*MAT_PAPER - a new orthotropic elastoplastic model for paper materials

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*MAT_PAPER (*MAT_274)

- A new orthotropic elastoplastic material for modeling creasing and folding of paperbord
- Supports both SMP and MPP
- Supports both solids and shells
  - Solids use hyper-elastoplasticity
  - Shells use hypo-elastoplasticity
- Only explicit

Motivation

- Beverage cartons
  - Produced by folding paperboard along creased lines
  - Creasing causes damage necessary for subsequent folding
  - Material failure, e.g. cracks, may here jeopardize a sterile environment

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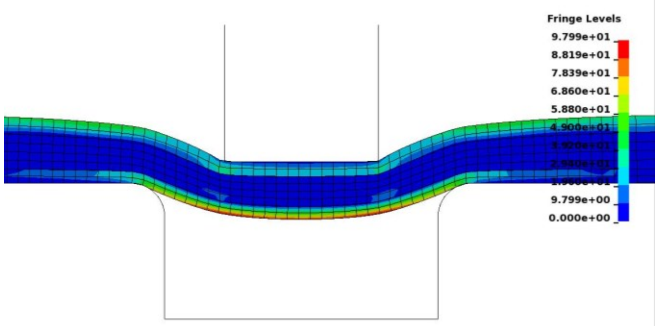
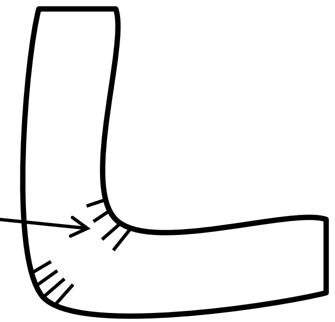
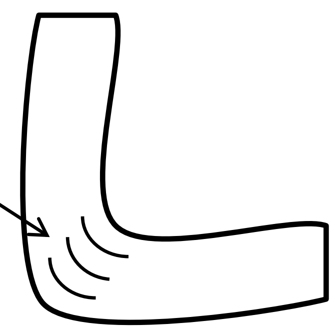
What to simulate

- Creasing
  - Introduces damage/delamination



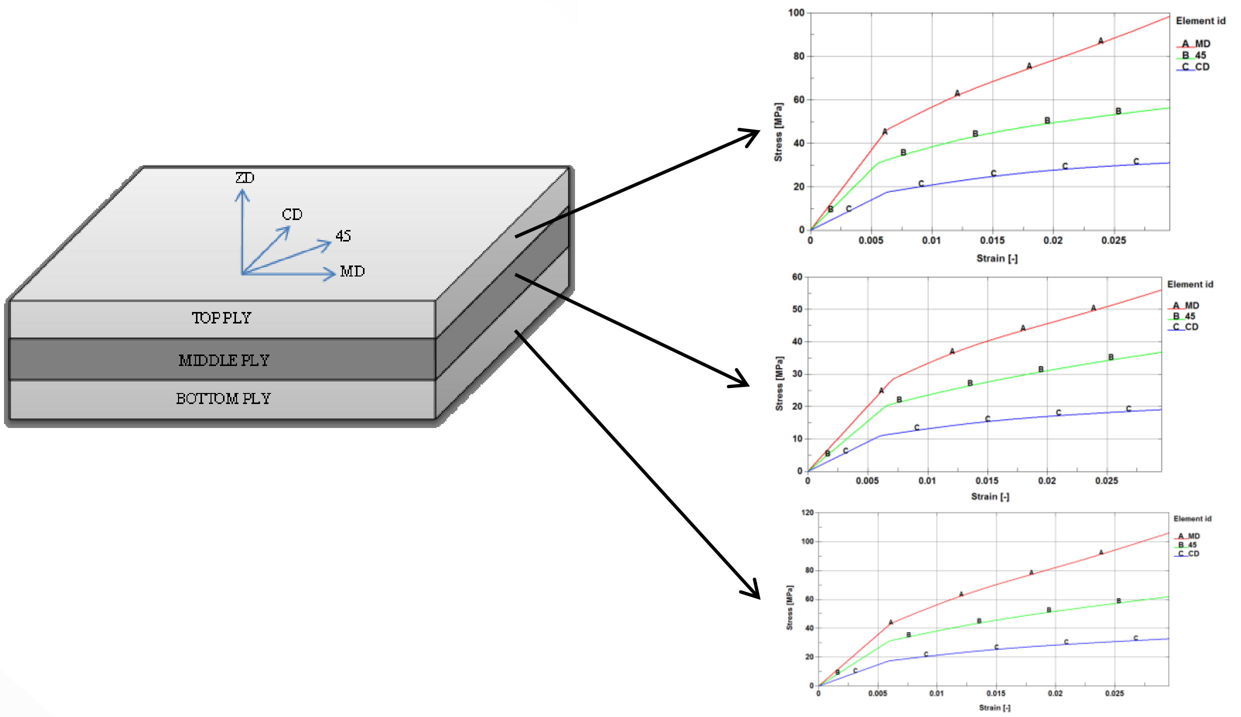
- Folding
  - Folding without creasing causes unwanted edge cracks
  - Folding with creasing causes controlled delamination





Characteristics of paperboard

- Paper is extremely anisotropic
- May have plies with vastly different properties
- Stiffness in MD 1-5 times the stiffness in CD and 100 times the stiffness in ZD



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Model

- Based on papers by Xia et al and Nygards et al:

  Xia, Q., Boyce, M., Parks, D. 2002. A Constitutive model for the anisotropic elastic-plastic deformation of paper and paperboard. Int. J. Sol. Struct. 39, 4053-4071

  Nygårds, M., Just, M., Tryding, J. 2009. Experimental and numerical studies of creasing of paperboard. Int. J. Sol. Struct. 46,2493-2505

- Hyperelastic

$$S = CE_e, \text{ where } F = F_e F_p \text{ and } E_e = \frac{1}{2}(F_e^T F_e - I),$$

- Orthotropic

$$\mathbf{C}^{-1} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\upsilon_{21}}{E_2} & -\frac{\upsilon_{31}}{E_3} & & & \\ -\frac{\upsilon_{12}}{E_1} & \frac{1}{E_2} & -\frac{\upsilon_{32}}{E_3} & & & \\ -\frac{\upsilon_{13}}{E_1} & -\frac{\upsilon_{23}}{E_2} & \frac{1}{E_3} & & & \\ & & & \frac{1}{G_{12}} & & \\ & & & & \frac{1}{G_{23}} & \\ & & & & & \frac{1}{G_{13}} \end{bmatrix}.$$

- Non-linear elastic in ZD compression

$$S_{33} = C_{31}E_{11}^e + C_{32}E_{22}^e + \begin{cases} E_3 E_{33}^e, & E_{33}^e \geq 0, \\ E_3^c(1 - \exp(-C_c E_{33}^e)), & E_{33}^e < 0. \end{cases}$$

Model - plastic properties

- In and out-of-plane properties uncoupled
- Three yield surfaces: in-plane, out-of-plane, and transverse shear
  - 6 in-plane yield ”planes”
    - 1 MD tension
    - 2 CD tension
    - 3 Positive shear
    - 4 MD compression
    - 5 CD compression
    - 6 Negative shear

$$f = \sum_{i=1}^{6} \left[\frac{\max(0, S : N_i)}{q_i(\varepsilon_p^f)} \right]^{2k} - 1 \leq 0,$$

$$q_i(\varepsilon_p^f) = S_i^0 + A_i^0 \tanh(B_i^0 \varepsilon_p^f) + C_i^0 \varepsilon_p^f.$$

  - Out-of-plane

$$g = \frac{-S_{33}}{A_\sigma + B_\sigma \exp(-C_\sigma \varepsilon_p^g)} - 1 \leq 0,$$

  - Transverse shear

$$h = \frac{\sqrt{S_{13}^2 + S_{23}^2}}{\tau_0 + [A_\tau - \min(0, S_{33}) B_\tau] \varepsilon_p^h} - 1 \leq 0.$$

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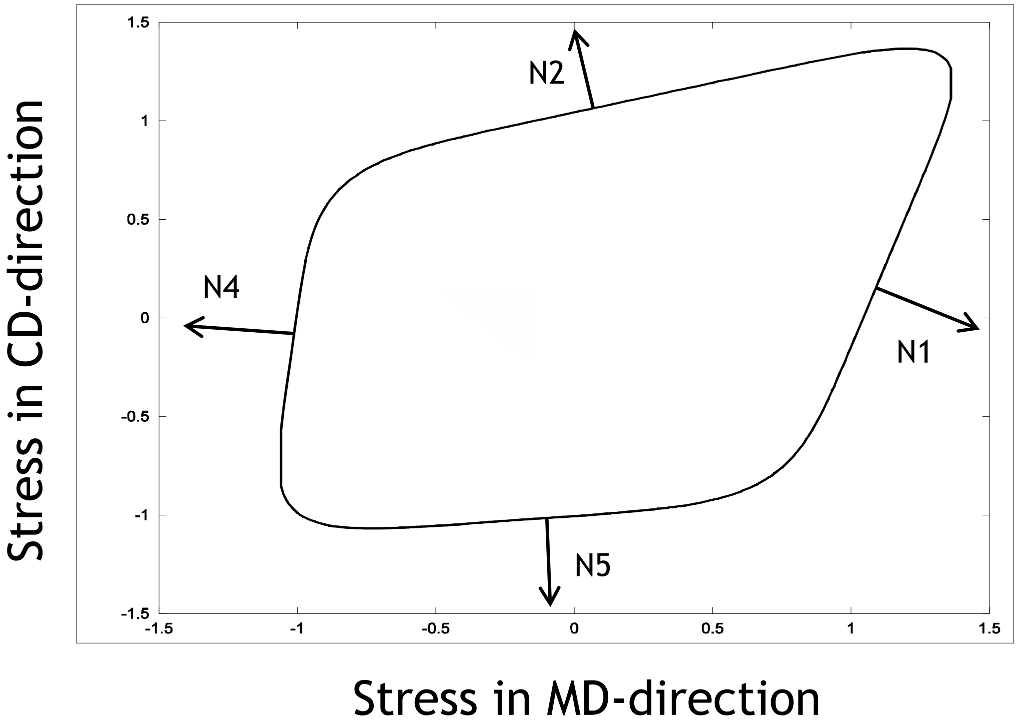
In-plane yield surface



- Hardening: yield planes move in their normal directions (N1-N6) independently of each other

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Model – shell implementation

- Shells
  - Hypoelastic: $\dot{\sigma} = CD_e$, where $D = D_e + D_p$,
  - No plasticity in ZD, only non-linear elasticity

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Input parameters - card 1

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	E1	E2	E3	PR21	PR32	PR31
Type	A8	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none

MID = Unique identifier ID or ASCII label
RO = Material density
E1 = Elastic modulus in MD direction
E2 = Elastic modulus in CD direction
E3 = Elastic modulus in thickness direction (tension)
PR21 = Poissons ratio in 21 direction
PR32 = Poissons ratio in 32 direction (0.)
PR31 = Poissons ratio in 31 direction (0.)

Input parameters - card 2

Card 2	1	2	3	4	5	6	7	8
Variable	G12	G23	G13	E3C	CC	TWOK		
Type	F	F	F	F	F	F		
Default	none	none	none	none	none	none		

G12 = Shear modulus in 12 direction
G23 = Shear modulus in 23 direction
G13 = Shear modulus in 13 direction
E3C = Young's modulus in thickness direction (compression)

$$S_{33} = C_{31}E_{11}^e + C_{32}E_{22}^e + \begin{cases} E_3 E_{33}^e, & E_{33}^e \geq 0, \\ E_3^c(1 - \exp(-C_c E_{33}^e)), & E_{33}^e < 0. \end{cases}$$

CC = Non linear elastic component in compression
TWOK= Exponent in in-plane yield surface

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Input parameters - card 3-5

- Cards 3, 4 and 5 sets the yield stresses, hardening and plastic flow directions for the in-plane model
- The different variables denotes the different in-plane yield planes
  - 1 MD tension
  - 2 CD tension
  - 3 Positive shear
  - 4 MD compression
  - 5 CD compression
  - 6 Negative shear

$$f = \sum_{i=1}^{6} \left[\frac{\max(0, S : N_i)}{q_i(\varepsilon_p^f)} \right]^{2k} - 1 \leq 0,$$

$$q_i(\varepsilon_p^f) = S_i^0 + A_i^0 \tanh(B_i^0 \varepsilon_p^f) + C_i^0 \varepsilon_p^f.$$

- The distinction of different yield planes allows for different hardening and different plastic flow directions in MD and CD directions both in tension and compression

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Input parameters - card 3-5

Card 3	1	2	3	4	5	6	7	8
Variable	S01	A01	B01	C01	S02	A02	B02	C02
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none

Card 4	1	2	3	4	5	6	7	8
Variable	S03	A03	B03	C03	S04	A04	B04	C04
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none

Card 5	1	2	3	4	5	6	7	8
Variable	S05	A05	B05	C05	PRP1	PRP2	PRP4	PRP5
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	1/2	2/15	1/2	2/15

Negative number in S0i refers to load curve ID ABS(S0i), otherwise

$$q_i(\varepsilon_p^f) = S_i^0 + A_i^0 \tanh(B_i^0 \varepsilon_p^f) + C_i^0 \varepsilon_p^f .$$

Input parameters - card 5

Card 5	1	2	3	4	5	6	7	8
Variable	S05	A05	B05	C05	PRP1	PRP2	PRP4	PRP5
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	1/2	2/15	1/2	2/15

PRPi determines the normal directions of the yield planes and hence the plastic flow direction due to the associated yield surface.

$$N_1 = \begin{bmatrix} \frac{1}{\sqrt{1+\upsilon_{1p}^2}} & -\frac{\upsilon_{1p}}{\sqrt{1+\upsilon_{1p}^2}} & 0 & 0 & 0 & 0 \end{bmatrix}^T,$$

$$N_2 = \begin{bmatrix} -\frac{\upsilon_{2p}}{\sqrt{1+\upsilon_{2p}^2}} & \frac{1}{\sqrt{1+\upsilon_{2p}^2}} & 0 & 0 & 0 & 0 \end{bmatrix}^T,$$

$$N_3 = \begin{bmatrix} 0 & 0 & 0 & \sqrt{2} & 0 & 0 \end{bmatrix}^T$$

$$N_4 = -\begin{bmatrix} \frac{1}{\sqrt{1+\upsilon_{4p}^2}} & -\frac{\upsilon_{4p}}{\sqrt{1+\upsilon_{4p}^2}} & 0 & 0 & 0 & 0 \end{bmatrix}^T,$$

$$N_5 = -\begin{bmatrix} -\frac{\upsilon_{5p}}{\sqrt{1+\upsilon_{5p}^2}} & \frac{1}{\sqrt{1+\upsilon_{5p}^2}} & 0 & 0 & 0 & 0 \end{bmatrix}^T,$$

$$N_6 = -N_3,$$

Input parameters - card 6

Card 6	1	2	3	4	5	6	7	8
Variable	ASIG	BSIG	CSIG	TAU0	ATAU	BTAU		
Type	F	F	F	F	F	F		
Default	none	none	none	none	none	none		

ASIG = Out of plane plastic yield
BSIG = Out of plane hardening parameter
CSIG = Out of plane parameter
TAU0 = Transverse shear yield
ATAU = Transverse shear hardening parameter
BTAU = Transverse shear hardening parameter (couples with thickness stress)

$$g = \frac{-S_{33}}{A_\sigma + B_\sigma \exp\left(-C_\sigma \varepsilon_p^g\right)} - 1 \leq 0, \qquad h = \frac{\sqrt{S_{13}^2 + S_{23}^2}}{\tau_0 + [A_\tau - \min(0, S_{33}) B_\tau]\varepsilon_p^h} - 1 \leq 0.$$

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Input parameters - card 7-8

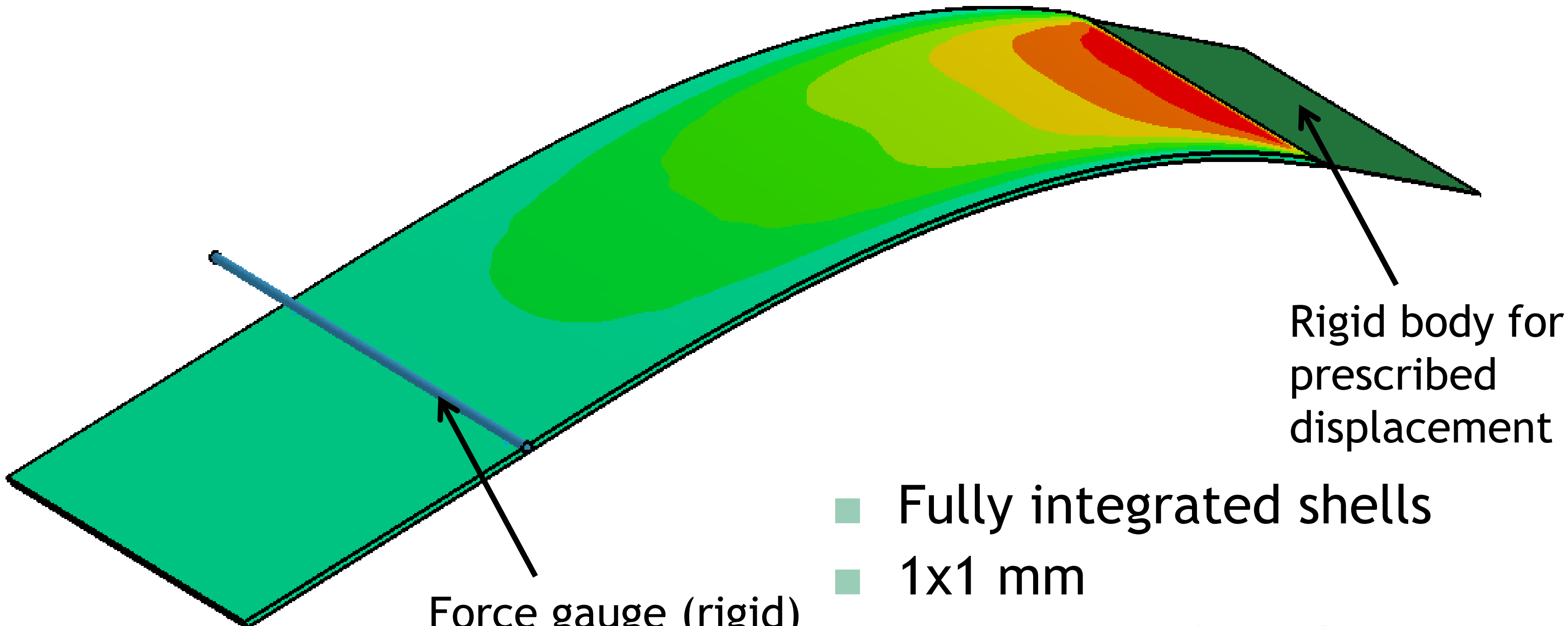
Cards 7 and 8 defines the orthotropic directions of the material.
Can be found for any anisotropic material.

Card 8	1	2	3	4	5	6	7	8
Variable	V1	V2	V3	D1	D2	D3	BETA	
Type	F	F	F	F	F	F	F	
Default	none	none	none	none	none	none	none	

Card 7	1	2	3	4	5	6	7	8
Variable	AOPT	MACF	XP	YP	ZP	A1	A2	A3
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none

Validation – bending of single ply

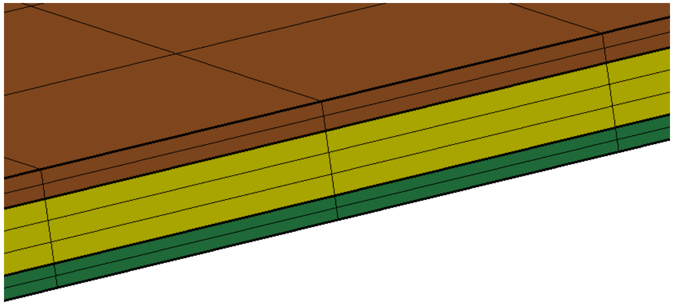
- Bending of uncreased paperboard MWV260mN



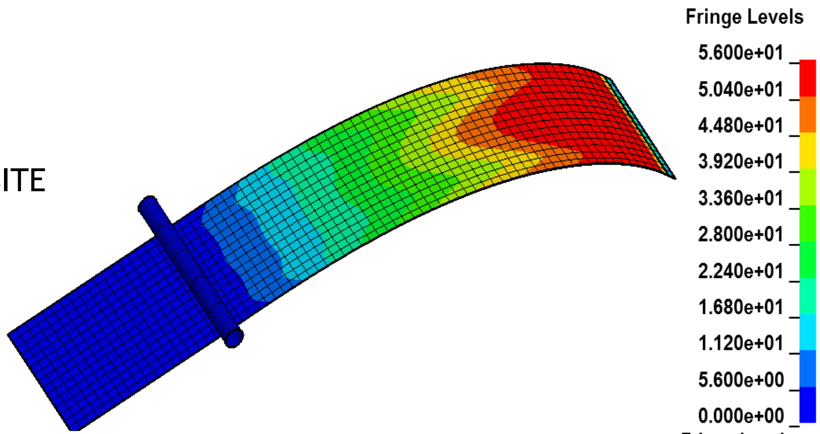
- Fully integrated shells
- 1x1 mm
- MWV260mN board
- 0.394 mm thick
- Double precision version of LS-DYNA
- 38 mm wide paper

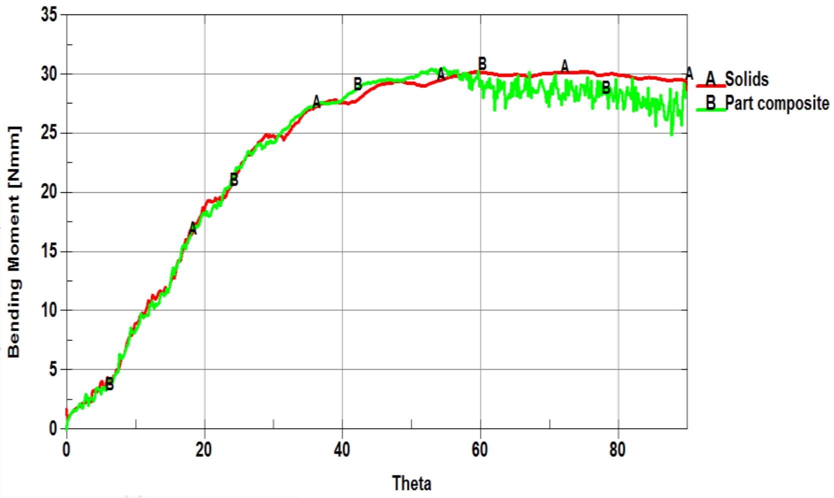
Validation – bending of three plies

- Stacking plies using *PART_COMPOSITE

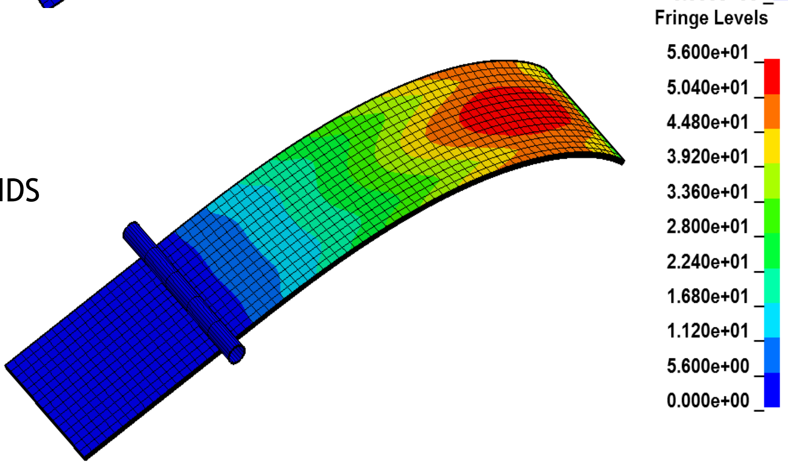


SHELLS with
*PART_COMPOSITE





SOLIDS



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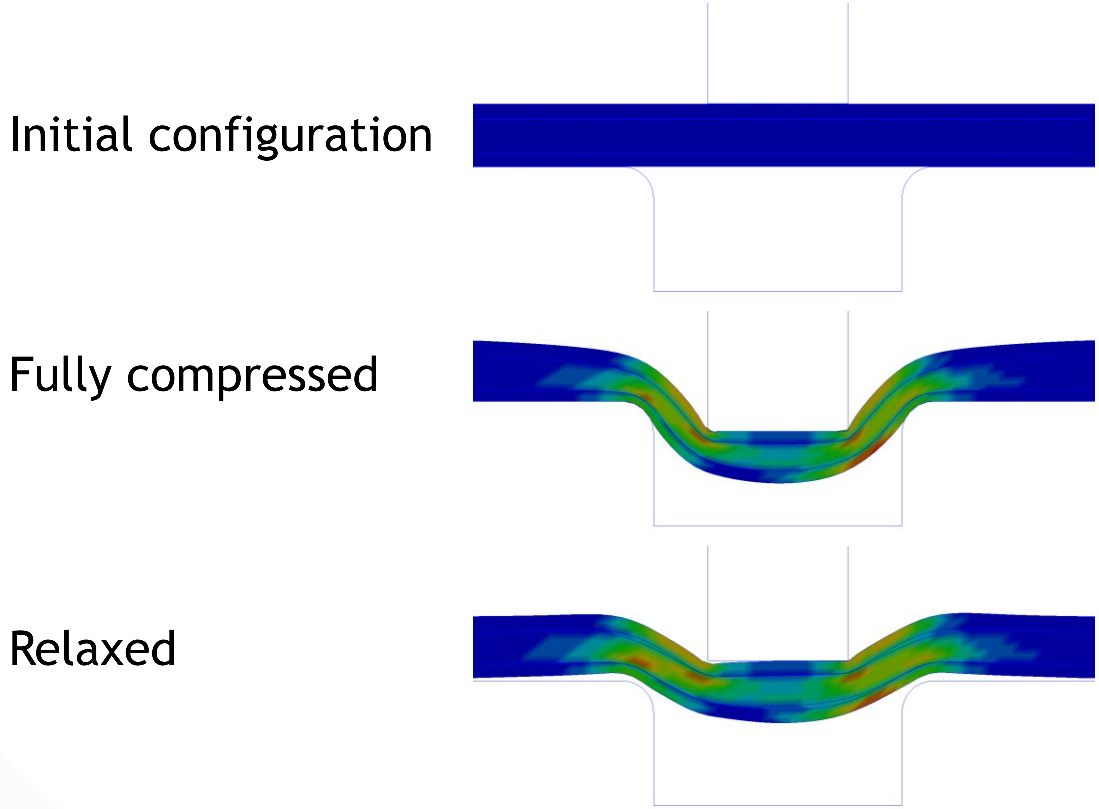
Validation - Creasing of three plies

- Experimental data from Nygårds et. al. (2009)
- To simulate delamination cohesive elements are used
- Cohesive zones are not necessarily related to the plies



Validation - Creasing of three plies

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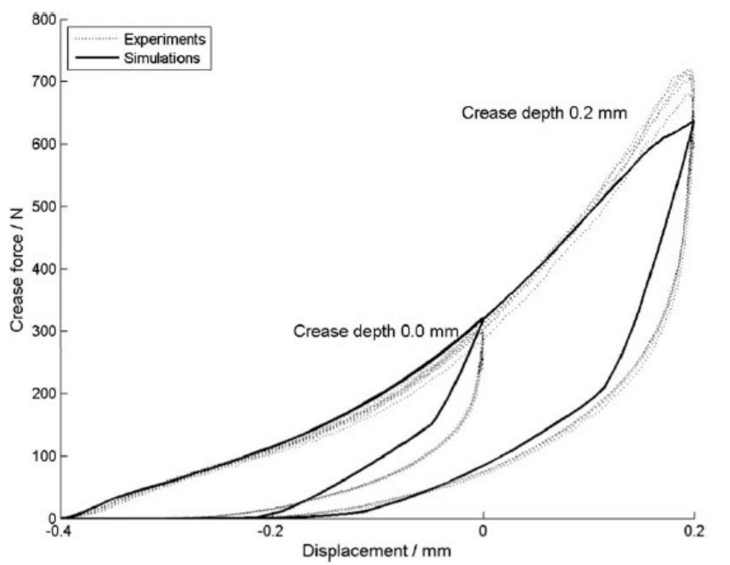
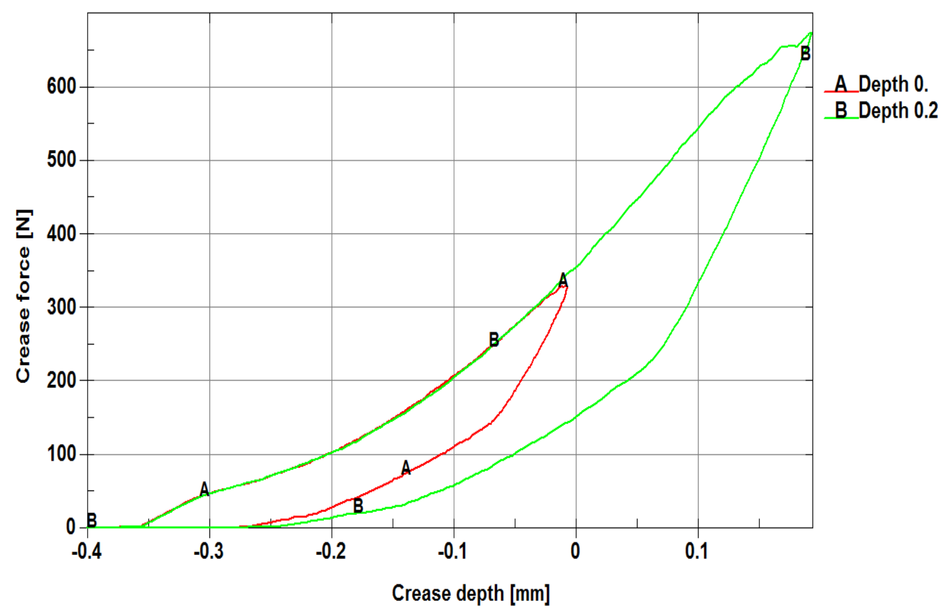
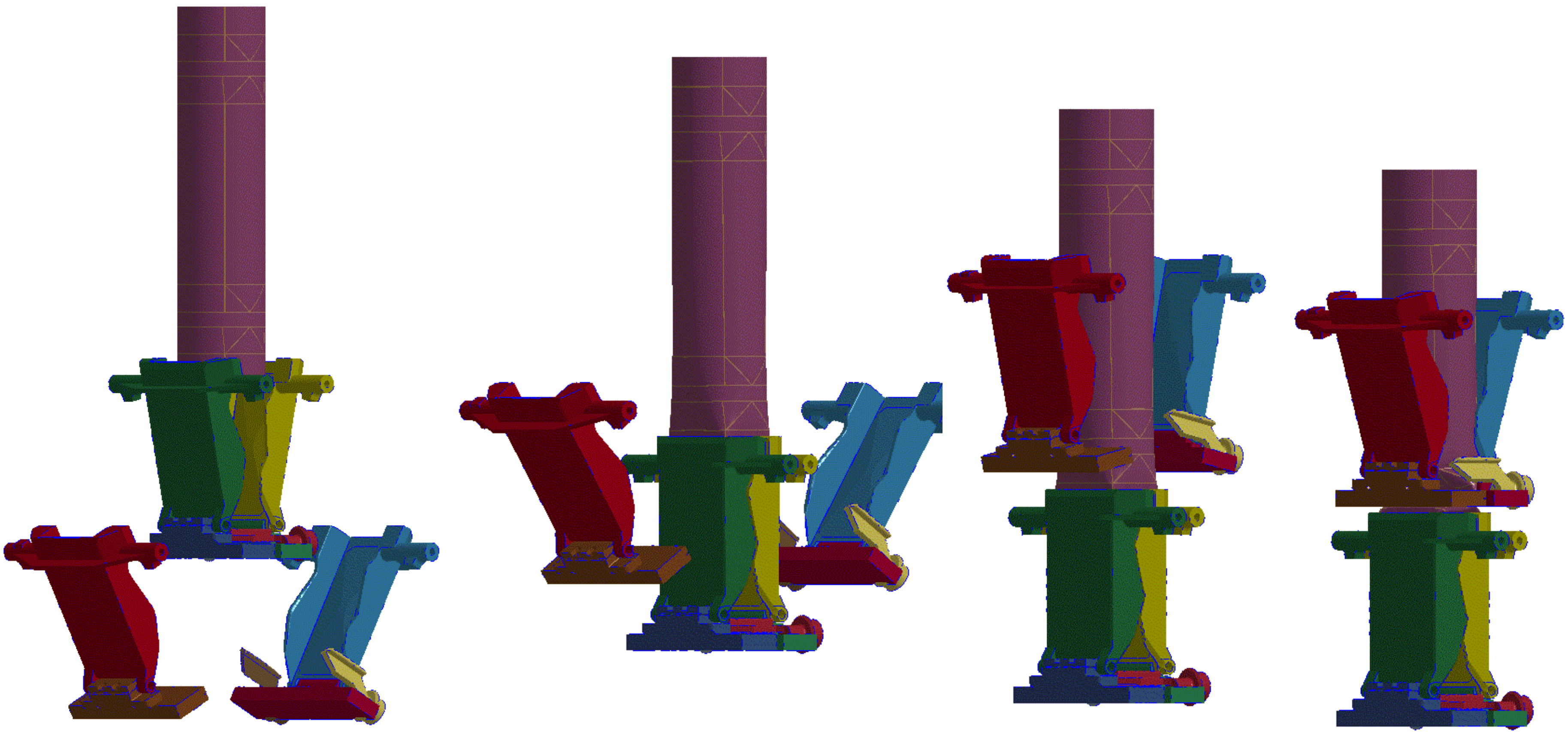


Fig. 6. Comparison between experimental data and simulations for crease depths 0.00 and 0.20 mm.



Current work – full forming simulation



Timelapse of package forming from beverage filled pre-creased paper tube

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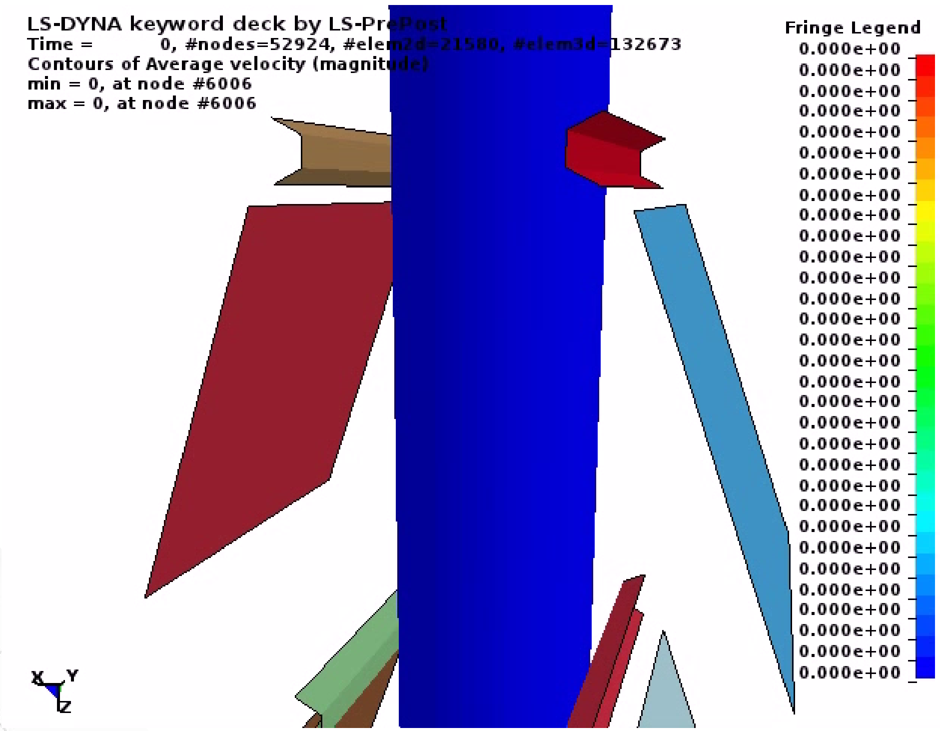
Future - ICFD



LS-DYNA keyword deck by LS-PrePost
Time = 0, #nodes=52924, #elem2d=21580, #elem3d=132673
Contours of Average velocity (magnitude)
min = 0, at node #6006
max = 0, at node #6006
Fringe Legend
0.000e+00
0.000e+00
0.000e+00
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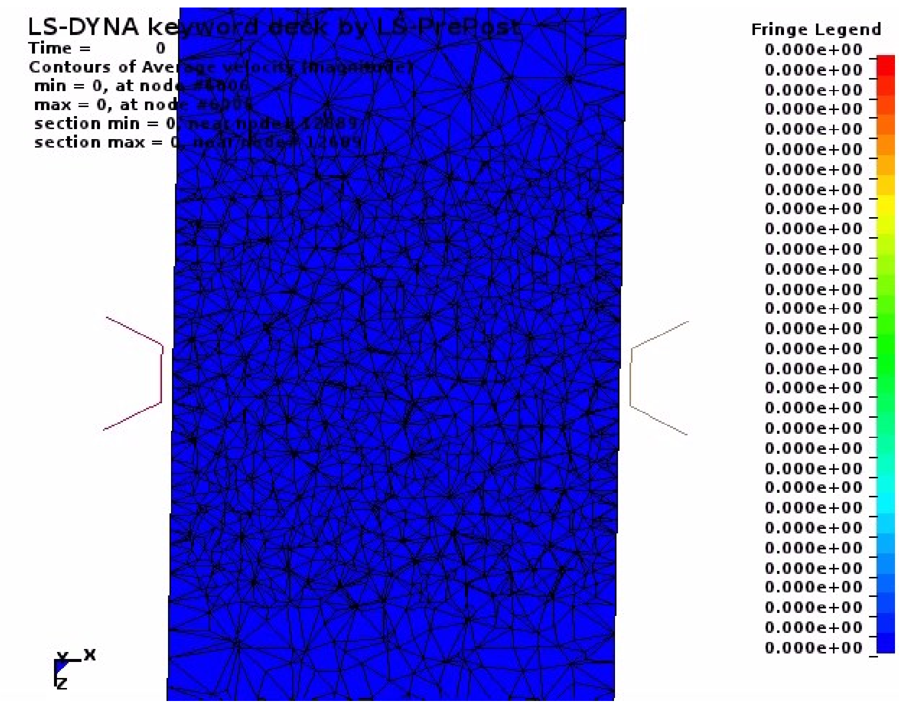
X Y Z



LS-DYNA keyword deck by LS-PrePost
Time = 0
Contours of Average velocity (magnitude)
min = 0, at node
max = 0, at node
section min = 0
section max = 0
Fringe Legend
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0.000e+00
0.000e+00
0.000e+00
0.000e+00
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0.000e+00
0.000e+00
Y X Z

Thank you!