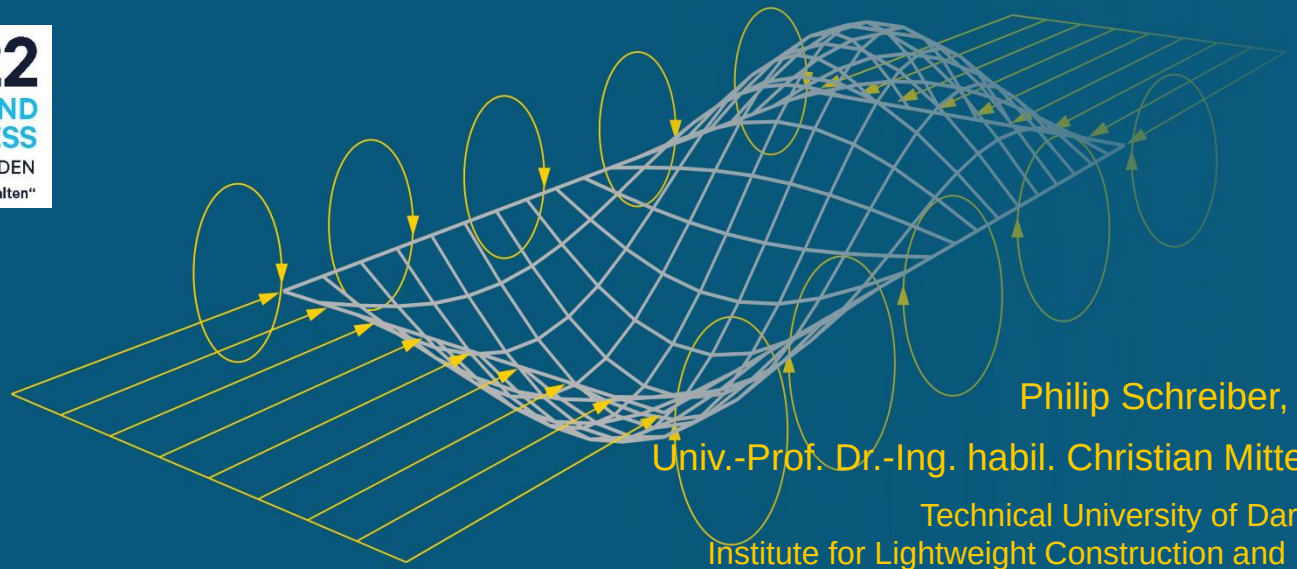
Beulanalyse von unsymmetrischen Laminaten mittels geschlossen-analytischer Verfahren

TECHNISCHE UNIVERSITÄT DARMSTADT

DLRK 2022
DEUTSCHER LUFT- UND RAUMFAHRTKONGRESS
DGLR
27. - 29. SEPTEMBER 2022 – DRESDEN
„Luft- und Raumfahrt - gemeinsam forschen und nachhaltig gestalten“



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MASCHINENBAU
We engineer future

Motivation

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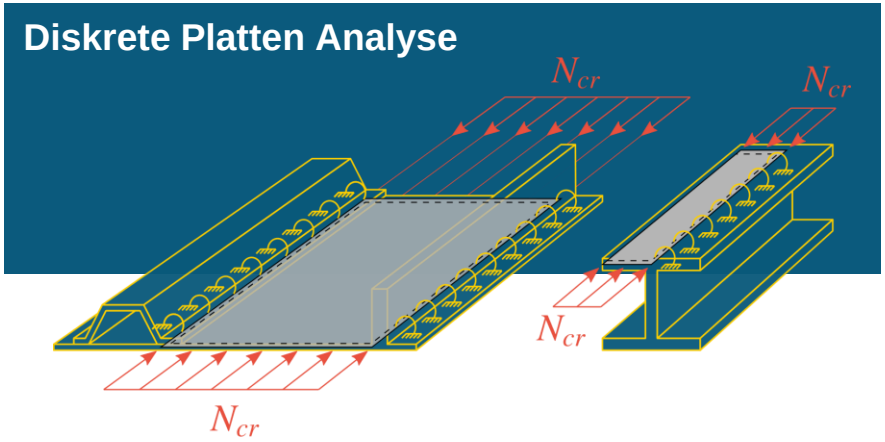
Leichtbauweise von FKV-Platten

- Grundlegende Strukturkomponenten
- Hohe spezifische Festigkeit und Steifigkeit
- Geringe transversale Querschubsteifigkeit

Analytische Methode

- Hohe Recheneffizienz
  - → Praktische Anwendung
  - → Vorauslegung
  - → Optimierung



www1

www2

www3

Berechnungsmethoden

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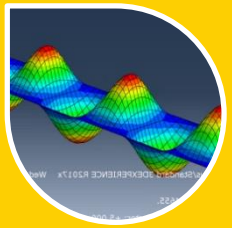

Numerik

FEM

FSM

$$u_0(x,y) = \sum_{m=1}^{M}\sum_{n=1}^{N} u_1^m$$

$$v_0(x,y) = \sum_{m=1}^{M}\sum_{n=1}^{N} v_1^m$$

$$(x,y) = \sum^{M}\sum^{N}$$

Semi-analytisch

Ritz-Methode

$$f_1'''' = +c_1 f_1 + c$$

$$f_2'' = c_5 f_1 + c_6$$

$$f_3'' = c_9 f_1' + c$$

Exakt

Levysche Lösung

$$N_{xx}^0 = \frac{\lambda_{11}\left(\lambda_{22}\right.}{}$$

Geschlossen-analytisch

Rayleigh-Quotient

Recheneffizienz

Lokale Stabilität von Strukturelementen

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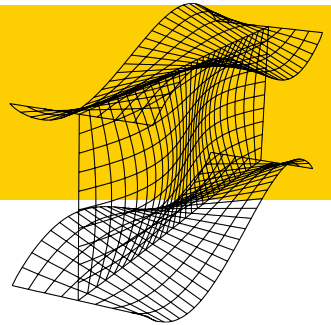
Beulen von FKV-Platten

- Umliegende Struktur (RB)
- Geometrie
- Materielle Eigenschaften

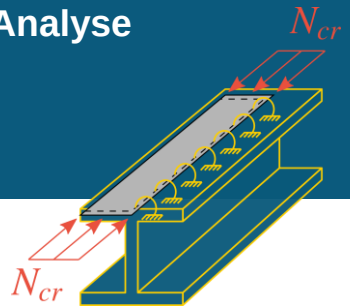
Strukturanbindung

- Dreheinspannung $\boldsymbol{k_0}$, $\boldsymbol{k_b}$
- Isotrop: Bleich (1952) [1]
- Orthotrop: Qiao and Shan (2005) [2]

Beulform



Diskrete Platten Analyse



Literaturübersicht

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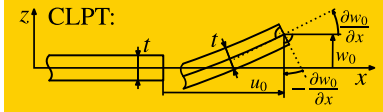
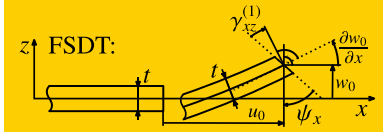
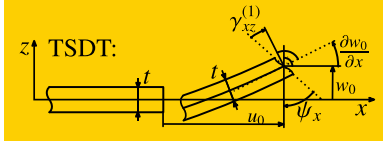
Symmetrisch – geschlossen-analytisch



- Kollár (2003) [3]
- Qiao und Shan (2005) [2]
- Beerhorst (2011) [4]



- Kuehn et al. (2014) [5]
- Beerhorst und Thirusala Suresh Babu (2020) [6]

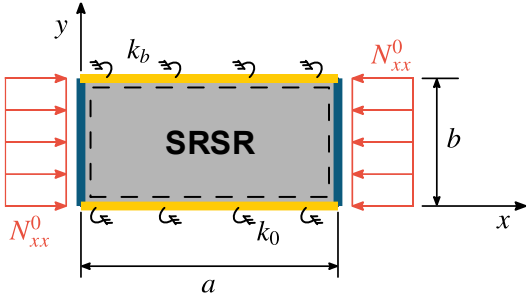


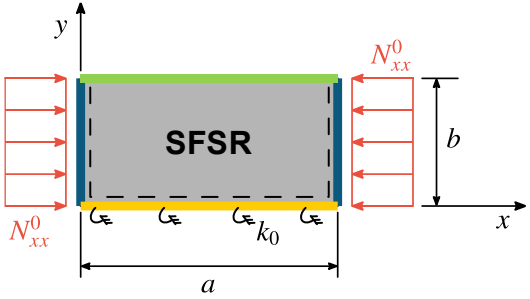
- Herrmann et al. (2018) [7]
- Schreiber et al. (2020) [8]

Unsymmetrisch

- Lévysche Lösung
  - Dreheinspannungen
  - Transzendente Gleichung
  - Orthotrope Laminate

Kopplungen und Randbedingungen





Kreuzverbund | Winkelverbund

$$\begin{bmatrix} N^0_{xx} \\ N^0_{yy} \\ N^0_{xy} \\ M^0_{xx} \\ M^0_{yy} \\ M^0_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & 0 & B_{12} & B_{22} & B_{26} \\ 0 & 0 & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & 0 \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & 0 \\ B_{16} & B_{26} & B_{66} & 0 & 0 & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon^0_x \\ \varepsilon^0_y \\ \gamma^0_{xy} \\ \kappa^0_x \\ \kappa^0_y \\ \kappa^0_{xy} \end{bmatrix}$$

Kreuzverbund: $N^0_{xx} = v_0 = 0,$

Winkelverbund: $N^0_{xy} = u_0 = 0,$

CLPT:

$$w_0 = M^0_{xx} = 0.$$

FSDT:

$$w_0 = M^0_{xx} = \psi_y = 0.$$

TSDT:

$$w_0 = M^0_{xx} = \psi_y = P_{xx} = 0.$$

Kreuzverbund

Winkelverbund

$N^0_{yy} = N^0_{xy} = 0,$

CLPT:

$$M^0_{yy} = \frac{\partial M^0_{yy}}{\partial y} + 2\frac{\partial M^0_{xy}}{\partial x} = 0.$$

FSDT:

$$M^0_{yy} = M^0_{xy} = Q_y = 0.$$

TSDT:

$$\begin{cases} M^0_{yy} - \frac{4}{3t^2}P_{yy} = P_{yy} = M^0_{xy} - \frac{4}{3t^2}P_{xy} \\ = \frac{4}{3t^2}\left(\frac{\partial P_{yy}}{\partial y} + 2\frac{\partial P_{xy}}{\partial x}\right) + Q_y - \frac{4}{t^2}R_y = 0. \end{cases}$$

Kreuzverbund: $N^0_{yy} = u_0 = 0,$

Winkelverbund: $N^0_{xy} = v_0 = 0,$

CLPT:

$$w_0 = \begin{cases} \left[-M^0_{yy} - k_0\frac{\partial w_0}{\partial y}\right]_{y=0} = 0. \\ \left[M^0_{yy} - k_b\frac{\partial w_0}{\partial y}\right]_{y=b} = 0. \end{cases}$$

FSDT:

$$w_0 = \psi_x = \begin{cases} \left[-M^0_{yy} + k_0\psi_y\right]_{y=0} = 0. \\ \left[M^0_{yy} + k_b\psi_y\right]_{y=b} = 0. \end{cases}$$

TSDT:

$$w_0 = \psi_x = P_{yy} = \begin{cases} \left[-M^0_{yy} + \frac{4}{3t^2}P_{yy} + k_0\psi_y\right]_{y=0} = 0. \\ \left[M^0_{yy} - \frac{4}{3t^2}P_{yy} + k_b\psi_y\right]_{y=b} = 0. \end{cases}$$

Prinzipieller Aufbau der Methode

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Ansatz Funktionen

$$\Phi_{1,\dots,n} = c_{1,\dots,n}\,\Phi^{(1)}_{1,\dots,n}\,\Phi^{(2)}_{1,\dots,n}, \begin{cases} n = 3 & \text{for CLPT} \\ n = 5 & \text{for FSDT and TSDT} \end{cases}$$

$$c_i = \begin{bmatrix} U \\ V \\ W \\ X \\ Y \end{bmatrix}, \quad \Phi^{(1)}_i = \begin{bmatrix} u_1(x) \\ v_1(x) \\ w_1(x) \\ \psi_{x_1}(x) \\ \psi_{y_1}(x) \end{bmatrix}, \quad \Phi^{(2)}_i = \begin{bmatrix} u_2(y) \\ v_2(y) \\ w_2(y) \\ \psi_{x_2}(y) \\ \psi_{y_2}(y) \end{bmatrix}.$$

Potential

$$\Pi = \frac{1}{2}\,\underline{c}^T\,\underline{\underline{\Lambda}}\,\underline{c} = \frac{1}{2}\,\Lambda_{ij}c_jc_i, \begin{cases} i,j = 1,2,3 & \text{for CLPT} \\ i,j = 1,..,5 & \text{for FSDT and TSDT} \end{cases}$$

$$\Lambda_{ij} = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & \lambda_{15} \\ \lambda_{12} & \lambda_{22} & \lambda_{23} & \lambda_{24} & \lambda_{25} \\ \lambda_{13} & \lambda_{23} & N_{\mathrm{cr}}\bar{\lambda}_{33} + \lambda_{33} & \lambda_{34} & \lambda_{35} \\ \lambda_{14} & \lambda_{24} & \lambda_{34} & \lambda_{44} & \lambda_{45} \\ \lambda_{15} & \lambda_{25} & \lambda_{35} & \lambda_{45} & \lambda_{55} \end{bmatrix}, \begin{cases} i,j = 1,2,3 \text{ for CLPT.} \\ i,j = 1,..,5 \text{ for FSDT and TSDT.} \end{cases}$$

Ritz-Gleichungen $\Longrightarrow$ lineares Gleichungssystem

$$\frac{\partial \Pi}{\partial c_i} = \Lambda_{ij}c_j = 0, \begin{cases} i,j = 1,2,3 & \text{for CLPT.} \\ i,j = 1,..,5 & \text{for FSDT and TSDT.} \end{cases}$$

Beulbedingung

$$\det(\Lambda_{ij}) = 0 \quad \Longrightarrow \quad N_{\mathrm{cr}}$$

Ansatzfunktionen

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Kreuzverbund

$$u_1 = \cos\left(\frac{m\pi x}{a}\right), \quad u_2 = \left(\frac{y}{b}\right) + W_2\left(\frac{y}{b}\right)^2 + W_3\left(\frac{y}{b}\right)^3 + W_4\left(\frac{y}{b}\right)^4,$$

$$v_1 = \sin\left(\frac{m\pi x}{a}\right), \quad v_2 = 1 + 2\,W_2\left(\frac{y}{b}\right) + 3\,W_3\left(\frac{y}{b}\right)^2 + 4\,W_4\left(\frac{y}{b}\right)^3,$$

$$w_1 = \sin\left(\frac{m\pi x}{a}\right), \quad w_2 = \left(\frac{y}{b}\right) + W_2\left(\frac{y}{b}\right)^2 + W_3\left(\frac{y}{b}\right)^3 + W_4\left(\frac{y}{b}\right)^4,$$

$$\psi_{x_1} = \cos\left(\frac{m\pi x}{a}\right), \quad \psi_{x_2} = \left(\frac{y}{b}\right) + W_2\left(\frac{y}{b}\right)^2 + W_3\left(\frac{y}{b}\right)^3 + W_4\left(\frac{y}{b}\right)^4,$$

$$\psi_{y_1} = \sin\left(\frac{m\pi x}{a}\right), \quad \psi_{y_2} = 1 + 2\,W_2\left(\frac{y}{b}\right) + 3\,W_3\left(\frac{y}{b}\right)^2 + 4\,W_4\left(\frac{y}{b}\right)^3.$$

Winkelverbund

$$u_1 = \sin\left(\frac{m\pi x}{a}\right), \quad u_2 = 1 + 2\,W_2\left(\frac{y}{b}\right) + 3\,W_3\left(\frac{y}{b}\right)^2 + 4\,W_4\left(\frac{y}{b}\right)^3,$$

$$v_1 = \cos\left(\frac{m\pi x}{a}\right), \quad v_2 = \left(\frac{y}{b}\right) + W_2\left(\frac{y}{b}\right)^2 + W_3\left(\frac{y}{b}\right)^3 + W_4\left(\frac{y}{b}\right)^4,$$

$$w_1 = \sin\left(\frac{m\pi x}{a}\right), \quad w_2 = \left(\frac{y}{b}\right) + W_2\left(\frac{y}{b}\right)^2 + W_3\left(\frac{y}{b}\right)^3 + W_4\left(\frac{y}{b}\right)^4,$$

$$\psi_{x_1} = \cos\left(\frac{m\pi x}{a}\right), \quad \psi_{x_2} = \left(\frac{y}{b}\right) + W_2\left(\frac{y}{b}\right)^2 + W_3\left(\frac{y}{b}\right)^3 + W_4\left(\frac{y}{b}\right)^4,$$

$$\psi_{y_1} = \sin\left(\frac{m\pi x}{a}\right), \quad \psi_{y_2} = 1 + 2\,W_2\left(\frac{y}{b}\right) + 3\,W_3\left(\frac{y}{b}\right)^2 + 4\,W_4\left(\frac{y}{b}\right)^3.$$

Genauigkeit hängt von den Ansätzen ab

Randbedingungen

- Verschiebung → exakt
- Kraft → näherungsweise
- Ergebnis: W_2, W_3, W_4

Reduced Bending Stiffness (RBS) Methode

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Konstitutivgesetz TSDT

$$\begin{bmatrix} \underline{N} \\ \underline{M} \\ \underline{P} \\ \underline{Q} \\ \underline{R} \end{bmatrix} = \begin{bmatrix} \underline{\underline{A}} & \underline{\underline{B}} & \underline{\underline{E}} & \underline{\underline{0}} & \underline{\underline{0}} \\ \underline{\underline{B}} & \underline{\underline{D}} & \underline{\underline{F}} & \underline{\underline{0}} & \underline{\underline{0}} \\ \underline{\underline{E}} & \underline{\underline{F}} & \underline{\underline{H}} & \underline{\underline{0}} & \underline{\underline{0}} \\ \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{A}}^S & \underline{\underline{D}}^S \\ \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{D}}^S & \underline{\underline{F}}^S \end{bmatrix} \begin{bmatrix} \underline{\varepsilon}^{(1)} \\ \underline{\varepsilon}^{(2)} \\ \underline{\varepsilon}^{(3)} \\ \underline{\gamma}^{(1)} \\ \underline{\gamma}^{(2)} \end{bmatrix}$$

Pseudoinverse

- **Scheiben und Plattenquadrant entkoppelt in Π**

$$\begin{bmatrix} \underline{\varepsilon}_1 \\ \underline{M} \\ \underline{P} \\ \underline{Q} \\ \underline{R} \end{bmatrix} = \begin{bmatrix} \underline{\underline{A}}^* & -\underline{\underline{B}}^* & -\underline{\underline{E}}^* & \underline{\underline{0}} & \underline{\underline{0}} \\ \underline{\underline{B}}^{*T} & \underline{\underline{D}}^* & \underline{\underline{F}}^* & \underline{\underline{0}} & \underline{\underline{0}} \\ \underline{\underline{E}}^{*T} & \underline{\underline{F}}^{*T} & \underline{\underline{H}}^* & \underline{\underline{0}} & \underline{\underline{0}} \\ \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{A}}^S & \underline{\underline{D}}^S \\ \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{D}}^S & \underline{\underline{F}}^S \end{bmatrix} \begin{bmatrix} \underline{N} \\ \underline{\varepsilon}_2 \\ \underline{\varepsilon}_3 \\ \underline{\gamma}_1 \\ \underline{\gamma}_2 \end{bmatrix}$$

$$\underline{\underline{A}}^* = \underline{\underline{A}}^{-1}, \qquad \underline{\underline{D}}^* = \underline{\underline{D}} - \underline{\underline{B}}\underline{\underline{A}}^{-1}\underline{\underline{B}},$$

$$\underline{\underline{B}}^* = \underline{\underline{A}}^{-1}\underline{\underline{B}}, \qquad \underline{\underline{F}}^* = \underline{\underline{F}} - \underline{\underline{B}}\underline{\underline{A}}^{-1}\underline{\underline{E}},$$

$$\underline{\underline{E}}^* = \underline{\underline{A}}^{-1}\underline{\underline{E}}, \qquad \underline{\underline{H}}^* = \underline{\underline{H}} - \underline{\underline{E}}\underline{\underline{A}}^{-1}\underline{\underline{E}}.$$

Konstitutivgesetz TSDT - RBS

$$\begin{bmatrix} \underline{M} \\ \underline{P} \\ \underline{Q} \\ \underline{R} \end{bmatrix} = \begin{bmatrix} \underline{\underline{D}}^* & \underline{\underline{F}}^* & \underline{\underline{0}} & \underline{\underline{0}} \\ \underline{\underline{F}}^{*T} & \underline{\underline{H}}^* & \underline{\underline{0}} & \underline{\underline{0}} \\ \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{A}}^S & \underline{\underline{D}}^S \\ \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{D}}^S & \underline{\underline{F}}^S \end{bmatrix} \begin{bmatrix} \underline{\varepsilon}_2 \\ \underline{\varepsilon}_3 \\ \underline{\gamma}_1 \\ \underline{\gamma}_2 \end{bmatrix}$$

Verifizierung

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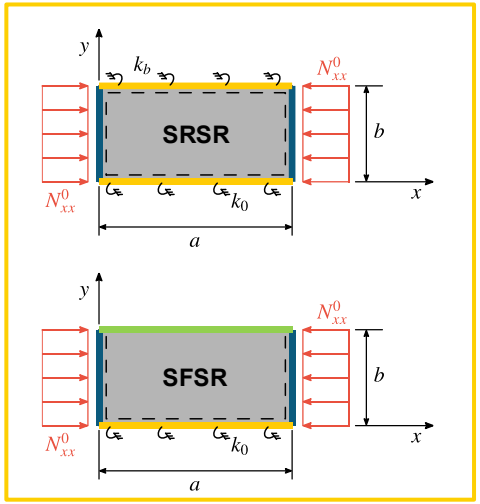
Lévysche Lösung als Referenzlösung
- Geschlossen-analytische Lösung (CF)
- FEA

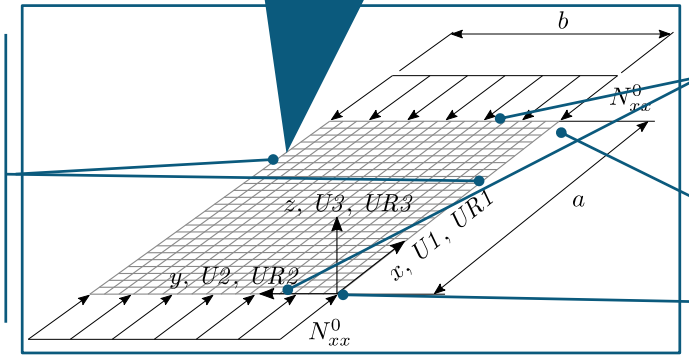
Finite Elemente Analyse (FEA)
- Quadratische Schalenelemente
  - S8R
  - FSDT



U3=UR2=0
- KV: U1=0
- WV: U2=0

Dreheinspannung
- $k_0^{FE} = \frac{k_0 a}{n_{edge}}$
- $k_b^{FE} = \frac{k_b a}{n_{edge}}$

Freier Rand
- Keine Verschiebungs-RB
- Keine Dreheinspannung



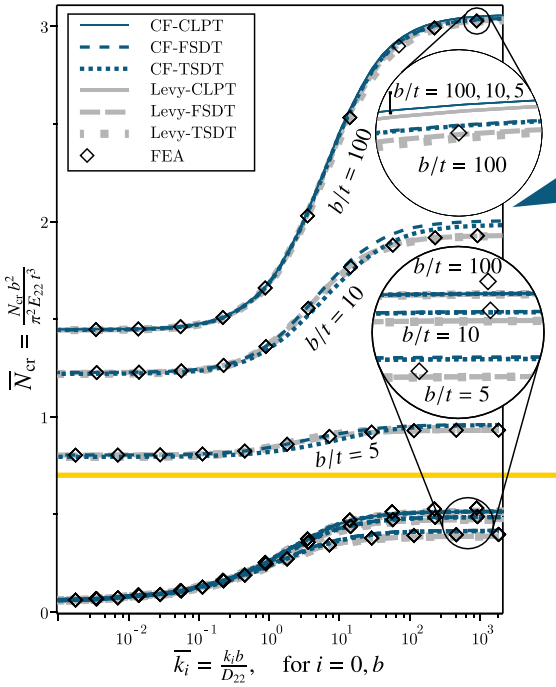
U3=UR1=0
- KV: U2=0
- WV: U1=0

U2=0

U1=0
U2=0

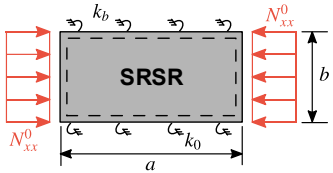
Dreheinspannsteifigkeit der unbelasteten Ränder

Kreuzverbund



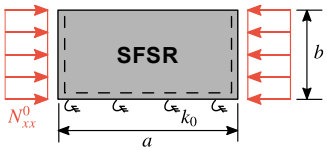
CF: Geschlossen-analytische Lösung

- $[(0°/90°)_2]$
- $b/t = [5, 10, 100]$
- $a/b = 10$



Max. Fehler bzgl. Lévy-TSDT

	CLPT	FSDT	TSDT
Lévy	225.35%	1.17%	-
CF	225.87%	4.04%	4.07%
FEA	-	-0.96%	-

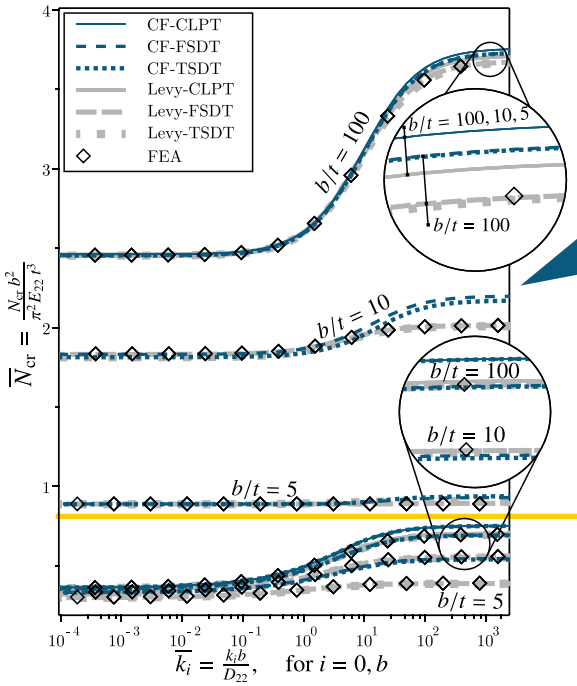


Max. Fehler bzgl. Lévy-TSDT

	CLPT	FSDT	TSDT
Lévy	32.74%	1.84%	-
CF	32.80%	7.96%	7.06%
FEA	-	3.52%	-

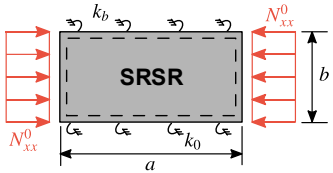
Dreheinspannsteifigkeit der unbelasteten Ränder

Winkelverbund



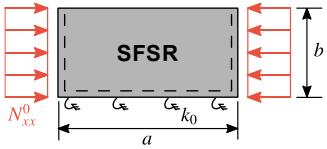
CF: Geschlossen-analytische Lösung

- $[(45°/-45°)_2]$
- $b/t = [5, 10, 100]$
- $a/b = 10$



Max. Fehler bzgl. Lévy-TSDT

	CLPT	FSDT	TSDT
Lévy	308.99%	-1.54%	-
CF	313.98%	9.43%	8.06%
FEA	-	-2.09%	-

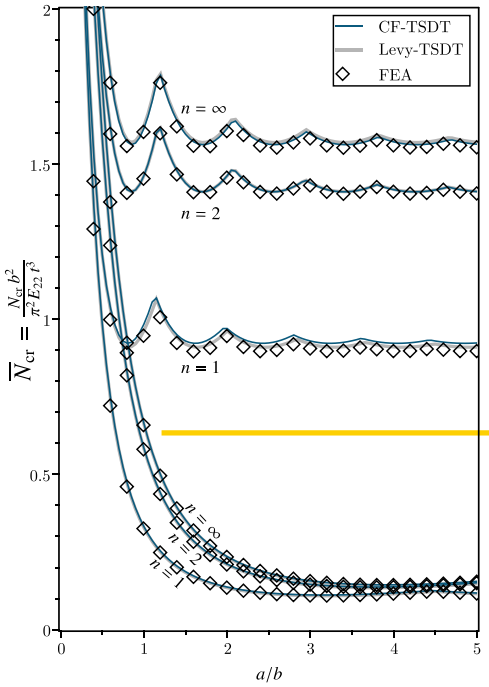


Max. Fehler bzgl. Lévy-TSDT

	CLPT	FSDT	TSDT
Lévy	81.87%	1.13%	-
CF	94.11%	40.95%	39.53%
FEA	-	0.97%	-

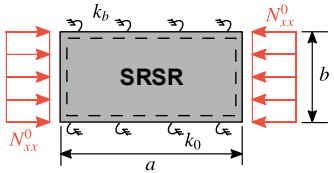
Aspektverhältnis und Lagenwiederholung

Kreuzverbund



CF: Geschlossen-analytische Lösung

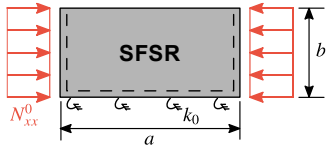
- $[(0°/90°)_n]$
- $b/t = 10$
- $n = [1, 2, \infty]$



Max. Fehler bzgl. Lévy

	Fehler	a/b	n
CF	-0.55%	1.16	1
FEA	-3.71%	0.6	1

$$\boldsymbol{k_0 = k_b = 10^5\ \mathrm{N}}$$



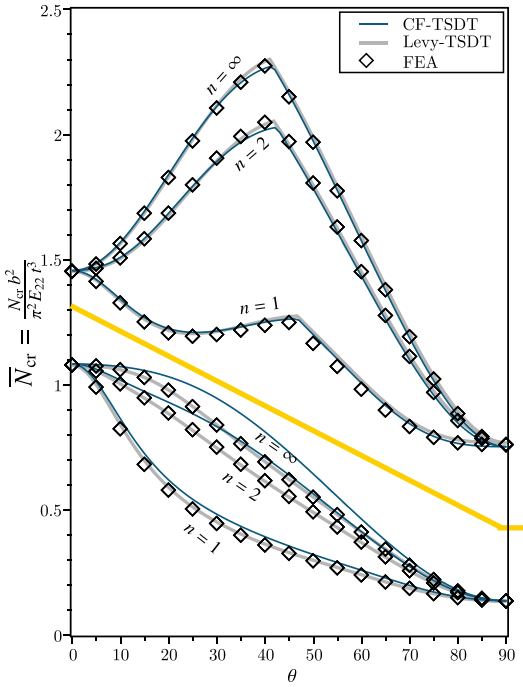
$$\boldsymbol{k_0 = 10^4\ \mathrm{N}}$$

Max. Fehler bzgl. Lévy

	Fehler	a/b	n
CF	2.23%	4.46	1
FEA	-1.41%	1	1

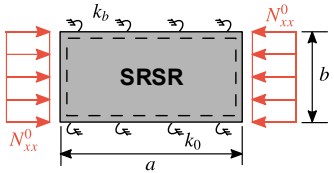
Faserwinkel und Lagenwiederholung

Winkelverbund



CF: Geschlossen-analytische Lösung

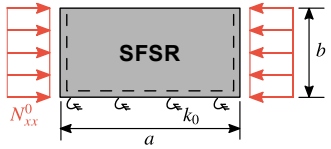
- $[(\theta/-\theta)_n]$
- $b/t = 10$
- $n = [1, 2, \infty]$
- $a/b = 1$



Max. Fehler bzgl. Lévy

	Fehler	θ	n
CF	-2.08%	90°	1,2,∞
FEA	-3.82%	50°	1

$$\boldsymbol{k_0 = k_b = 10^5\ \mathrm{N}}$$



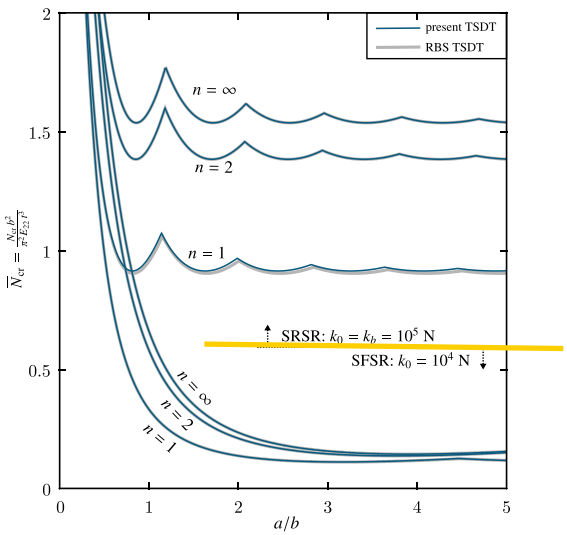
$$\boldsymbol{k_0 = 10^4\ \mathrm{N}}$$

Max. Fehler bzgl. Lévy

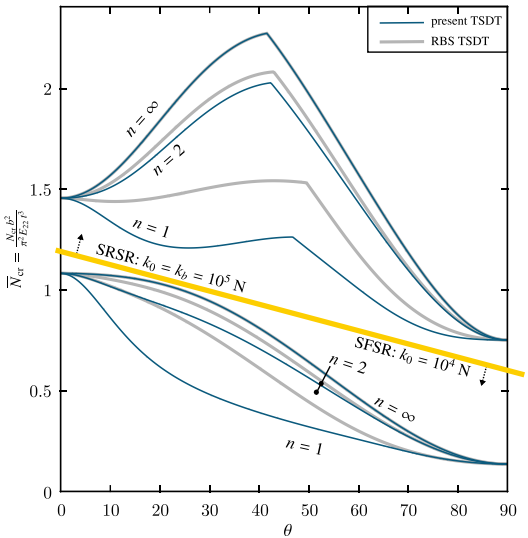
	Fehler	θ	n
CF	17.67%	44°	∞
FEA	-2.21%	50°	1

Faserwinkel und Lagenwiederholung

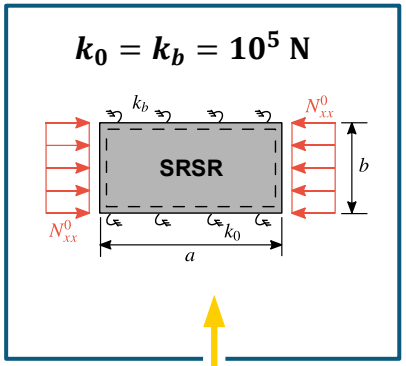
Reduced Bending Stiffness (RBS) Methode

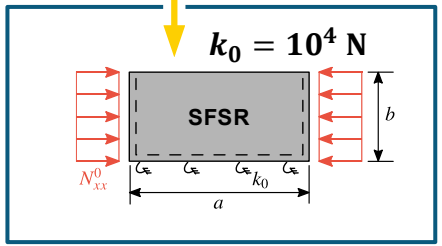


Kreuzverbund



Winkelverbund





Fazit / Ausblick

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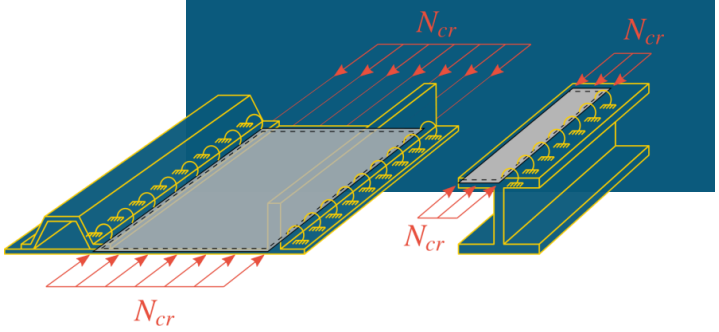
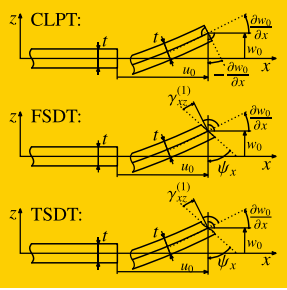
Diskrete Platten Analyse



Laminattheorien



Deutliche Überschätzungen der kritischen Belastung bei niedrigem b/t

SFSR-Winkelverbund: Abw. bis zu 40 %

Gute Übereinstimmung zu FEA und Levyscher Lösung

Kreuzverbund | **Winkelverbund**

$$\begin{bmatrix} N^0_{xx} \\ N^0_{yy} \\ N^0_{xy} \\ M^0_{xx} \\ M^0_{yy} \\ M^0_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & 0 & B_{12} & B_{22} & B_{26} \\ 0 & 0 & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & 0 \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & 0 \\ B_{16} & B_{26} & B_{66} & 0 & 0 & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon^0_x \\ \varepsilon^0_y \\ \gamma^0_{xy} \\ \kappa^0_x \\ \kappa^0_y \\ \kappa^0_{xy} \end{bmatrix}$$

Geschlossen-analytische Lösungen

- Explizite Beullast
- Zeiteffitient

Zukünftige Arbeiten

- Experimentelle Studien (Validierung)
- Optimierungen

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[8] SCHREIBER, Philip ; MITTELSTEDT, Christian ; BEERHORST, Matthias: *Buckling of shear-deformable orthotropic laminated plates with elastic restraints*. In: *Thin-Walled Structures* 157 (2020), S. 107071

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www3: https://www.compositesworld.com/news/carbon-fiber-enables-new-low-co2-skyrora-orbital-launch-vehicle

Beulanalyse von unsymmetrischen Laminaten mittels geschlossen-analytischer Verfahren

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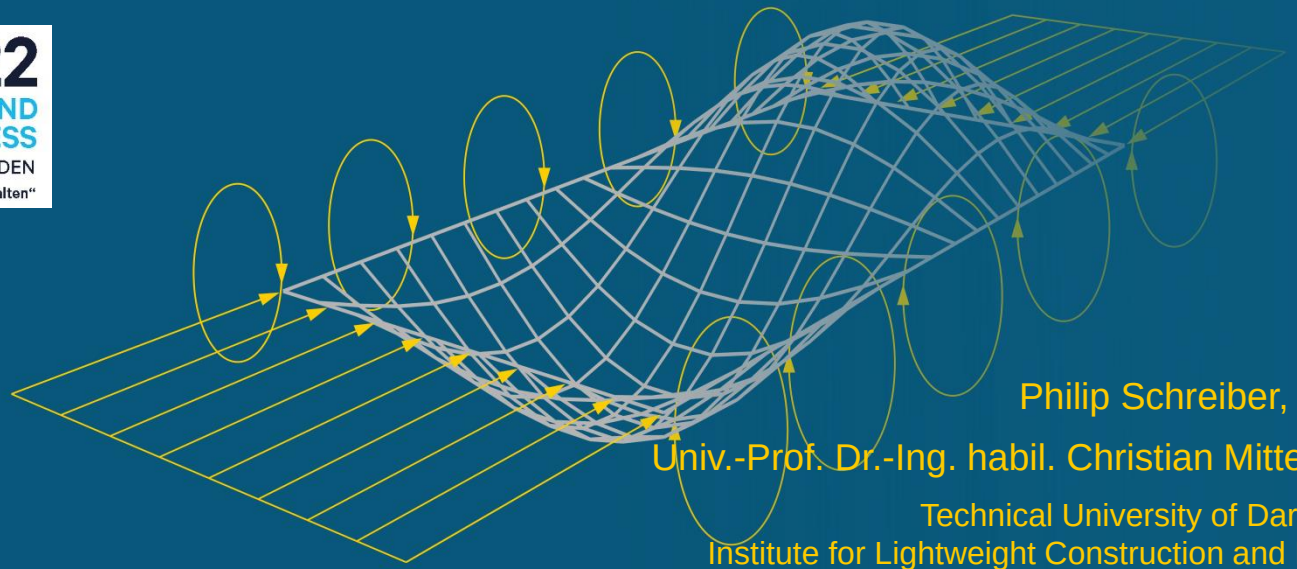
„Luft- und Raumfahrt - gemeinsam forschen und nachhaltig gestalten“



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