Calculation and design of fastenings loaded in shear

J. Hofmann

Why research on shear loading?

1. Check if the influence parameters of anchor groups are considered in a correct way (e.g., corner distance, anchor spacing, ...).
2. Behavior of single anchors and anchor groups under arbitrary loading direction.
3. Behavior of anchor groups under arbitrary loading direction with eccentricity.

Part 1

\[
V_{\text{nom}} = 0.9 \cdot \frac{d_{\text{nom}}^2}{c} \cdot f_{\text{c}} \cdot \frac{d_{\text{nom}}}{1.5} \cdot \frac{1}{\cos(\alpha)} \cdot \sin(\alpha) 
\]

Part 2

\[
V_{\text{nom}} = \frac{A_{\text{nom}}}{A_{\text{sec}}} \cdot \psi \cdot \frac{V_{\text{nom}}}{V_{\text{sec}}}
\]

Part 3

\[
\psi = \frac{1}{\ln(c) - 0.5 \cdot \ln(c)}
\]

Part 4

\[
\psi_{\text{sec}} = \frac{1}{1 + 2e / h}
\]

Investigations

* Tests: 310 tests + 160 tests (Rössle/Huber 1999)
* FE - calculations: 400 FE - calculations (≈ 1200 tests)
* Investigations with a model based on fracture mechanics

Used test setup for the experimental investigations

* Bonded anchors: threaded bar (steel 8.8 or 10.9), bonded agent based on resin
* Normal strength concrete (25 N/mm²), drill hole cleaning according to ETAG
* Torque moment of 60 Nm

Test setup:
* Hydraulic jack (200 kN), fixing floor, back restraint, measurement (LDTV's, strain gauges)

Used Finite Element model for the investigations

Modelled details:
- Clearance
- Teflon Layer
- Screw nut
- Tension bar
- Anchor plate
- Mortar

Simulation of the anchor and the mortar

Comparison of tests and numerical simulations

- Good prediction of the failure loads
- Good agreement between calculated crack pattern and the crack pattern observed in the tests
Comparison of tests and investigations with model based on fracture mechanics

- Good prediction of the failure loads
- Good agreement between calculated crack pattern and the crack pattern observed in the tests

Basic concept of the improved CC - method

Design loads: Resistances:

\[
\begin{align*}
V_{R_{k0^\circ}} & \quad V_{R_{k90^\circ}} & \quad V_{R_{k180^\circ}} & \quad V_{R_{k270^\circ}} \\
M_{R_{k}} & \quad ?
\end{align*}
\]

Interaction between the decisive loads

\[
\left( \frac{F_{C} \cos(\alpha)}{F_{R_{k0^\circ}} \cdot (1 - M_{J}/M_{A})} \right)^{2} + \left( \frac{F_{C} \sin(\alpha)}{F_{R_{k180^\circ}} \cdot (1 - M_{J}/M_{A})} \right)^{2} \leq 1.0
\]

Necessary characteristic resistances:

- Load based on fracture mechanics [kN]
- Load tests [kN]

A: Single anchors

- Single anchors
- Two anchors
- Four anchors

With and without hole clearance

\[
V_{R_{k0^\circ}} - V_{R_{k90^\circ}} - V_{R_{k180^\circ}} - V_{R_{k270^\circ}} - M_{R_{k}}
\]

A: Influence of load transfer mechanism of the anchor (single anchor)

- Load transfer mechanism has nearly no influence on the shear load capacity
- Test are performed with bonded anchors because of more flexibility

A: Influence of hole clearance (single anchor)

- Flexible: more realistic for post installed anchors with small failure displacements
- Stiff: more realistic for post installed anchors with large failure displacements and cast in place anchors

Most tests were performed with a clearance according to ETAG (2mm), therefore the anchors were partly restraint
A: Influence of embedment depth (single anchor)

- Influence of embedment depth is dependent on the ratio $h_{ef} / d_{nom}$
- Influence of the bolt diameter is dependent on the ratio $c_1 / d_{nom}$
- Influence of the embedment depth is dependent on the ratio $c_1 / d_{nom}$

A: Summary (single anchor)

- Single anchor loaded orthogonal to the edge
- Influence of the bolt diameter is dependent on the ratio $h_{ef} / d_{nom}$
- Influence of the embedment depth is dependent on the ratio $c_1 / d_{nom}$

**Coeficient of variation is reduced to 15%**

**The influence parameters are considered in accurate way**
A: Anchors loaded parallel to the edge (single anchor)

- Single anchor

- CC-method

- FE-calculations

Failure load for single anchors loaded orthogonal to the edge

\[ V_{uc} = A_{ef} / \beta, \psi \]

A: Anchors loaded parallel to the edge (single anchor)

- Single anchor

- CC-method

- FE-calculations

Failure load for single anchors loaded parallel to the edge

\[ V_{uc} = A_{ef} / \beta, \psi \]

A: Comparison with test results and FE-calculations (single anchor)

- Single anchor in the corner

Furche/Eligehausen

Tests DeVries (Blow out)

Tests Asmus (FEPII with headed studs)

A: Calculation of the characteristic resistances (single anchor)

- Single anchor at the edge

- Single anchor in the corner

\[ V_{fz} = \alpha \left( \frac{d}{f_{y}} \right)^{0.5} \]

\[ V_{fuc} = \psi \left( \frac{d}{f_{y}} \right)^{0.5} \]

Factor \( \psi \) is considered in an accurate way
A: Modification of the CC – method (single anchor)

CC-method: Modified CC-method:

Characteristic resistance of a single anchor at the corner

\[ V_{\text{c,0°},\text{cr}} = \frac{A_j}{d_{\text{nom}}} \psi \psi V_{\text{c,0°}} \]

with: \( \psi = 0.5 \)

Characteristic resistance for the load directions 0°, 90°, 180° and 270°

\[ V_{\text{c,0°},\text{cr}} = \frac{A_j}{d_{\text{nom}}} \psi \psi V_{\text{c,0°}} \]

with: \( \psi = 0.5 \)

\[ V_{\text{c,90°},\text{cr}} = \frac{A_j}{d_{\text{nom}}} \psi \psi V_{\text{c,90°}} \]

with: \( \psi = 0.5 \)

\[ V_{\text{c,180°},\text{cr}} = \frac{A_j}{d_{\text{nom}}} \psi \psi V_{\text{c,180°}} \]

with: \( \psi = 0.5 \)

\[ V_{\text{c,270°},\text{cr}} = \frac{A_j}{d_{\text{nom}}} \psi \psi V_{\text{c,270°}} \]

with: \( \psi = 0.5 \)

Characteristic resistance of a single anchor at the edge

\[ V_{\text{c,0°},\text{cr}} = \frac{A_j}{d_{\text{nom}}} \psi \psi V_{\text{c,0°}} \]

with: \( \psi = 0.5 \)

Interaction

\[ V_{\text{p,0°},\text{cr}} = \frac{A_j}{d_{\text{nom}}} \psi \psi V_{\text{p,0°}} \]

with: \( \psi = 0.5 \)

\[ V_{\text{p,90°},\text{cr}} = \frac{A_j}{d_{\text{nom}}} \psi \psi V_{\text{p,90°}} \]

with: \( \psi = 0.5 \)

\[ V_{\text{p,180°},\text{cr}} = \frac{A_j}{d_{\text{nom}}} \psi \psi V_{\text{p,180°}} \]

with: \( \psi = 0.5 \)

\[ V_{\text{p,270°},\text{cr}} = \frac{A_j}{d_{\text{nom}}} \psi \psi V_{\text{p,270°}} \]

with: \( \psi = 0.5 \)

A: New influence parameters (single anchor)

Influence of the factor \( \psi_c \)

Influence of the embedment depth

Influence of the bolt diameter

Influence of the factor \( c_1 \)

A: Comparison of the CC-method with the modified CC-method

Higher loads for small edge distances and small bolt diameters

Lower loads for big edge distances and big bolt diameters
A: Comparison of the CC- method with the modified CC- method

- Higher loads for small edge distances and small bolt diameters
- Lower loads for big edge distances and big bolt diameters

B: Two anchors

- Influence of anchor spacing and corner distance (two anchors)

B: Anchor groups - influence of anchor spacing $s_1$

- Parametric study with the model based on fracture mechanics

For $s_1 > 0.85 c_1$, the front anchors have no influence on the failure load of the back anchor
Failure is visible only starting from the back anchor. Failure is visible from the front anchor.

For small anchor spacing $s_1$ the crack growth will be delayed.

B: Anchor groups - influence of anchor spacing $s_1$ (no hole clearance)

- For $s_1 > 0.5 c_1$, the front anchors have no influence on the failure load of the back anchor.
- For $V_{u,back} < 2.0 V_{u,front}$ ($s_1 < 0.5 c_1$), no crack will occur from the front anchor.
- For $V_{u,back} > 2.5 V_{u,front}$ ($s_1 > 0.85 c_1$), failure crack maybe visible at the front anchor.

Failure load for grouped anchor loaded orthogonal to the edge.

Pressure is reduced to $1/n$:

$$V_{u,front} = V_{u,test} / n$$

$$V_{u,back} = V_{u,test} / n$$

$$k_i = 20$$

Failure load for grouped anchor loaded orthogonal to the edge:

$$V_{u,front} = V_{u,test} - V_{u,front}$$

with $V_{u,test} = 20$ and $V_{u,front} = 4.0$.
B: Comparison with test results and FE - calculations

\[ \psi_90 \text{ is considered in an accurate way} \]

\[ \begin{align*}
\psi_90 = 2.0 & \quad d = 16 \text{ mm} \\
hef = 130 \text{ mm} & \quad d = 24 \text{ mm} \\
hef = 130 \text{ mm}
\end{align*} \]

B: Load distribution for grouped anchors without hole clearance

Load distribution: Decisive loads distribution

Before relocation:

Decisive loads distribution

After relocation:

B: Load distribution for grouped anchors with hole clearance

Load distribution: Decisive loads distribution

Before relocation:

Decisive loads distribution

After relocation:

B: Interaction for arbitrary loading direction

\[ \left( \frac{V_\theta \cdot \cos(\alpha)}{V_{\theta/90}} \right)^2 + \left( \frac{V_\theta \cdot \sin(\alpha)}{V_{\theta/90}} \right)^2 \leq 1.0 \]

B: Calculation of the characteristic resistances

Two anchors at the edge

Two anchors in the corner

B: Modification of the CC - method

Modified CC- method:

Characteristic resistance for two anchors at the corner

\[ V_{90,0} = A_{90,0} / A_{70,0,90} \cdot \psi_90 \cdot V_{90,0} \]

\[ V_{0,90} = A_{0,90} / A_{70,0,90} \cdot \psi_{90} \cdot V_{0,90} \]

Characteristic resistance for the load directions 0°, 30°, 180° and 270°

\[ \begin{align*}
V_{0,0} &= \psi_0 \cdot V_{0,0} \\
V_{0,30} &= \psi_{30} \cdot V_{0,0} \\
V_{0,180} &= \psi_{180} \cdot V_{0,0} \\
V_{0,270} &= \psi_{270} \cdot V_{0,0}
\end{align*} \]

with: \( \psi_0 = 2 \)
B: Modification of the CC-method

CC-method: Modified CC-method:

Characteristic resistance of two anchors under arbitrary loading direction

\[
\begin{align*}
\frac{V_u \cos(\alpha)}{V_{u,c}} + \frac{V_u \sin(\alpha)}{V_{u,\psi}} &\leq 1.0, \\
\frac{V_u \cos(\alpha)}{V_{u,c}} + \frac{V_u \sin(\alpha)}{V_{u,\psi}} &\leq 1.0,
\end{align*}
\]

with: \( \psi = 2 \)

with: \( \psi = 20 \)

\[
\begin{align*}
\frac{V_u \cos(\alpha)}{V_{u,c}} + \frac{V_u \sin(\alpha)}{V_{u,\psi}} &\leq 1.0, \\
\frac{V_u \cos(\alpha)}{V_{u,c}} + \frac{V_u \sin(\alpha)}{V_{u,\psi}} &\leq 1.0,
\end{align*}
\]

B: Comparison with the test results

Influence of anchor spacing is considered in accurate way

B: Influence of a torque moment (Tests)

Tests with bonded anchors (R. Malleé)

Anchor spacing has nearly no influence on the failure load

B: Calculation of characteristic moment

Numerical simulations with bonded anchors (Rüdinger / Hofmann)

Numerical simulations compare well with the test results

Anchor spacing has nearly no influence on the failure load

Reduction of the resistance of a single anchor placed in a corner
B: Modification of the CC-method

Characteristic resistance for eccentric loading:
\[ V_{Rk,c} = \frac{1}{1 + \psi} V_{Rk} - \frac{1}{2} M_{k,c} \]

\[ M_{k,c} = 0.5 \left( V_{Rk,c} \right)^2 - \frac{V_{Rk,c}}{2} \]

CC-method: Modified CC-method:
\[ V_{Rk,c} = V_{Rk} - \frac{1}{2} M_{k,c} \]

\[ M_{k,c} = 0.5 \left( V_{Rk,c} \right)^2 - \frac{V_{Rk,c}}{2} \]

C: Four anchors

Four anchors at the edge
\[ V_{Rk} = \max \left( \frac{V_{Rk,1}}{V_{Rk,1}}, \frac{V_{Rk,2}}{V_{Rk,2}} \right) \]
\[ V_{Rk} = \max \left( \frac{V_{Rk,1}}{V_{Rk,1}}, \frac{V_{Rk,2}}{V_{Rk,2}} \right) \]

Four anchors in the corner
\[ V_{Rk} = \max \left( \frac{V_{Rk,1}}{V_{Rk,1}}, \frac{V_{Rk,2}}{V_{Rk,2}} \right) \]
\[ V_{Rk} = \max \left( \frac{V_{Rk,1}}{V_{Rk,1}}, \frac{V_{Rk,2}}{V_{Rk,2}} \right) \]

C: Load distribution for grouped anchors without hole clearance

Load distribution: Decisive load distribution before relocation:
\[ V_{sd} = V_{sd,0} \]

Decisive load distribution after relocation:
\[ V_{sd} = V_{sd,0} \]

\[ V_{sd} = V_{sd,0} \]

C: Load distribution for grouped anchors with hole clearance

Load distribution: Decisive load distribution before relocation:
\[ V_{sd} = V_{sd,0} \]

Decisive load distribution after relocation:
\[ V_{sd} = V_{sd,0} \]

C: Interaction for arbitrary loading direction

Interaction between the decisive loads:
\[ \left( \frac{V_{sd} \cos(\alpha)}{V_{sd,0}} \right)^2 + \left( \frac{V_{sd} \sin(\alpha)}{V_{sd,0}} \right)^2 \leq 1.0 \]
C: Modification of the CC-method

**CC-method:**

Characteristic resistance of two anchors at the corner

\[ V_{\alpha,cc} = V_{\alpha,cc}^F / \psi_{\alpha} \cdot V_{\alpha,cc}^R \]

Characteristic resistance for the load directions 0°, 90°, 180° and 270°

\[ V_{\alpha,cc} = V_{\alpha,cc}^F / \psi_{\alpha} \]

with: \( \psi_{\alpha} = 2 \)

\[ \psi_{\alpha} \leq \left( \frac{V_{\alpha,cc}^F}{V_{\alpha,cc}^R} \right)^{1/2} \]

with: \( \psi_{\alpha} = 20 \)

\[ \psi_{\alpha} = \frac{V_{\alpha,cc}^F}{V_{\alpha,cc}^R} \]

C: Modification of the CC-method

**CC-method:**

Characteristic resistance of two anchors under arbitrary loading direction

\[ V_{\alpha,cc} = V_{\alpha,cc}^F / \psi_{\alpha} \cdot V_{\alpha,cc}^R \]

\[ \psi_{\alpha} \leq \left( \frac{V_{\alpha,cc}^F}{V_{\alpha,cc}^R} \right)^{1/2} \]

\[ \psi_{\alpha} = 20 \]

C: Comparison with the test results

Influence of anchor spacing is considered in accurate way

- **CC-method**
  - Load direction: 0°
  - Anchor spacing: 10 mm
  - Load ratio: 1.0

- **modified CC-method**
  - Load direction: 0°
  - Anchor spacing: 10 mm
  - Load ratio: 1.0

Influence of load direction is considered in accurate way

- **CC-method**
  - Anchor spacing: 10 mm
  - Load ratio: 1.0

- **modified CC-method**
  - Anchor spacing: 10 mm
  - Load ratio: 1.0

C: Calculation of the characteristic moment without hole clearance

Four anchors at the edge

\[ M_{\alpha,F} = V_{\alpha,cc}^F \cdot \psi_{\alpha} \cdot \left( s_1^2 + s_2^2 \right) \]

with: \( \psi_{\alpha} = \left( \frac{s_1^2 + (s_2 - s_1)^2}{s_1^2} \right) \)

- \( s_1 \to 0 \) mm: \( M_{\alpha,F} = V_{\alpha,cc}^F \cdot s_1^2 \)
- \( s_2 \to 0 \) mm: \( M_{\alpha,F} = V_{\alpha,cc}^F \cdot s_2^2 \)

Four anchors in the corner

\[ M_{\alpha,F} = \min \left( M_{\alpha,F}^{cc}, \psi_{\alpha,R} \cdot M_{\alpha,F}^{cc} \right) \]

with: \( \psi_{\alpha,R} = \frac{0.5 \cdot c_1 + c_2}{s_1} \cdot \psi_{\alpha} \)
C: Calculation of the characteristic moment with hole clearance

Four anchors at the edge

\[ M_{c,4} = \min \left( M_{c,4} \left( t_i = 0 \right) \right) \]

\[ M_{c,4} = \prod_{i=1}^{4} \psi_{i,\alpha} \left( x_i + s_i \right) \]

with \( \psi_{i,\alpha} = \left( \frac{\alpha_i + \alpha_j}{\alpha_i} \right) \)

Four anchors in the corner

\[ M_{c,4} = \min \left( M_{c,4} \left( t_i = 0 \right) \right) \]

\[ M_{c,4} = \prod_{i=1}^{4} \psi_{i,\alpha} \left( x_i + s_i \right) \]

with \( \psi_{i,\alpha} = \left( \frac{\alpha_i + \alpha_j}{\alpha_i} \right) \)

Summary

A: Single anchor
- Influence of the bolt diameter is dependent on the ratio \( h_d / d_m \).
- Influence of the embedment depth is dependent on the ratio \( c_1 / d_m \).

B: Grouped anchors
- Influence of the corner distance \( c_2 \) and anchor spacing \( s_1 / s_2 \) is considered in a realistic way.
  - For \( s_1 > 0.85 c_1 \), the front anchors have no influence on the failure load of the back anchor.
  - For \( s_1 < 0.5 c_1 \), no crack is visible at the front anchor, so failure is visible only starting from the back anchor.
  - For \( s_1 > 0.5 c_1 \), failure crack maybe visible at the front anchor.

C: Modification of the CC-method

\[ V_{u,calc} = \frac{1}{M_{s,4}} \left( V_{u,calc} - V_{s,4} \right) \]

Without hole clearance

\[ M_{s,4} = 0.5 \left( V_{u,calc} \psi_{i,\alpha} \right) \left( x_i + s_i \right) \]

With hole clearance

\[ M_{s,4} = \min \left( M_{s,4} \left( t_i = 0 \right) \right) \]

Influence of load direction is more accurate for a quadratic interaction (k=2).
- Ratio between splitting forces and tensile forces is not constant but dependent on the bolt diameter, edge distance, ...,
- Anchors loaded contrary to the free edge have no influence on the failure load of the anchor loaded towards the edge.
- Anchor spacing has no influence on the ultimate torque moment.
Comparison with all results

\[ \frac{V_{\text{test}}}{V_{\text{cal}}} \]