Dr. Li

General method for calculating the anchor tension loads on a base plate

fib TG 2.9, WP 8
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+ Lotze, Thiele

prepared by Longfei Li

Contributed by
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Content

Dr. Li

Introduction

Draft, Eurocode 2: Design of concrete structures — Part 4: Design of Fastenings for Use in Concrete, CEN/TC 250/SC 2/WG 2, 2014-07-08 prEN 1992-4rev6

6.2 Headed fasteners and post-installed fasteners
6.2.1 Tension loads

(1) The anchor tension loads on a rigid fixture may be calculated assuming a linear distribution of strains using the following assumptions (Figure 6.2):

a) The fixture is sufficiently rigid such that linear strain distribution will be valid (analogous to Bernoulli hypothesis). …

(2) The assumption in a) may be considered to be satisfied if the base plate remains elastic under design actions ($\sigma_{Ed} \leq \sigma_{Rd}$) and its deformation remains negligible in comparison with the axial displacement of the fasteners.

If this requirement for the deformation is not fulfilled the elastic deformation behavior of the fixture has to be taken into account adequately to determine the design value of tension loads acting on each fastener.

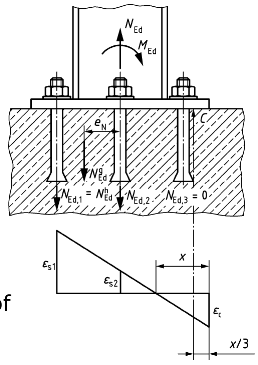

Figure 6.2

of CEN/TC 250/SC 2/WG 2

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Introduction

Translation of the draft regulations to practical equations for defining the rigid base plate

1. Stress condition of base plate under design actions: $\sigma_{Ed} \leq \sigma_{Rd} = f_{yk}/\gamma_M$,
   for example Steel S 235 $\sigma_{Rd} = f_{yk}/\gamma_M = 235/1.1 = 213.6$ N/mm², and
2. δ (base plate) << δ_N (anchor). Deformation of the base plate is much smaller than the anchor displacement.

If the condition 2. is not fulfilled, the anchor tension loads can not be determined by Bernoulli hypothesis (rigid base plate).

Can the practical Engineers calculate the anchor tension loads with above descriptions?

No, not really, because

1. They do not know the axial anchor displacement δ_N. Can the displacements given in the current ETAs or ICC-ER used for the calculation?
2. It is not clear which deformation of base plate should be compared with the anchor displacement.
3. Calculation method for base plate deformation is not defined clearly.

=> More details may be needed for practical purposes.

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Observation of base plate behavior in test 1

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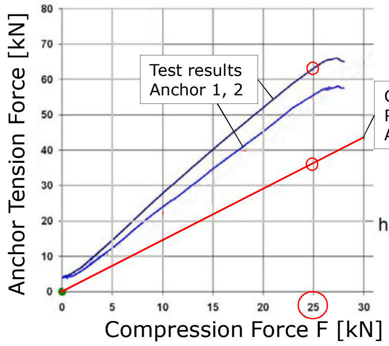
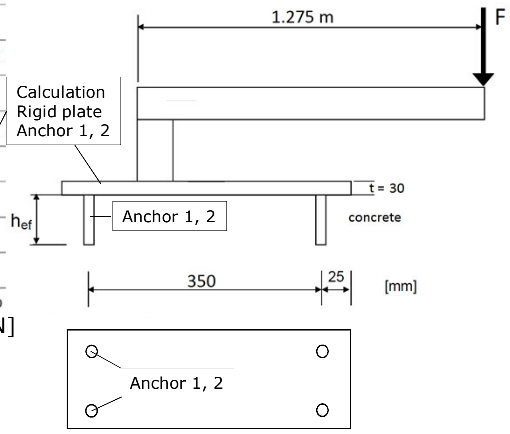
Test 1 , investigated by Fichtner/Eligehausen with bonded anchors





Comparison at F = 25 kN:

$\frac{\text{Tested anchor force}}{\text{Calculated anchor force}}$ = 62.5/36.3=1.72

Test results from the dissertation of Fichtner 2011

Observation of base plate behavior in test 2

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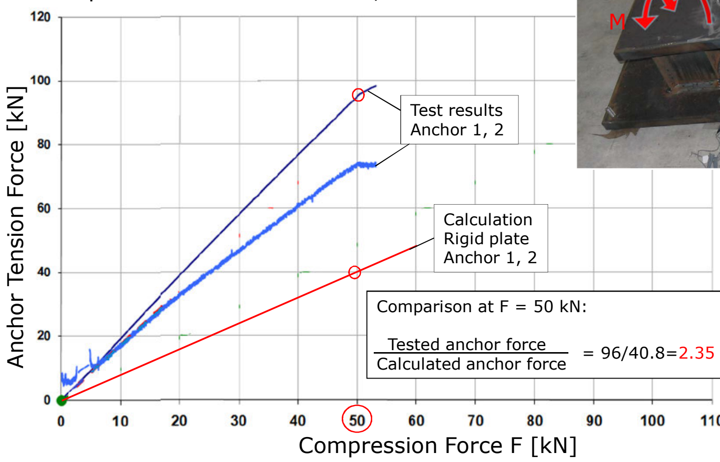
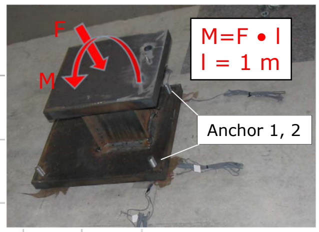
Test 2 , investigated by Fichtner/Eligehausen
Base plate thickness t = 40 mm, bonded anchors





Comparison at F = 50 kN:

$\frac{\text{Tested anchor force}}{\text{Calculated anchor force}}$ = 96/40.8=2.35

Test results and photo from the dissertation of Fichtner 2011

Observation of base plate behavior in test 3

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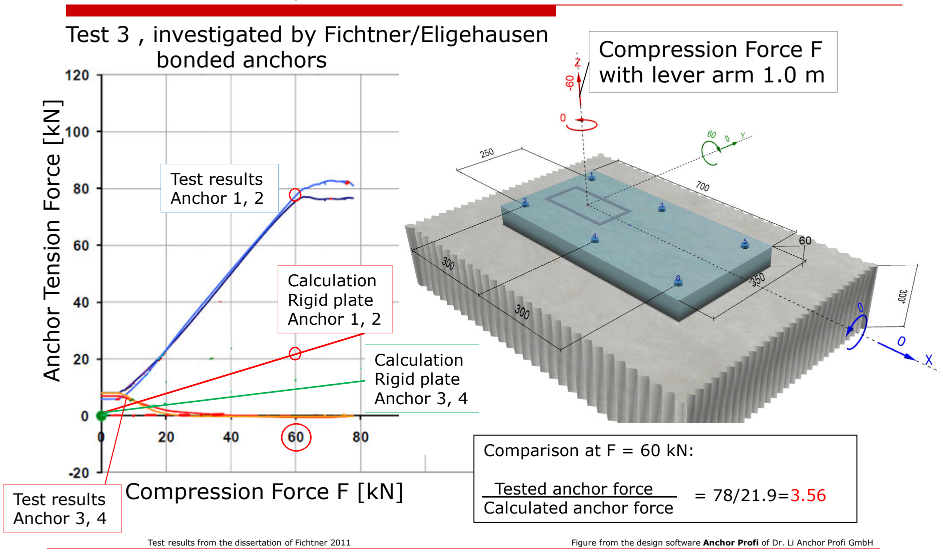

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Questions and Task

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Questions:

1. Why are the real anchor forces much higher than the calculated ones with the assumed rigid plate in the shown examples?
2. How can we calculate the real anchor tension forces on a base plate?
3. In which cases can we calculate the anchor tension force with rigid plate?

Task:

We need a general calculation method to cover general application cases in order to answer these questions.

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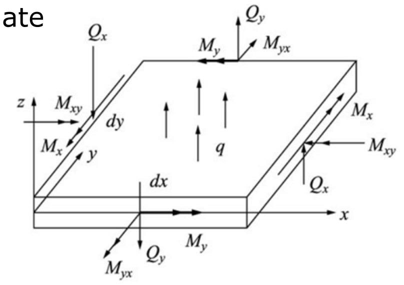
General calculation method

General calculation method FEM (Finite-Element-Method) with the following simple parameters:

1. Anchor Stiffness K under design resistance N_{Rd}
2. Concrete bedding factor C
3. Connect profile on the base plate
4. Base plate thickness t_{fix}



General calculation method Anchor stiffness

Anchor Stiffness k under design resistance may be expressed by

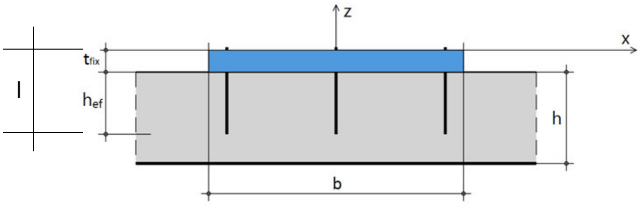
$$K = \alpha \cdot E \cdot A_s / l$$

α: Stiffness factor, depends on anchor type
- α = 1, an ideal rod with fixed one end
- α ≥ 1, bonded anchors due to tension stiffening
- α < 1, expansion anchors due to slip of anchor body

E: Elasticity module, steel E =210,000 N/mm²

A_s: Stressed cross section, for M12 A_s = 84.3 mm²

l: Stressed length, $l = h_{ef} + t_{fix}$



General calculation method

Evaluation of anchor stiffness

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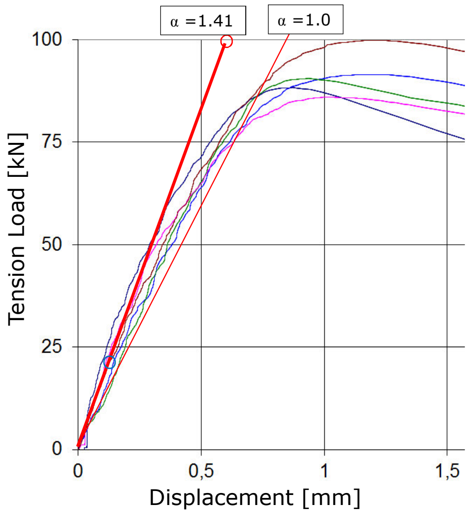

Test results from MKT

Test conditions:
Injection system A, confined tests, uncracked concrete C20/25, M12, h_{ef} = 110 mm, t_{fix} = 40 mm, T_{inst} = 10 Nm

Estimated characteristic load:
N_{Rk} = 35 kN

Design resistance N_{Rd} = 23.3 kN

$\alpha = K_{test} / (E \cdot A_s / l)$

$= (100/0.6)/(210 \cdot 84.3/150)$

$= 166.7/118 = 1.41 > 1.0$

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General calculation method

Evaluation of anchor stiffness

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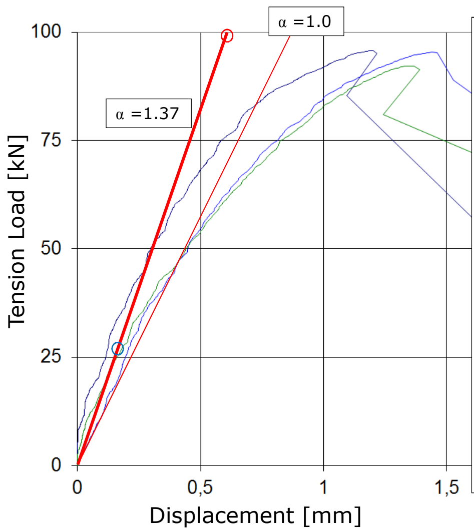

Test results from MKT

Test conditions:
Injection system B, confined tests, uncracked concrete C20/25, M12, h_{ef} = 110 mm, t_{fix} =40 mm, T_{inst} = 10 Nm

Estimated characteristic load:
N_{Rk} = 40 kN

Design resistance N_{Rd} = 26.7 kN

$\alpha = K_{test} / (E \cdot A_s / l)$

$=(100/0.62)/(210 \cdot 84.3/150)$

$=161.3/118 = 1.37 > 1.0$

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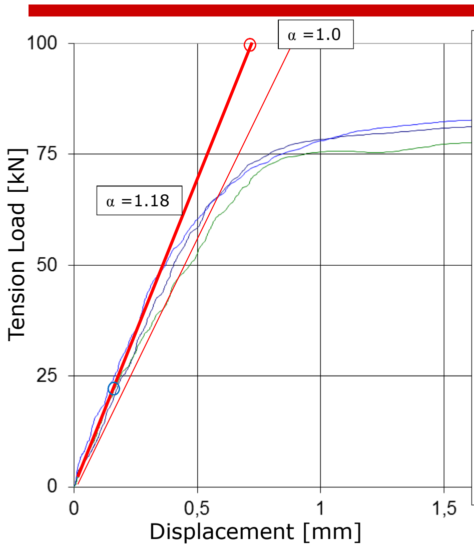
General calculation method Evaluation of anchor stiffness Dr.Li



Test results from MKT

Test conditions:
Injection system C, confined tests, uncracked concrete C20/25, M12, h_{ef} = 110 mm, t_{fix} =40 mm, T_{inst} = 10 Nm

Estimated characteristic load:
N_{Rk} = 35 kN

Design resistance N_{Rd} = 23.3 kN

$\alpha = K_{test} / (E \cdot A_s / l)$

$= (100/0.72)/(210 \cdot 84.3/150)$

$= 138.9/118 = 1.18 > 1.0$

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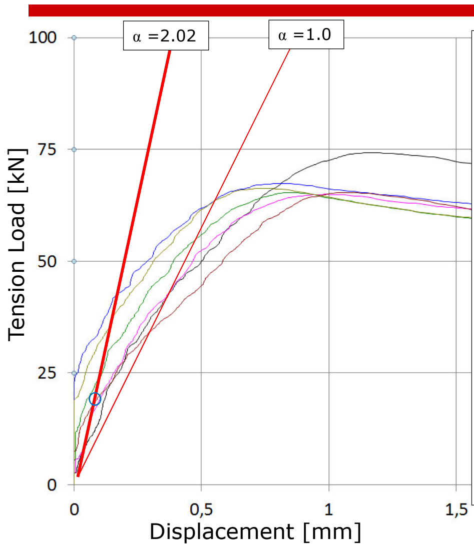
General calculation method Evaluation of anchor stiffness Dr.Li



Test results from MKT

Test conditions:
Injection system D, confined tests, uncracked concrete C20/25, M12, h_{ef} = 110 mm, t_{fix} =40 mm, T_{inst} = 10 Nm

Estimated characteristic load:
N_{Rk} = 30 kN

Design resistance N_{Rd} = 20.0 kN

$\alpha = K_{test} / (E \cdot A_s / l)$

$= (100/0.42)/(210 \cdot 84.3/150)$

$= 238.1/118 = 2.02 > 1.0$

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General calculation method — Evaluation of anchor stiffness

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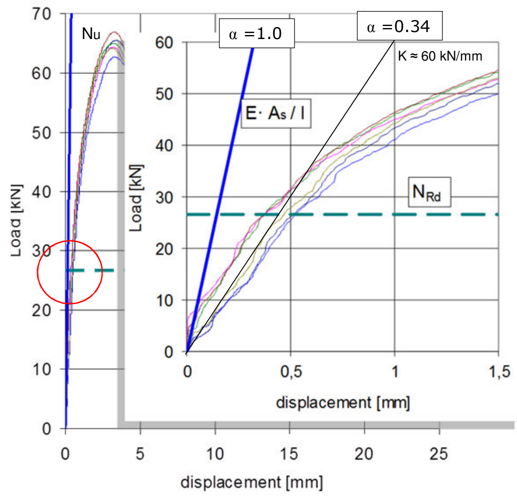

Test results from MKT

Test conditions:
expansion anchor A,
unconfined tests,
uncracked concrete C20/25,
T_{inst} = 0 Nm

$\alpha = K_{test} / (E \cdot A_s / l)$

$= 60/(210 \cdot 84.3/100)$

$= 60/177.1 = 0.34 < 1.0$

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General calculation method — Evaluation of anchor stiffness

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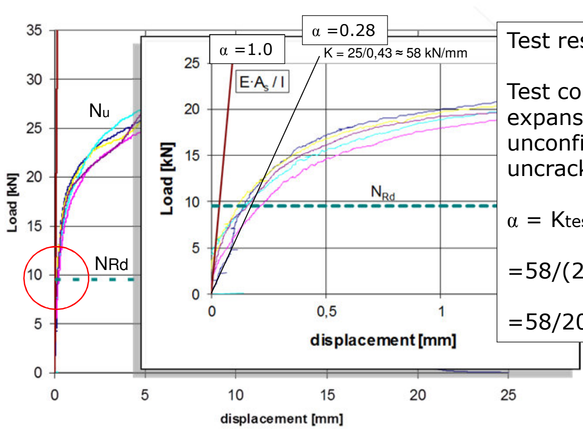

Test results from MKT

Test conditions:
expansion anchor B,
unconfined tests,
uncracked concrete C20/25,

$\alpha = K_{test} / (E \cdot A_s / l)$

$= 58/(210 \cdot 84.3/85)$

$= 58/208.3 = 0.28 < 1.0$

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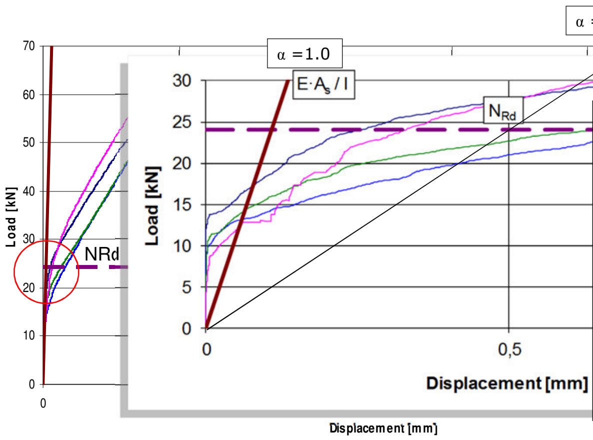
General calculation method — Evaluation of anchor stiffness



Test results from MKT

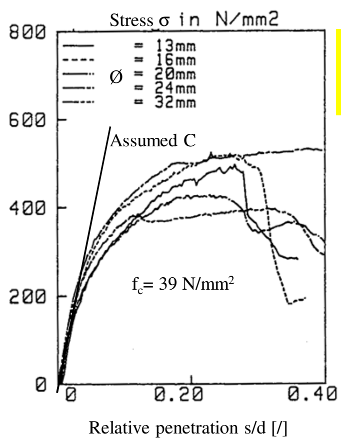
Test conditions:
expansion anchor C,
unconfined tests,
uncracked concrete C20/25,

α = Ktest /(E · As /l)

=48/(210 · 84.3/100)

=48/177.1 =0.27 < 1.0

General calculation method — concrete bedding factor



Load-displacement behavior of concrete exposed to local high compressive stress according to Lieberum 1990

Concrete bedding factor evaluated by test results

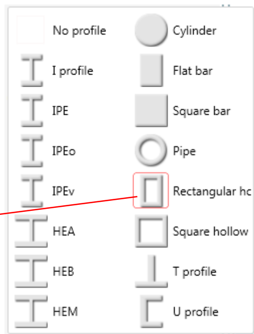
C ≈ 15 · f_c [N/mm³]

(Ø = 13 mm)

For example C20/25

C=15 · 25 = 375 N/mm³

General calculation method connection profile and base plate thickness



Connection profiles

Test 3 , investigated by Fichtner/Eligehausen
Base plate thickness t = 60 mm

Photo from the dissertation of Fichtner 2011

Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

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General calculation method in the software ***Anchor Profi***

In the software ***Anchor Profi*** of Dr. Li Anchor Profi GmbH this calculation method is integrated for research purposes currently. The software is used for the studies of this presentation.

Definitions

For the simplification the following definitions are used in the next presentation.

Flexural method: (or elastic method?)
Finite-Element-Method using real load/deformation behavior of base plate, anchor, concrete and connection profile.

Rigid method:
The base plate is assumed to be rigid such that linear strain distribution can be used for calculating the anchor loads on base plate.

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Comparison of calculation and test 1

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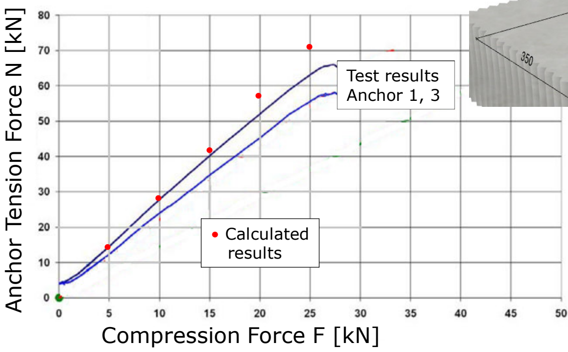
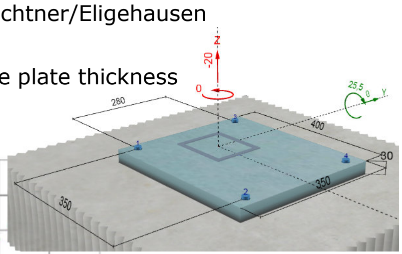
Calculation of Test 1 , investigated by Fichtner/Eligehausen

Parameters of calculation:
α = 1.0, C = 450 N/mm² (C25/30), base plate thickness and connection profile acc. to test





Calculated results

Compression Force F [kN]	Anchor 1, 3 Force N [kN]
5	14.15
10	28.31
15	42.46
20	56.60
25	70.76

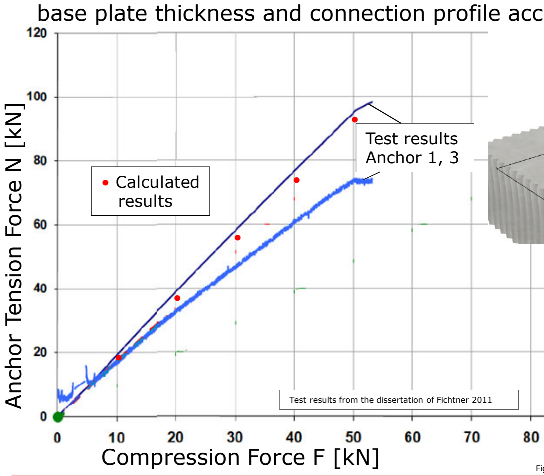
Test results from the dissertation of Fichtner 2011

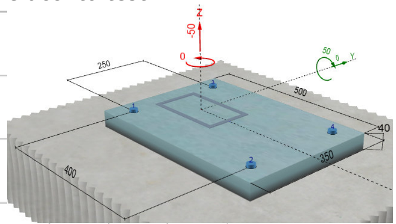
Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

Comparison of calculation and test 2

Dr.Li

Calculation of Test 2 , investigated by Fichtner/Eligehausen
Parameters of calculation: α = 1,0, C = 450 N/mm² (C25/30), base plate thickness and connection profile acc. to test





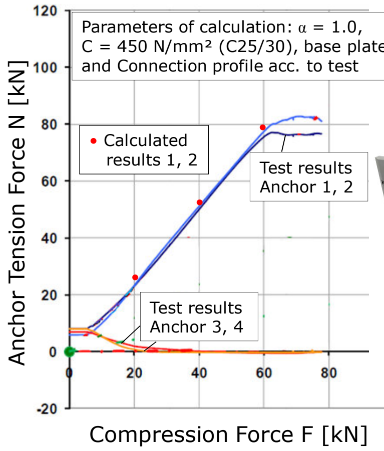
Calculated results

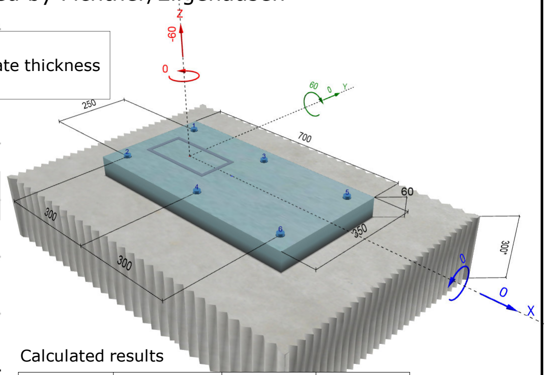
Compression Force F [kN]	Anchor 1, 3 Force N [kN]
10	18,55
20	37,10
30	55,65
40	74,20
50	92,75

Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

Comparison of calculation and test 3

Calculation of Test 3 investigated by Fichtner/Eligehausen





Calculated results

Compression force F [kN]	Anchor 1, 2 force N [kN]	Anchor 3, 4 N [kN]	Anchor 5, 6 N [kN]
20	26.34	0	0.64
40	52.68	0	1.27
60	79.02	0	1.91

Test results from the dissertation of Fichtner 2011

Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

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Discussion of current rigid method

Questions:

Under which conditions can we calculate the fastening of test 3 with rigid base plate?

In which cases may the rigid method be generally applicable?

To clarify the questions the following parameters are studied.

1. For very soft anchors with α =0.2 or 0.05

2. To increase the base plate thickness unlimited

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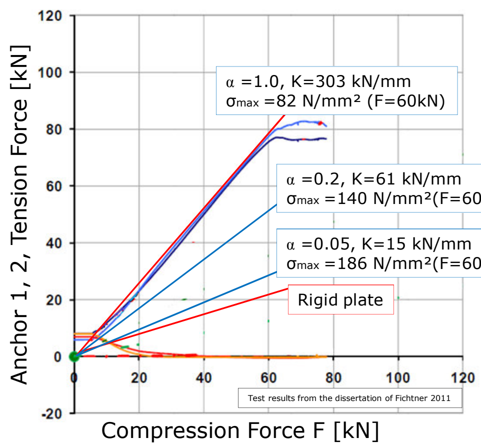
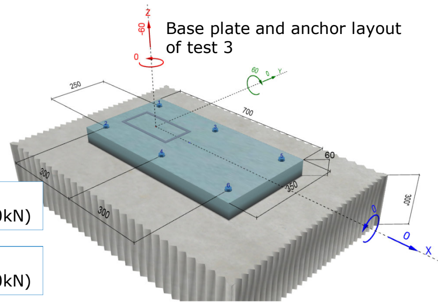
Discussion of current rigid method — Anchor stiffness

Is the rigid method applicable for the fastening of test 3, if soft anchors are used?



Base plate and anchor layout of test 3



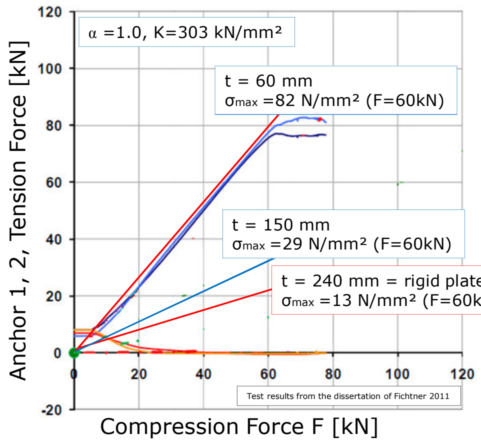
Results:
With the base plate thickness of 60 mm the rigid method is not applicable.

σmax : maximum stress of base plate

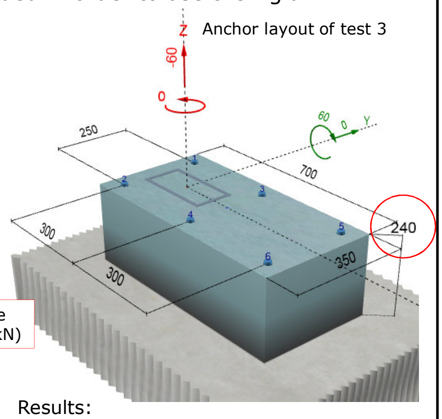
Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

Discussion of current rigid method — Base plate thickness for stiff anchors

Which thickness of the base plate is needed in order to use the rigid method for the fastening of test 3?



Anchor layout of test 3



Results:
For stiff anchors we need a base plate thickness 240 mm in order to use the rigid method.

σmax : maximum stress of base plate

Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

Discussion of current rigid method Base plate thickness for soft anchors

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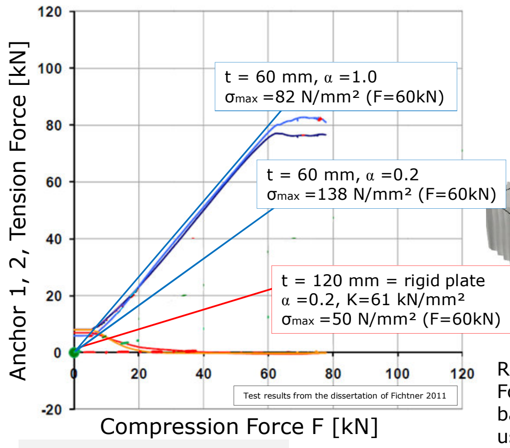
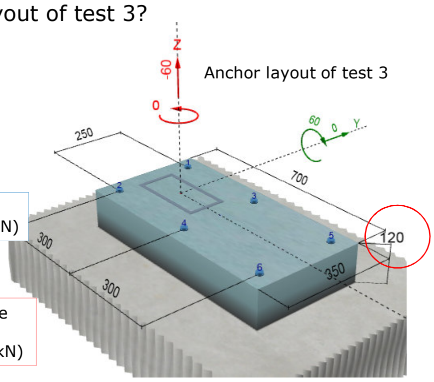
Which thickness of the base plate is needed in order to use the rigid method for soft anchors (α =0.2) with anchor layout of test 3?





Results:
For soft anchors with α = 0.2 we need a base plate thickness 120 mm in order to use the rigid method.

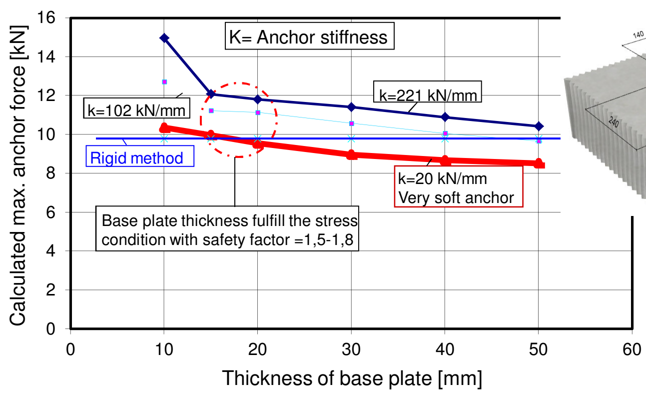
σ_{max} : maximum stress of base plate

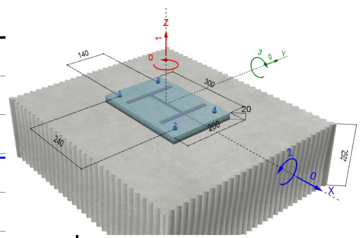
Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

Discussion of current rigid method with practical examples

Dr. Li

In which cases is the rigid method applicable?





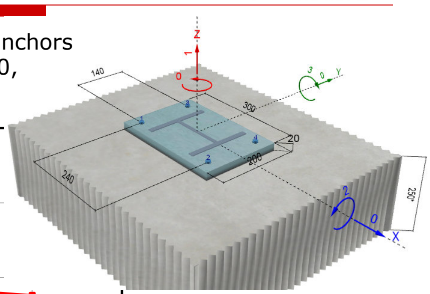
FEM calculations
by Dr. Stork 2012

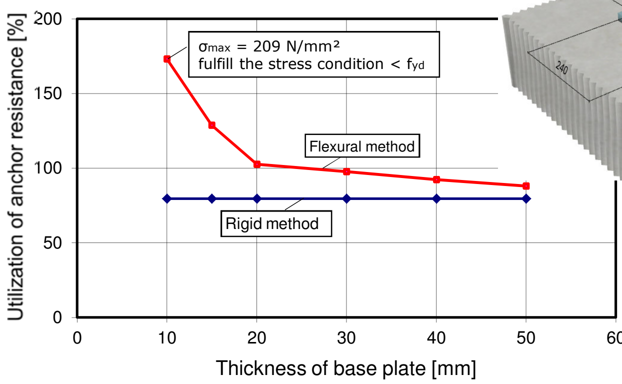
For this example the rigid method may be applicable only for very soft anchors.

Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

Discussion of current rigid method with design examples

Design example with approved bonded anchors
M12, h_{ef} = 70 mm, stiffness factor α =1.0,
K=253 kN/mm²



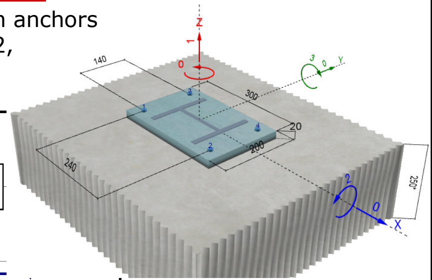


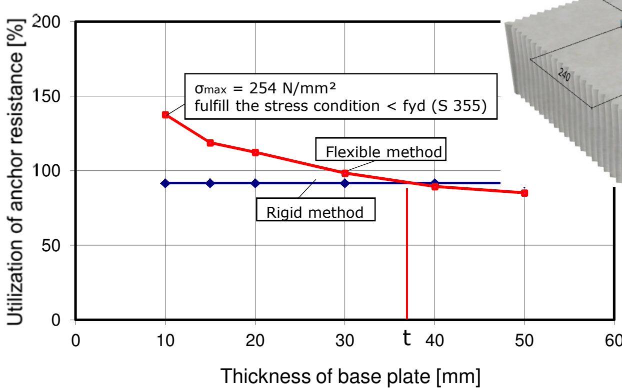
For this example the rigid method may not be suitable.

Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

Discussion of current rigid method with design examples

Design example with approved expansion anchors
M12, h_{ef} = 70 mm, stiffness factor α =0.2,
K=51 kN/mm²





For this example the rigid method may be suitable only for t >35 mm.

Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

Discussion of current rigid method with design examples

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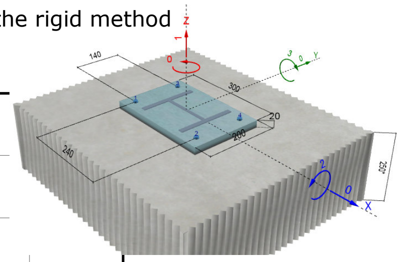
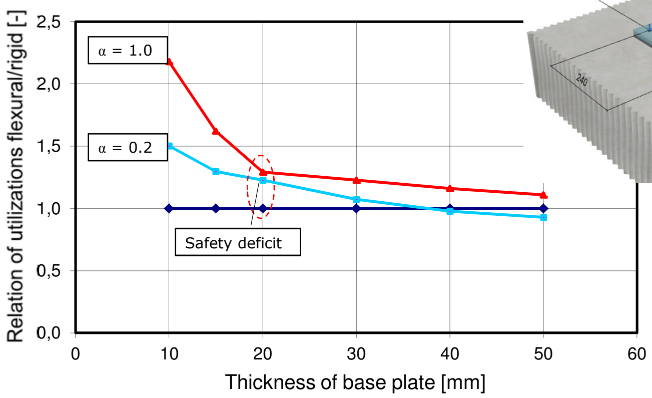
How high may the safety deficit be to use the rigid method in this example?





The safety deficit may amount 30% in this example.

Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

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Discussion of current rigid method with design examples

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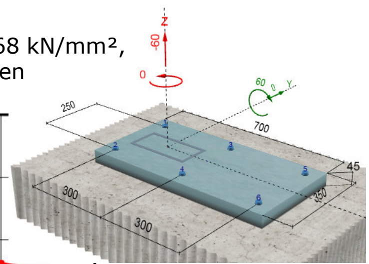
Design example with approved bonded anchors M20, h_{ef} = 140 mm, stiffness factor α =1.0, K=368 kN/mm², anchor layout acc. to test 3 of Fichtner/Eligehausen



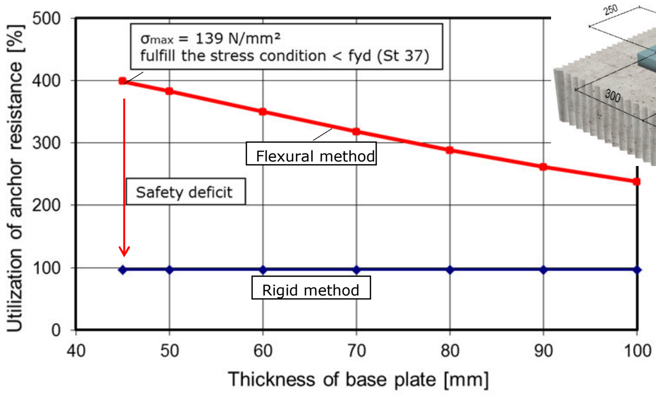


Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

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Discussion of current rigid method design of base plate

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Current situation

The base plate thickness is determined by following stress limit condition

$$\sigma_{sd} \leq f_{yd}$$

with

σ_{sd} : max. stress in base plate induced by design actions N_d, M_{xd} und M_{yd}. This stress depends on the connection profile on the base plate and is generally calculated by means of Finite-Element-Method. The calculated stress peak is averaged in certain range. The average method is currently not regulated.

f_{yd} : $= f_{yk}/\gamma_M$ with γ_M =1.10 according to EC3 for steel structures

Calculation method: not defined uniformly

There are 2 methods in use currently:
1. Quasi rigid method: The base plate thickness is calculated by using the action loads from anchors, concrete and connection profile which are determined by rigid method.
2. Quasi flexural method: The base plate thickness is calculated by using anchor stiffness, concrete bedding factor and connection force from profile.

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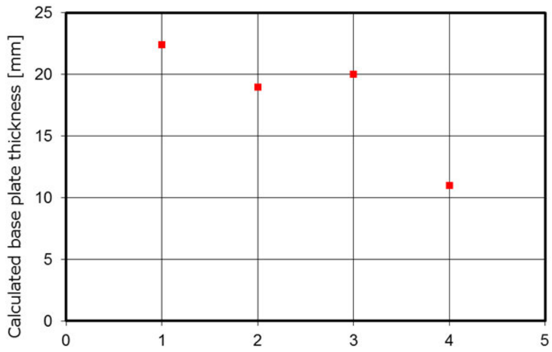
Discussion of current rigid method design of base plate

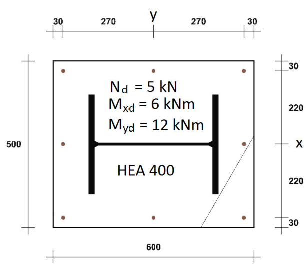
Dr. Li

Current situation

Calculations with different design software offered by anchor manufacturers provide very different base plate thickness for a same anchorage.



No. 1-4: Design programs from anchor manufacturer



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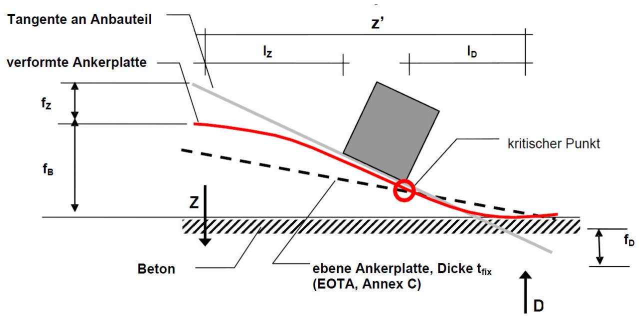
Discussion of current rigid method design of base plate

Design format proposed by Fichtner 2011 for base plate:

$$\sigma_{sd} \leq f_{yd} \quad \text{and} \quad \frac{f_D}{f_B + f_Z} \leq 1{,}0$$



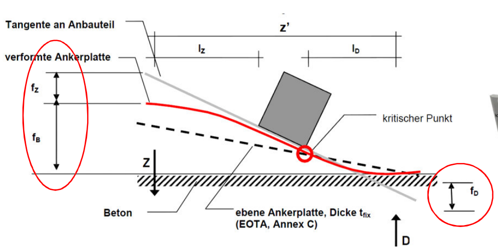
For verification of anchor resistances the rigid method is used to calculate the anchor tension loads.

Figure from the dissertation of Fichtner 2011

Discussion of current rigid method design proposal of Fichtner

Open questions of the Fichtner design proposal:

1. How can the displacements f_D, f_Z and f_B be calculated in general cases?
2. Which base plate thickness would be required for the test 3 acc. to the proposal as example?



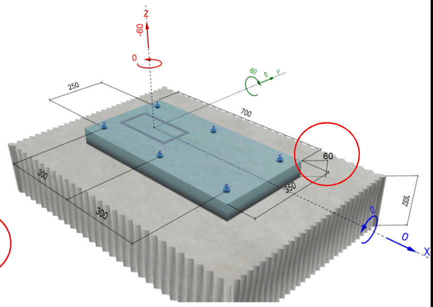


Figure from the dissertation of Fichtner 2011

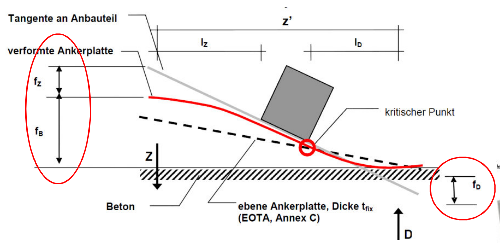
Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

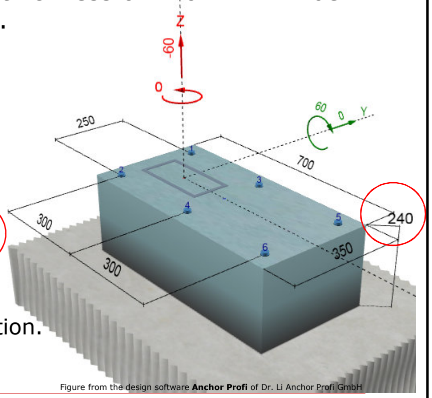
Discussion of current rigid method design proposal of Fichtner

Dr.Li

Possible answers of the questions:

1. The displacements f_D, f_Z and f_B may be calculated by FEM method in general cases.
2. With high probability a base plate thickness of 240 mm will be required for the test 3 as example.





Results:

1. The proposal does not simplify the calculation.
2. The proposal may not be economical.

Figure from the dissertation of Fichtner 2011

Figure from the design software **Anchor Profi** of Dr. Li Anchor Profi GmbH

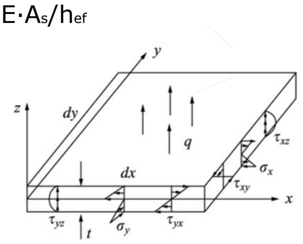
New proposal

Dr.Li

Flexural method with following parameters

1. Anchor stiffness factor α, with K= α · E·A_s/h_{ef}

   α =0.2 for design of base plate
   α =1.0 for design of anchors



2. Concrete bedding factor C

   C =15 · $f_{c,\ cube}$

3. Geometry of connection profile

   Connection forces on base plate may be determined by Bernoulli hypothesis.

4. Base plate thickness with stress condition

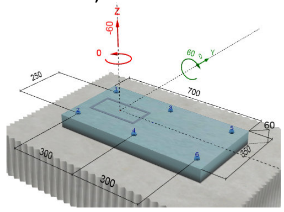
   $\sigma_{sd} \leq f_{yd}$ $f_{yd} = f_{yk}/\gamma_M$ with γ_M =1.5

New proposal

practical tests of the new proposal

Dr.Li

The new proposal is implemented in the software ***Anchor Profi*** and tested by calculations with the anchor group of the Fichtner test 3 under design load F=60 kN. The practical anchors M20, Injection system Epoxy with ETA, are used for the calculation.



The design examples show that the new proposal is easy to use.

Calculation results acc. to the new proposal

				Software ***Anchor Profi***				Anchor manufacturer: Software 2	Anchor manufacturer: Software 3
				flexural method		Rigid method		Rigid method	Rigid method
Product with European Technical Approval (ETA)				A	B	A	B	A	B
Anchor stiffness factor	α			0.2					
Required base plate thickness under condition $\sigma_{max} < f_{yk}/\gamma_M$	t	mm	$\gamma_M = 1.5$	60	60	71	71		75
			$\gamma_M = 1.1$			60	60	61	64
Anchor stiffness factor	α			1.0					
Anchorage depth	h_{ef}	mm		100	100	100	100	100	100
Utilization of anchor resistance		%		262.2	366.8	64.9	90.8	66	92
Anchor stiffness factor	α			1.0					
Anchorage depth	h_{ef}	mm		210	210	210	210	210	210
Utilization of anchor resistance		%		98.7	138.2	31.9	44.6	32.5	46

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Summary

Dr.Li

1. The Rigid method appears to be an approximation for very soft anchors, for example some mechanical anchors.
2. Test results show that the bonded anchors have a high stiffness. Under design load the stiffness factor of bonded anchors is lager than 1.0 due to the tension stiffening of bond around the anchor body.
3. For calculation of real anchor loads on base plate the flexural method based on FEM may be used to cover general application cases.
4. The flexural method can be defined with simple parameters. The calculation results of the flexural method agree well with test results.
5. The real anchor loads on base plate calculated by flexural method can be used for verification of anchor resistance to avoid the safety deficit caused by rigid method.

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