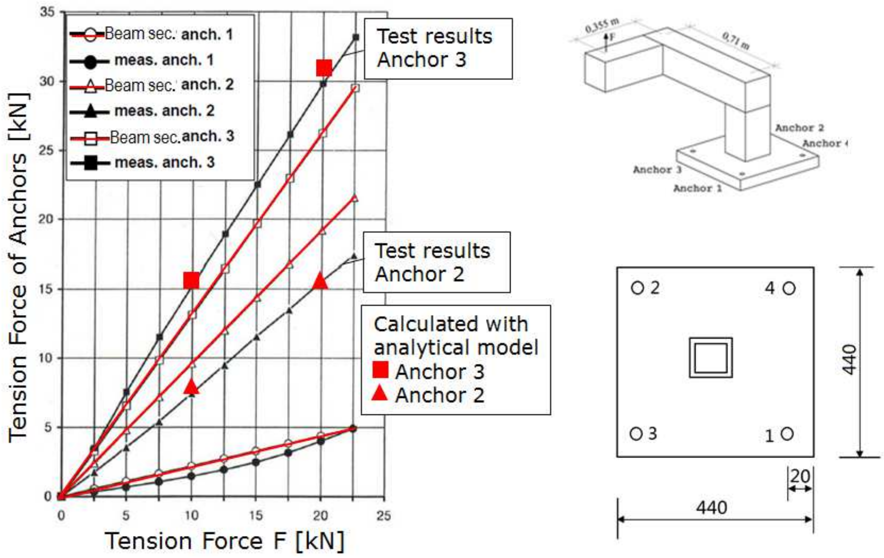


Fig. 2.3-5 Comparison of calculated and tested max. anchor tension force, No 5

The calculated anchor tension force by the plane distribution method agrees well with the tested one shown in figure 2.3-4. But in figure 2.3-5, it underestimates the maximum anchor tension forces by about 12%.

3. Stiffness condition for flexurally rigid baseplate

The results in section 2.3 show that the elastic baseplate model can accurately predict anchor tension force distributions on baseplate. With this in mind, the following stiffness condition for plane distribution method is proposed:

a) The baseplate is treated as elastic under design actions $\sigma_{Ed} \leq \sigma_{Rd} = f_{yk}/\gamma_M$ and
b) Stiffness condition is met if the max. anchor tension forces, $N_{r,\max}$, using plane distribution method and $N_{e,\max}$, using the elastic baseplate method are equal:

$$N_{r,\max} = N_{e,\max}$$

This stiffness condition will be illustrated by two examples. The first example in fig. 3-1

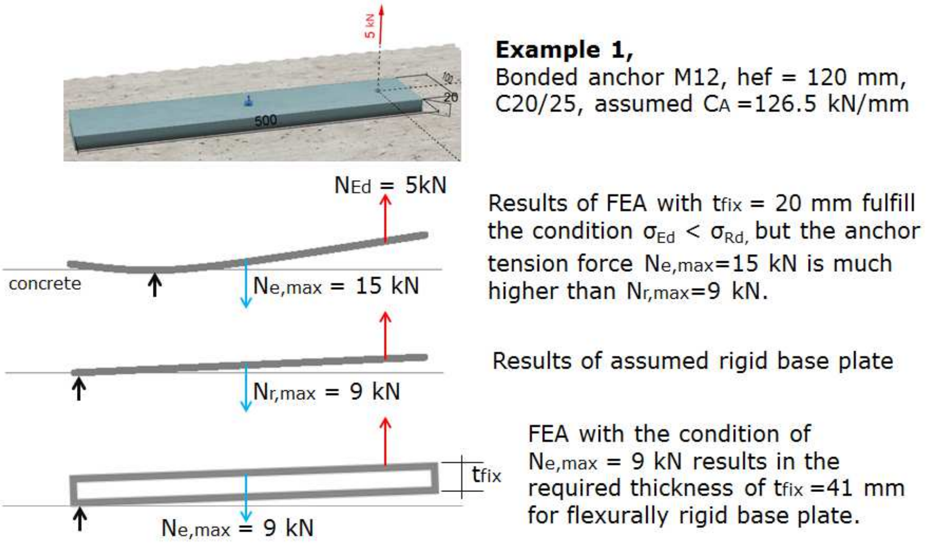


Fig. 3-1 Determination of required thickness of rigid baseplate, Example 1

shows a fastening with baseplate and one bonded anchor with a design load of 5 kN. The max. stress for a 20mm thick plate(S235) fulfills the stress condition σ_{Ed} (186) ≤ σ_{Rd} (f_{yk}/γ_M = 235/1.5 = 214) N/mm². The anchor tension force, $N_{e,\,max}$, from elastic baseplate method is 15 kN, compared with $N_{r,max}$ of 9 kN using plane distribution method. To fulfil the stiffness condition with $N_{e,\,max}$ = 9 kN, the plate thickness has to be increased to 41 mm.

The second example in Fig. 3-2 is a fastening with 2 bonded anchors and a design load of 20 kN. The maximum stress for a 23 mm thick baseplate fulfills the stress condition σ_{Ed} (179) ≤ σ_{Rd} (214) N/mm². The max. anchor tension force is, $N_{e,\,max}$ = 16.8 kN due to prying force, whereas $N_{r,\,max}$ = 10 kN. The thickness has to be increased to 35 mm to fulfil the stiffness condition of $N_{e,\,max}$ = 10 kN.

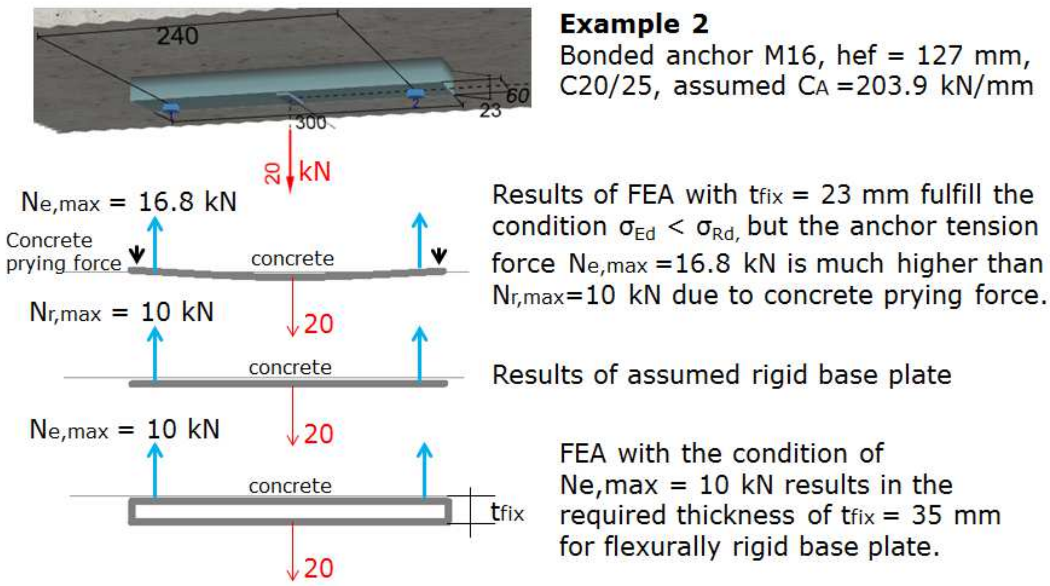
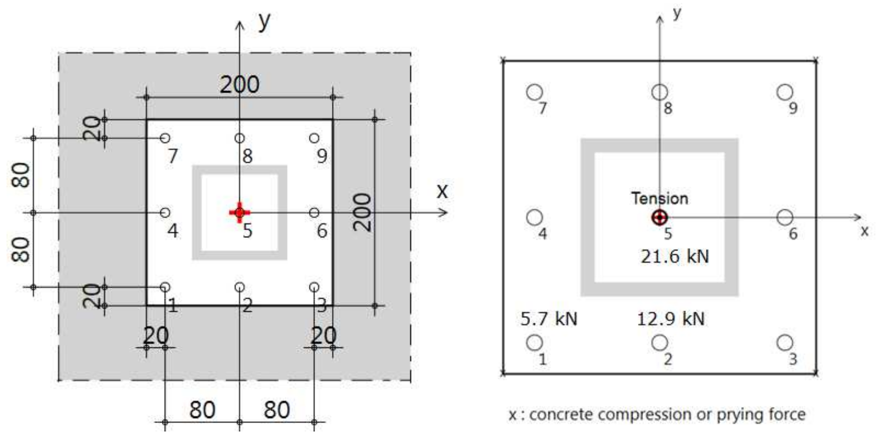


Fig. 3-2 Determination of required thickness of rigid baseplate, Example 2

4. Required additional proof of multiple-anchor resistance with elastic baseplate

The investigation in section 2 shows that the elastic baseplate model can accurately calculate the anchor tension force distribution. A stiffness condition for plane distribution method was then proposed. As shown in Figs. 3-1 and 3-2, this stiffness condition may lead to unrealistic plate thicknesses /13,14/. That means, there are application cases where the plane distribution method cannot be used. In these cases, elastic baseplate model must be used. But the current design method /1/ lacks any provision for the elastic baseplate model /11/. For example, the resistance of the tested 9-anchor group /12/ (fig. 4-1) at concrete cone failure cannot be calculated by /1/ because the reduction factor for non-uniformly distributed anchor tension loads cannot be considered by load eccentricity on anchors.

Therefore additional proof to /1/ is necessary for anchor groups at concrete cone failure if the elastic baseplate is to be used where anchor tension forces are not distributed in a plane. For this additional proof, the use of $\Psi_{ec,N}$ =1,0, $N_{Ed,\,max} \leq N_{Rd,c}/n$, as shown in fig. 4-2 may be proposed conservatively.



$f_{c,150}$ = 43.4 N/mm², h_{ef} =65 mm, t_{fix}=15mm, C_A= 76.1 kN/mm

Fig. 4-1 Calculated anchor tension forces of test /12/ by /8/

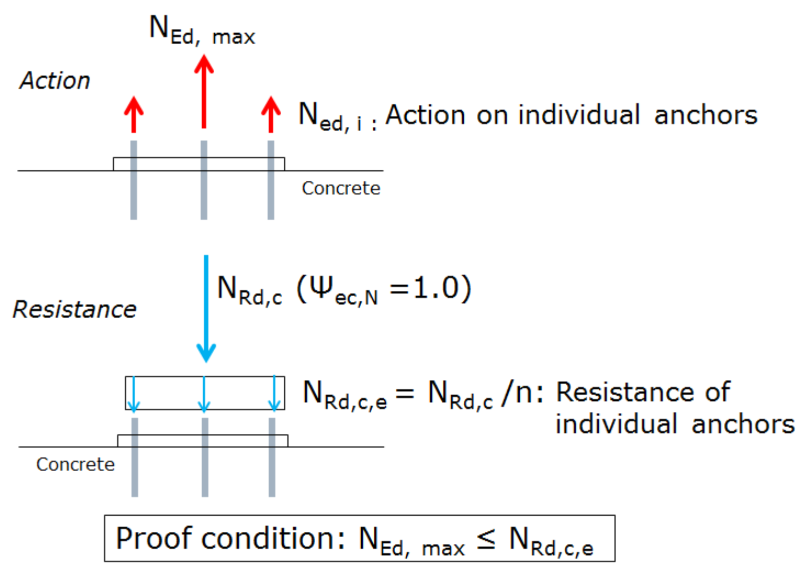


Fig. 4-2 Schematic representation of the additional proof for anchor group with non-plane distribution of anchor tension forces on elastic baseplate

Table 4-1 compares the design resistances N_{Rd} of anchor groups calculated according to the above proposal and those with the tested failure loads N_{Ru} /12/. The calculated minimum safety factor $\gamma_{Mc} = N_{Ru}/N_{Rd}$ =1.6 is higher than the minimum required of 1.5.

Table 4-1 Verification of the proposed additional proof for elastic baseplate

Baseplate stiffness	Concrete cone resistance [kN]		Safety factor	
t_{fix} [mm]	$N_{Rd,}$ calculated	$N_{Ru,}$ tested/12/	N_{Ru}/N_{Rd}	Req. N_{Ru}/N_{Rd}
10	33.1	93	2.8	≥ 1.5
15	43.9	94	2.1	
20	56.3	92	1.6	
Rigid	90.7	-	-	

5. Conclusions

According to prEN1992-4 /1/, the anchor tension forces on baseplate are assumed to have a plane distribution when designing multiple anchor fastenings with baseplate. In order to fulfil this condition, the baseplate has to be sufficiently stiff. Many base plates used in practice may not be stiff (thick) enough to meet this condition.

An elastic baseplate model has been developed, taking into account the plate relative deflection and concrete prying forces. The model can very accurately calculate the anchor tension force distribution with output in good agreement with test results.

A stiffness condition for the plane distribution method has been defined. Baseplate thicknesses were calculated for a number of cases, fulfilling this condition. Results indicate that the required thickness for the plane distribution method to be valid is unrealistic in many cases /13,14/.

An additional proof to /1/ for concrete cone failure is necessary in order to use the elastic baseplate model. The procedure for this additional proof has been proposed and verified with test results. With this additional proof, elastic baseplates could be generally used in the design of multiple anchor fastenings.

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