ETH zürich

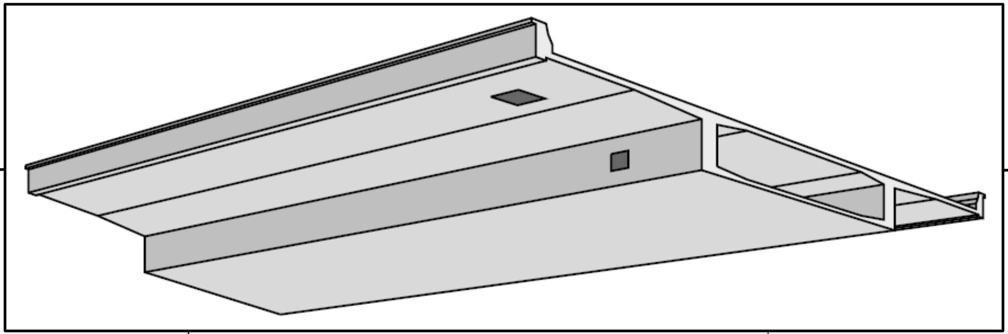
2D/3D CSFM
Theorie, Verifikation und Anwendung

Nichtlineare Finite-Elemente-Analyse von Stahlbetonbauteilen

Ingware SoftwareForum
Erlenbach, 12.09.2024

Dr. Marius Weber
Professur für Massiv- und Brückenbau, ETHZ
Institut für Bauingenieurwesen, HSLU T&A

Motivation



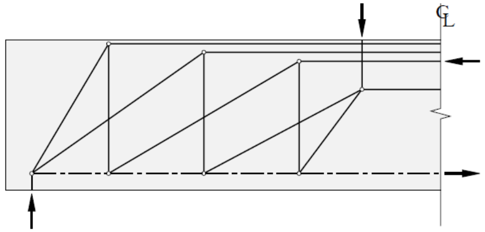
Linear elastische Analyse

Nichtlineare Finite Elemente Analyse

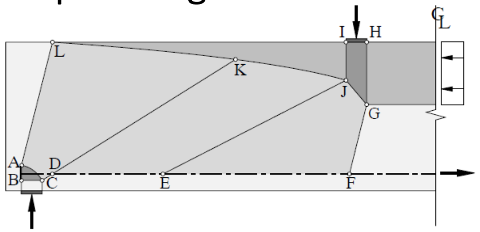
Auswirkungen

Auswirkungen

Fachwerkmodelle



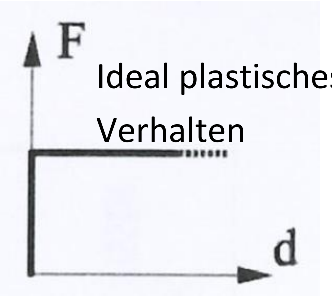
Spannungsfeldmodelle



Verständnis des Tragverhaltens

Unterer Grenzwert

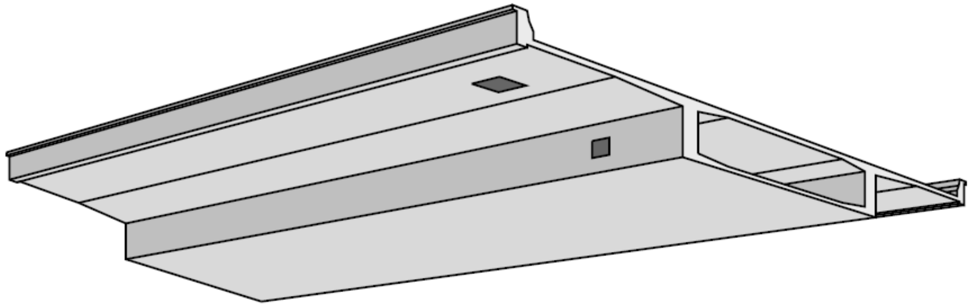
Keine Beurteilung der Gebrauchstauglichkeit möglich (Verformungen, Rissbreiten, etc.)



Ideal plastisches Verhalten

Mechanische Modellierung?
Numerische Umsetzung?
Materialparameter?
Sensitivität?
Verifikation?

Motivation



Linear elastische Analyse

Nichtlineare Finite Elemente Analyse

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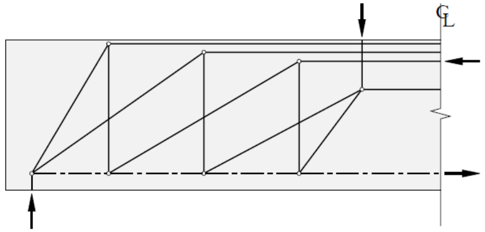

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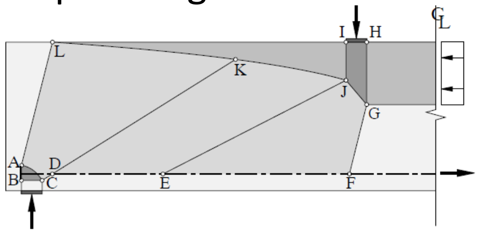

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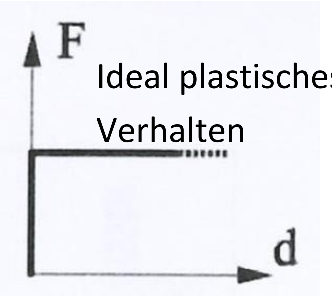
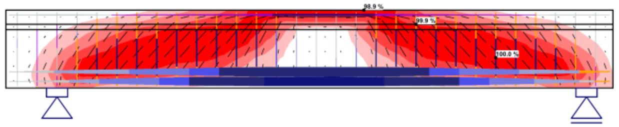
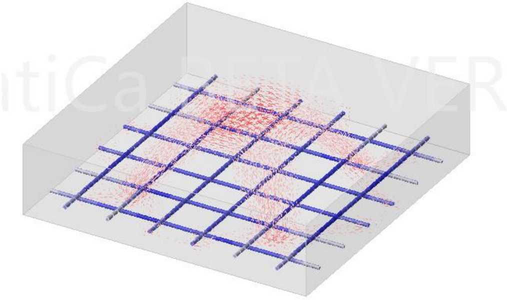


2D CSFM



3D CSFM



IDEA StatiCa®

Calculate yesterday's estimates

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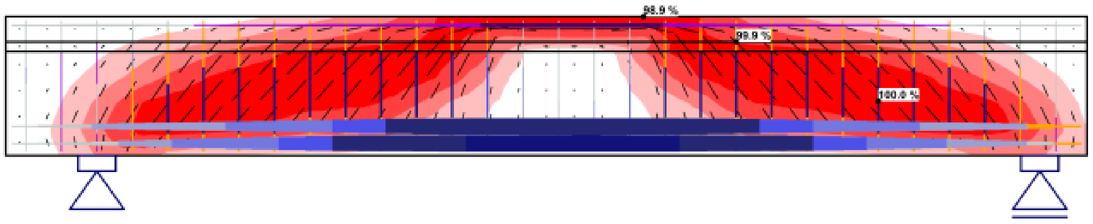
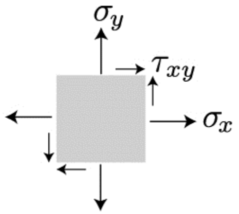
Compatible Stress Field Method

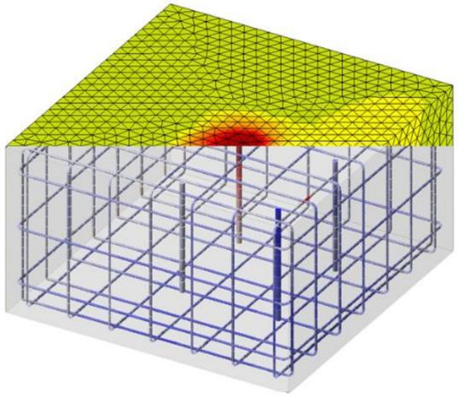
2D CSFM

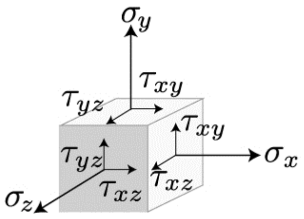




Plane Elemente für Beton

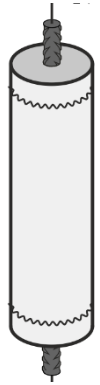
3D CSFM





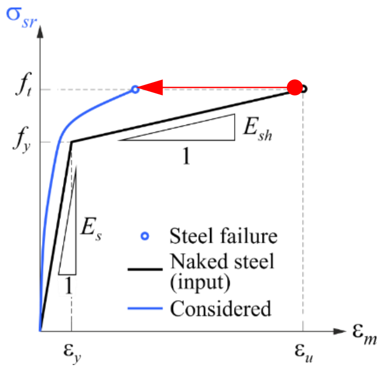
Solid Elemente für Beton

Diskrete Modellierung der Bewehrung (1D)



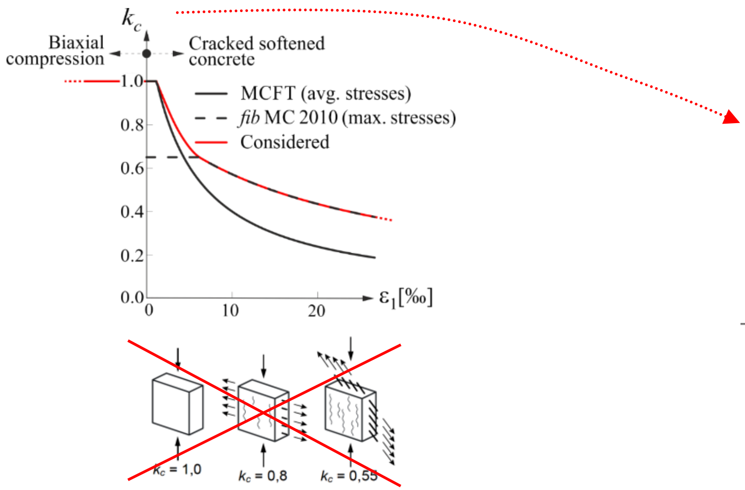
1D Elemente

Zugversteifung in der Bewehrung berücksichtigt

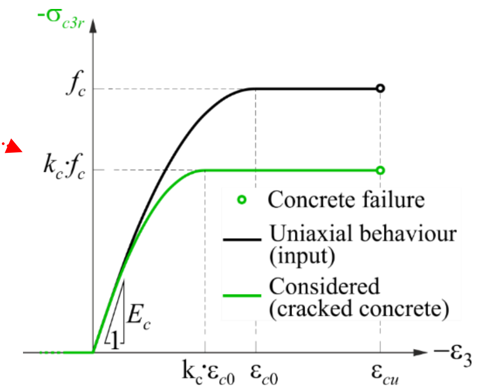


TCM/POM

Compression softening automatisch berücksichtigt

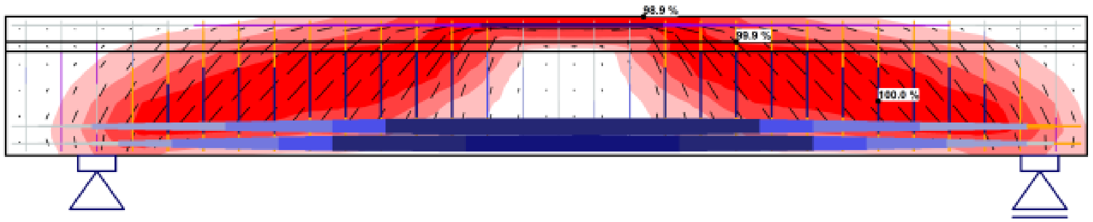


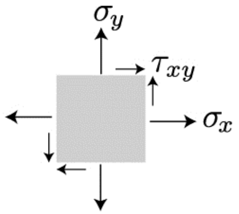
Einachsiale Werkstoffgesetze (f_{ct}=0)



Compatible Stress Field Method

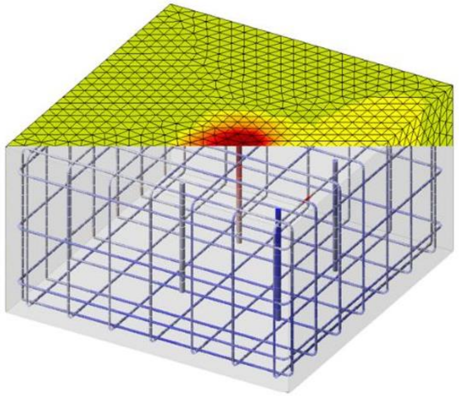
2D CSFM

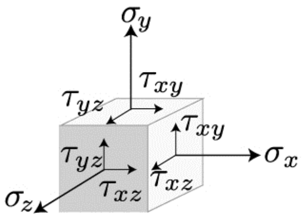




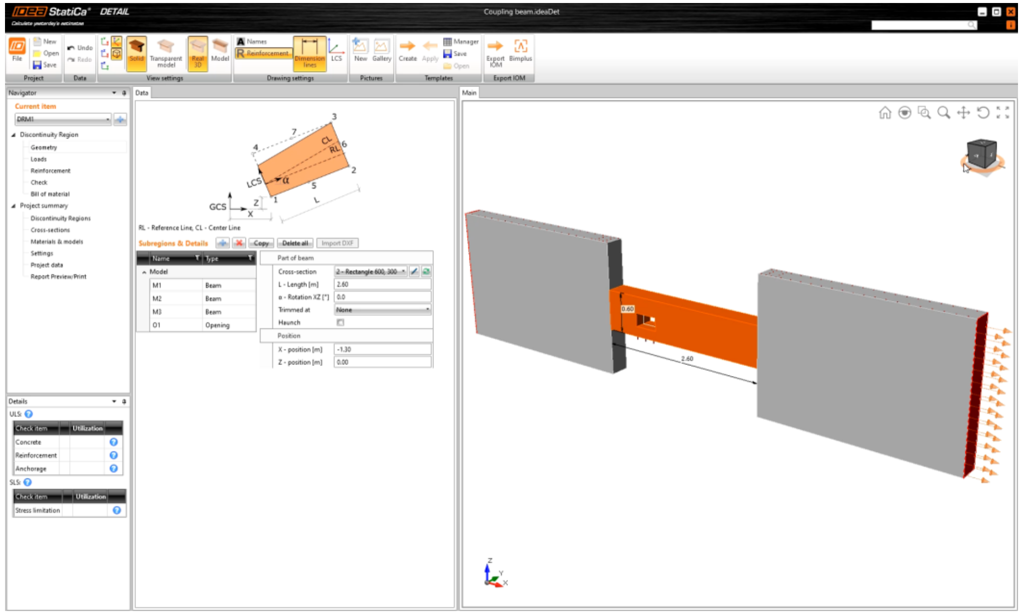
Plane Elemente für Beton

3D CSFM





Solid Elemente für Beton

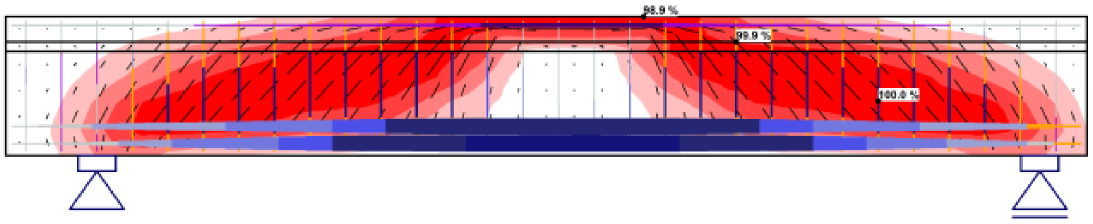


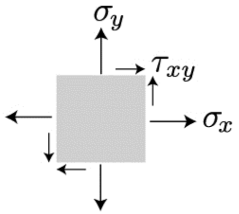
Benutzerfreundliches UI

Automatisierte ULS/SLS Checks gemäss Normen

Compatible Stress Field Method

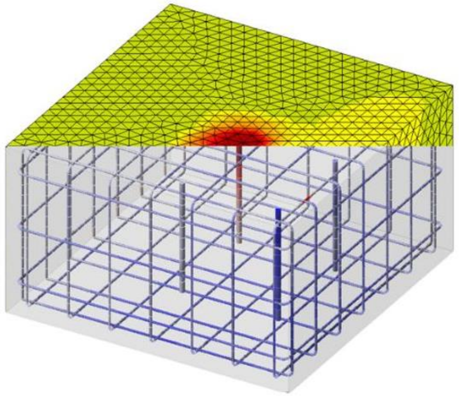
2D CSFM

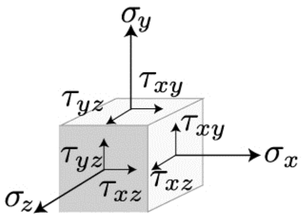




Plane Elemente für Beton

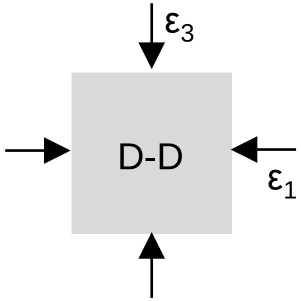
3D CSFM





Solid Elemente für Beton

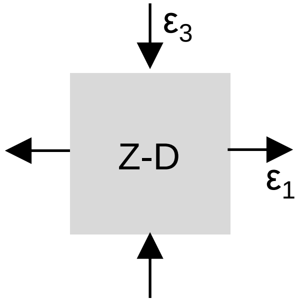
Unterschied 2D vs 3D: Bestimmung der Betonfestigkeit



$f_{c3}=f_c(\varepsilon_1=0)$

$f_{c1}=f_c(\varepsilon_1=0)$

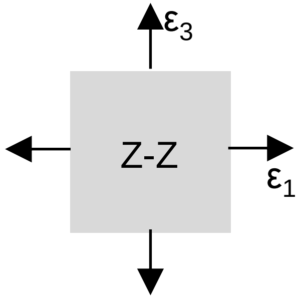
Einachsiale Druckfestigkeit



$f_{c3}= f_{c3red} =f_c(\varepsilon_1>0)$

$f_{ct1}=f_{ct}=0$

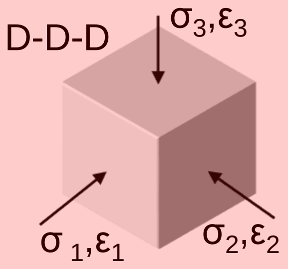
Compression Softening



$f_{c3}= f_{ct}=0$

$f_{ct1}=f_{ct}=0$

Zugfestigkeit Beton vernachlässigt

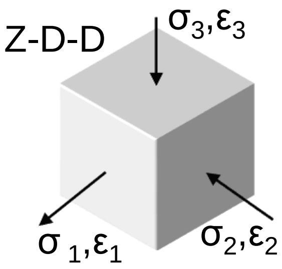


$f_{c3}=f_c(\sigma_1,\sigma_2,\sigma_3)$

$f_{c2}=f_c(\sigma_1,\sigma_2,\sigma_3)$

$f_{c1}=f_c(\sigma_1,\sigma_2,\sigma_3)$

Triaxiale Druckfestigkeit

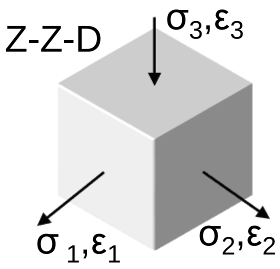


$f_{c3}= f_{c3red} =f_c(\varepsilon_1>0)$

$f_{c2}= f_{c2red} =f_c(\varepsilon_1>0)$

$f_{ct1}=f_{ct}=0$

Compression Softening

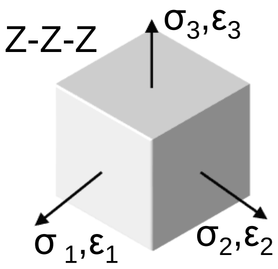


$f_{c3}= f_{c3red} =f_c(\varepsilon_{1,2}>0)$

$f_{ct2}=f_{ct}=0$

$f_{ct1}=f_{ct}=0$

Compression Softening



$f_{ct3}=f_{ct}=0$

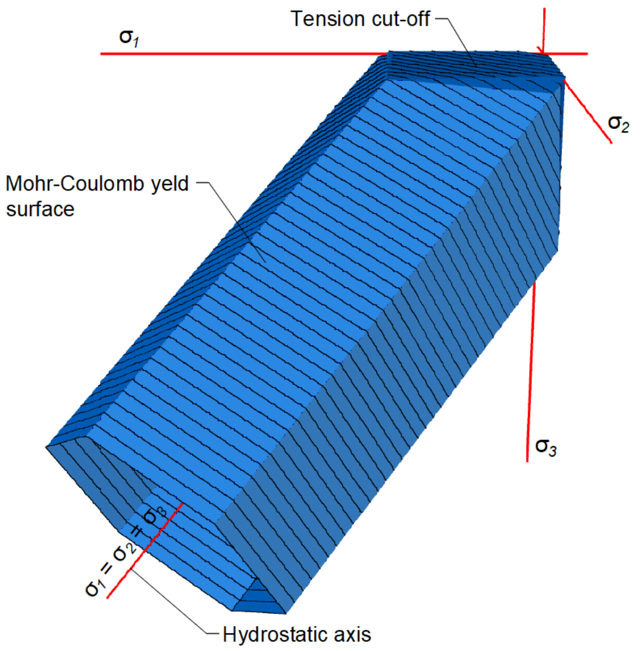
$f_{ct2}=f_{ct}=0$

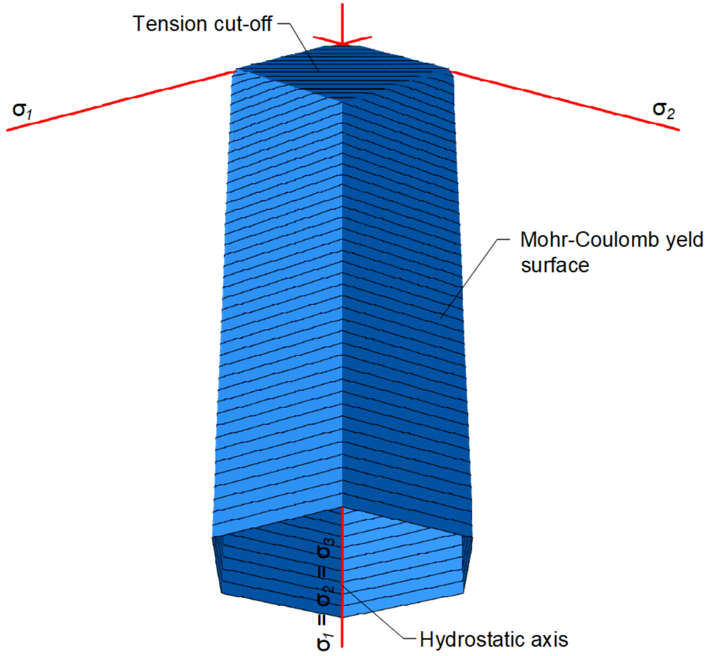
$f_{ct1}=f_{ct}=0$

Zugfestigkeit Beton vernachlässigt

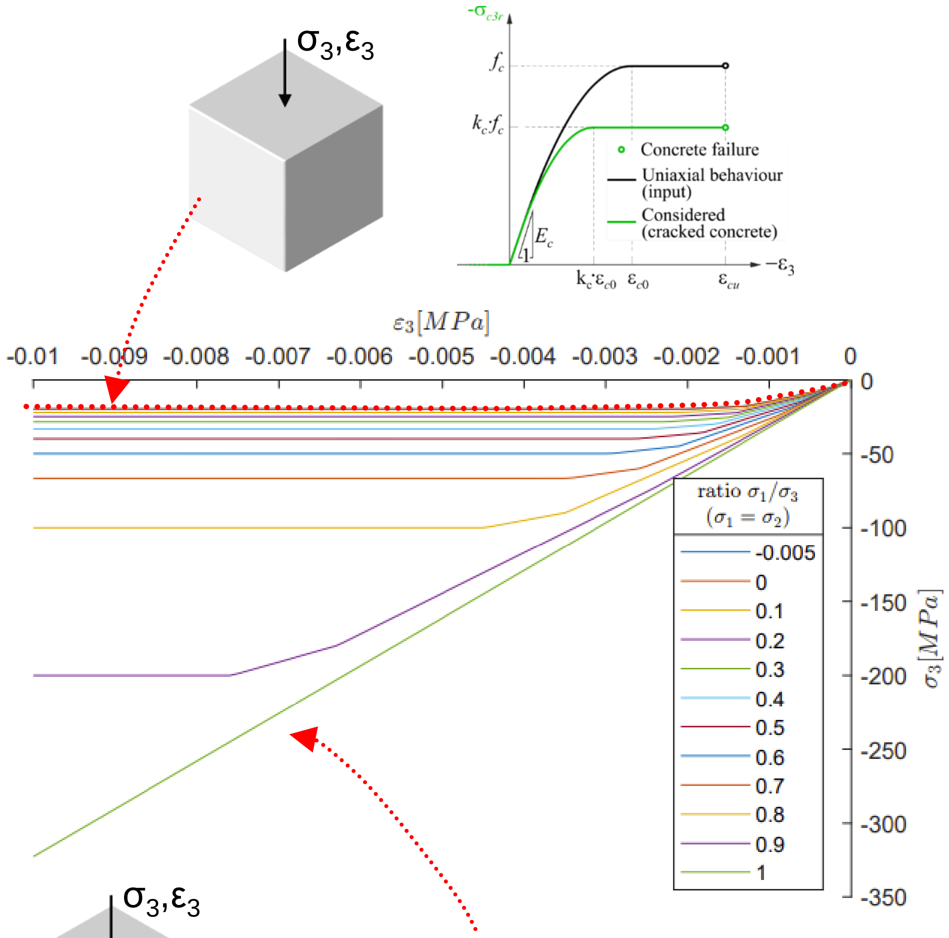
Multiachsiale Druckfestigkeit

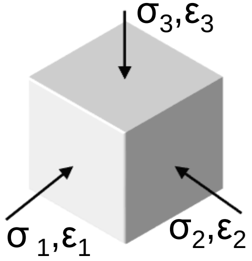
Mohr-Coulomb





Analog 2D CSFM





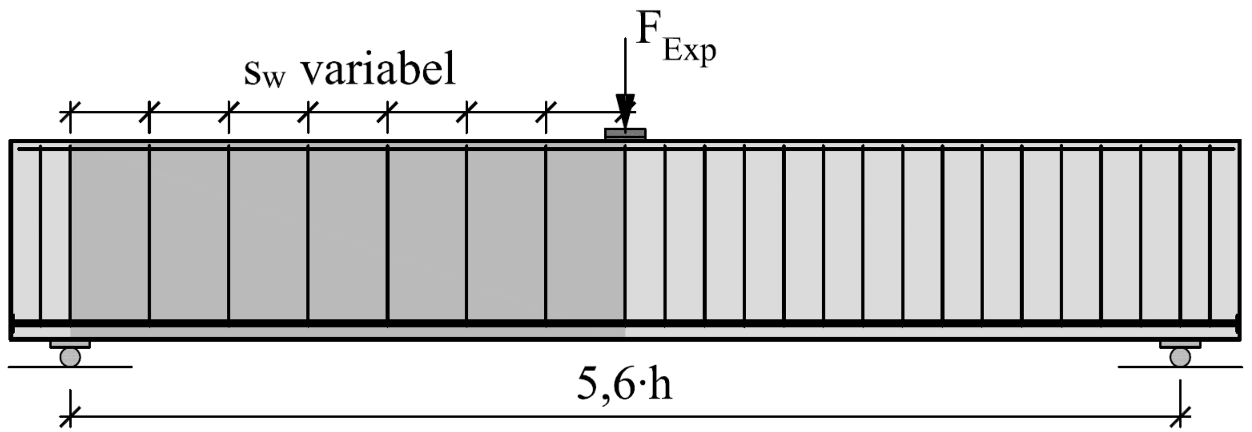
Festigkeitszunahme infolge triaxialem Druckspannungszustand

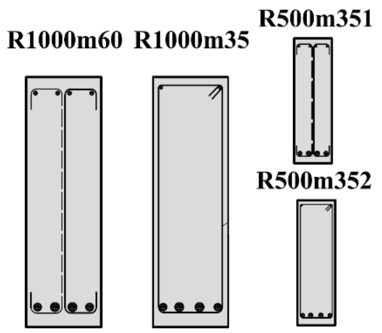
Verifikation 2D CSFM

Huber et al. [2016]

Versuchskörper	R1000m35	R1000m60	R500m352	R500m351
Höhe	1.00 m	1.00 m	0.50 m	0.50 m
Breite	0.30 m	0.30 m	0.15 m	0.15 m
ρ_w	0.094 %	0.094 %	0.084 %	0.094 %
$Ø_w$	Ø6	Ø12	Ø4	Ø6
f_c	29.6 MPa	60.9 MPa	35.9 MPa	37.9 MPa

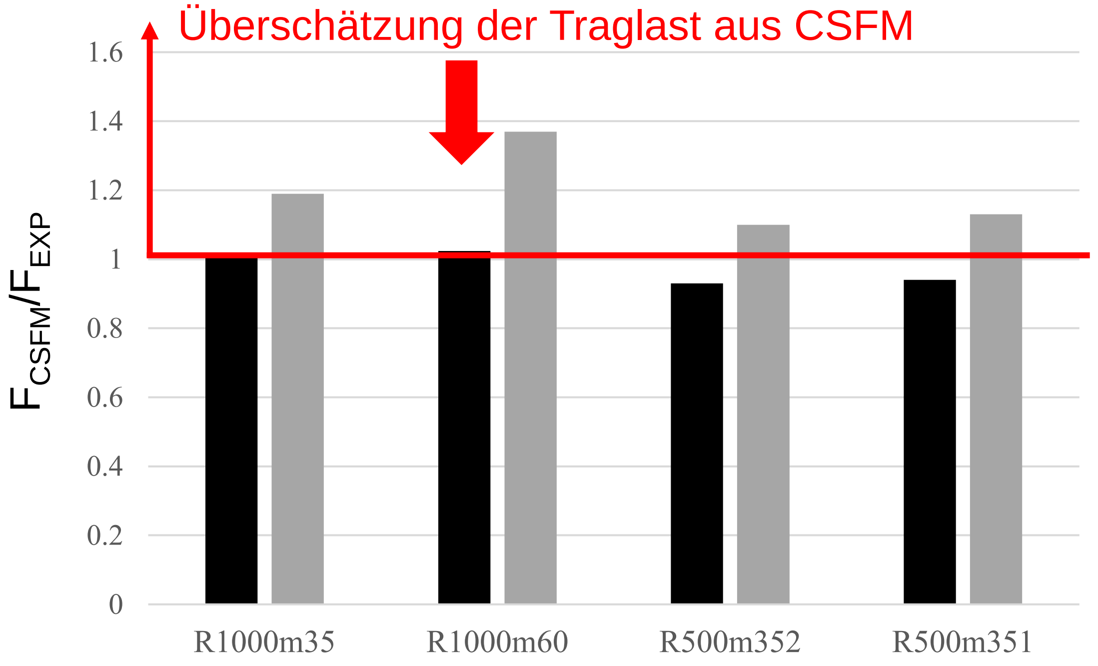
$Ø_w$ (mm)	f_y (MPa)	f_t (MPa)	ε_u (%)
4	653	710	4.9
6	569	658	3.1
12	552	654	3.4



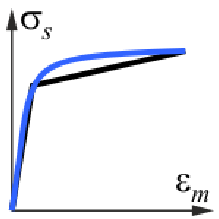


Verifikation 2D CSFM

Huber et al. [2016]



Einfluss Idealisierung der Bewehrungen



Kaltverformter Stahl

→ Duktilität/Traglast nehmen ab (≈10%)

→ Bil. Idealisierung auf der unsicheren Seite!

Einfluss Zugversteifung

CSFM (ohne Zugversteifung)

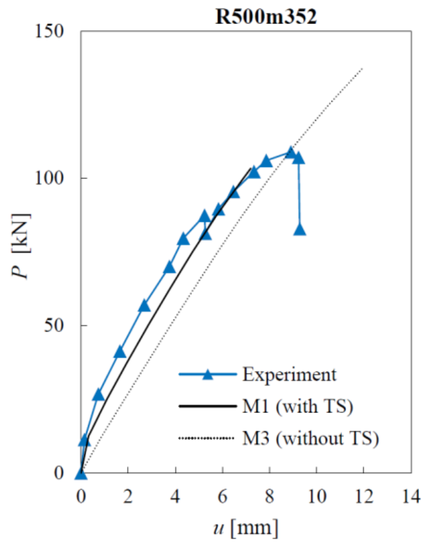
Mittelwert = 0.81

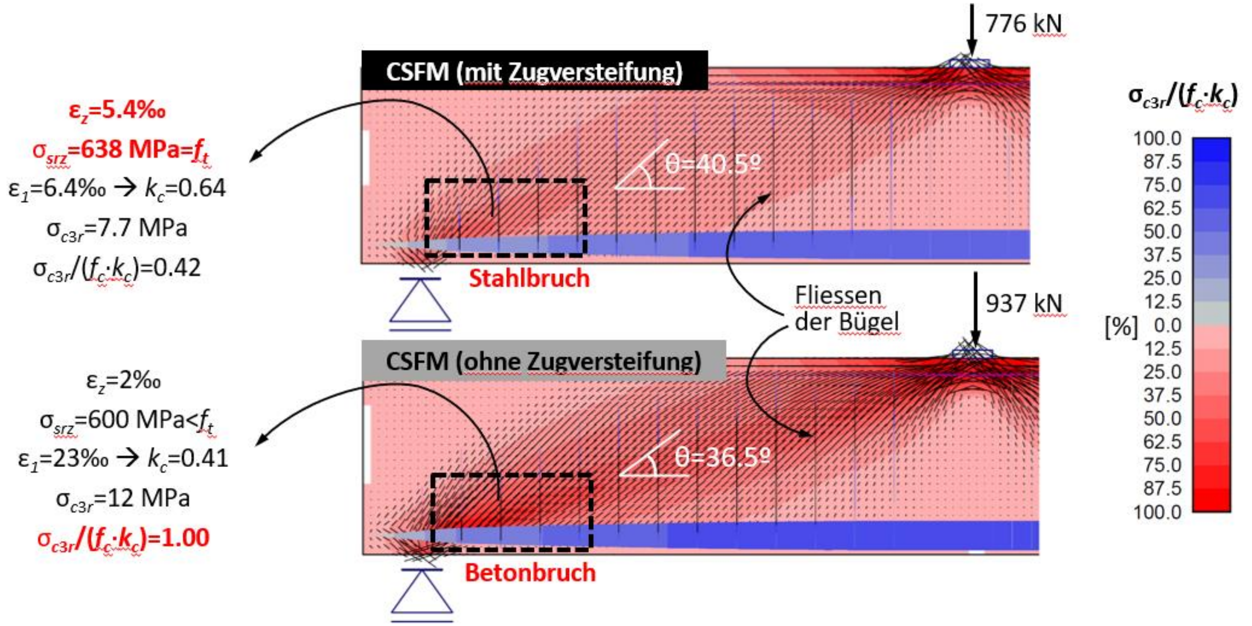
Betonversagen

CSFM (mit Zugversteifung)

Mittelwert = 0.99

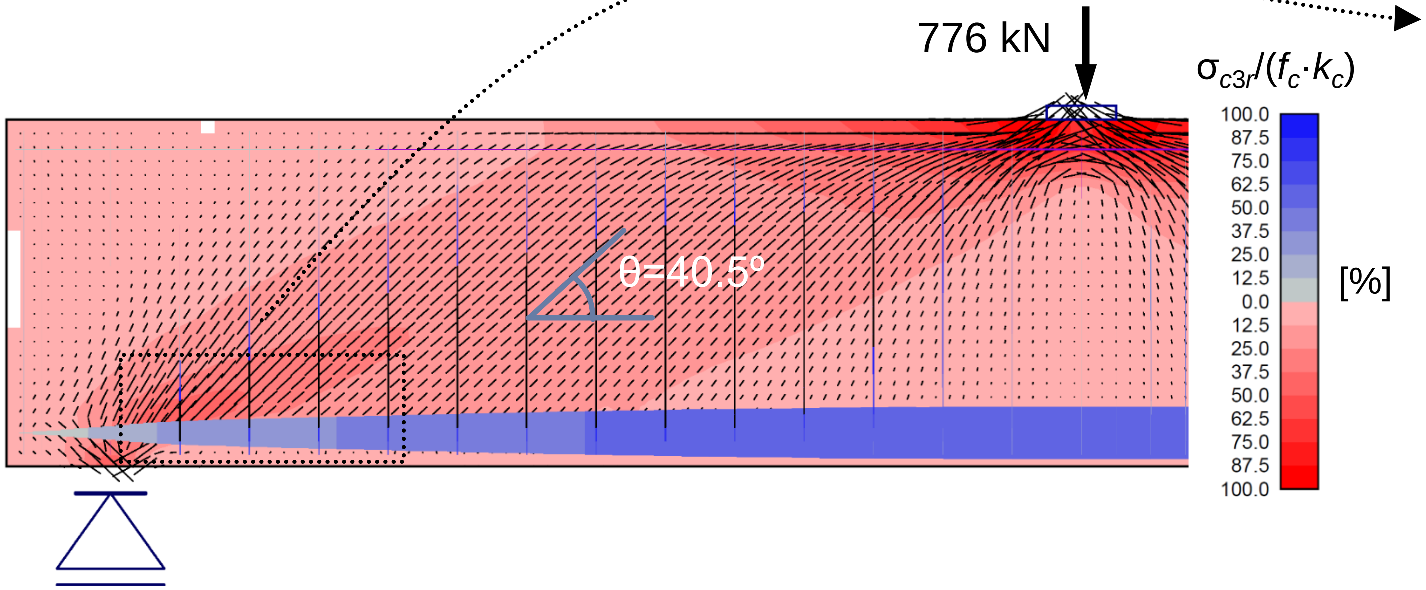
Bügelversagen (analog Exp.)





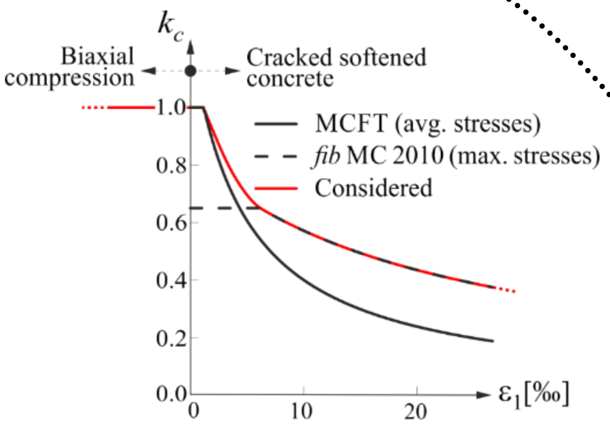
Verifikation 2D CSFM

Huber et al. [2016]



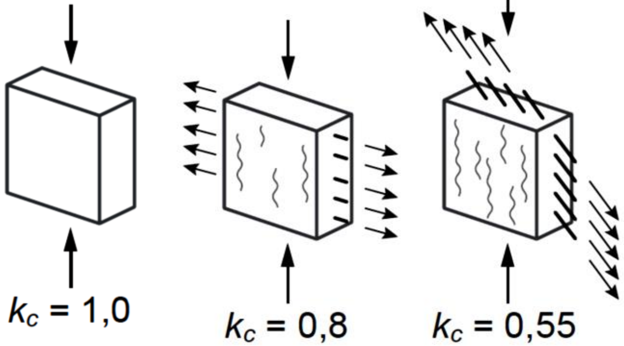
Einfluss Compression Softening

ε_1=6.4‰ → k_c=0.64



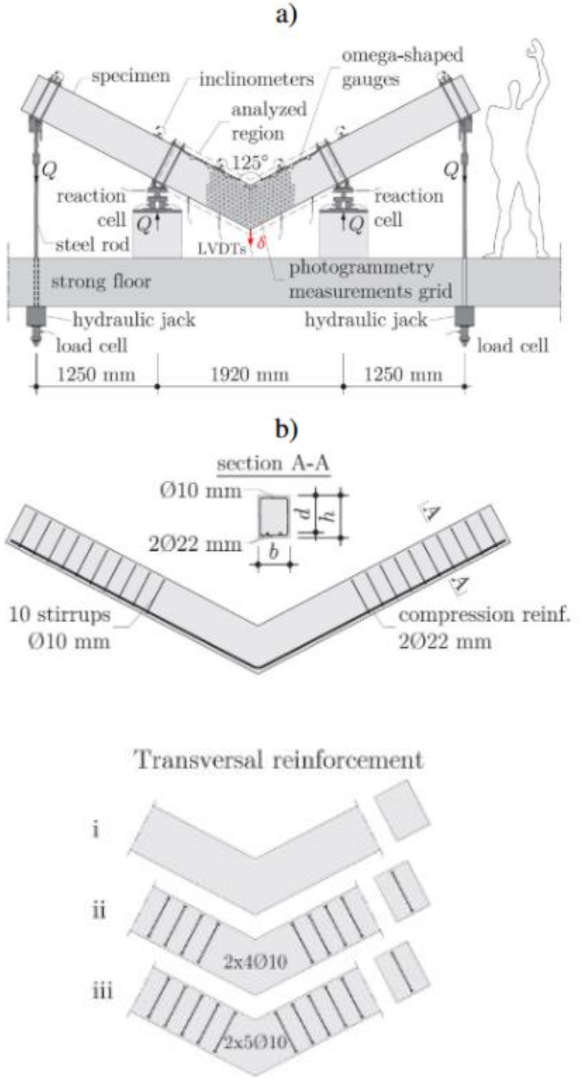
Differenz ca. 16%

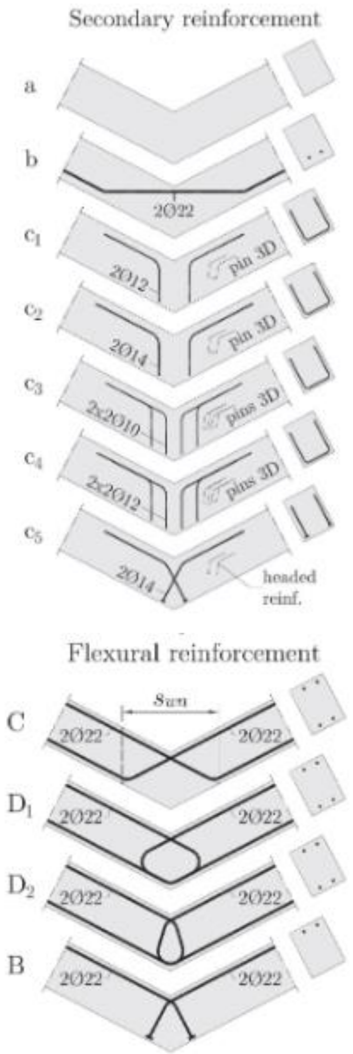
Ansatz k_c der SIA 262 → zu konservativ

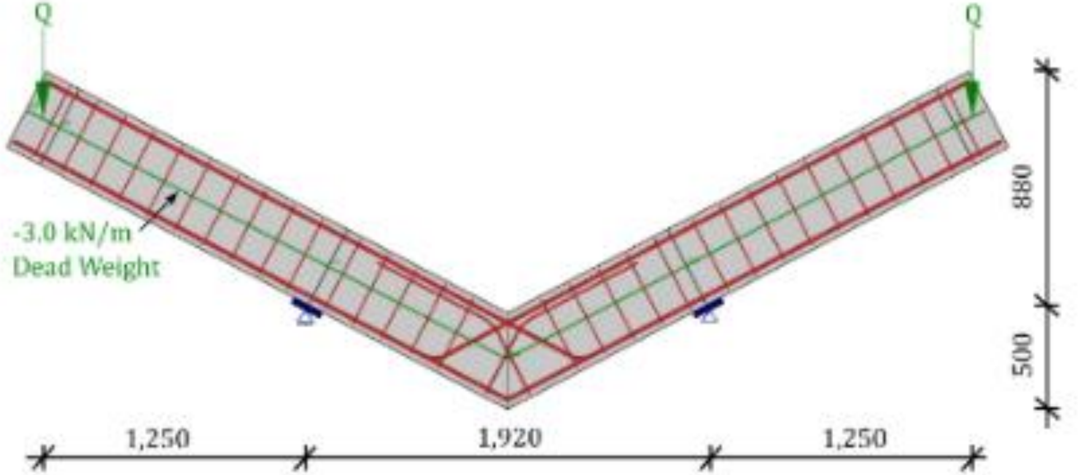


Verifikation 2D CSFM

Campana et al. (2013)







Test	Flexural Reinforcement					Secondary Reinforcement					Transversal Reinforcement					Concrete
	Layout	D [mm]	f_y [MPa]	f_t [MPa]	ϵ_u [%]	Layout	D [mm]	f_y [MPa]	f_t [MPa]	ϵ_u [%]	Layout	D [mm]	f_y [MPa]	f_t [MPa]	ϵ_u [%]	f_c [MPa]
SC 26	D1	22	515	630	11.1	a	-	-	-	-	i	-	-	-	-	41.9
SC 27	D1	22	515	630	11.1	b	22	515	630	11.1	i	-	-	-	-	41.6
SC 30	D2	22	515	630	11.1	a	-	-	-	-	i	-	-	-	-	42.0
SC 31	D2	22	515	630	11.1	b	22	515	630	11.1	i	-	-	-	-	41.7
SC 34	B	22	515	652	11.6	a	-	-	-	-	i	-	-	-	-	41.4
SC 35	B	22	515	652	11.6	b	22	515	630	11.1	i	-	-	-	-	42.1
SC 38	C	22	500	596	11.4	c1	12	555	610	4.70	ii	10	568	641	6.20	31.3
SC 39	C	22	500	596	11.4	c1	12	555	610	4.70	iii	10	568	641	6.20	31.1
SC 40	C	22	500	596	11.4	c2	14	560	600	4.10	ii	10	568	641	6.20	30.9
SC 41	C	22	500	596	11.4	c2	14	560	600	4.10	iii	10	568	641	6.20	30.9
SC 42	C	22	500	596	11.4	c3	10	575	620	3.60	iii	10	568	641	6.20	31.0
SC 43	C	22	500	596	11.4	c4	12	555	610	4.70	iii	10	568	641	6.20	31.0
SC 44	C	22	500	596	11.4	c5	14	560	614	4.30	ii	10	568	641	6.20	30.9
SC 45	C	22	500	596	11.4	c5	14	560	614	4.30	iii	10	568	641	6.20	30.8

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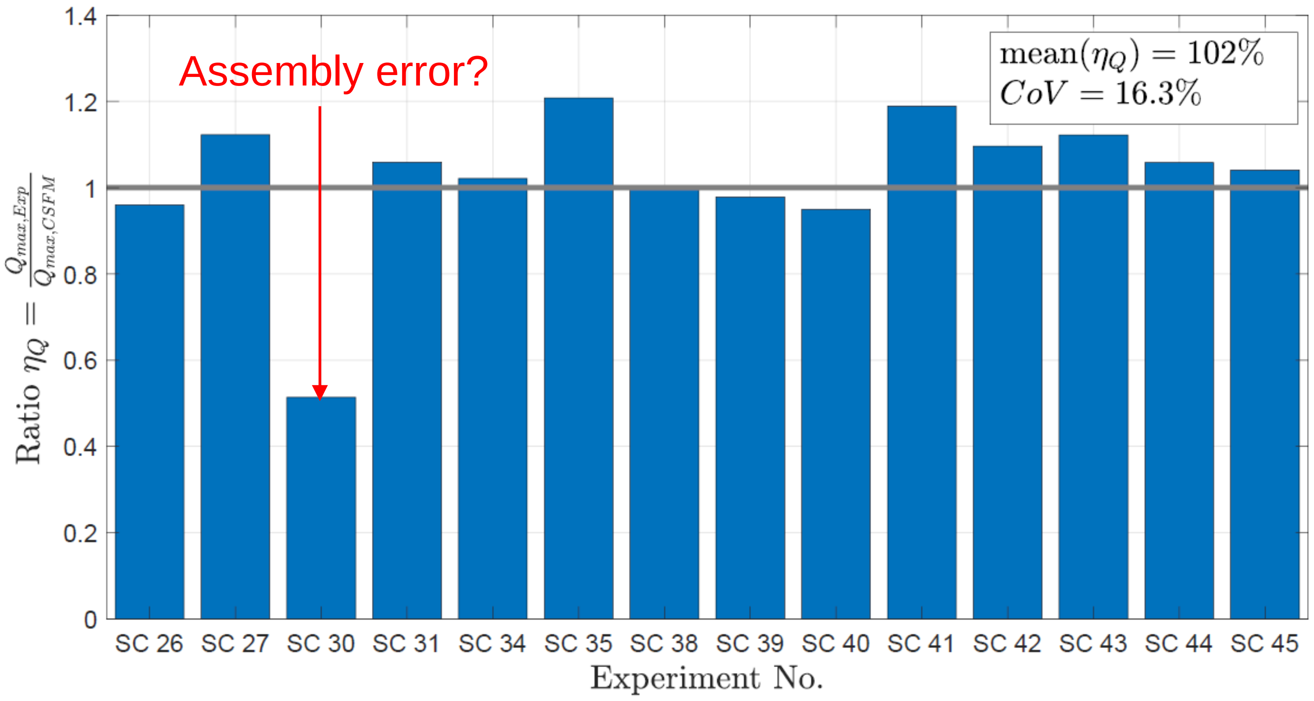
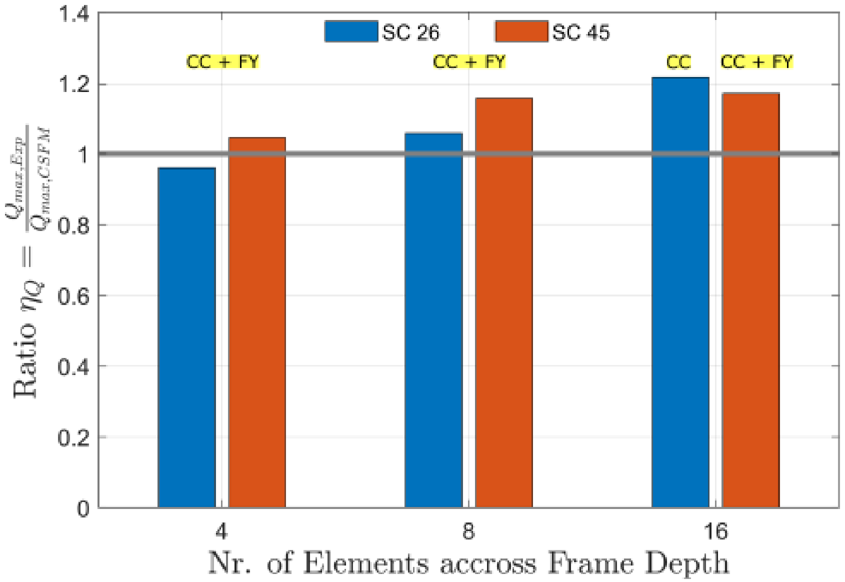
Verifikation 2D CSFM

Campana et al. (2013)



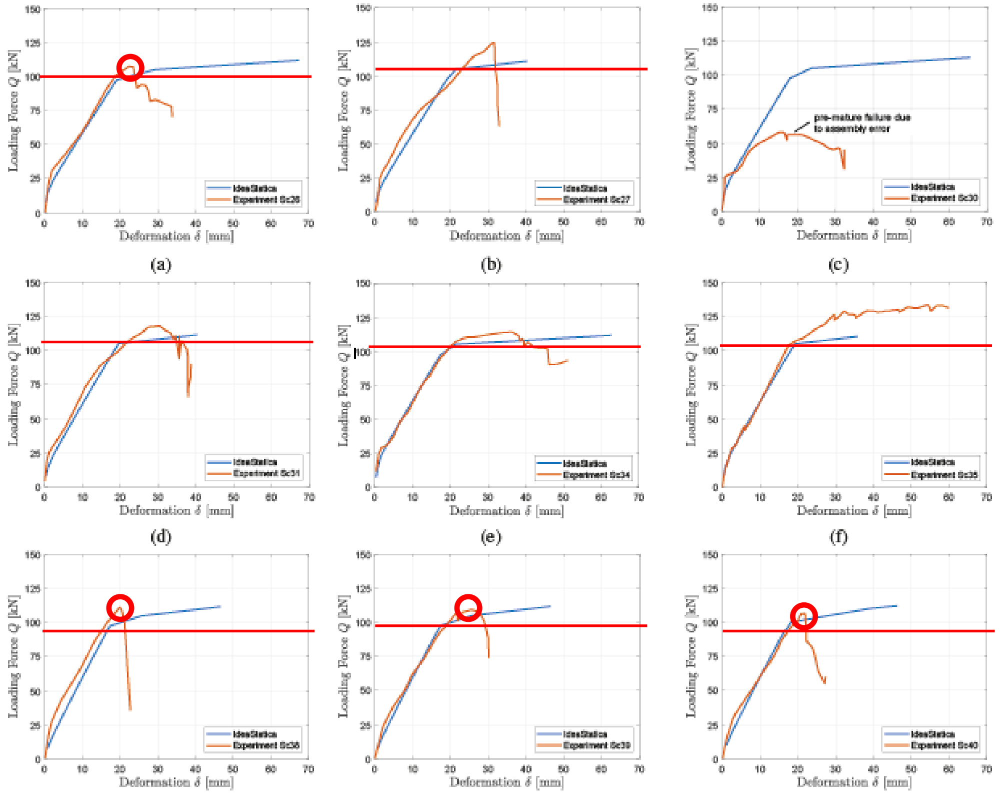
Einfluss Mesh Size



Verfeinerung Mesh → konservative Seite

Verifikation 2D CSFM

Campana et al. (2013)



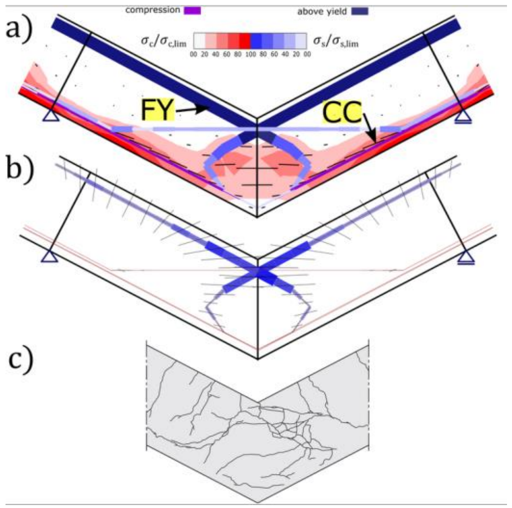
$\sigma_{sr} = f_{sy}$

brittle failure

Experiment

CSFM

Einfluss Versagensart



$\sigma_{c,}$ σ_{sr}

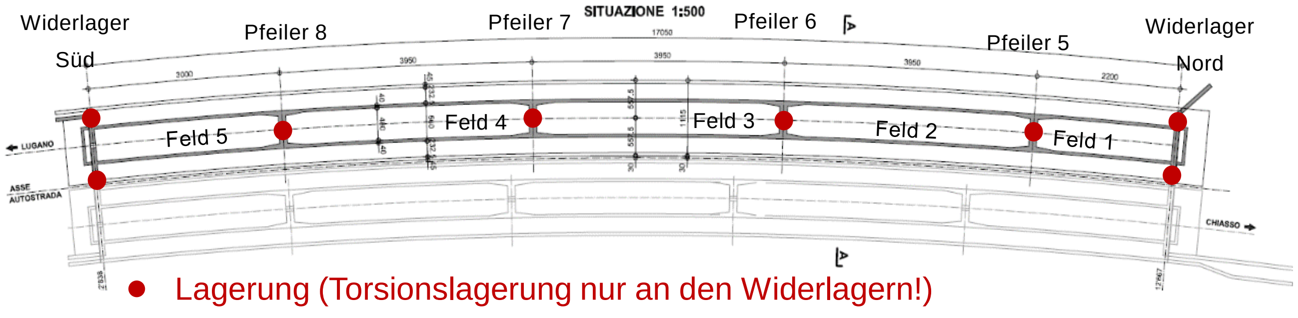
Rissbild CSFM

Rissbild Experiment

- Übereinstimmung bis Fliessen der Bewehrung sehr gut → Gebrauchstauglichkeit!
- CSFM überschätzt die Verformungen bei spröden Versagensmechanismen → CSFM ist nicht für spröde Versagensmechanismen geeignet (Konstruktive Ausführung!)

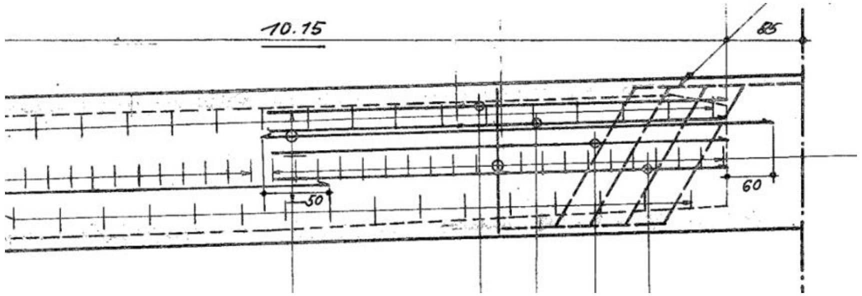
Praxisbeispiel 2D CSFM

Querschnittsanalysen und starr-plastische Spannungsfelder ergaben eine ungenügende Querkrafttragsicherheit der Längsträger und Tragsicherheit der Querträger (indirekte Lagerung)

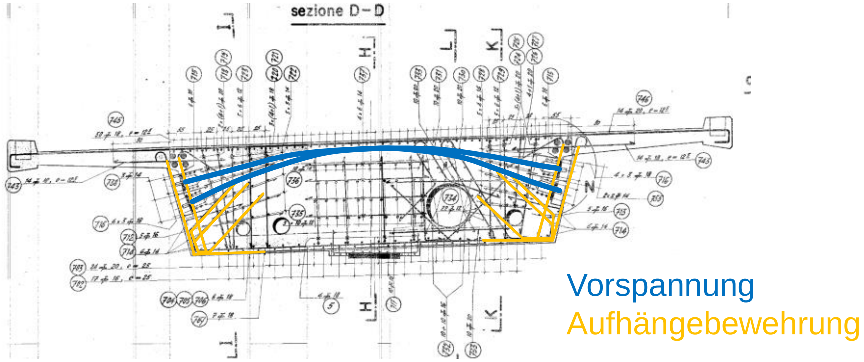


➡ Nichtlineare Analyse mit dem CSFM

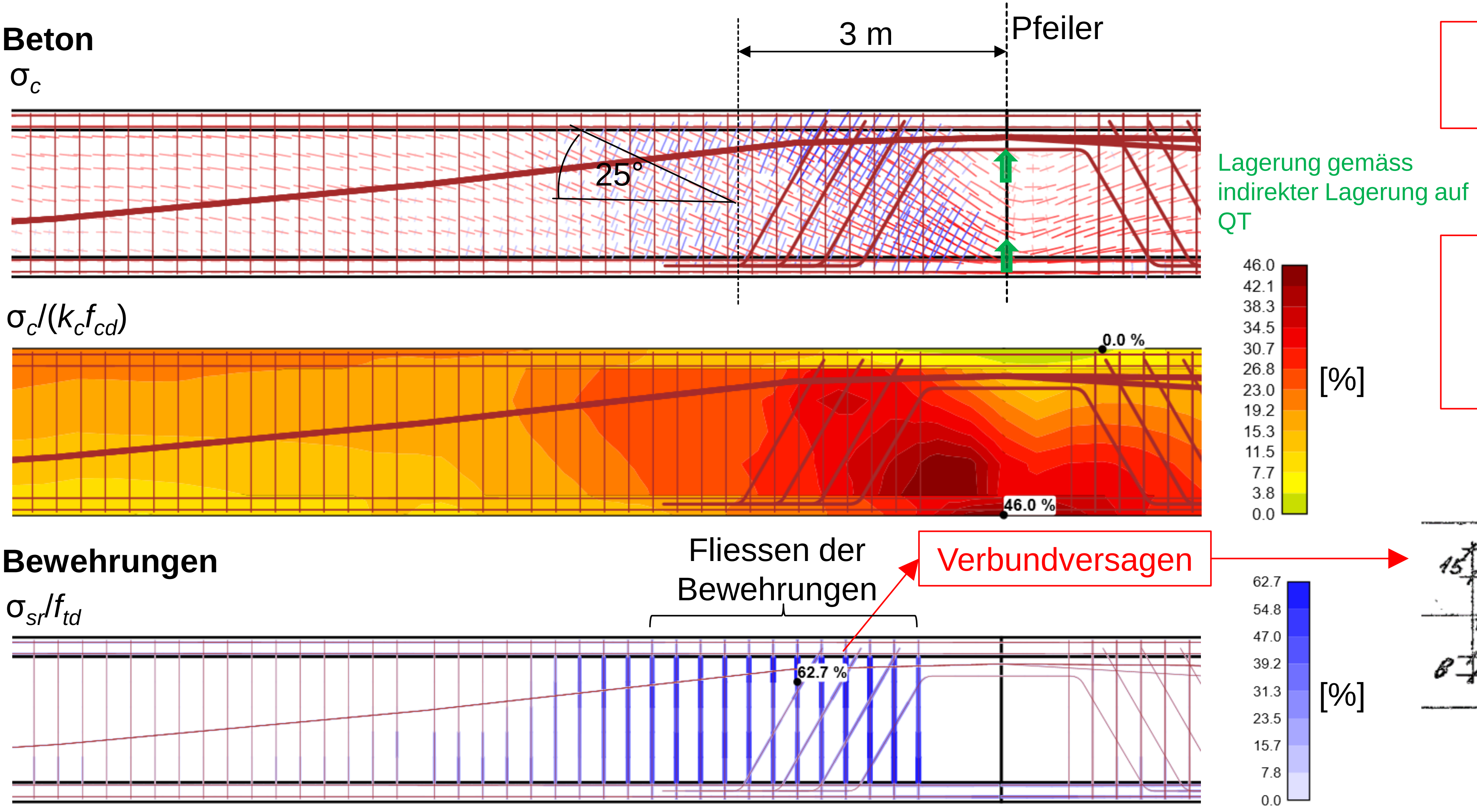
Längsträger im Bereich der Pfeiler



Querträger an den Pfeilern



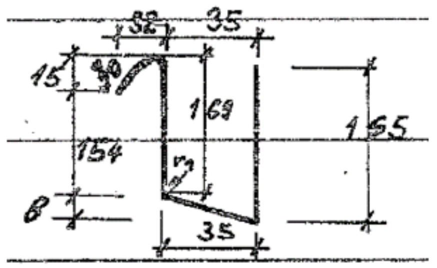
Praxisbeispiel 2D CSFM



Erfüllungsgrad

V_{Rd}/V_{Ed}=1.38

Steigerung um 60% gegenüber herkömmlicher Berechnung



Praxisbeispiel 2D CSFM

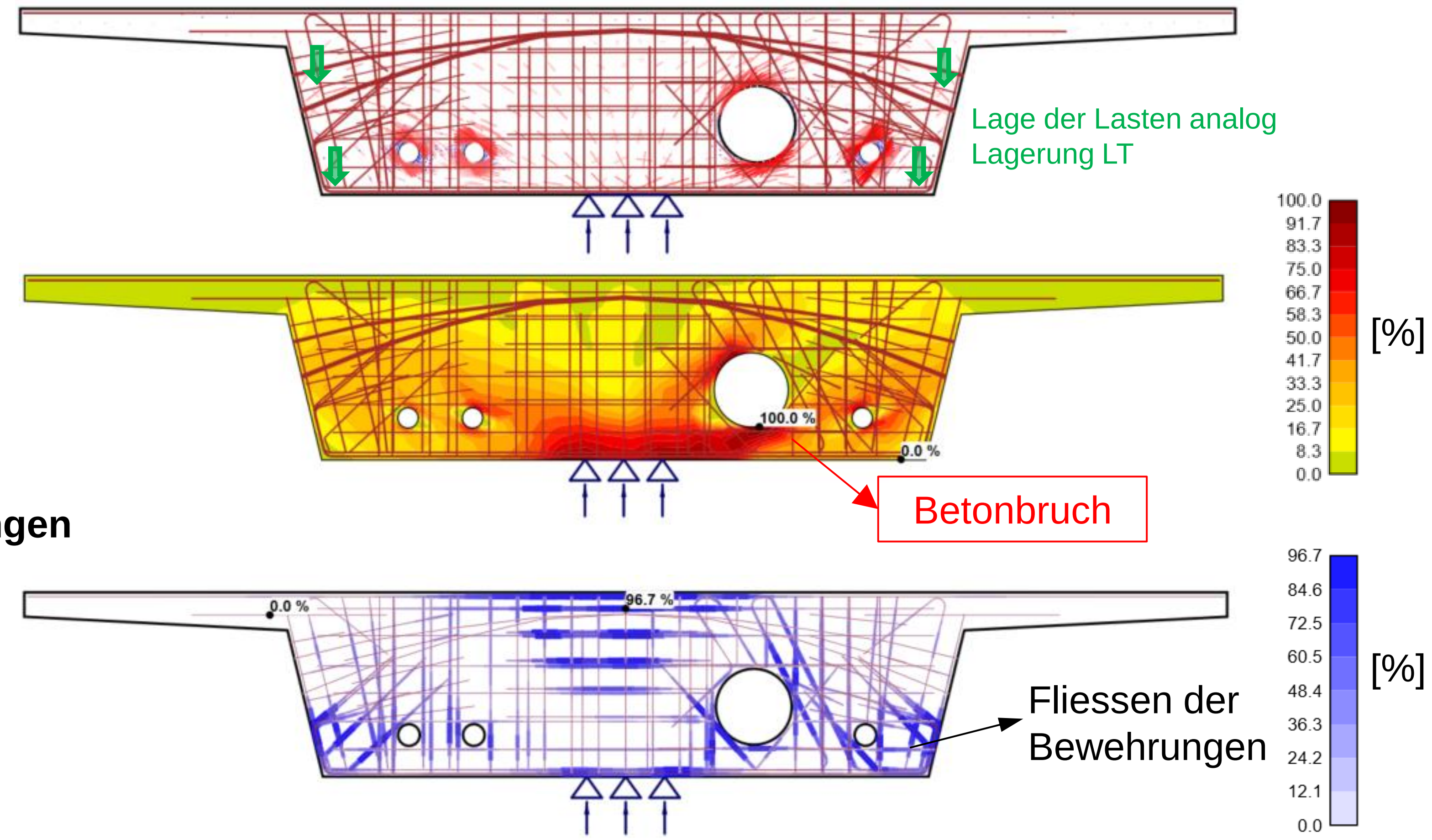
Beton

σ_c

$\sigma_c/(k_c f_{cd})$

Bewehrungen

σ_{sr}/f_{td}



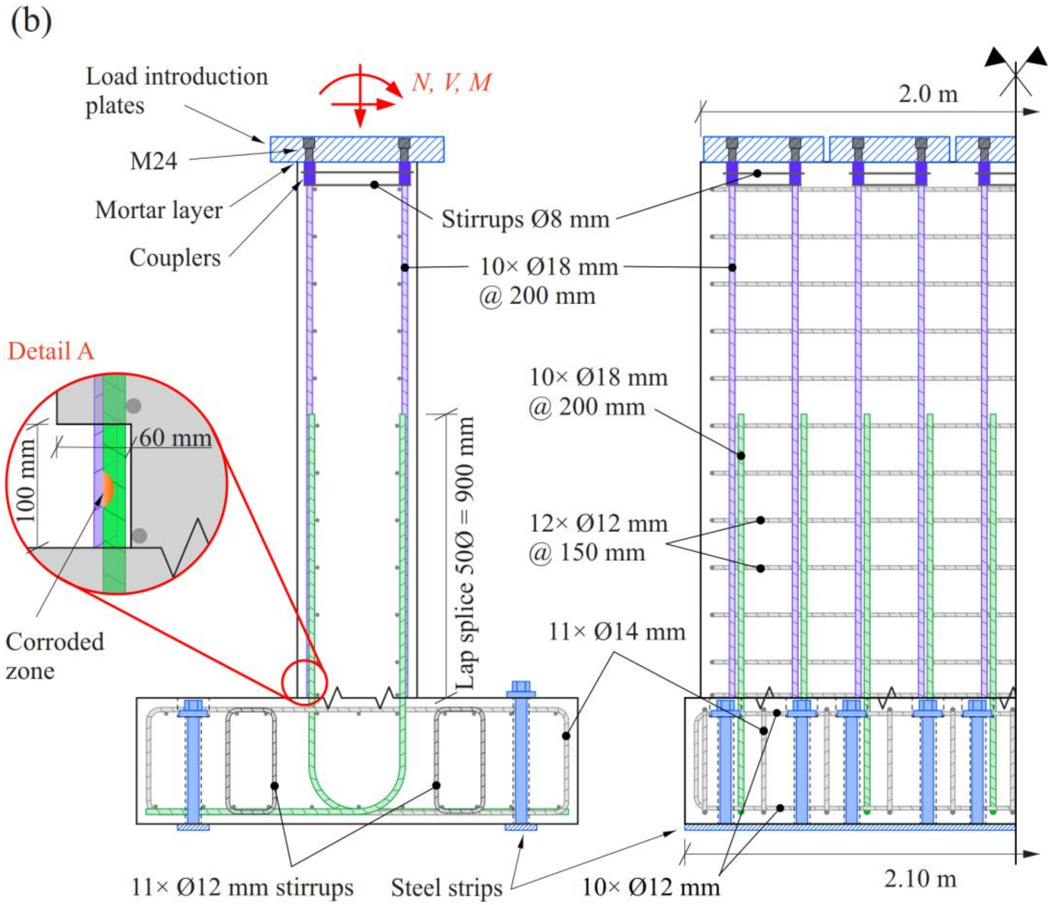
Erfüllungsgrad

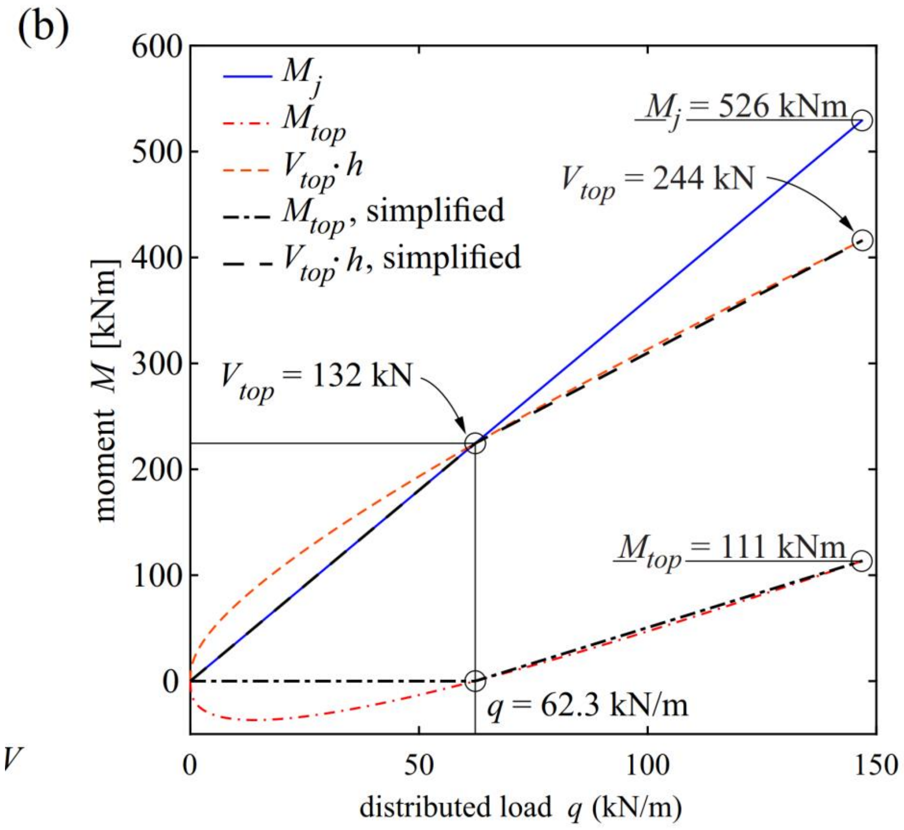
R_{Rd}/R_{Ed}=1.68

Steigerung um 63% gegenüber herkömmlicher Berechnung

Verifikation 3D CSFM

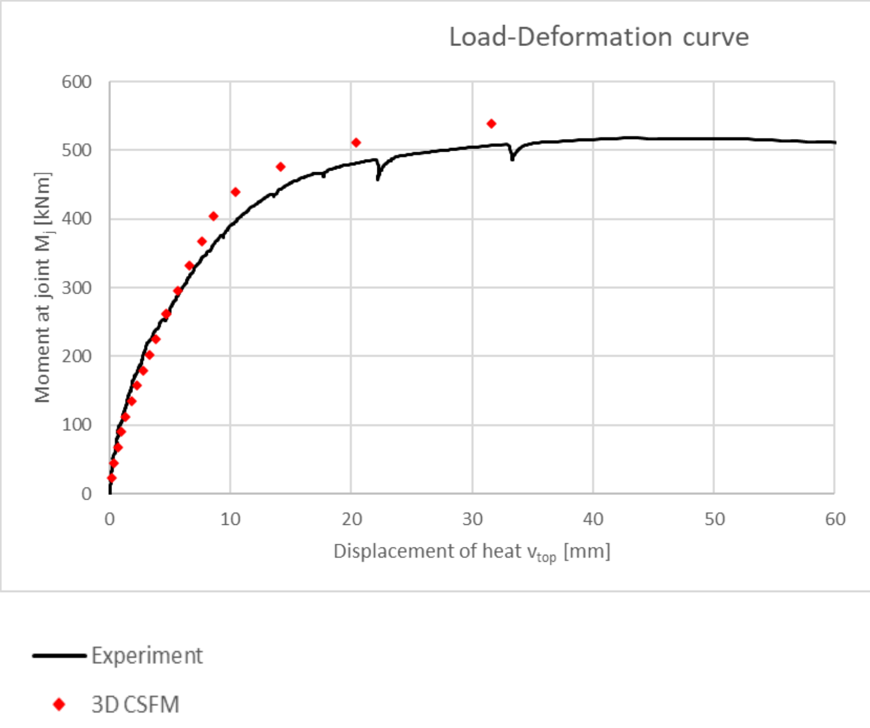
Häfliger et al. (2013)





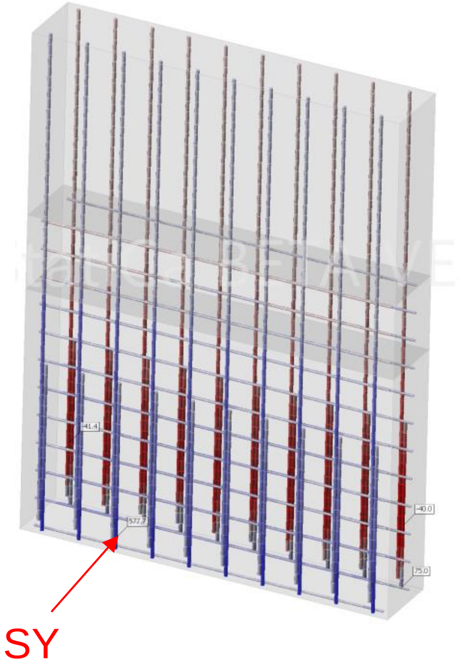
Verifikation 3D CSFM

Häfliger et al. (2013)



	Experiment	3D CSFM (default)
Versagensart	SF (σ_{sr}=f_{su}=609 MPa)	CC (f_c=34 MPa) + SY (σ_{sr}=580 MPa)
max. Moment	518 kNm	586 kNm (+7.3%)
Verformung	43 mm	32 mm (-16%)

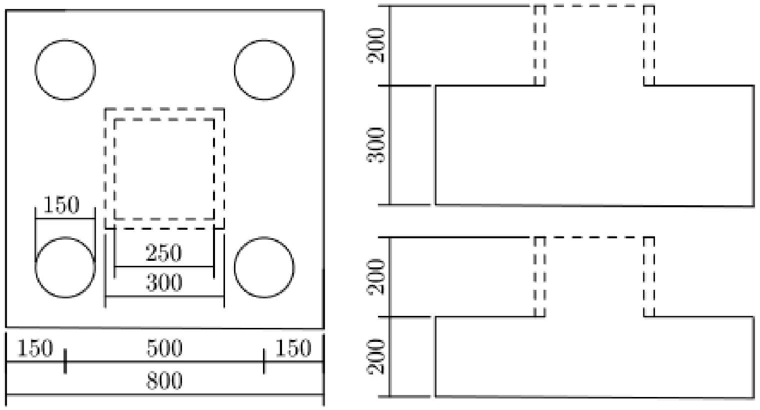
Stahlspannungen 3D CSFM



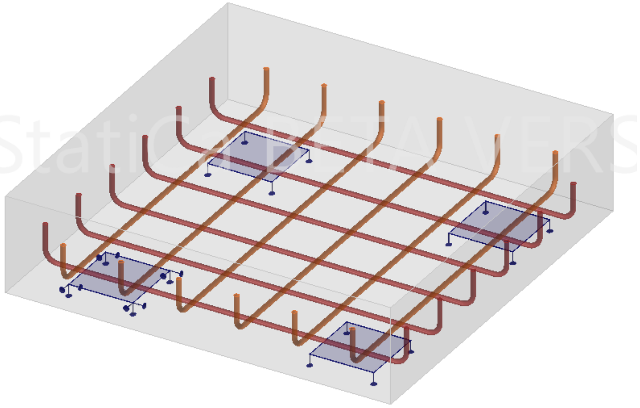
Betonhauptspannungen 3D CSFM

Verifikation 3D CSFM

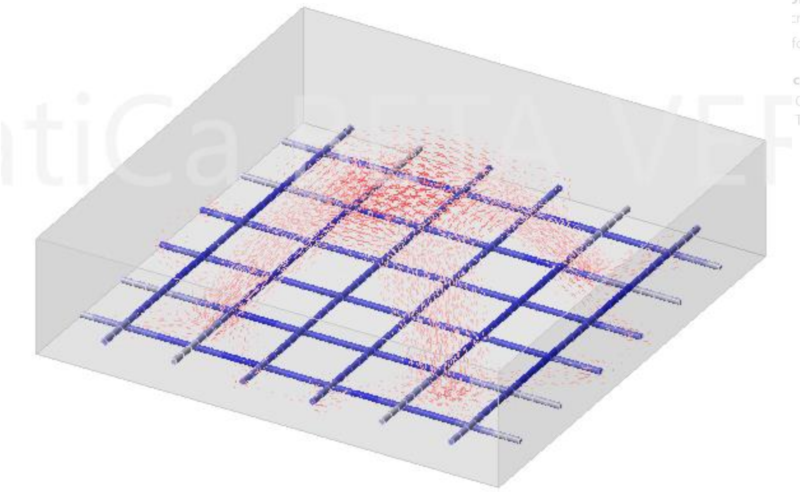
Suzuki et al.



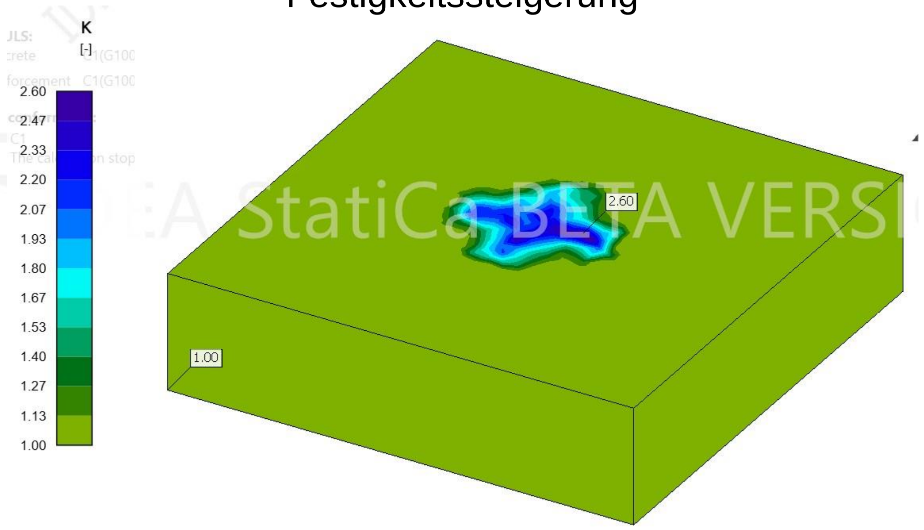
Specimen	h (mm)	c (mm)	f_{c0} (MPa)	Reinforcement	P_{test} (kN)	Fail. Mode
BP-20-30-2	200	300	29.8	$2 \times 6\phi10(G)$	480	y+s
BPC-20-30-2	200	300	29.8	$4 \times 3\phi10(B)$	495	y
BP-30-25-2	300	250	26.3	$2 \times 8\phi10(G)$	725	s
BPC-30-25-2	300	250	29.2	$4 \times 4\phi10(B)$	872	y+s
BP-30-30-2	300	300	28.5	$2 \times 8\phi10(G)$	907	y+s
BPC-30-30-2	300	300	30.9	$4 \times 4\phi10(B)$	1029	y+s



Verlauf der Hauptdruckspannungen



Festigkeitssteigerung



	Exp [kN]	single-brick models Detail-3D [kN]	F_{exp}/F_{3D}
BP-20-30-2	480	494	0.97
BPC-20-30-2	495	540	0.92
BP-30-25-2	725	805	0.90

Schlussfolgerungen

Verfeinerte Analyse des Tragerhaltens

- Ausnutzung von Tragreserven (Erhöhter k_c Faktor; Ausnutzung der Bruchfestigkeit der Bewehrungen)
- Optimierung von Tragsystemen
- Minimierung von Verstärkungsmassnahmen bei der statischen Überprüfung
- Aussagen über den Grenzzustand der Gebrauchstauglichkeit möglich (Verformungen, Rissweiten)

Hinweise für die Anwendung in der Praxis

- Modellvorstellungen und deren Grenzen kennen (Einfluss Stahlkennlinie ?)
- Anwendung auf vorliegende Problemstellung prüfen (Versagensart ?)
- Paramaterstudie unbekannter Grössen (Mesh Size ?)
- Konstruktive Details für die FE-Modellierung beachten (Modellierung ?)
- Plaubilisierung der Resultate (Rückführung auf grundlegende baustatische Zusammenhänge ?)