



Stahlbetonbau im Wandel

Zukunftstrends und maßgeschneiderte Methoden zu ihrer Erforschung

Martin Claßen

62. Forschungskolloquium und 10. Jahrestagung des Deutschen Ausschuss für Stahlbeton

Motivation

Forschungstreiber - Megatrends



Urbanisierung



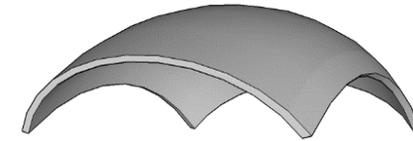
Ressourcenknappheit/
Klima



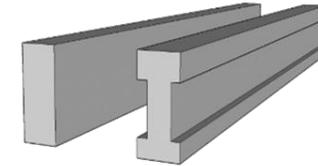
Mobilität



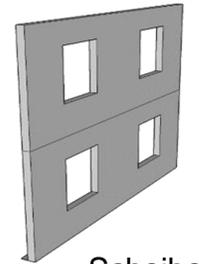
Digitalisierung/
Automatisierung



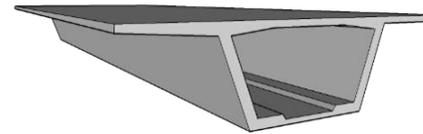
Schalen



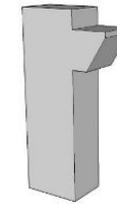
Balken



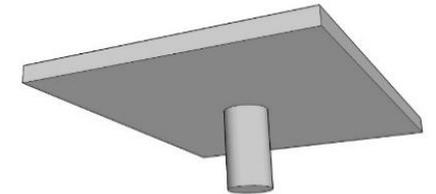
Scheiben



Brückenstrukturen



Druckglieder



Platten



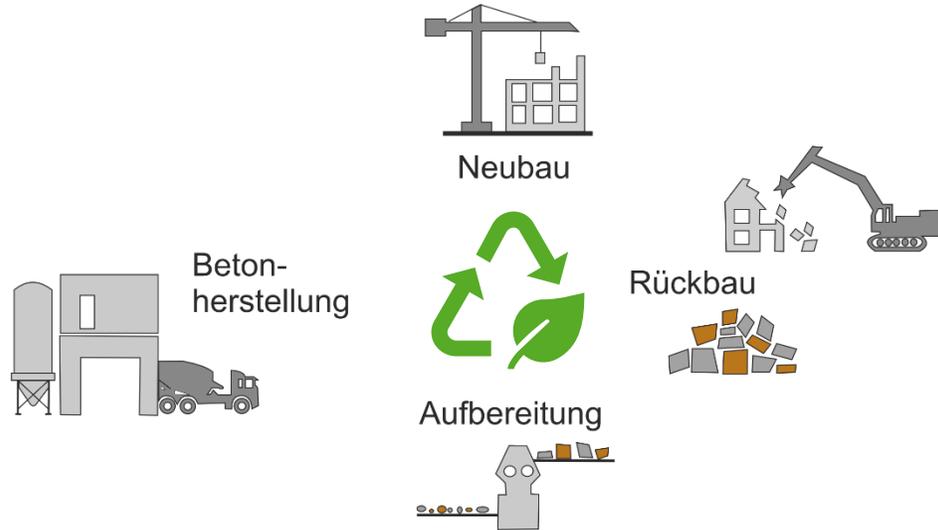
Hochleistungsmaterialien

Neue Bewehrungskonzepte (Textilbeton/Carbonbeton)



Hochleistungsmaterialien

Neue Betonzusammensetzungen (R-Beton, CO₂-reduzierte Zemente)



Strukturleichtbau

Lastangepasste Materialkonzentration



Krümmen / Falten

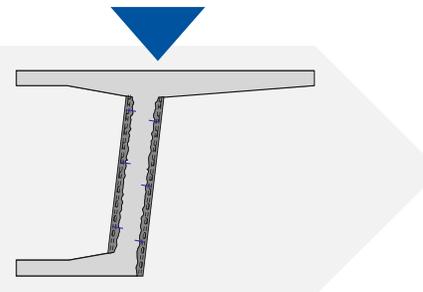
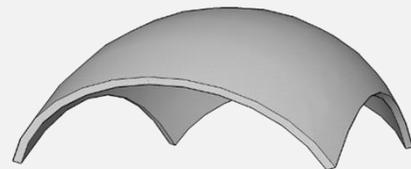
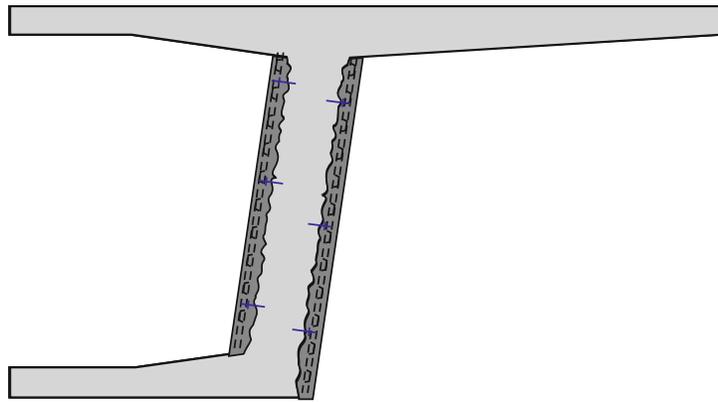


Aufgelöste Strukturen



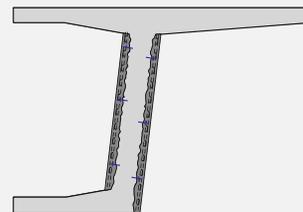
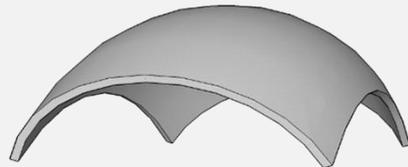
Verstärken, Weiternutzen, Wiedernutzen

Brückenverstärkung



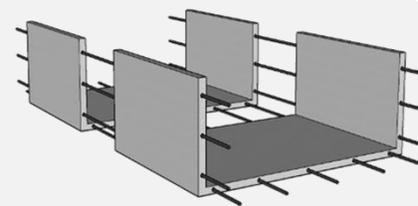
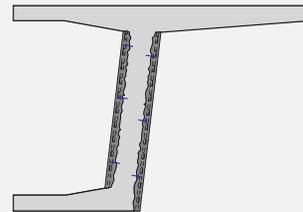
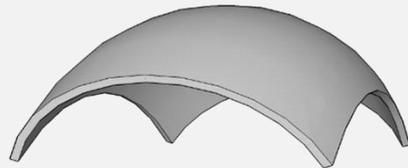
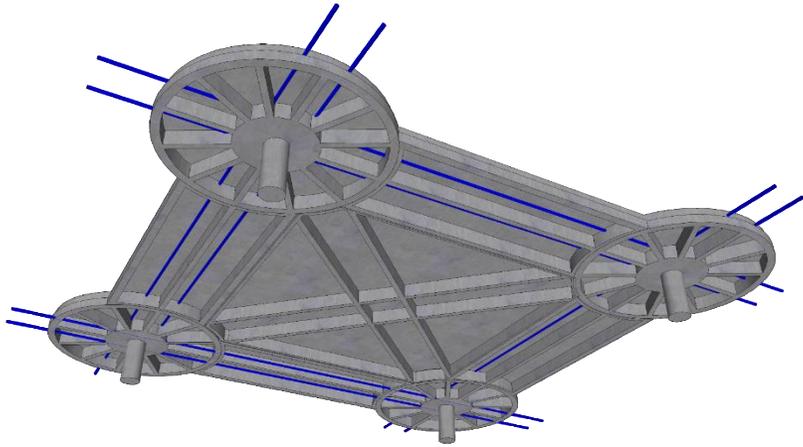
Verstärken, Weiternutzen, Wiedernutzen

Reuse



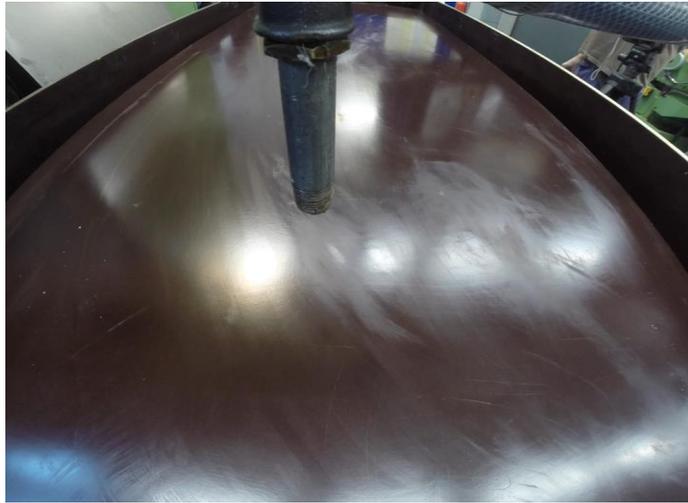
Modulares Bauen

Fertigteilkonstruktionen

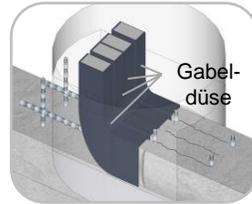


Digitale Fertigung

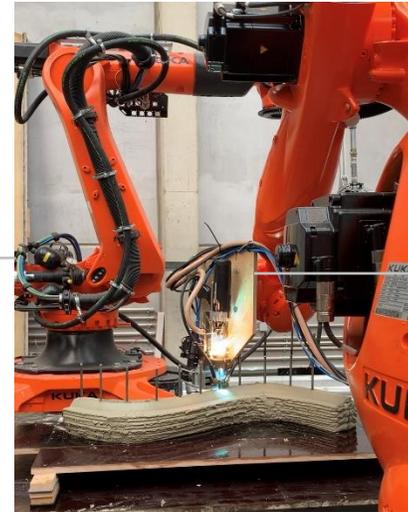
Beton 3D-Druck und Bewehrungsintegration



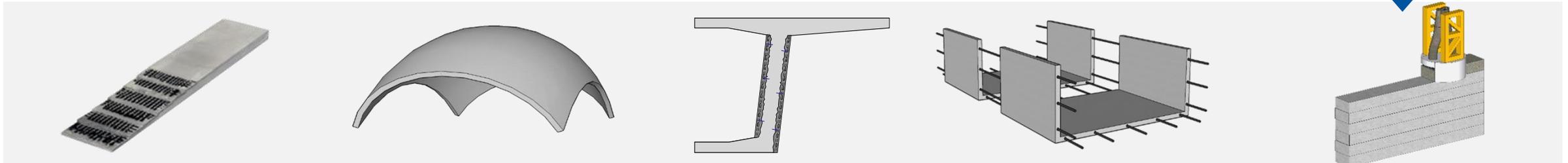
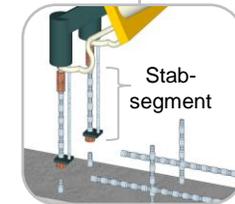
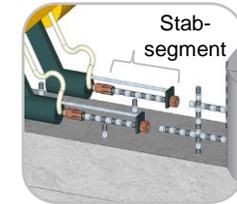
AMoRC-Prozess



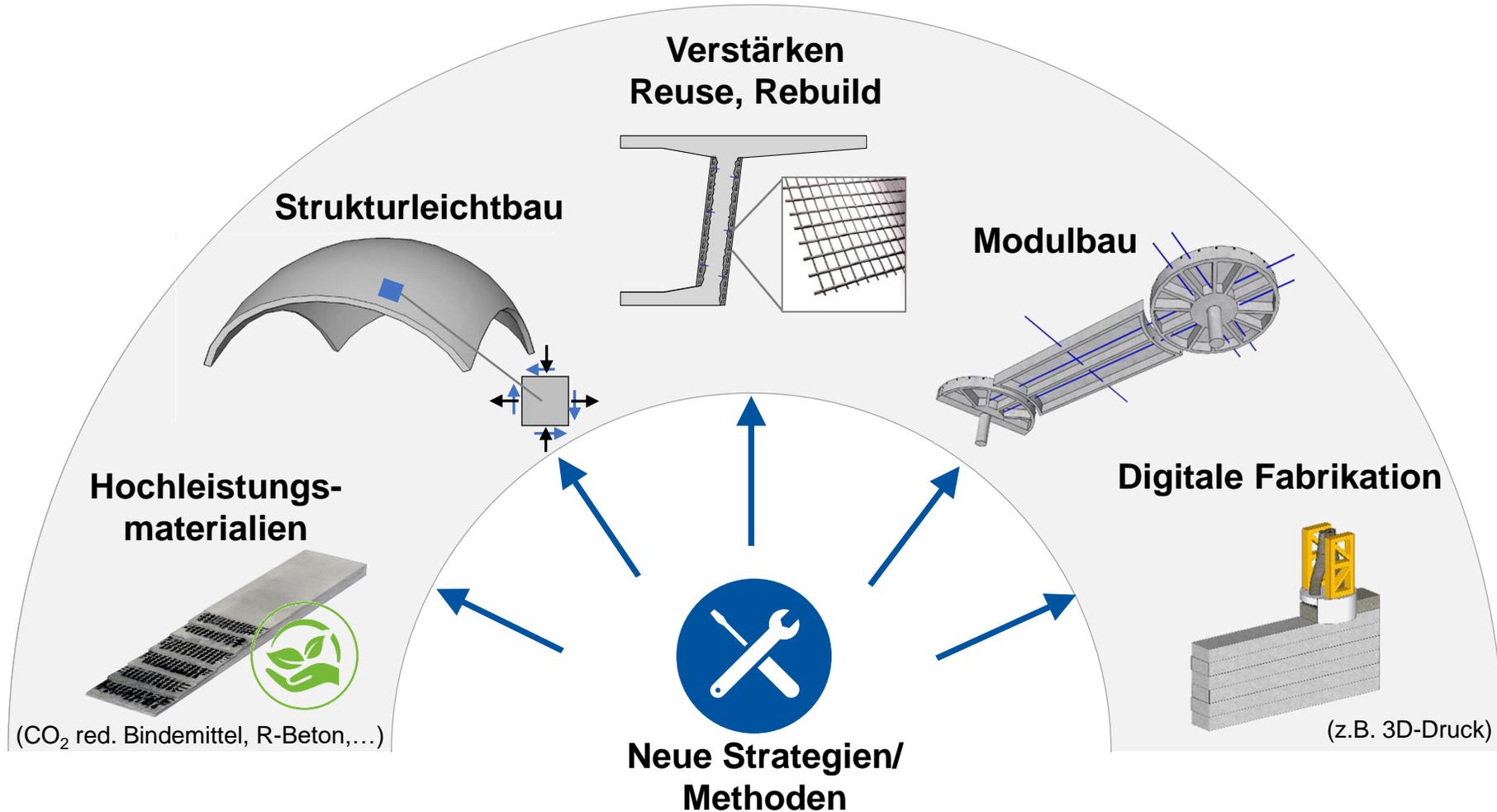
Betonextrusion



Bewehrungsschweißen



Spektrum



Problem: Fehlende Skalierbarkeit heutiger Modelle

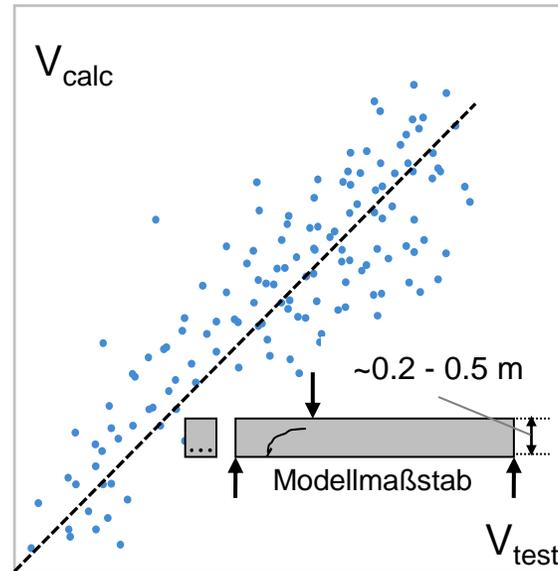
Aktuelle Bemessung

EN1992-1-1: Querkraft

$$V_{Rd,c} = C_{Rd,c} \cdot k \cdot (100 \cdot \rho_l \cdot f_{ck})^{1/3} \cdot b_w \cdot d$$

- k Maßstabsfaktor
- ρ_l Bewehrungsgrad
- f_{ck} Betonfestigkeit
- b_w Bauteilbreite
- d Statische Höhe

Versuchsdatenbank



Ingenieurbauwerke im Realmaßstab



- Ohne mechanischen Hintergrund/ Vernachlässigung wesentlicher Parameter
- Vollempirisch, durch Regressionsanalyse an Versuchsdaten abgeleitet

Problem: Fehlende Skalierbarkeit heutiger Modelle

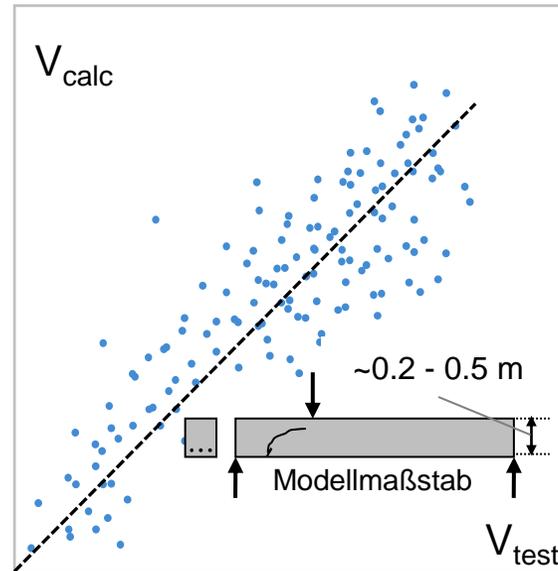
Aktuelle Bemessung

EN1992-1-1: Querkraft

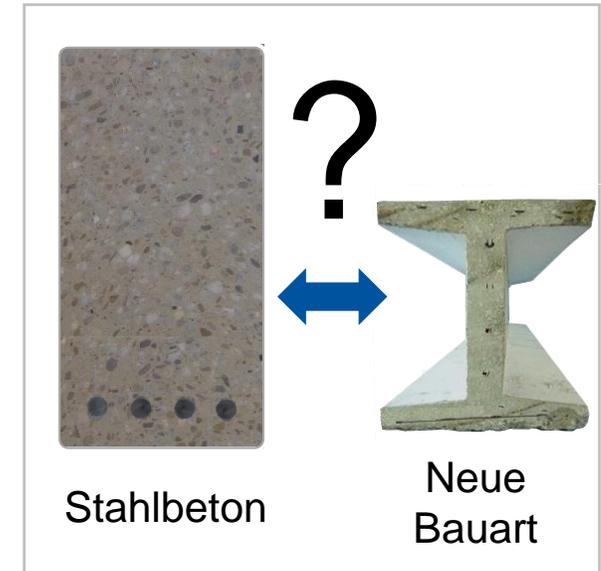
$$V_{Rd,c} = C_{Rd,c} \cdot k \cdot (100 \cdot \rho_l \cdot f_{ck})^{1/3} \cdot b_w \cdot d$$

- k Maßstabsfaktor
- ρ_l Bewehrungsgrad
- f_{ck} Betonfestigkeit
- b_w Bauteilbreite
- d Statische Höhe

Versuchsdatenbank



Änderung Material/ Geometrie



- Ohne mechanischen Hintergrund/ Vernachlässigung wesentlicher Parameter
- Vollempirisch, durch Regressionsanalyse an Versuchsdaten abgeleitet

→ Nicht skalierbar über den experimentell abgesicherten Bereich hinaus!

■ Zukunftsthemen im Massivbau

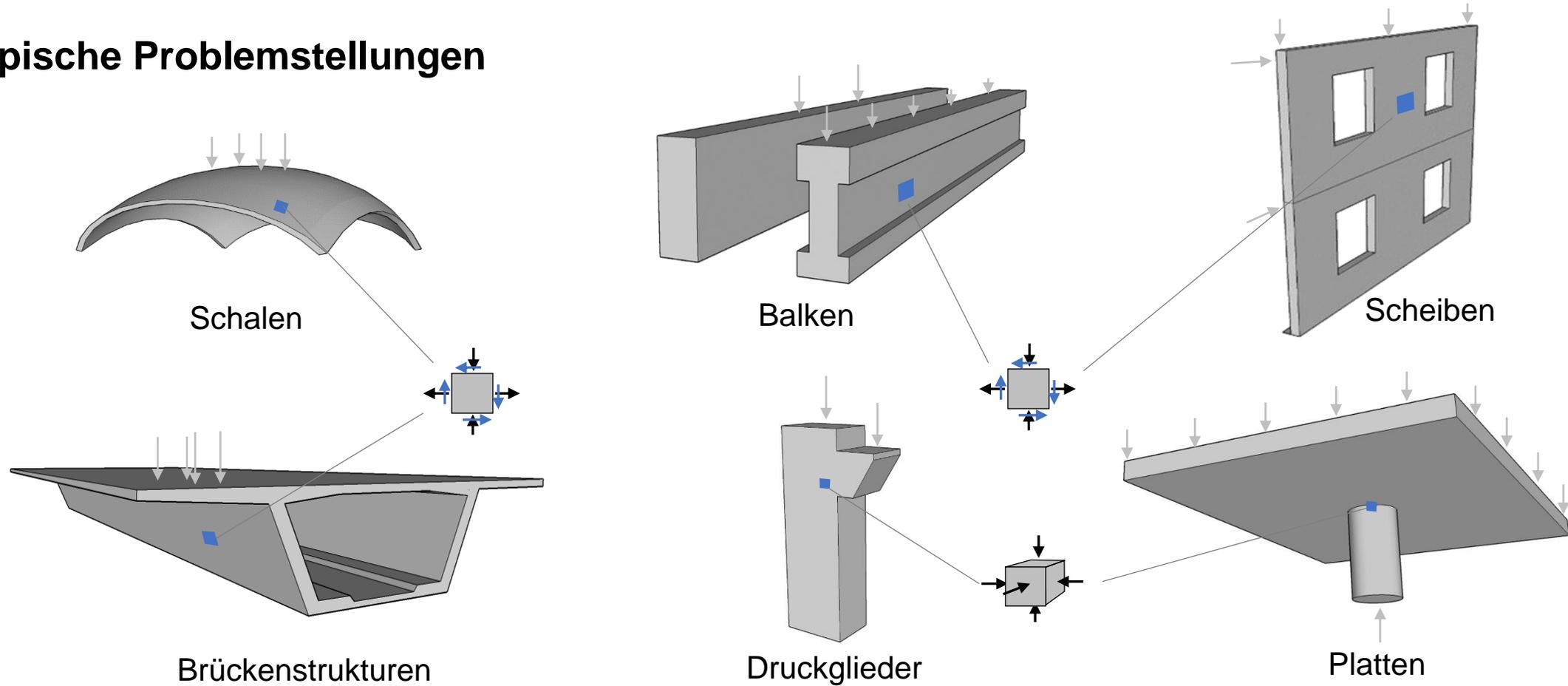
■ **Mechanische Modelle**

■ Charakterisierungsmethoden

■ Zusammenfassung - Methodik

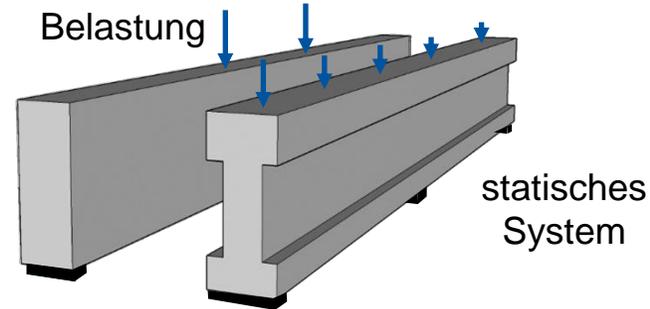
■ Ausblick

Typische Problemstellungen

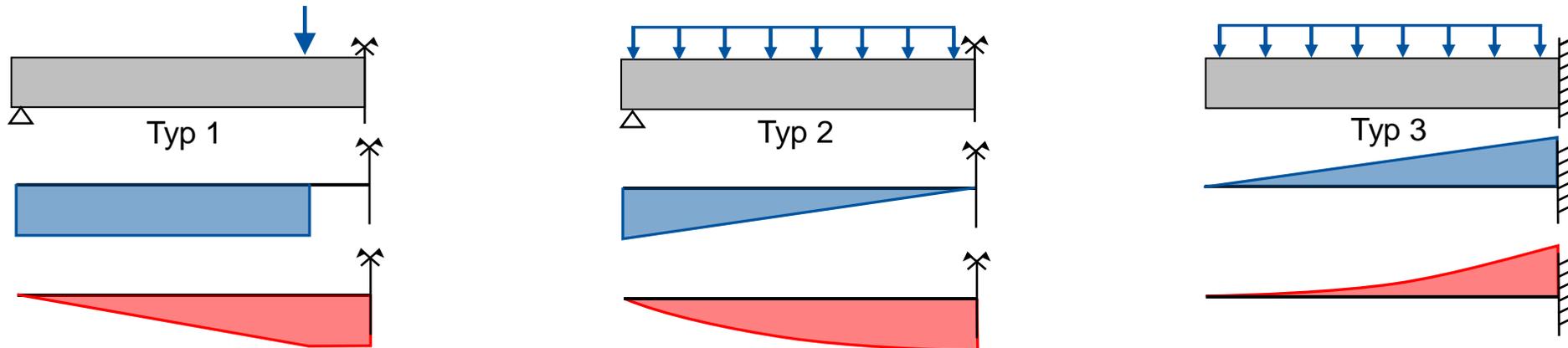


Lösung: mechanisch-physikalisch basierte Modelle

Anforderungen (1) - Gleichgewicht -



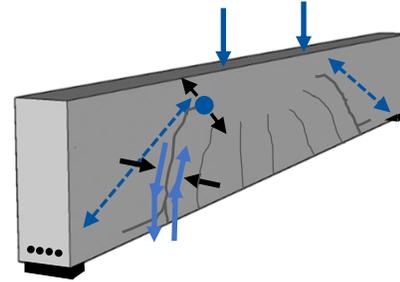
Interaktion von Schnittgrößen



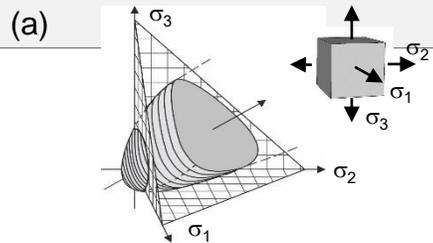
Reissen, K., **Classen, M.**, & Hegger, J. (2018). Shear in reinforced concrete slabs—Experimental investigations in the effective shear width of one-way slabs under concentrated loads and with different degrees of rotational restraint. *Structural Concrete*, 19(1), 36-48.

Anforderungen (2) - Konstitutives Verhalten -

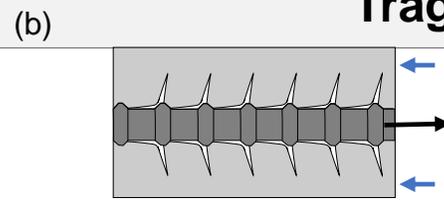
ohne Querkraftbewehrung



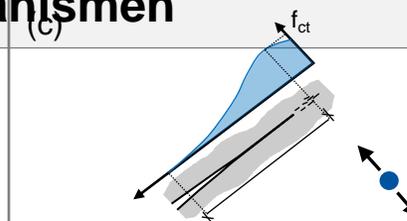
Tragmechanismen



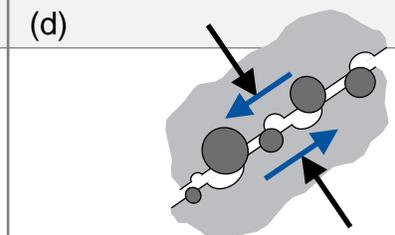
(a) Kontinuum (ungerissen)



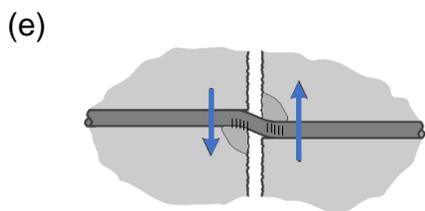
(b) Verbund



(c) Nachrisszugfestigkeit

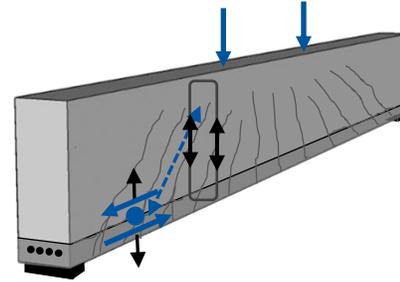


(d) Rissreibung



(e) Dübelwirkung

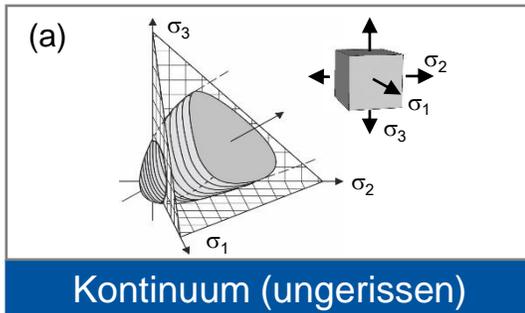
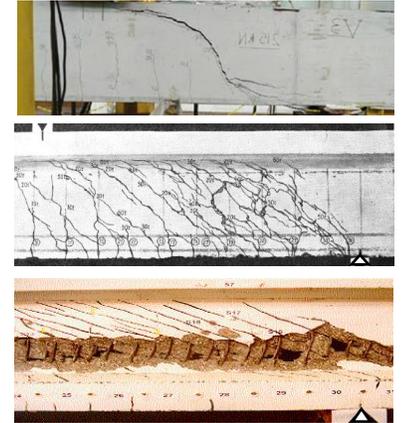
Anforderungen (2) - Konstitutives Verhalten -



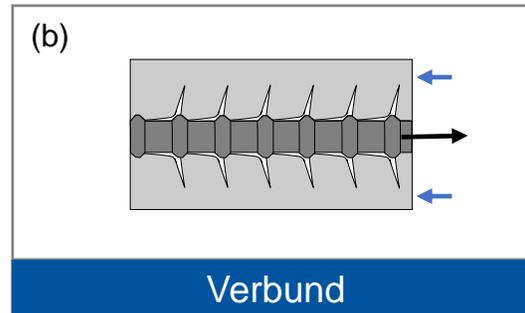
ohne Querkraftbewehrung

$$\rho_w / \rho_{w,\min} = 10,5$$

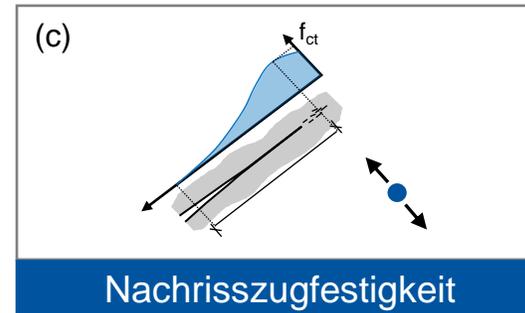
$$\rho_w / \rho_{w,\min} = 22,8$$



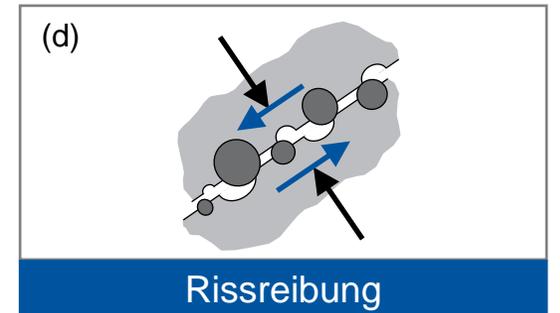
Kontinuum (ungerissen)



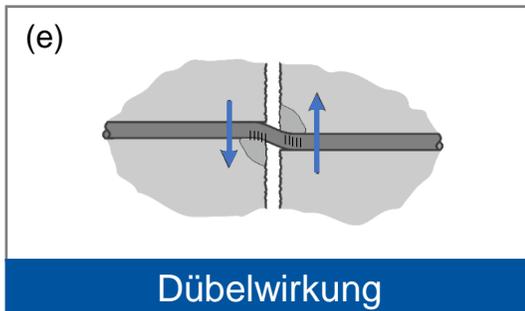
Verbund



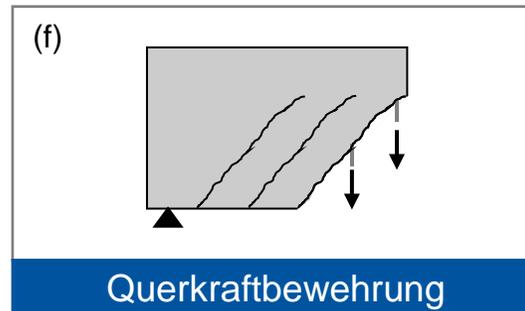
Nachrisszugfestigkeit



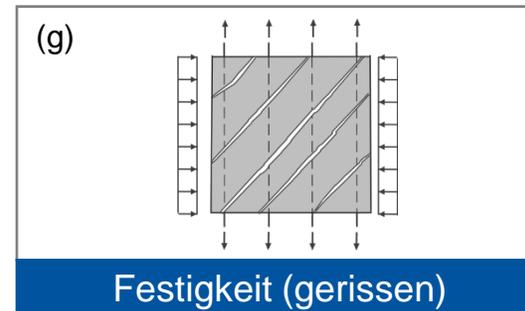
Rissreibung



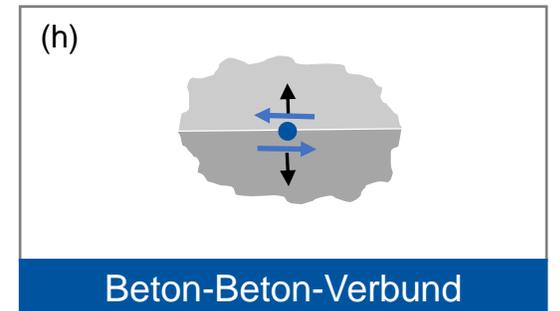
Dübelwirkung



Querkraftbewehrung

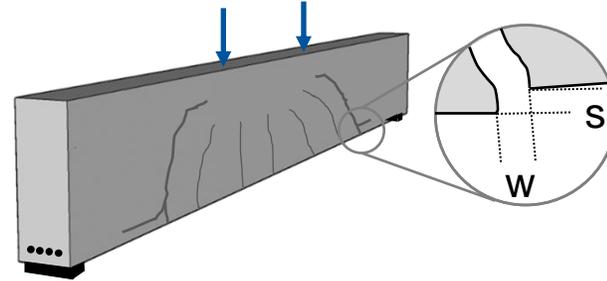


Festigkeit (gerissen)

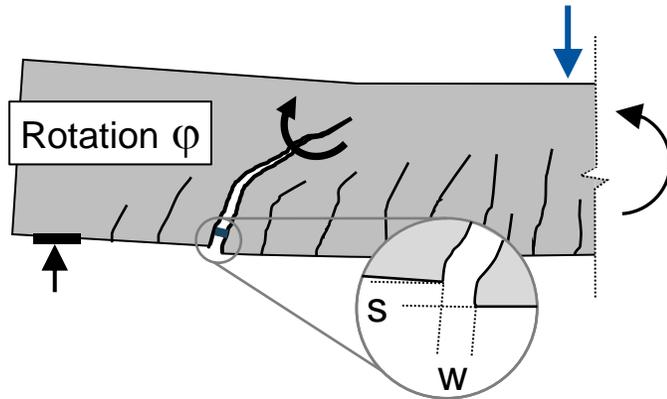


Beton-Beton-Verbund

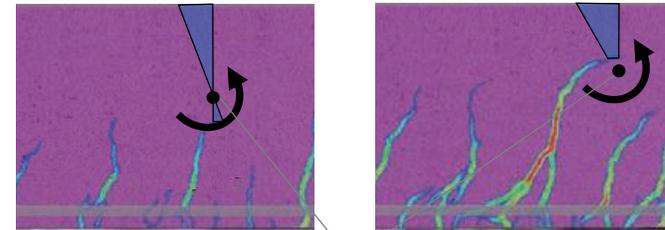
Anforderungen (3) - Kinematik -



Kompatibilität der Verformungen



Freiheitsgrade

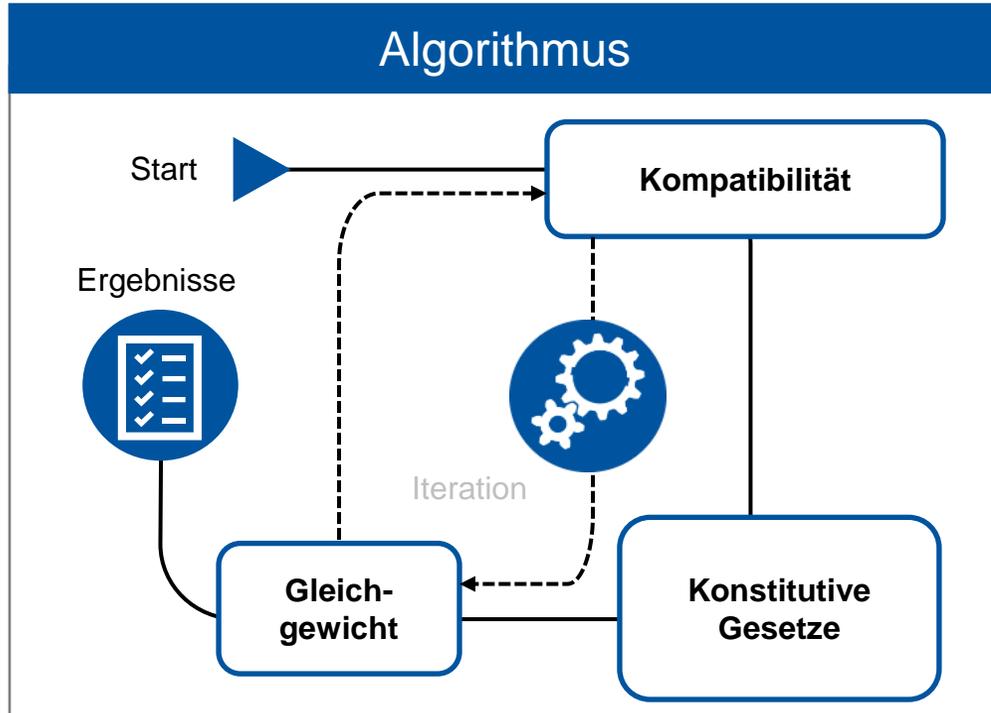


Rotationspunkt

Rissfortschritt

Herbrand, M., Kueres, D., **Classen, M.**, & Hegger, J. (2018). *Experimental Investigations on the Shear Capacity of Prestressed Concrete Continuous Beams with Rectangular and I-Shaped Cross-Sections*. *High Tech Concrete: Where Technology and Engineering Meet* (pp. 658-666), Springer, Cham.

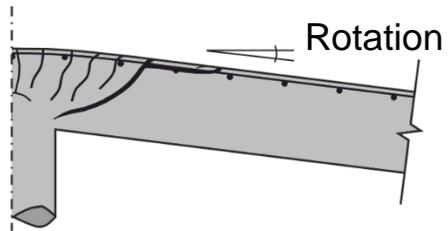
Modellentwicklung



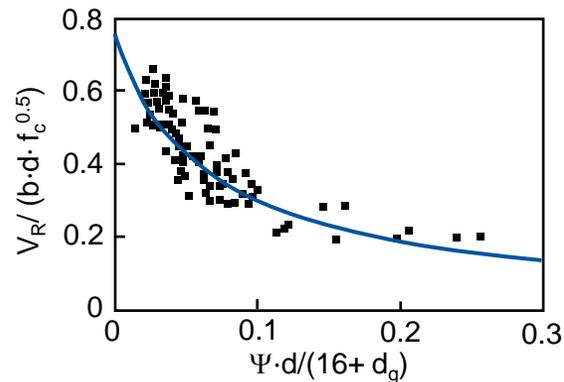
Classen, M. (2020). Shear Crack Propagation Theory (SCPT)–The mechanical solution to the riddle of shear in RC members without shear reinforcement. Engineering Structures, 210, 110207.

Stand der Forschung

High-End Durchstanzmodelle



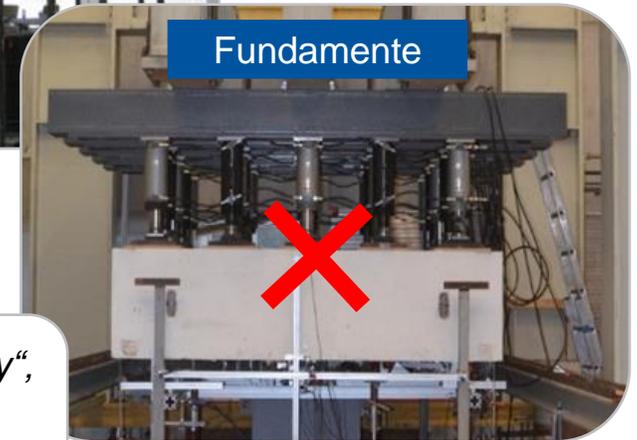
- Starke Vereinfachung der Kinematik



- Verwendung empirischer Bruchkriterien



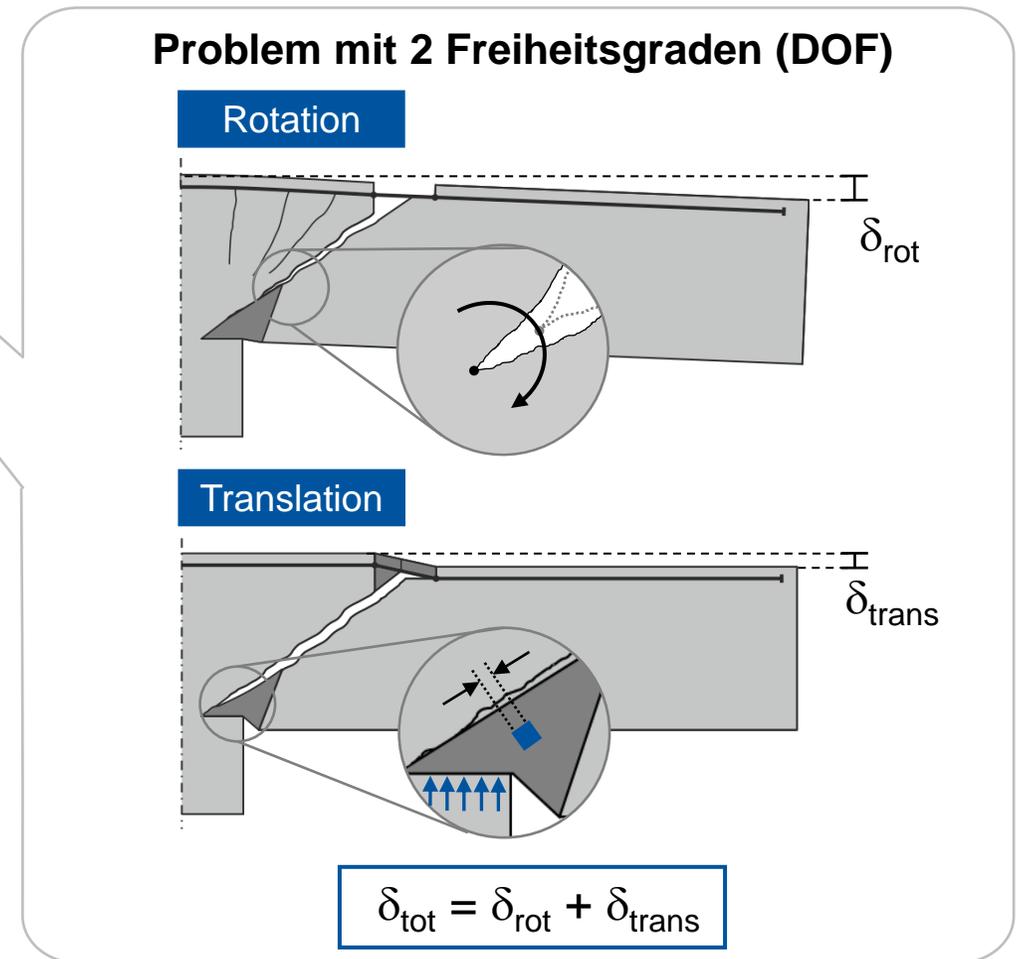
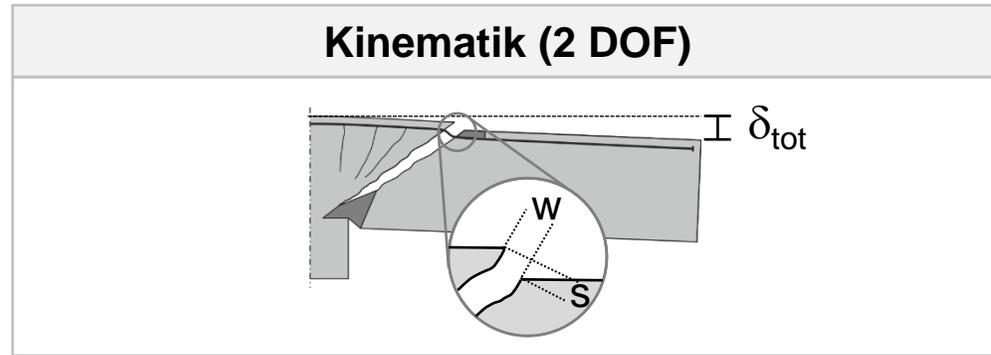
Flachdecken



Fundamente

z.B. "Critical Shear Crack Theory",
Muttoni (2008);
"Punching Shear Model",
Mari & Cladera (2018)

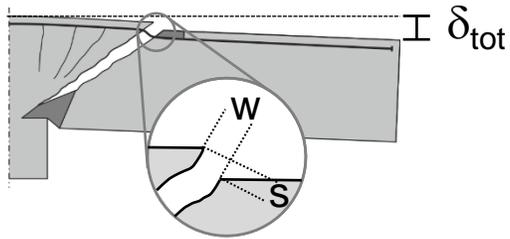
Mechanische Modelle – Punching Shear Response Theory (PSRT)



Kueres, D., Ricker, M., **Classen, M.**, & Hegger, J. (2018). Fracture kinematics of reinforced concrete slabs failing in punching. *Engineering Structures*, 171, 269-279.

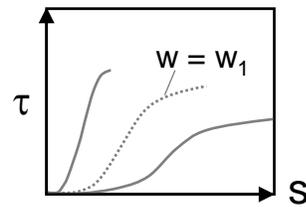
Mechanische Modelle – Punching Shear Response Theory (PSRT)

Kinematik (2 DOF)

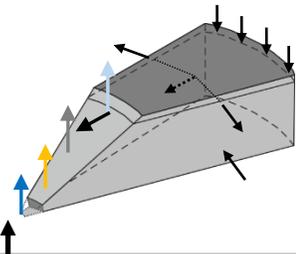


Konstitutive Gesetze

Druckring (db)
Rissreibung (ai)
Dübelwirkung (da)
Risspitze (rts)



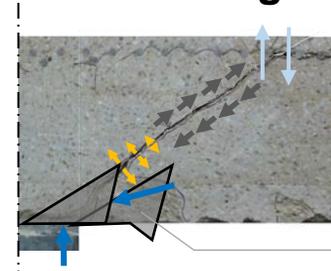
Gleichgewicht



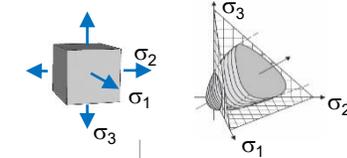
$$\Sigma V = 0$$

$$\Sigma M = 0$$

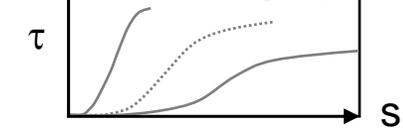
Tragmechanismen



Druckring (db)



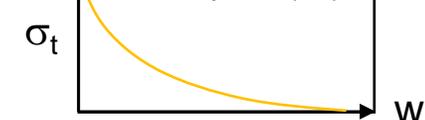
Rissreibung (ai)



Dübelwirkung (da)



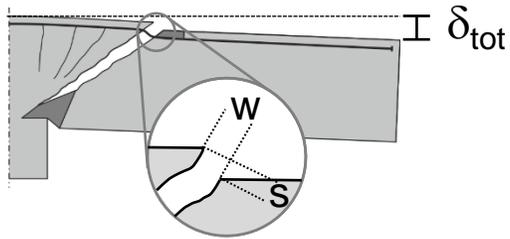
Risspitze (rts)



Ungermann, J. & Classen, M. (2020). Fictitious Rough Crack Model (FRCM): A Smeared Crack Modelling Approach to Account for Aggregate Interlock and Mixed Mode Fracture of Plain Concrete. *Materials*, 13(12), 2774.

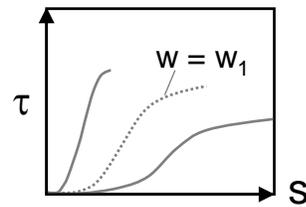
Mechanische Modelle – Punching Shear Response Theory (PSRT)

Kinematik (2 DOF)

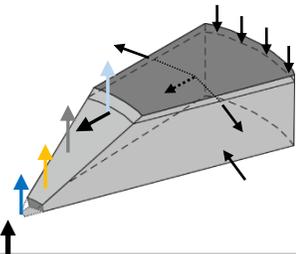


Konstitutive Gesetze

Druckring (db)
Rissreibung (ai)
Dübelwirkung (da)
Risspitze (rts)



Gleichgewicht



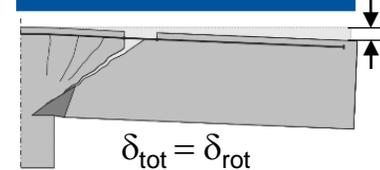
$$\Sigma V = 0$$

$$\Sigma M = 0$$

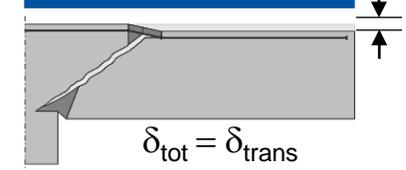
Lösungsstrategie

$$\text{Vorgabe: } \delta_{tot} = \delta_{rot} + \delta_{trans}$$

pure Rotation



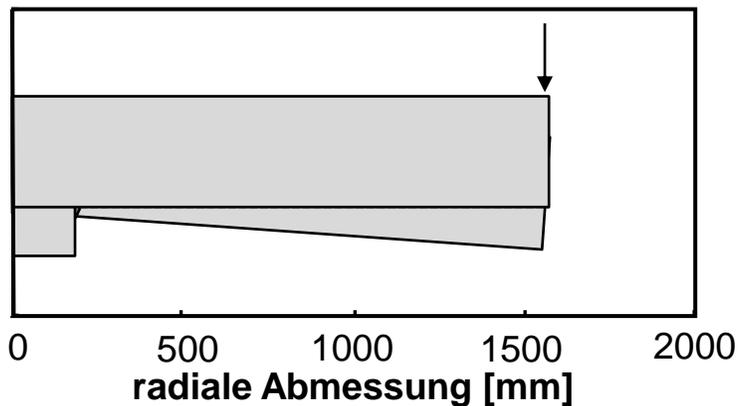
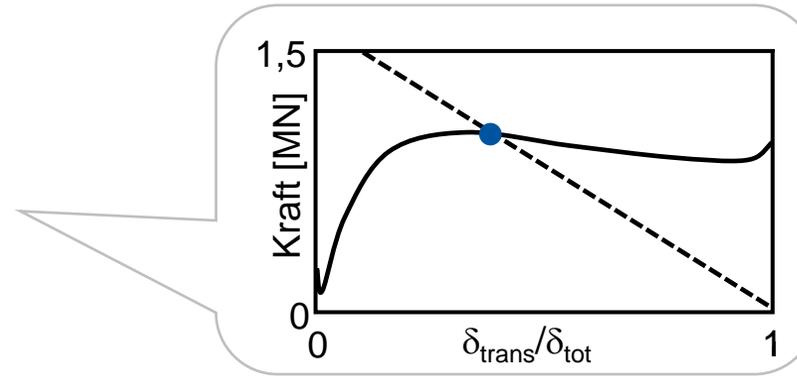
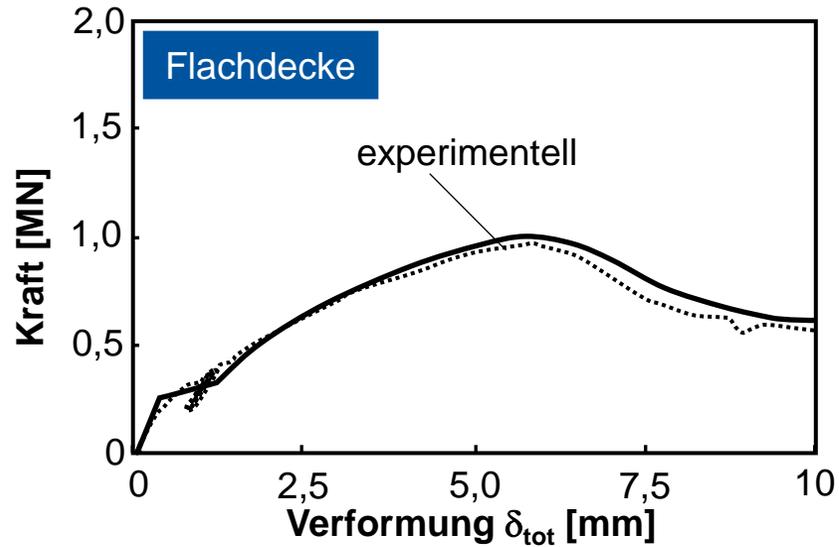
pure Translation



Classen, M., & Kalus, M. (2023). *Punching Shear Response Theory (PSRT)—A two degree of freedom kinematic theory for modeling the entire punching shear vs. deformation response of RC slabs and footings.* *Engineering Structures*, 116197.

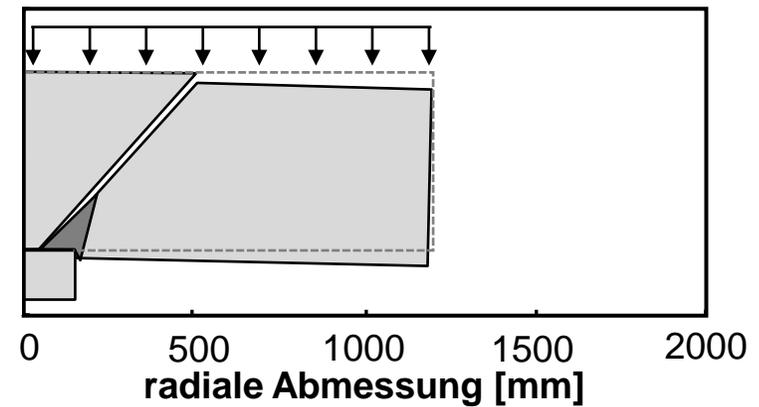
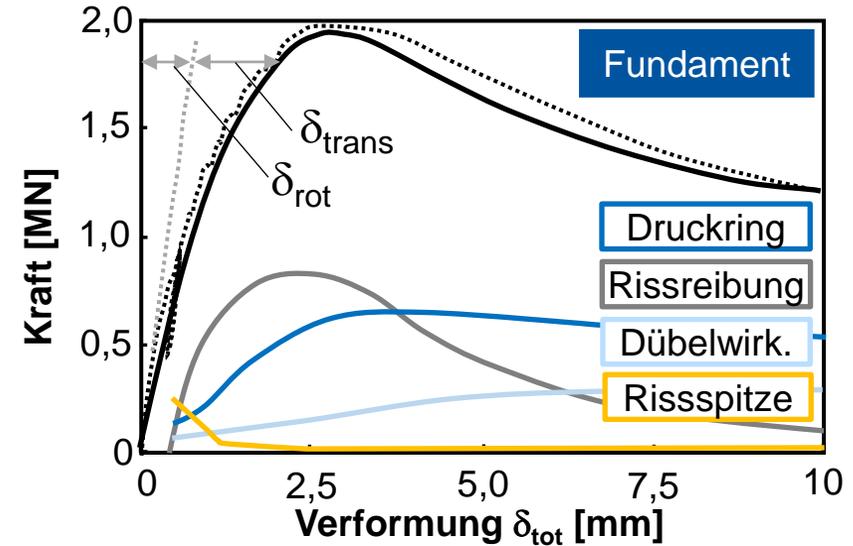
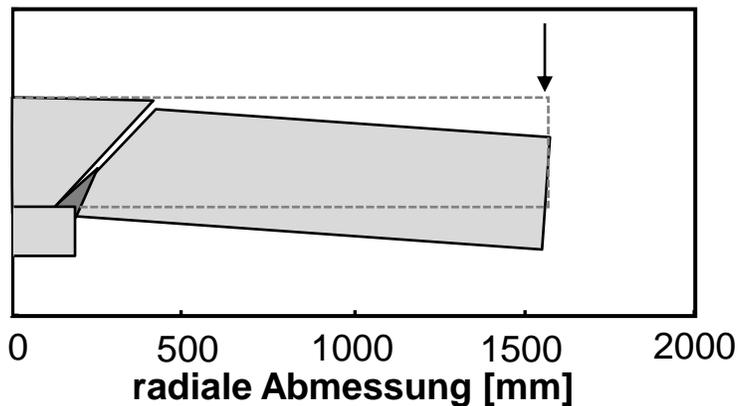
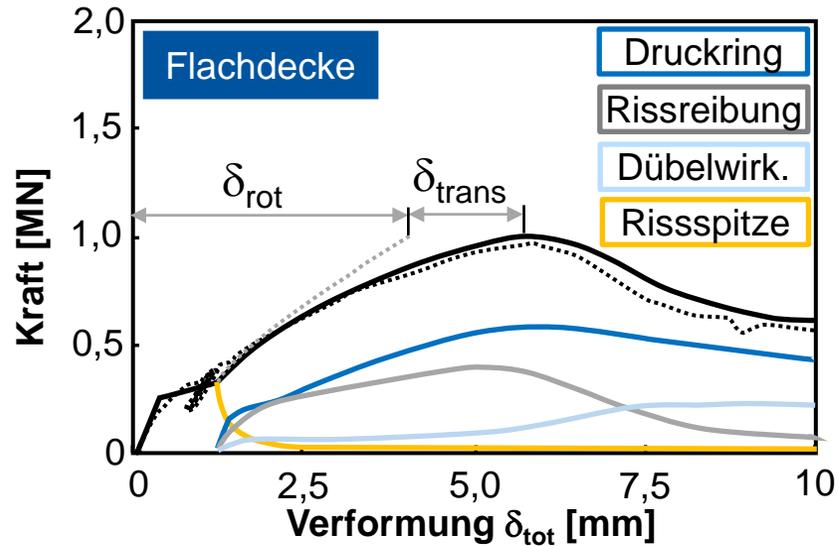
Mechanische Modelle – Punching Shear Response Theory (PSRT)

Ergebnisse

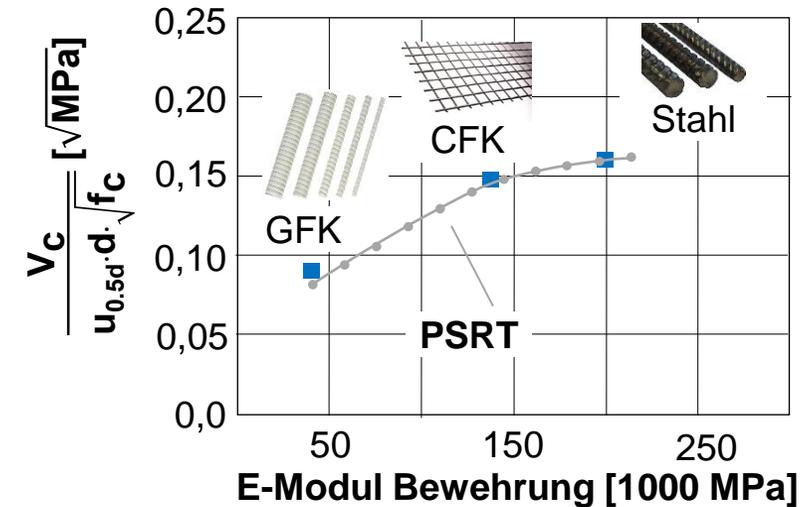
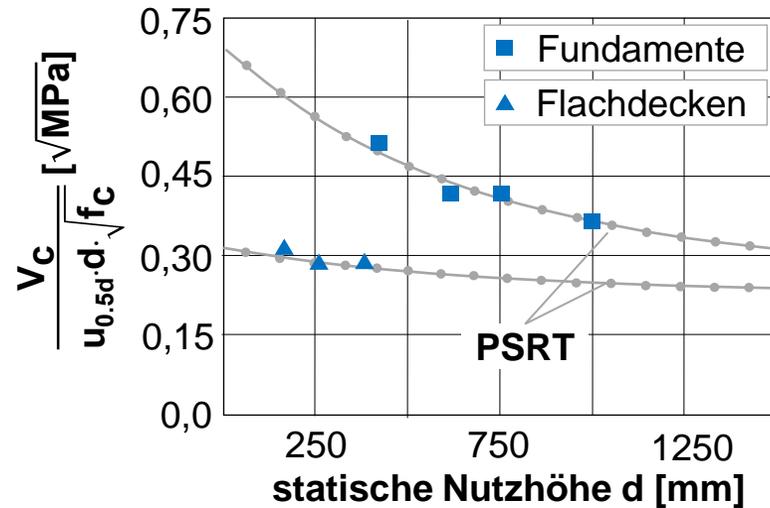


Mechanische Modelle – Punching Shear Response Theory (PSRT)

Ergebnisse



Validierung PSRT - Vergleich mit systematischen Versuchsserien



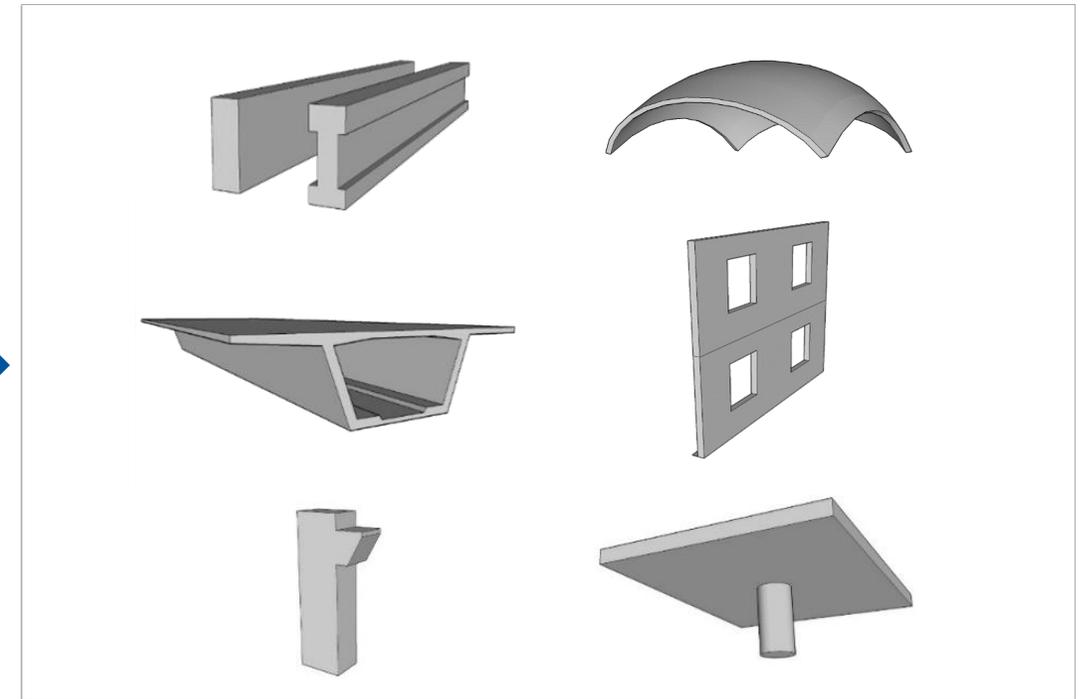
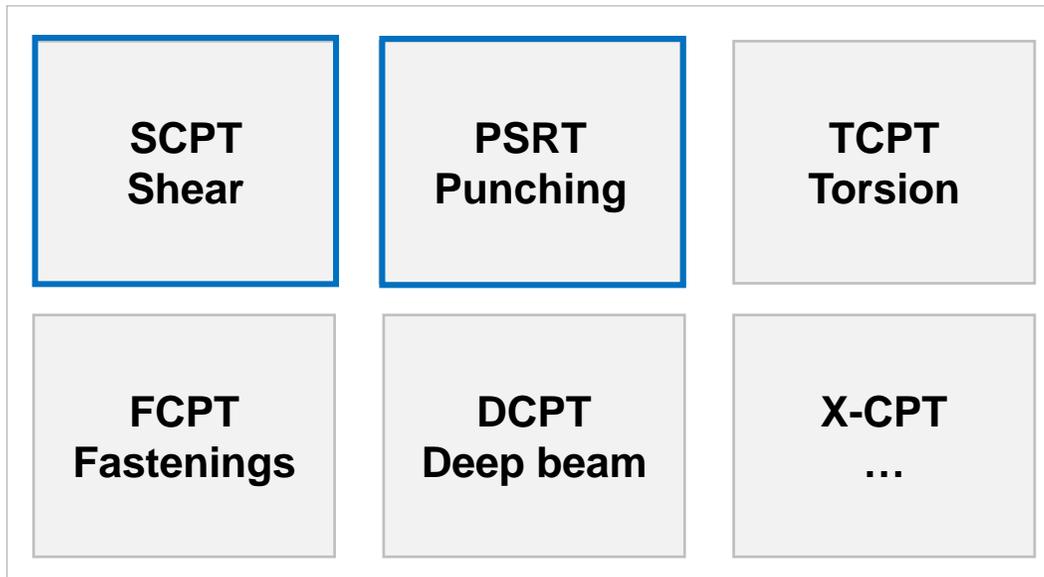
Vorteile

- Maßstabseffekt zutreffend abgebildet (skalierbar)
- übertragbar auf neue Materialien (z. B. Textilbeton, Carbonbeton, Faserbeton)

→ PSRT behebt die Schwachstellen bisheriger Durchstanzmodelle!

Vision

Mechanisch-kinematische Modelle



Classen, M. (2020). Shear Crack Propagation Theory (SCPT)–The mechanical

- **Vision:** Neue, nachhaltige Modellierungsstrategie für den gesamten Massivbau & skalierbar auf Bauweisen der Zukunft

■ Zukunftsthemen im Massivbau

■ Mechanische Modelle

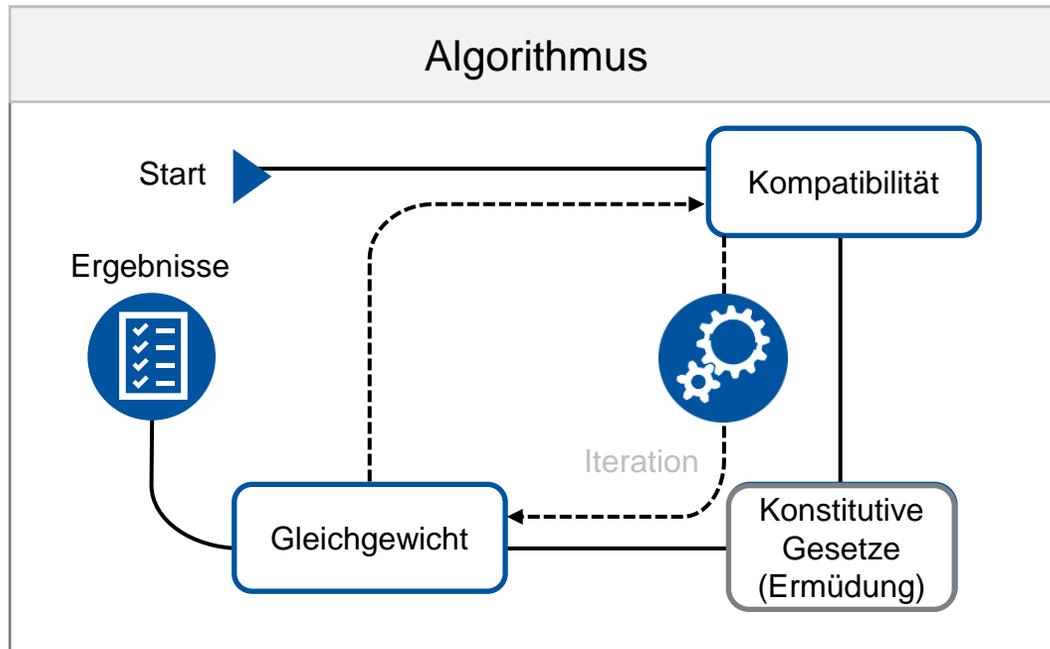
■ **Charakterisierungsmethoden**

■ Zusammenfassung - Methodik

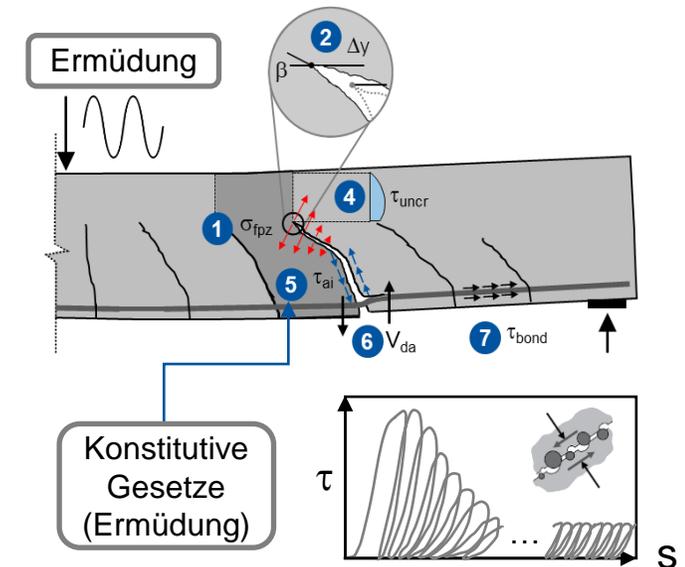
■ Ausblick

Forschungslücke

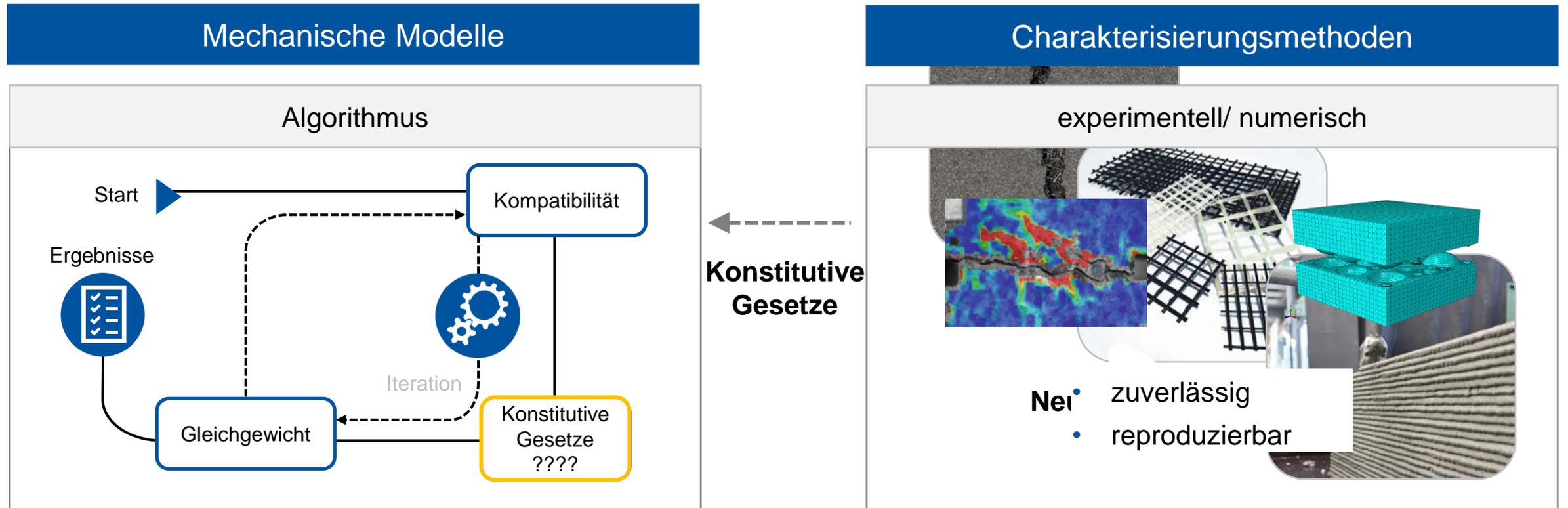
Mechanische Modelle



Shear crack propagation theory SCPT



Forschungslücke

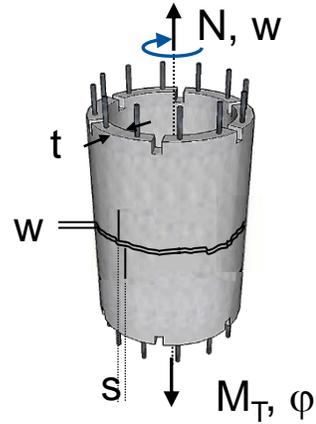
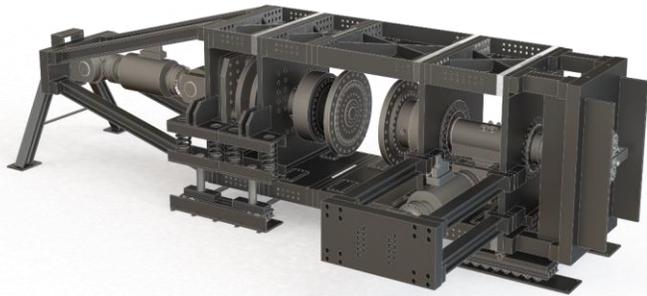


- **Ziel:** Neue, verbesserte Methoden zur maßgeschneiderten Charakterisierung konstitutiver Gesetze

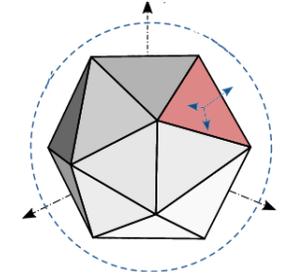
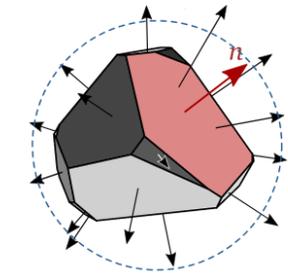
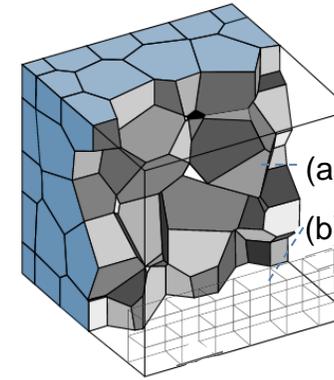
Zusammenfassung - Methodik

Experimente

Mesoskala



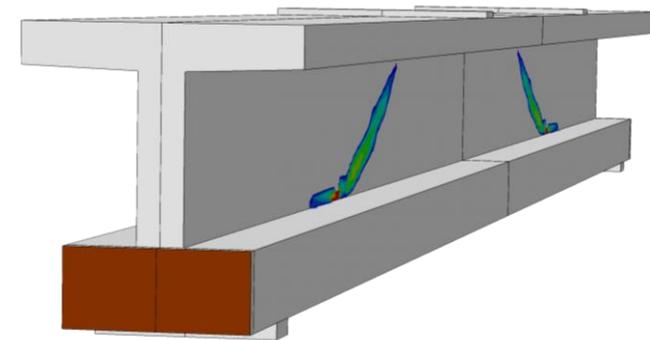
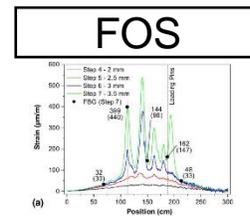
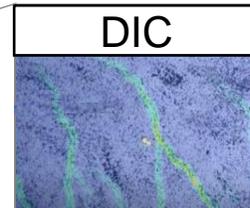
Simulation



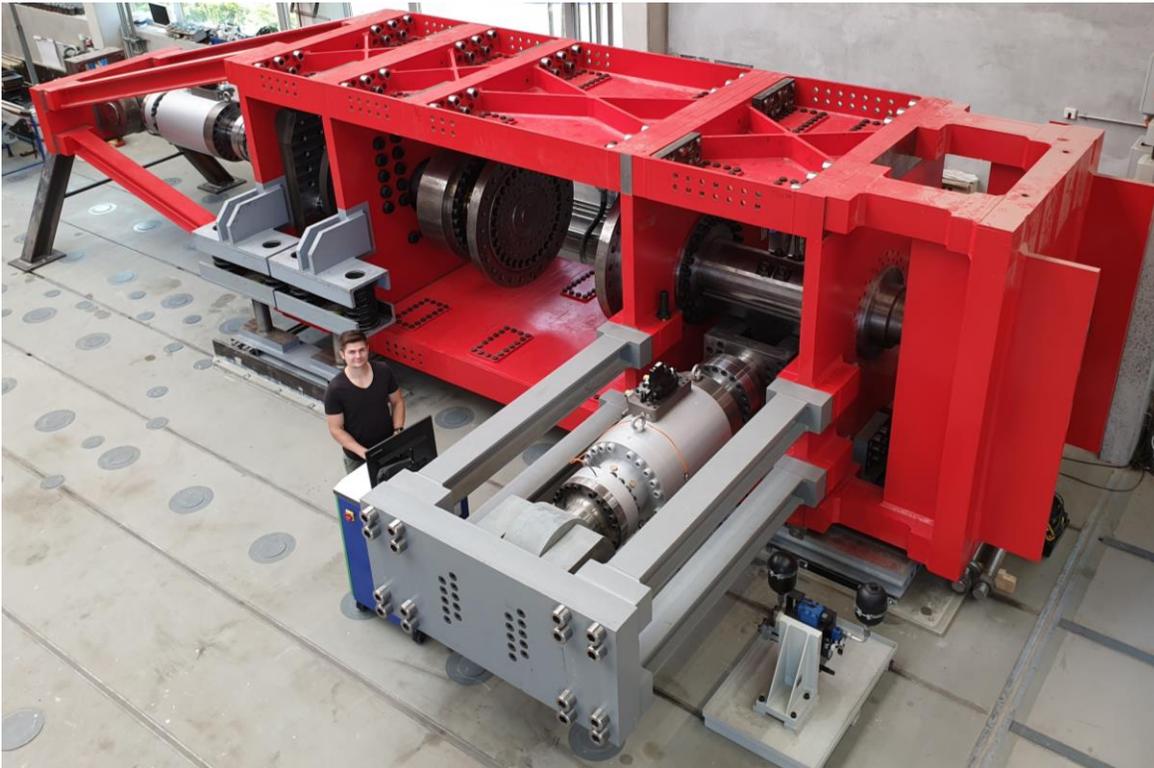
(a) discrete model

(b) microplane model

Makroskala

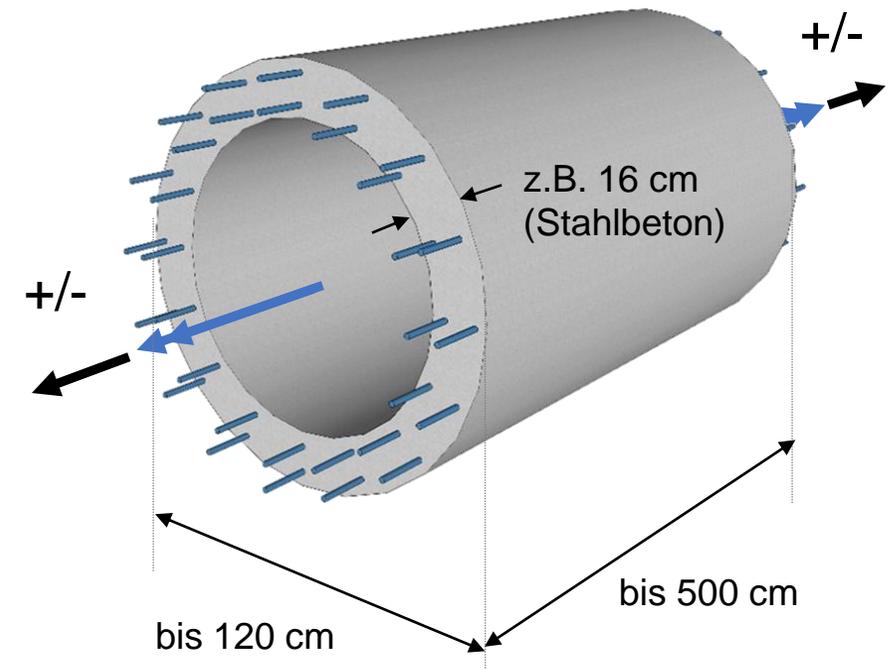


TORAX - Torsions- und Axialprüfmaschine



Kenndaten:

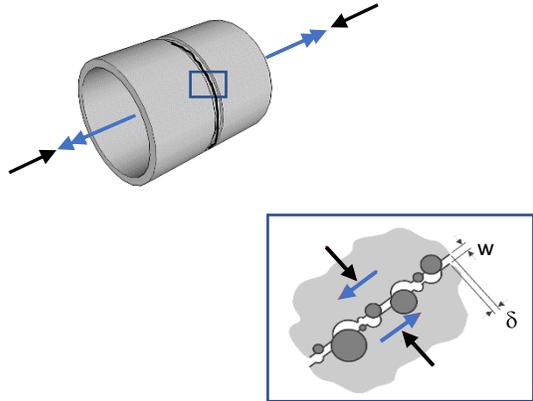
- Axiallasteinheit: 2 MN
- Torsionseinheit: 1 MNm
- Servohydraulik



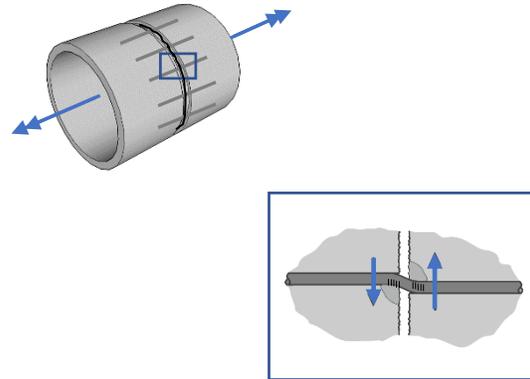
Classen, M., Adam, V., & Hillebrand, M. (2019). Torsion test setup to investigate aggregate interlock and mixed mode fracture of monolithic and 3D-printed concrete. FIB Symposium, Krakow, Poland.

Charakterisierungsmethoden

Rissreibung

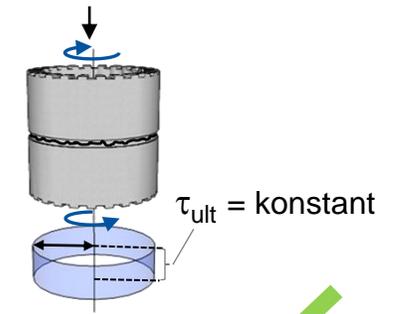
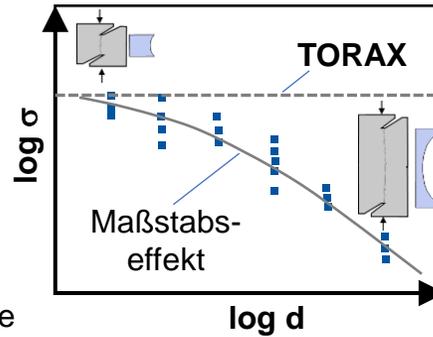
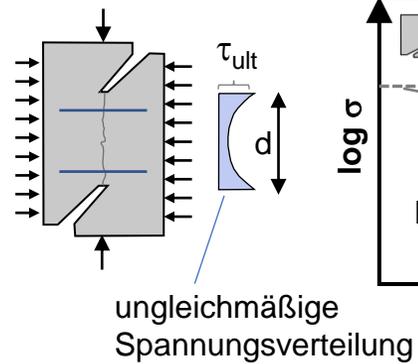


Dübelwirkung



Sagasetta (1986)

Abscherversuch

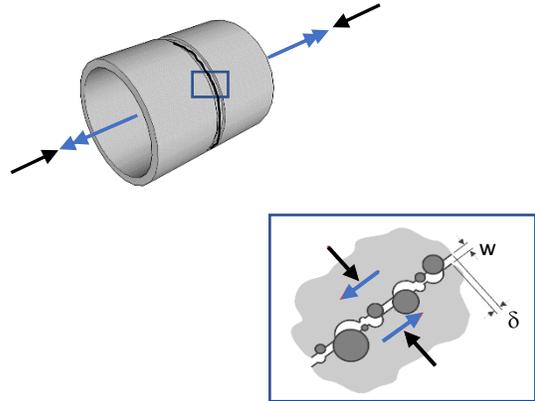


TORAX

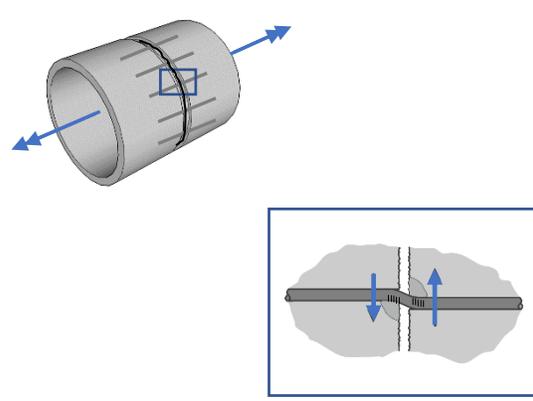


Charakterisierungsmethoden

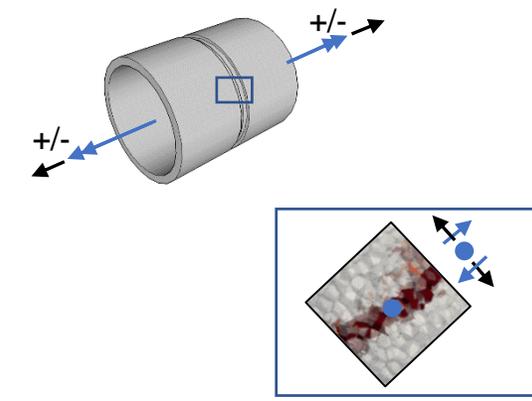
Rissreibung



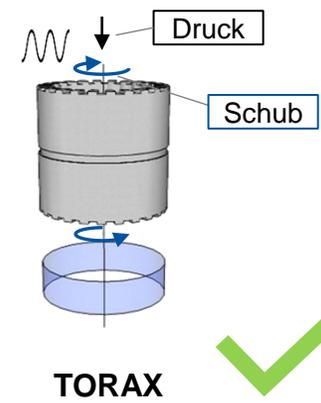
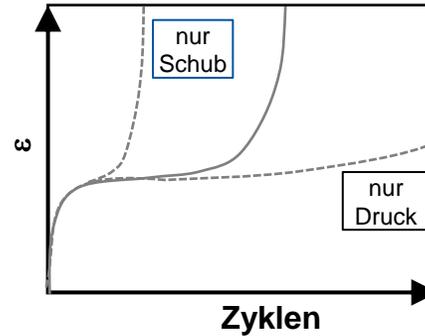
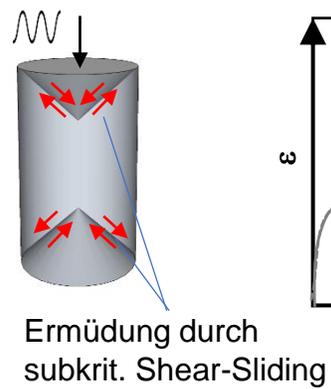
Dübelwirkung



Beton-Ermüdung

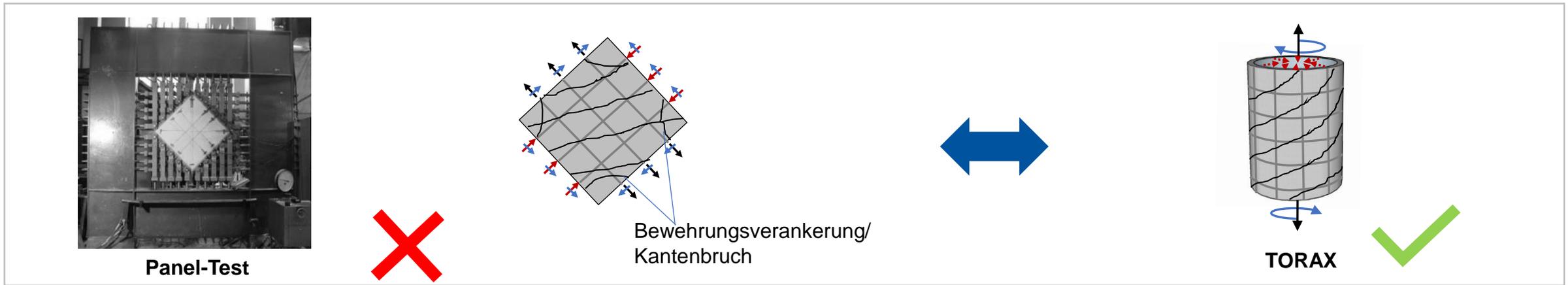
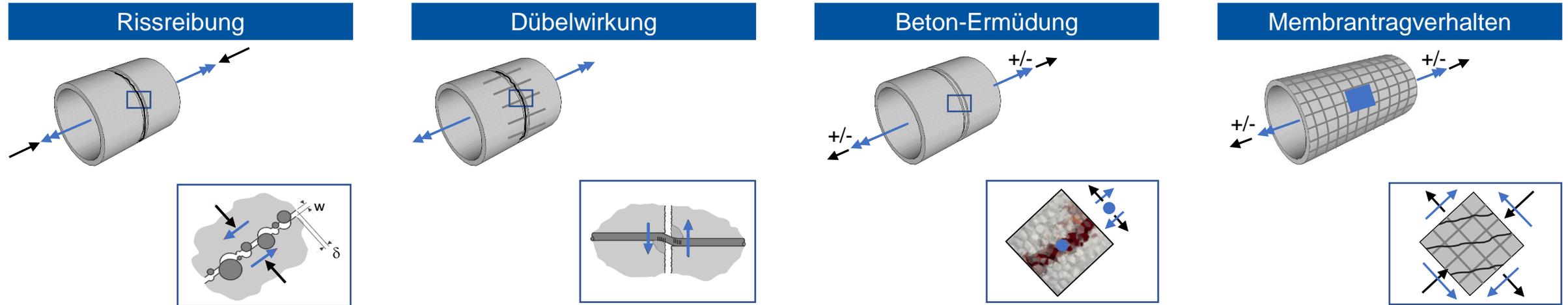


Ermüdungsversuch



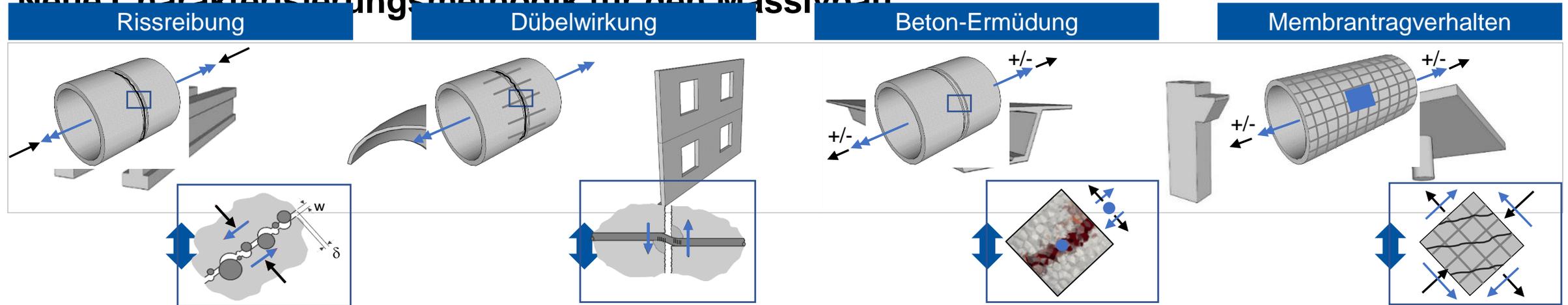
TORAX

Charakterisierungsmethoden



Charakterisierungsmethoden

Neue Charakterisierungsmethodik für den Massivbau



➔ **Prüfmaschine liefert konstitutive Gesetze (Einzelwerkstoffe/Verbundwerkstoff) für Modellentwicklung**

■ Zukunftsthemen im Massivbau

■ Mechanische Modelle

■ Charakterisierungsmethoden

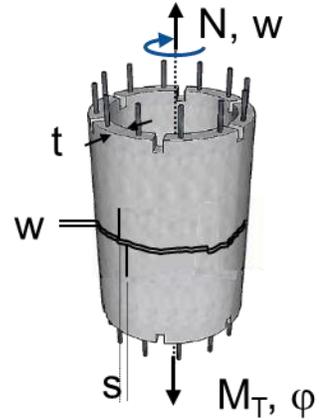
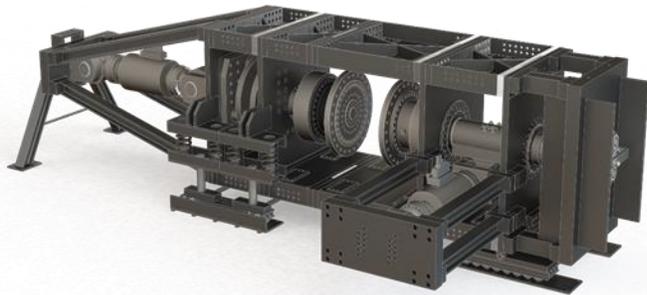
■ Zusammenfassung - Methodik

■ Ausblick

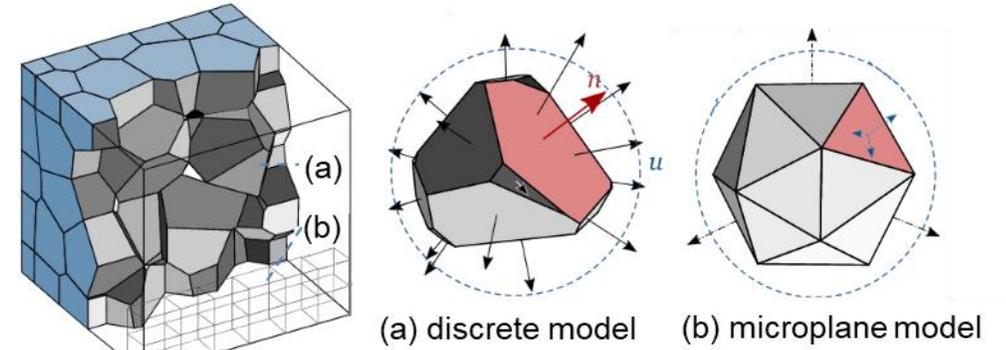
Zusammenfassung - Methodik

Experimente

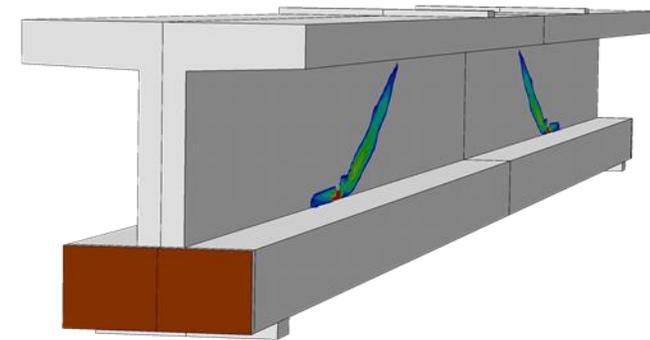
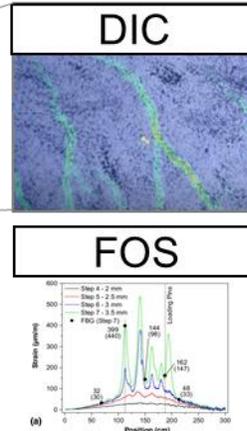
Mesoskala



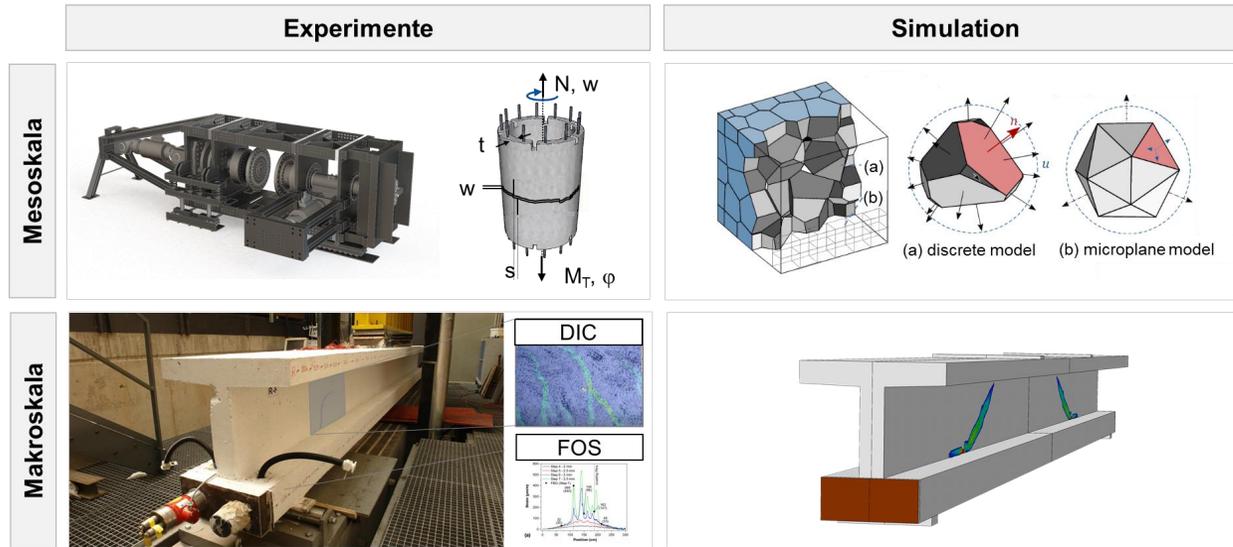
Simulation



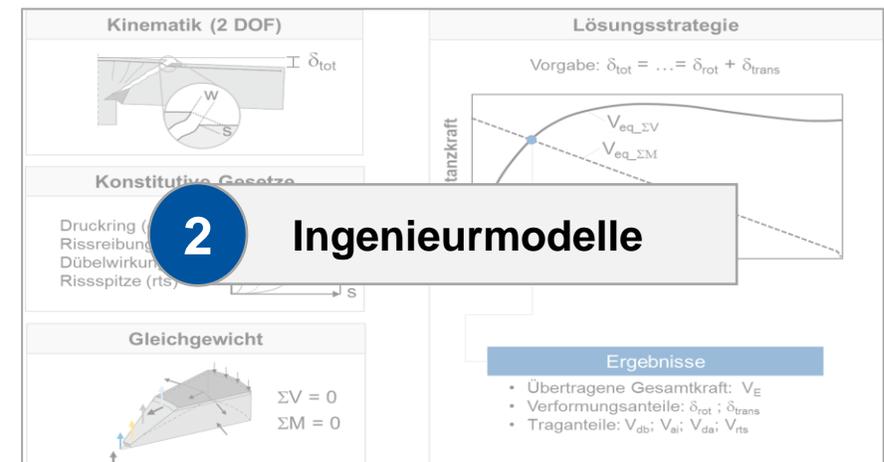
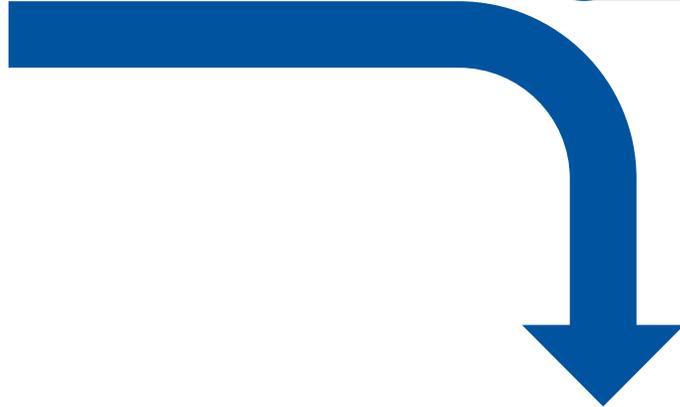
Makroskala



Zusammenfassung - Methodik



1 Charakterisierung konstitutiver Gesetze



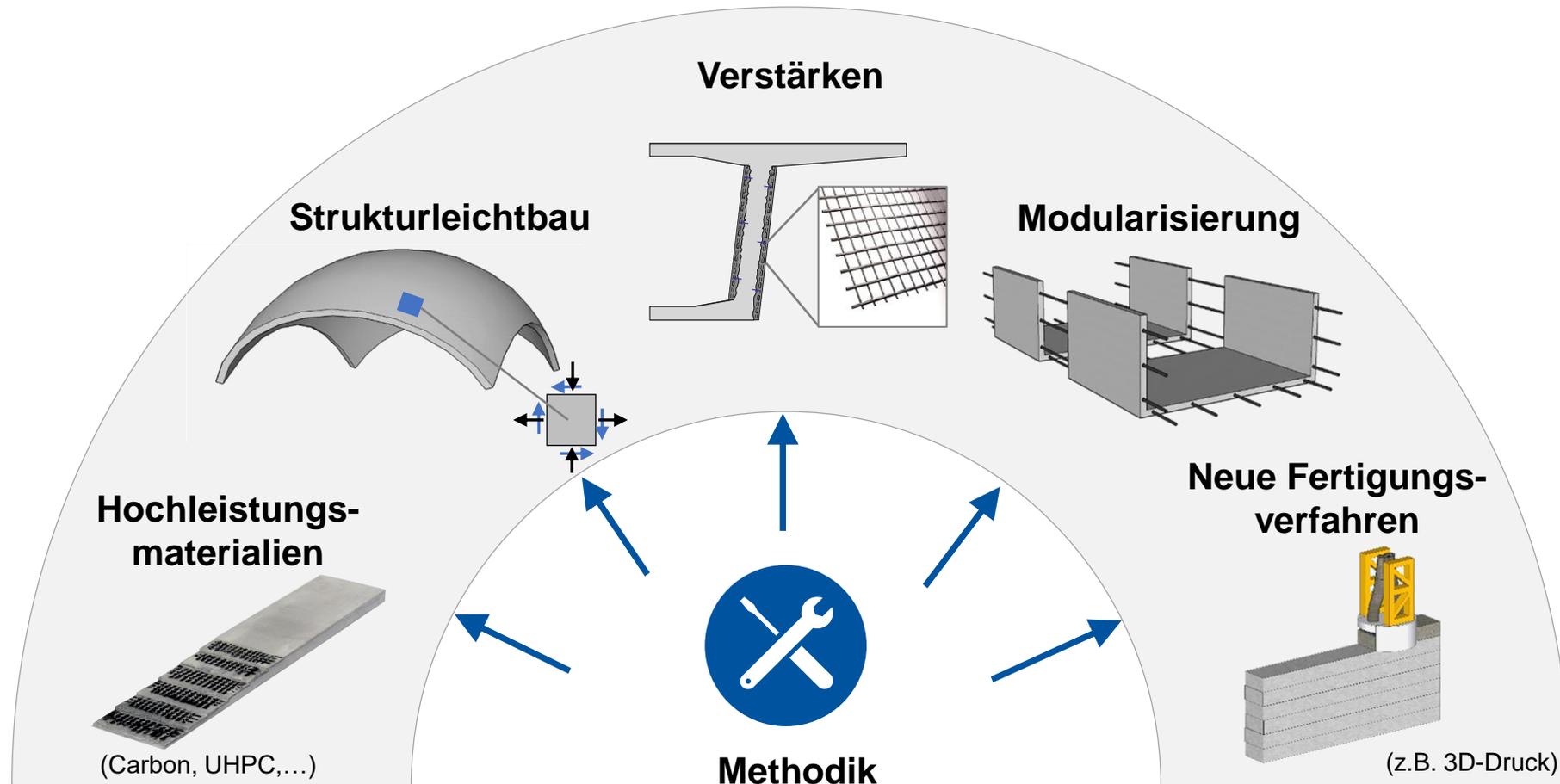
2 Ingenieurmodelle



3 Validierung (Makroskala)

4 Aufbereitung für die Praxis

Identifizierte Zukunftsthemen - Anwendungsforschung



■ Zukunftsthemen im Massivbau

■ Mechanische Modelle

■ Charakterisierungsmethoden

■ Zusammenfassung - Methodik

■ **Ausblick**

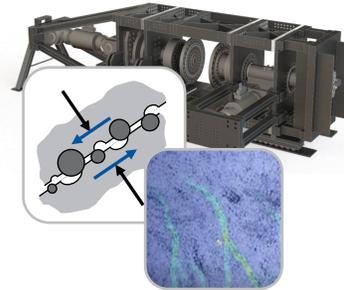
IMB-Teams

Bewehrung + Verbund



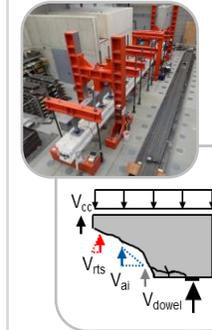
- metallisch vs. nichtmetallisch (Stahl-/ Carbon-/ Textilbeton)
- schlaff bewehrt vs. vorgespannt
- Verbund/ Rissbreiten/ Stöße
- Kurzzeit/ Dauerstand

Querkraft + Tragmechanismen



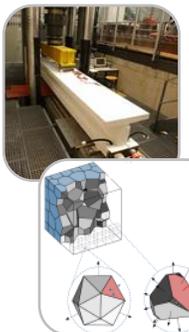
- Charakterisierung von Tragmechanismen (Rissreibung, etc.)
- Neue Prüfverfahren (TORAX, etc.)
- Neue Messtechnik (DIC/ FOS, etc.)

Querkraft + Durchstanzen



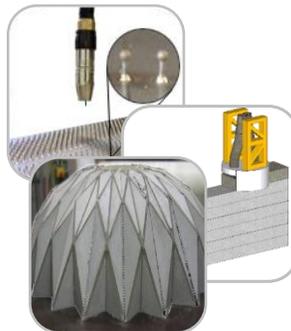
- Makroskalige Versuche (Brückenträger, Fundamente)
- Sytemeinflüsse (Durchlauf-, Membranwirkung, verteilte Last)
- Mechanische Modelle (PSRT)

Ermüdung + Schädigung



- Ermüdungsphänomene Beton/ Verbund/ Stahlbeton
- Meso- vs. makroskalige Untersuchungen
- Brückenmonitoring

Fügen + Fertigen



- 3D-Druck (Beton- u. Stahlbeton)
- Oricrete
- Stahl-Beton-Verbundbau
- Nachträglich ergänzte Betonquerschnitte

**Vielen Dank
für Ihre Aufmerksamkeit**



Vielen Dank für Ihre Aufmerksamkeit!

Externe Quellen:

- Kovaleva, D., Nistler, M., Blandini, L., Sobek, W. & Verl, A. (2022).** Rezyklierbare Sandschalungen – Auf dem Weg zur Kreislaufproduktion leichter Betonbauteile. *Beton- und Stahlbetonbau*, 117: 333-342. <https://doi.org/10.1002/best.202200009>.
- Marí, A., Cladera, A., Oller, E., & Bairán, J. M. (2018).** A punching shear mechanical model for reinforced concrete flat slabs with and without shear reinforcement. *Engineering Structures*, 166, 413-426.
- Muttoni, A. (2008).** Punching shear strength of reinforced concrete slabs without transverse reinforcement. *ACI Structural Journal*, 4, 440-450.
- Nervi, P. L., Rogers, E. N. & Joedicke, J. (1957).** Pier Luigi Nervi – Bauten und Projekte. Stuttgart: Gerd Hatje, 1957, 141.
- Sagaseta, J. A. (2008).** The influence of aggregate fracture on the shear strength of reinforced concrete beams, Phd- Thesis, University of London.
- Teworte, F. (2014).** Zum Querkrafttragverhalten von Spannbetonträgern unter Ermüdungsbeanspruchung. Dissertation, IMB, RWTH Aachen.
- van Mele, T., Echenagucia, T. M., Pigram, D., Liew, A. & Block, P. (2018).** A prototype of a thin, textile reinforced concrete shell built using a novel, ultralightweight, flexible formwork system. *DETAIL structure* 1, 50–53.
- Vecchio, F. J., & Collins, M. P. (1986).** The modified compression-field theory for reinforced concrete elements subjected to shear. *ACI J.*, 83(2), 219-231.