Mehrlagige Gewebestrukturen unter Impaktbelastung

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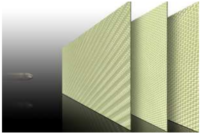
LS-DYNA Update Forum
Filderstadt bei Stuttgart
12. November 2009



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Anwendungen von Technischen Textilien

Persönliche Sicherheit / Schutz

- Schutzkleidung
  - Ballistische Körperschutzwesten
  - Hitze- und feuerfeste Schutzkleidung
  - Freizeit- und Sportausrüstungen
  - Arbeitschutzkleidung
- Bauwesen
  - Schutzzäune und Sicherheitsbarrieren
  - Leichte ballistische Schutzstrukturen
- Transport- und Verkehrswesen
  - Airbag-Systeme
  - Fallschirme und Bremssysteme


[Twaron]


[Twaron]


[Twaron]


[Unbekannt]


[Sicurauto]


[Wikipedia]


[NASA]

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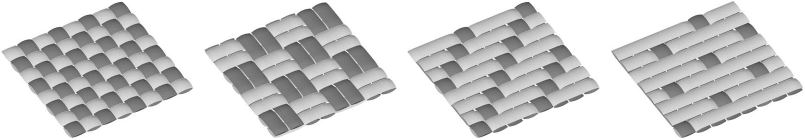
Werkstoffeigenschaften

Grundlagen

- Zweidimensionale Konstruktionswerkstoffe
- Sehr gute Flexibilität und Drapierbarkeit
- Hoch Festigkeit und hohe Steifigkeiten bei sehr niedriger Dichte
- Fertigung durch systematisches Ineinanderlegen zweier Fadengruppen: **Kett-** und **Schussfäden**
- Entkoppelte Betrachtung von Volumenänderung (Streckung entlang Fadenrichtungen) und Gestaltänderung (Scherung der Fäden) zulässig
- Starker Einfluss der Gewebemesostruktur auf Materialverhalten



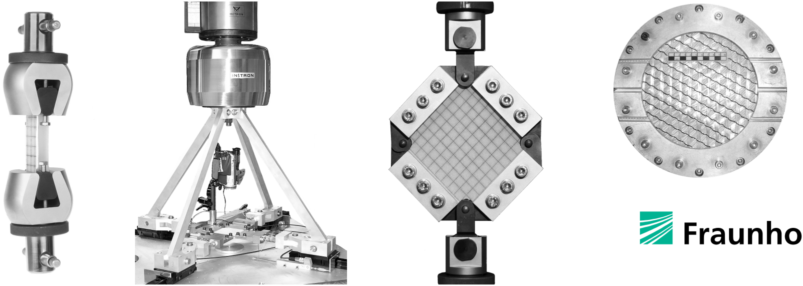
Herausforderungen

Werkstoffcharakterisierung

- Parameteridentifikation für homogenisierte Modelle schwierig
- Probeneinspannung kritisch, durchdachte Klemmensysteme erforderlich

Numerische Simulation

- Phänomenologische Modellierung weder zuverlässig noch austauschbar
- Mesostrukturmodellierung arbeits- und rechentechnisch äußerst aufwändig



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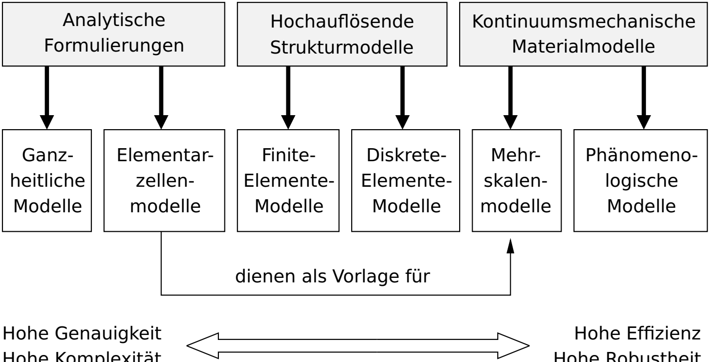
Modellierungstechniken

Literaturüberblick



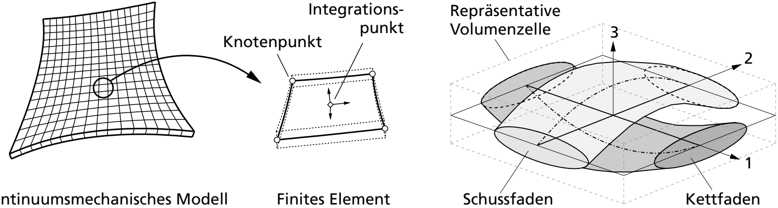
Hohe Genauigkeit
Hohe Komplexität

Hohe Effizienz
Hohe Robustheit

Elementarzellenbasierte Mehrskalenansätze

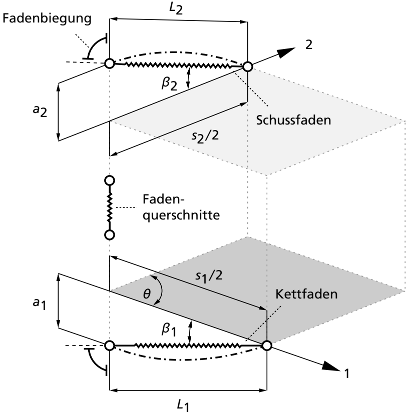
Generelle Vorgehensweise

1. Finde eine repräsentative Volumenzelle und richte ein Kinematikmodell ein
2. Definiere und konfiguiere Materialparameter der eingesetzten Komponenten
3. Koppele die Kinematik des Modells an die makroskopische Deformation
4. Berechne die mesostrukurellen Kräfte und Momente
5. Transformiere Kräfte und Momente in Kontinuumsspannungen



Modellkomponenten (1)

Krümmungswechselwirkung



1. Fadenquerschnitte

$$F_c(d_c) = \begin{cases} K_c\left[\exp(n_c d_c) - 1\right] & , d_c \geq 0 \\ K_c n_c d_c & , d_c < 0 \end{cases}$$

2. Faserdehnung

$$\left(1 + \frac{K_b}{K_a}\right)\sigma_f + \frac{\mu_b}{K_a}\dot{\sigma}_f = K_b \varepsilon_f + \mu_b \dot{\varepsilon}_f$$

3. Fadenbiegung

$$M_{bi} = K_b\left(\beta_i - \beta_i^{(0)}\right)$$

Modellkomponenten (2)

Gewebeschermodell

1. Fadenbiegung

$$M_\mathrm{d} = K_\mathrm{s} \gamma_\mathrm{e}$$

2. Verscherung (»Trellising«)

$$\dot{\gamma}_\mathrm{f} = \dot{\gamma}_0 \left(\frac{|M_\mathrm{d}|}{M_0} \right)^b \operatorname{sgn}(M_\mathrm{d})$$

wobei $\gamma = \gamma_\mathrm{e} + \gamma_\mathrm{f}$

3. Fadenblockade (»Locking«)

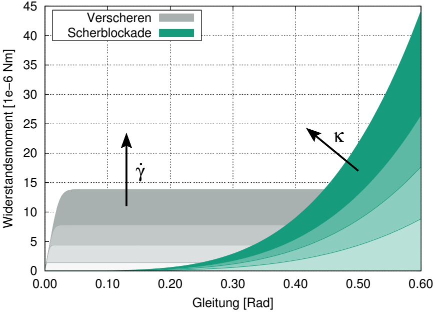
$$M_\mathrm{p} = \kappa \, s_1 \, s_2 \, F_\mathrm{p} \sin \gamma$$

wobei $F_\mathrm{p}(\gamma) \overset{!}{=} K_\mathrm{p} \, |\gamma|$

und bindungsabhängig $\kappa \in \left]0, 1\right]$

- Gesamtwiderstand

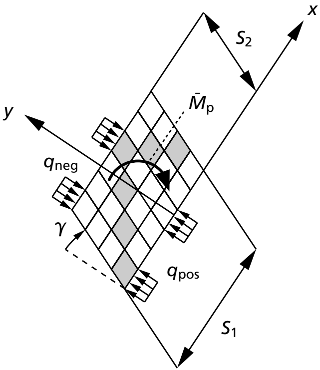
$$M(\gamma, \dot{\gamma}) = M_\mathrm{d} + M_\mathrm{p}$$



Fadenblockade

Einfluss der Gewebebindungsart

- Direkter Kontakt nebeneinander liegender Fäden bei hohen Scherwinkeln
- Ursprung des abrupten Anstiegs der Schersteifigkeit
  bei transversal zur Fadenrichtung wirkenden Kompressionskräften
- Bindungsartabhängige Verteilung dieser Streckenlasten
  auf der Umrandung der Grundbindungszelle (»Rapport«)



$$M_p = \int_{\frac{1}{2}(S_1 \sin\gamma + S_2)}^{\frac{1}{2}(S_1 \sin\gamma - S_2)} q_{pos}(x)\, x \,\mathrm{d}x - \int_{\frac{1}{2}(-S_1 \sin\gamma + S_2)}^{\frac{1}{2}(-S_1 \sin\gamma - S_2)} q_{neg}(x)\, x \,\mathrm{d}x$$

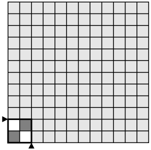
mit $q_{pos} = q_{neg} = F_p(\gamma)$ resultiert in:

$$\bar{M}_p = \kappa\, S_1\, S_2\, F_p(\gamma) \sin\gamma .$$

$$\rightsquigarrow \quad M_p = \kappa\, s_1\, s_2\, F_p(\gamma) \sin\gamma .$$

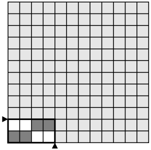
Bindungseinfluss auf Fadenblockade

Leinwandbindungen



10-01 01-01-00

$K = 1$



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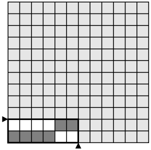
$K = 3/4$



10-01-01-04 02-00

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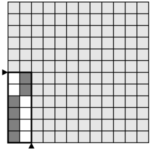

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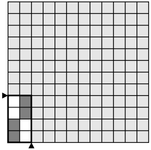

10-02 02-01-00

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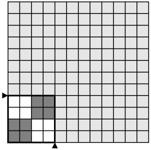

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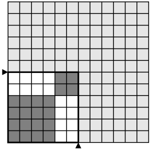
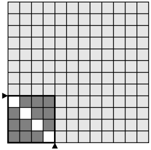


10-04 02-04 02-00

$K = 1/3$

Bindungseinfluss auf Fadenblockade

Köperbindungen



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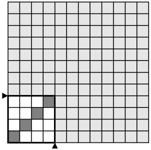

20-01 03-01-01

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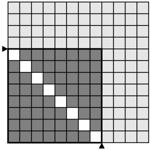

20-07 01-01-07

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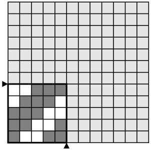
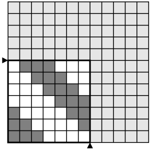


20-03 02-01-01

$K = 2/5$



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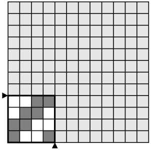

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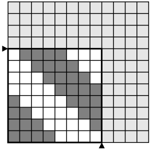
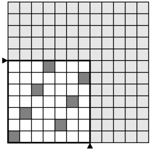


20-04 04-01-07

$K = 1/4$

Bindungseinfluss auf Fadenblockade

Atlasbindungen



30-01 06-01-02

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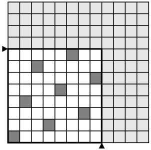

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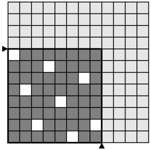
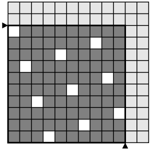


30-07 01-01-05

$K = 1/4$



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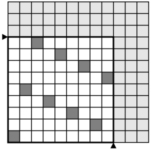
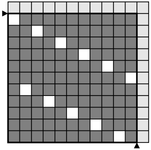


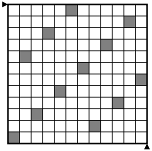
30-01 08-01-04

$K = 2/9$



30-10 01-01-05

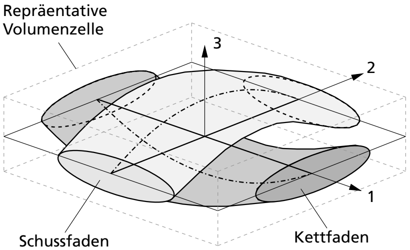
$K = 2/11$

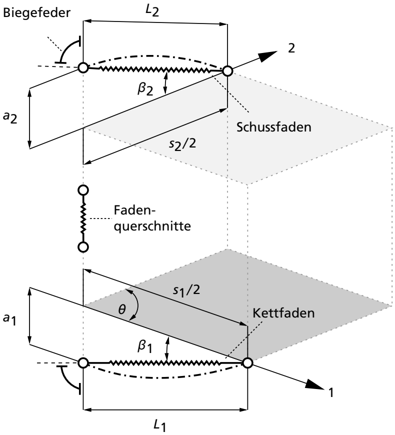


30-01 11-01-07

$K = 1/6$

Kinematikmodell





Konfiguration

- Unbekannte
  - 1 Elastischer Scheranteil γ_e
  - 1 Dissipativer Scheranteil γ_f
  - 2 Fadenspannlängen s_i
  - 2 Fadenamplituden a_i
- Auflösung
  - 3 Deformationsgradient $\boldsymbol{F}$
  - 3 zusätzliche Zwangsbedingungen

Zwangsbedingungen

Krümmungswechselwirkung

1. Vertikales Kräftegleichgewicht zwischen Kett- und Schussfaden

$$F_{c1} = F_{c2} \quad \Leftrightarrow \quad 2\,T_1 \sin\beta_1 + 2\frac{M_{b1}}{L_1}\cos\beta_1 = 2\,T_2 \sin\beta_2 + 2\frac{M_{b1}}{L_2}\cos\beta_2$$

2. Vertikaler kinematischer Zusammenschluß zwischen Kett- und Schussfaden

$$a_1^{(0)} + a_2^{(0)} = a_1 + a_2 + d_{c1} + d_{c2}$$

Gewebeschermodell

3. Superposition der elastischen und dissipativen Gleitung

$$\gamma = \gamma_e + \gamma_f \quad \Leftrightarrow \quad K_s\gamma_e = M_d \quad \text{where} \quad \dot{\gamma}_f = \dot{\gamma}_0 \left(\frac{|M_d|}{M_0}\right)^b \operatorname{sgn}(M_d)$$

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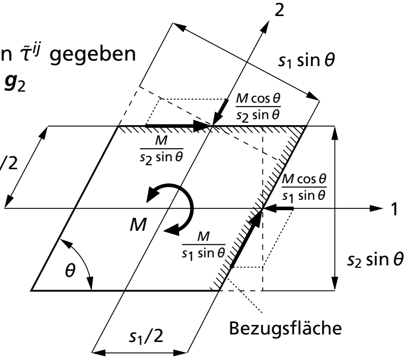
Cauchy Spannungstensor

$$\boldsymbol{\sigma} = \tilde{\tau}^{11}\,(\boldsymbol{g}_1 \otimes \boldsymbol{g}_1) + \tilde{\tau}^{22}\,(\boldsymbol{g}_2 \otimes \boldsymbol{g}_2) + \tilde{\tau}^{12}\,(\boldsymbol{g}_1 \otimes \boldsymbol{g}_2 + \boldsymbol{g}_2 \otimes \boldsymbol{g}_1)$$

Kontravariante Spannungstensorkomponenten $\tilde{\tau}^{ij}$ gegeben bezogen auf kovariante Basisvektoren $\boldsymbol{g}_1$ und $\boldsymbol{g}_2$



$$\tilde{\tau}^{11} = \frac{T_1\cos\beta_1}{s_2\sin\theta} - \frac{M_{b1}\sin\beta_1}{s_2 L_1\sin\theta} - \frac{M\cos\theta}{s_1 s_2\sin^2\theta}$$

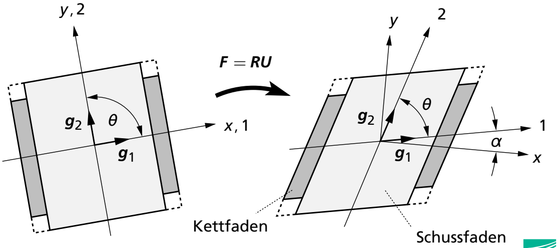
$$\tilde{\tau}^{22} = \frac{T_2\cos\beta_2}{s_1\sin\theta} - \frac{M_{b2}\sin\beta_2}{s_1 L_2\sin\theta} - \frac{M\cos\theta}{s_1 s_2\sin^2\theta}$$

$$\tilde{\tau}^{12} = \frac{M}{s_1 s_2\sin^2\theta}$$

Mitrotierendes Elementkoordinatensystem

Spannungstensortransformation

$$\begin{pmatrix} \tau_x \\ \tau_y \\ \tau_{xy} \end{pmatrix} = \begin{bmatrix} \cos^2\alpha & \cos^2(\alpha+\theta) & 2\cos\alpha\cos(\alpha+\theta) \\ \sin^2\alpha & \sin^2(\alpha+\theta) & 2\sin\alpha\sin(\alpha+\theta) \\ \sin\alpha\cos\alpha & \sin(\alpha+\theta)\cos(\alpha+\theta) & \sin(2\alpha+\theta) \end{bmatrix} \begin{pmatrix} \tilde{\tau}^{11} \\ \tilde{\tau}^{22} \\ \tilde{\tau}^{12} \end{pmatrix}$$



Probenmaterial

Material	**3961**	**3965**	**3971**	
Bindung	Leinwand	Köper	Panama	
DIN 9354	10-01 01-01-00	20-04 04-01-01	10-02 02-02-00	
Fasername	Twaron CT	Twaron T	Twaron CT	
Faserdichte	1.45	1.44	1.45	$\mathrm{g\,cm^{-3}}$
Garnfeinheit	930	3360	1680	dtex
Fadendichte	10.5	9.2	12.6	$\mathrm{cm^{-1}}$
Gewicht	200	655	410	$\mathrm{g\,m^{-2}}$
Festigkeit	1520	4000	2800	$\mathrm{N\,cm^{-1}}$

Versuchsmatrix (1)

Modellparameter

1. Herstellerangaben
    - Mikroskopische Untersuchungen
    - Informationen über Gewebemesostruktur
    - Betroffene Parameter: ρ_{fib}, t_{eff}, s_1, s_2, A_1, A_2, θ, c_1, c_2, κ

2. Uniaxialzugversuche an Fadenproben
    - Unterschiedliche Dehnraten
    - Messung der Bruchkraft und der Bruchdehnung
    - Informationen über Faserverhalten
    - Betroffene Parameter: E, K_{a}, μ_{b}, $\varepsilon_{\max}$, $\varepsilon_{\mathrm{a,\,max}}$

3. Druckversuche an Gewebeproben
    - Quasistatische Lastaufprägung entlang Dickenrichtung
    - Informationen über Verformungsverhalten der Fadenquerschnitte
    - Betroffene Parameter: K_{c}, n_{c}

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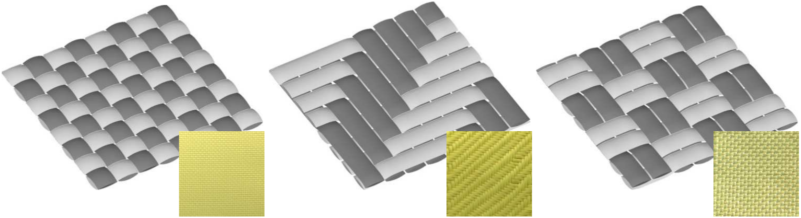
Versuchsmatrix (2)

Modellparameter

4. Uniaxialzugtests an Gewebeproben
    - Quasistatische Versuche im Strukturdehnungsbereich
    - Informationen über Biegesteifigkeit der Faserbündel
    - Betroffene Parameter: K_b

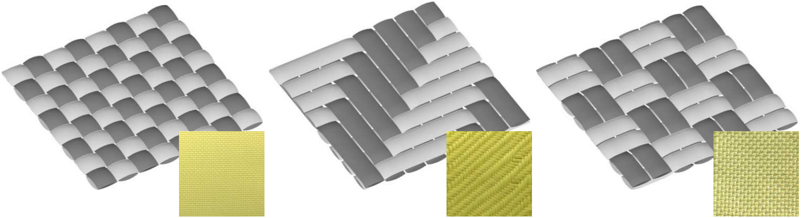
5. Schrägzugversuche an Gewebeproben
    - Unterschiedliche Dehnraten
    - Umrechnung auf äquivalente Scherrahmenzugversuche
    - Informationen über Fadenverscherung und Scherblockade
    - Betroffene Parameter: K_s, $\dot{\gamma}_0$, M_0, b, K_p

Geometrie der Gewebemesostruktur



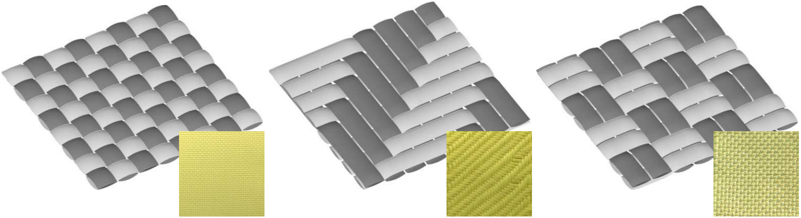
Material	**3961**	**3965**	**3971**	
Fadenspannen	0.952	1.087	0.794	mm
Fadenquerschnitt	0.0641	0.2333	0.1159	mm^2
Kettfadenkrümmung	1.6	1.2	1.3	%
Schussfadenkrümmung	3.7	2.2	3.7	%
Gewebewinkel	90	90	90	deg
Physikalische Dicke	0.276	0.814	0.537	mm
Effektive Dicke	0.138	0.454	0.283	mm

Krümmungswechselwirkung



Material	**3961**	**3965**	**3971**	
Faser, Elastizität	94	75	94	GPa
Faser, Steifigkeit primär	130	95	130	GPa
Faser, Viskosität	12	8	12	MPa s
Faser, Versagen gesamt	3.0	3.1	3.0	%
Faser, Versagen primär	2.9	3.0	2.9	%
Faserbündel, Biegung	(0)	(0)	(0)	Nm rad^{-1}
Querschnitte, Steifigkeit	2.00	0.80	0.03	mN
Querschnitte, Exponent	120	40	150	mm^{-1}

Gewebescherung



Material	**3961**	**3965**	**3971**	
Biegung, Steifigkeit	8e-4	12e-4	10e-4	Nm rad^{-1}
Verscherung, Referenzrate	2e-3	2e-3	2e-3	rad s^{-1}
Verscherung, Referenzmoment	4e-6	5e-6	7e-6	Nm
Verscherung, Exponent	8	12	20	–
Blockade, Bindungsart	1.00	0.25	0.50	–
Blockade, Steifigkeit	0.4	5.8	1.2	N mm^{-1}rad^{-1}

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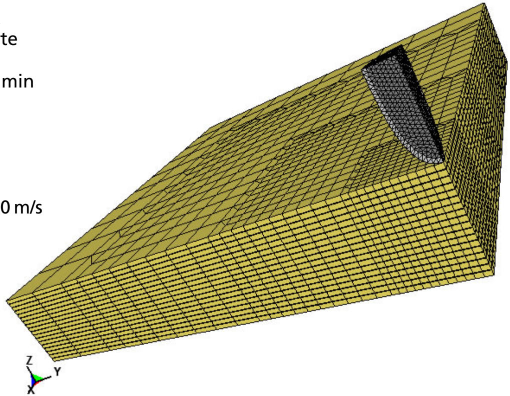
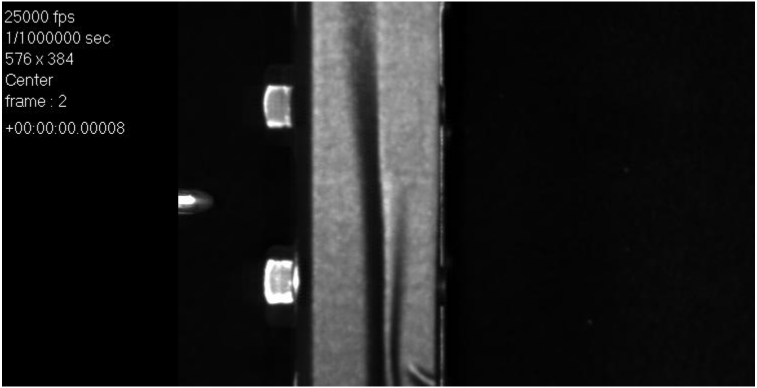
Validierung

Impaktexperiment

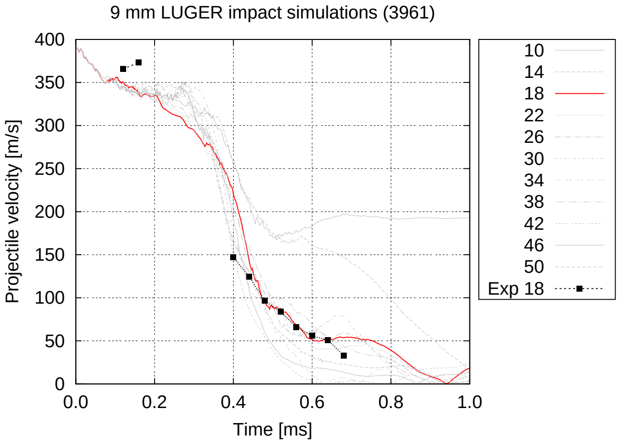
- Modellbeschreibung
  - Expliziter FE-Code LS-DYNA
  - Modellgröße 15000 Elemente
  - Problemdauer 1.2 ms
  - Berechnungsdauer etwa 90 min
  - Xeon 64 EMT Linux Cluster
- 9 mm LUGER Projektil
  - Aufprallgeschwindigkeit 390 m/s
  - Masse 8 g
- 18 Gewebelagen
  - Aramidgewebe (3961)
  - Abmessungen 20×20 cm



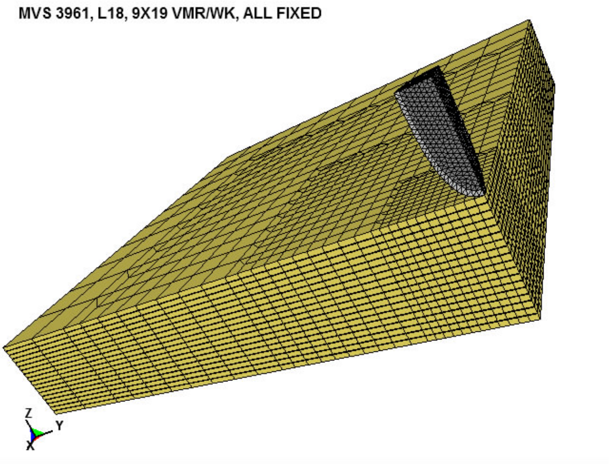
Impaktexperiment



Projektilgeschwindigkeiten



Animation der Berechnungen



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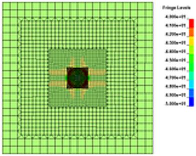
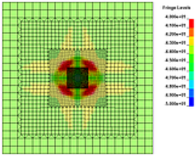
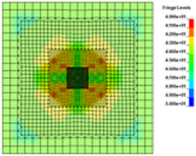
Richtungsänderung der Kettfäden



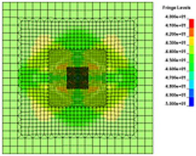
0.2 ms



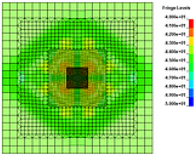
0.4 ms



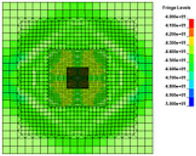
0.6 ms



0.8 ms



1.0 ms



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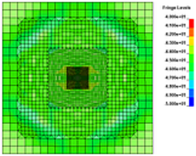
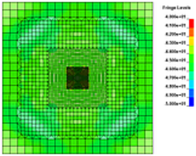
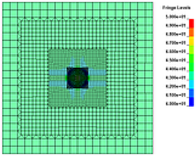


1.4 ms

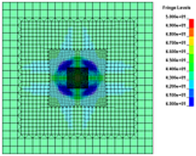


1.6 ms

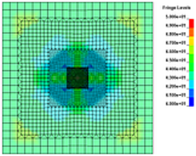
Richtungsänderung der Schussfäden



0.2 ms



0.4 ms



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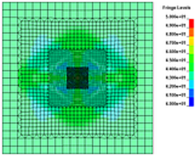
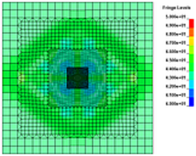


0.8 ms



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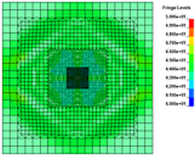
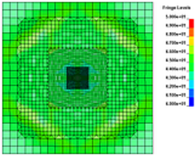
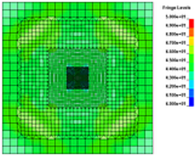


1.2 ms

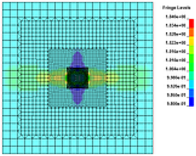


1.4 ms

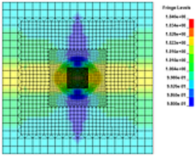


1.6 ms

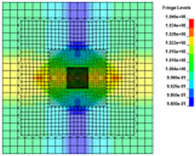
Streckung entlang Kettfadenrichtung



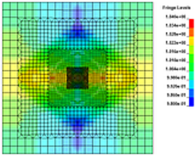
0.2 ms



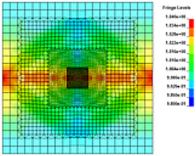
0.4 ms



0.6 ms



0.8 ms



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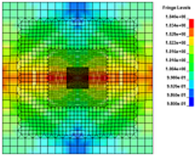

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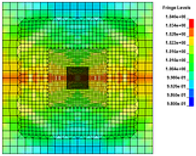

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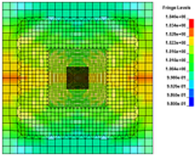

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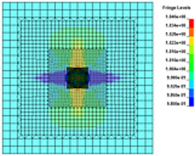
Streckung entlang Schussfadenrichtung



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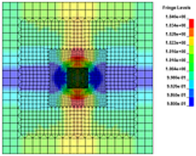

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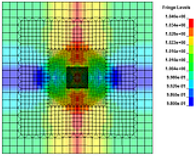

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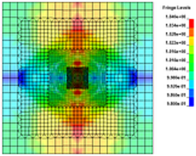

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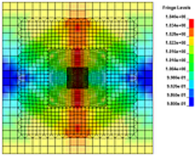

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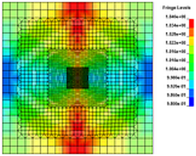

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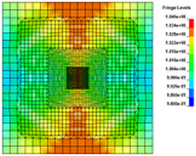

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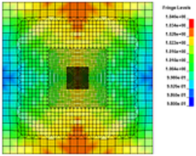
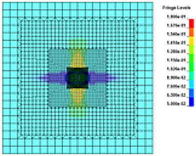


1.6 ms

Kettfadenwelligkeit



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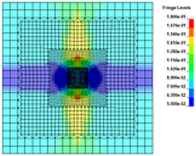

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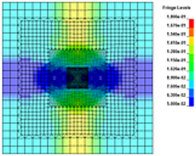

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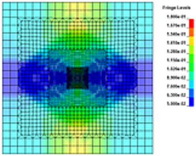

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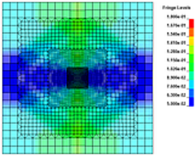

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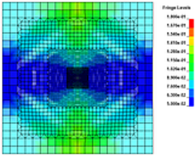

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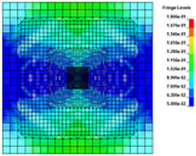

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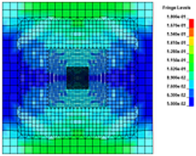

1.6 ms

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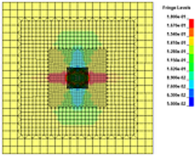
Schussfadenwelligkeit



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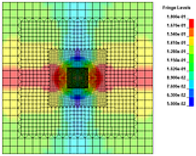

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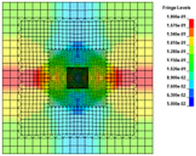

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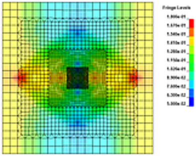

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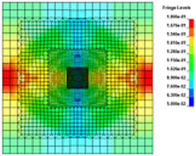

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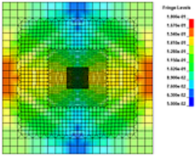

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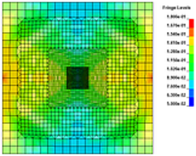

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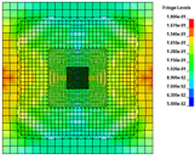
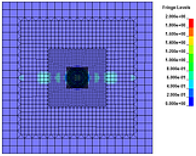


1.6 ms

Kettfadenspannungen



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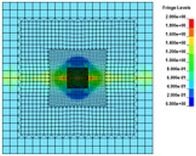

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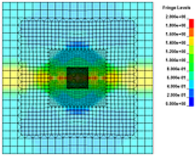

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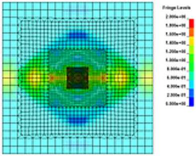
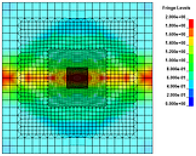


0.8 ms



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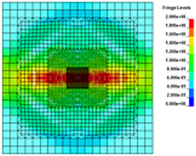

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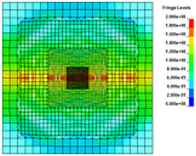

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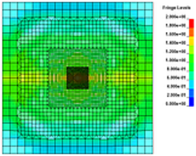
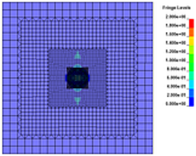


1.6 ms

Schussfadenspannungen



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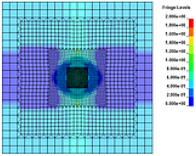

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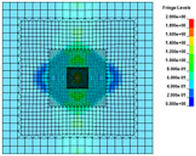

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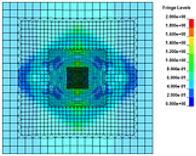
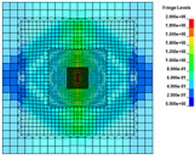


0.8 ms



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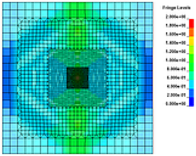
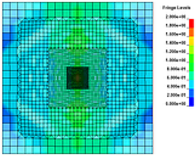
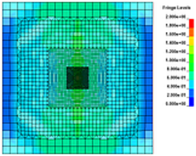


1.2 ms



1.4 ms



1.6 ms

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Zusammenfassung

Zielsetzung

Zusammenführung der Vorzüge bestehender Modellierungstechniken in einem universell anwendbaren **Materialmodell für Gewebe**:

- Effektivität und Schnelligkeit phänomenologischer Kontinuumsmodelle
- Genauigkeit von mesostrukturbasierten Gewebemodellen

Fähigkeiten

- Faserviskoelastizität
- Komprimierbarkeit in Dickenrichtung
- Fadenbiegesteifigkeit
- Viskoplastischer Scherwiderstand
- Bindungsarteinfluss auf nichtlineare Scherblockade

Literaturverweise

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A continuum constitutive model for the mechanical behavior of woven fabrics
International Journal of Solids and Structures, 42(13):3867-3896, 2005.

I. Ivanov, A. Tabiei:

Loosely woven fabric model with viscoelastic crimped fibres for ballistic impact simulations
International Journal for Numerical Methods in Engineering, 61(10):1565-1583, 2004.

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