14. LS-DYNA Forum 2016

A Novel Approach to Model Laminated Glass

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Content

- Introduction and Motivation
- Common approach to model laminated glass
- New approach
  - Theory
  - Implementation in LS-DYNA: *MAT_280
- First simulation results

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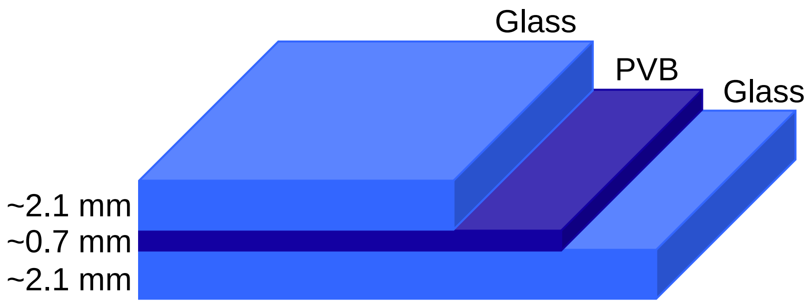
Introduction

- Usage of glass in automotive industry increases: Design elements
- Mechanical behaviour of glass plays a role for the stiffness of the car
- Therefore the numerical treatment is important in crash applications

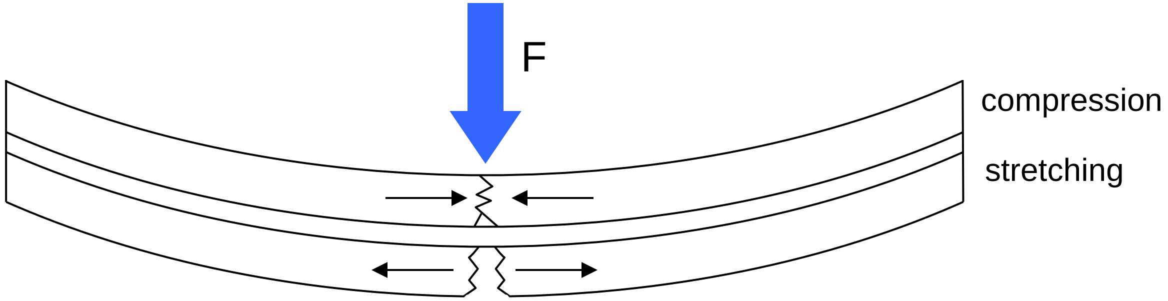
Laminated Safety Glass

- Two types of safety glass commonly used:
  - Tempered glass ➔ side windows
  - Laminated glass ➔ windshields, panorama sunroofs
- Laminated glass consists of 3 layers
  - 2x glass
  - PVB interlayer



- Glass fragments are bonded

  ➔ Difficult mechanical behaviour



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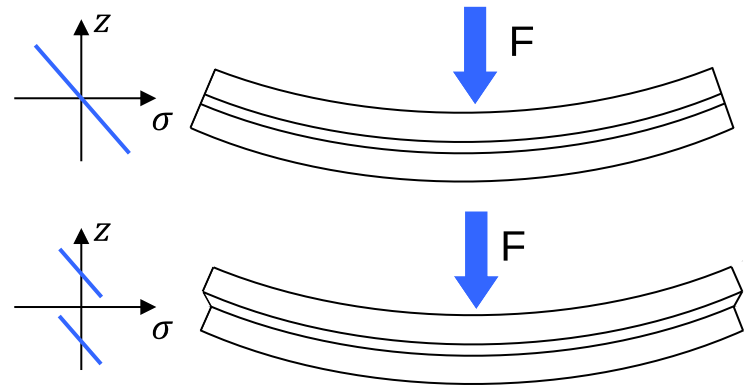
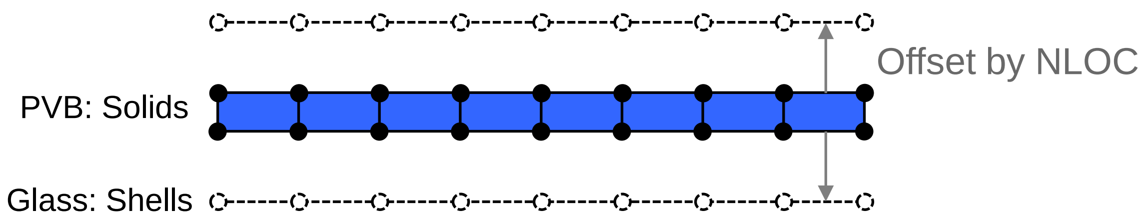
State of the Art: Discretisation

- Discretisation:
  - PVB: transverse shear deformation important
    ➔ solid elements
  - Glass: shell elements



- Contact between layers: Shared nodes

- Offset the glass layers by NLOC parameter

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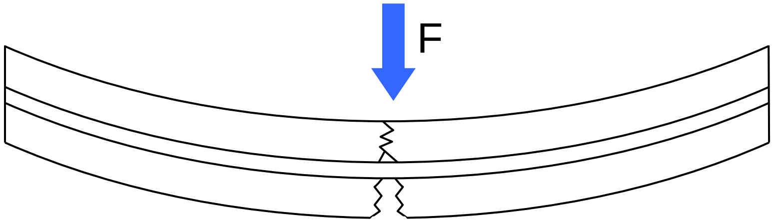
*SECTION_SHELL
$     SECID    ELFORM      SHRF       NIP     PROPT   QR/IRID     ICOMP     SETYP
        103         2       1.0         7       3.0       0.0
$        T1        T2        T3        T4      NLOC     MAREA
        2.1       2.1       2.1       2.1     -1.00
$
```

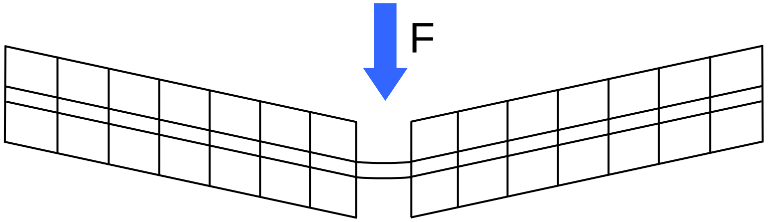
State of the Art: Material Models

- Material Models:
  - PVB: viscoelastic-plastic
  - Glass: linear-elastic with failure, e.g. MAT_24 + MAT_ADD_EROSION

- In case of failure in the glass layers, elements are deleted:
  - Only the stiffness of PVB interlayer is left
  - No residual load bearing capacity
  - Unrealistic post-breakage behaviour

➔ Currently used approaches for the glass‘ material model are not satisfying !





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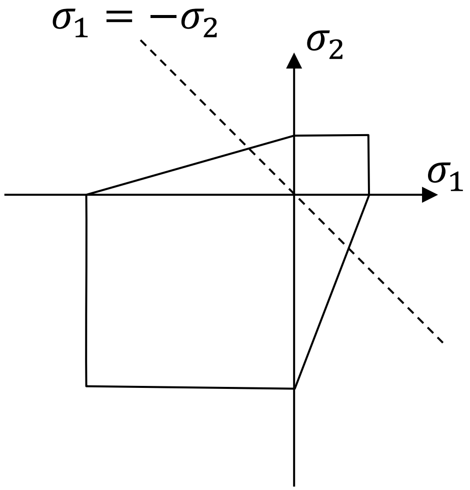
New approach – requirements for glass material model

- Implementation for shell elements
- Isotropic linear elastic material law with brittle failure
- Stress based failure criteria with tension – compression asymmetry
- **Treatment of failure withouth deleting elements**
- **Crack closure and opening effects**
- Further: Easy to use, low computation times, usable in crash simulations..

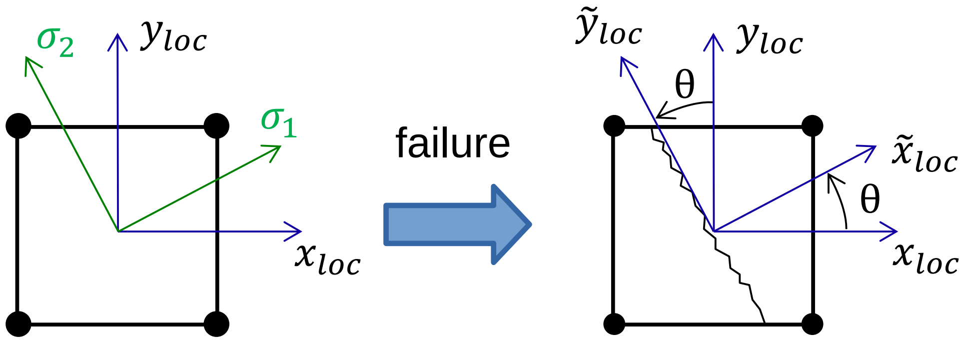
➔ Smeared fixed crack material model

Detection of failure

- Failure criteria: stress based, e.g. simple Mohr-Coulomb

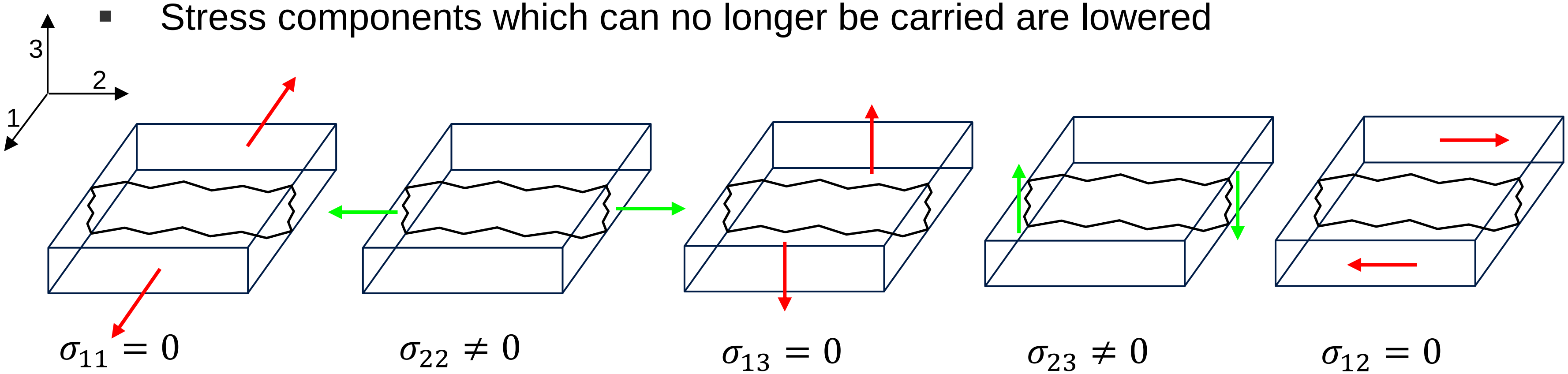


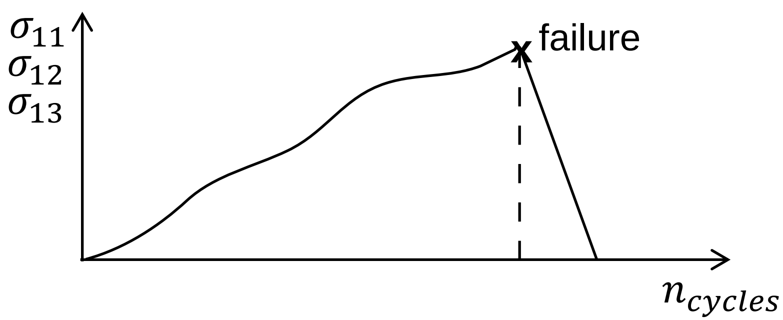
- If current stress meets criteria, decide between
  - Compression: Material is ‘crumbled‘, no stiffness left
  - Tension: Single crack occurs
- Crack direction perpendicular to the first principal stress
- Individual coordinate systems along the crack directions are established in each ‘cracked‘ integration point



Stress Reduction

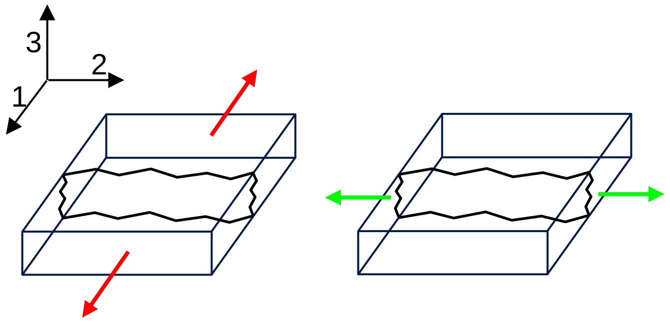
- Done directly after a crack was detected
- Stresses are rotated into crack coordinate system $\boldsymbol{\sigma}_{cr} = \boldsymbol{Q}\boldsymbol{\sigma}\boldsymbol{Q}^T$
- Stress components which can no longer be carried are lowered





Stiffness Calculation and Stress Update

- If a crack occured, the constitutive equation in the IP needs to be updated
- $\mathbb{C}$: 4th order stiffness tensor, isotropic
- $\mathbb{C}^{cr}$: updated stiffness tensor, orthotropic:
  - $C^{cr}_{1111} = \alpha\, C_{1111}$
  - $C^{cr}_{2222} = C_{2222}$
  - … according to crack kinematics



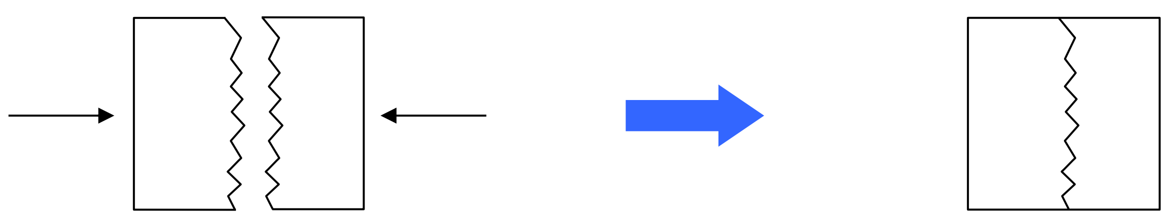
- α depends on the crack opening:
  - $\alpha = 1$ if crack closed (full stiffness applied)
  - $\alpha < 1$ if crack open (reduced stiffness, usually $\alpha = 0$)
- Rotate $\mathbb{C}^{cr}$ from crack to element coordinate system $C_{ijkl} = Q_{im} Q_{jn} Q_{ko} Q_{lp} C^{cr}_{mnop}$
- Update the stresses

Crack Closure Effects

- When crack is detected, a so called crack strain is initialized, two options:
  - Compute from current strain: $\varepsilon_{cr}^{0} = Q_{1i}Q_{1j}\varepsilon_{ij}$
  - Initialize with 0: $\varepsilon_{cr}^{0} = 0$

- Crack strain is updated in every timestep $\varepsilon_{cr}^{i+1} = \varepsilon_{cr}^{i} + Q_{1i}Q_{1j}\Delta\varepsilon_{ij}$

- If crack strain is negative, it is considered as closed



$\varepsilon_{cr} > 0$

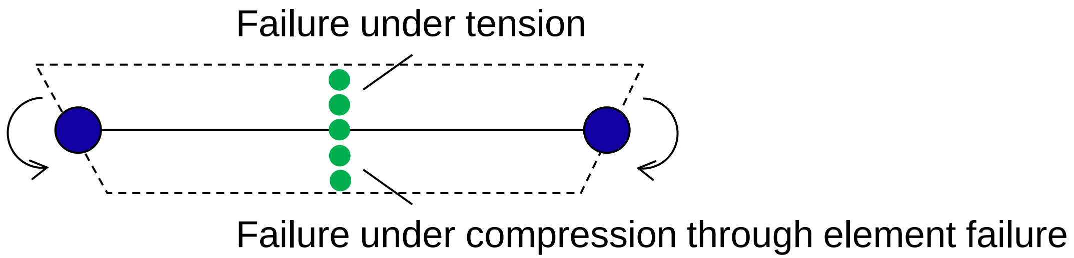
$\varepsilon_{cr} \leq 0$

Lowered stiffness components (Orthotropic)

Full stiffness applied ($\alpha = 1$)

Element failure

- If a certain number of IP in one element failed, whole element will fail
- The crack direction in the IP which failed first sets the direction for the whole element
- Crack strain is computed individually in each IP



- If failure criteria is met a second time after failure:
  - Second crack occurs
  - Orthogonal to the first crack
  - Individual crack strain for each crack ➔ can open and close independendly

*MAT_280

- Shown material model was implemented in LS-DYNA R9.0

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	E	PR				
Type	A8	F	F	F				

Card 2	1	2	3	4	5	6	7	8
Variable	FMOD	FT	FC					
Type	F	F	F					

Card 3	1	2	3	4	5	6	7	8
Variable	SFSTI	SFSTR	CRIN	ECRCL	NCYCR	NIPF		
Type	F	F	F	F	F	F		

- Input Parameters:
- FMOD: Failure model (Mohr-Coulomb, Continuous Surface Cap, Comi)
- SFSTI: Stiffness scale factor in case of failure
- SFSTR: Stress scale factor in case of failure
- CRIN: Flag for crack strain initialisation
- ECRCL: Crack strain from which on the crack is considered as completely closed
- NCYCR: Number of cycles in which the stress is lowered
- NIPF: Number of failed integration points for element failure

*MAT_280

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Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	E	PR				
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Card 2	1	2	3	4	5	6	7	8
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Type	F	F	F					

Card 3	1	2	3	4	5	6	7	8
Variable	SFSTI	SFSTR	CRIN	ECRCL	NCYCR	NIPF		
Type	F	F	F	F	F	F		

- Output variables:
- Crack Flag:
  - 1: 1 crack in element (failure under tension)
  - 2: 2 cracks in element (failure under tension)
  - -1: Failure under compression
- Crack direction: In °rad to the element coordinate system

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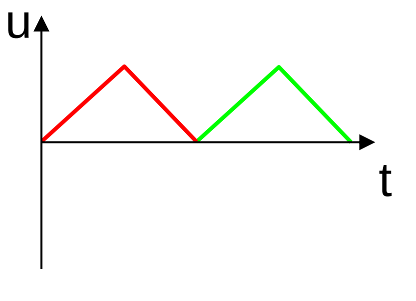
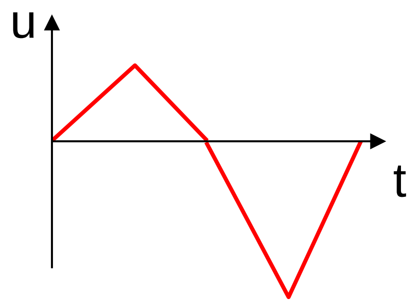
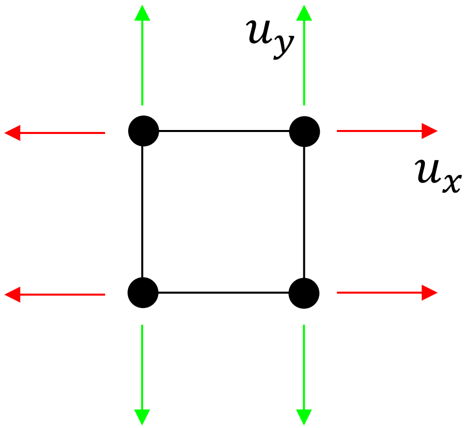
Single Element Tests

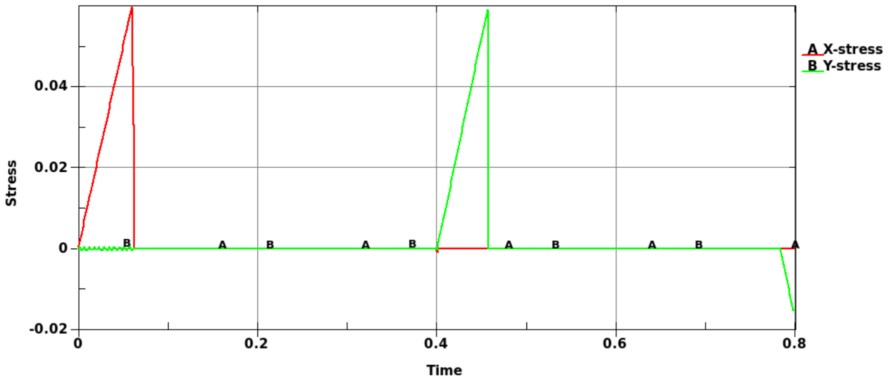
- Nodal displacements:

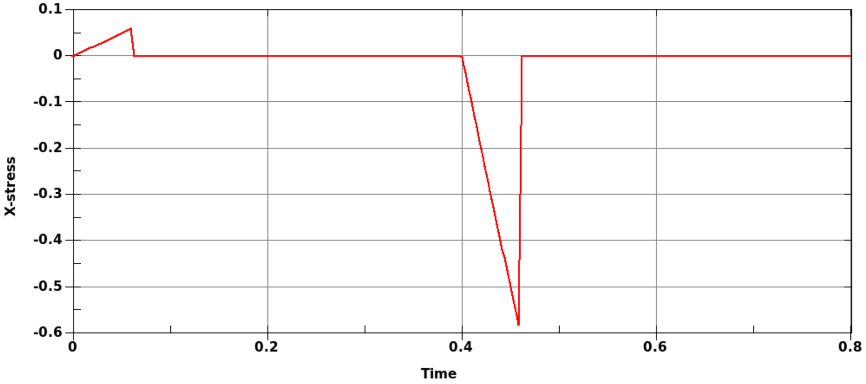




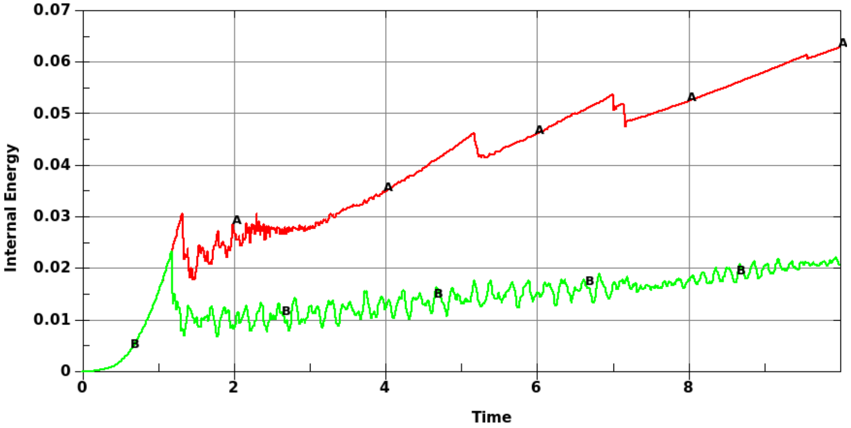


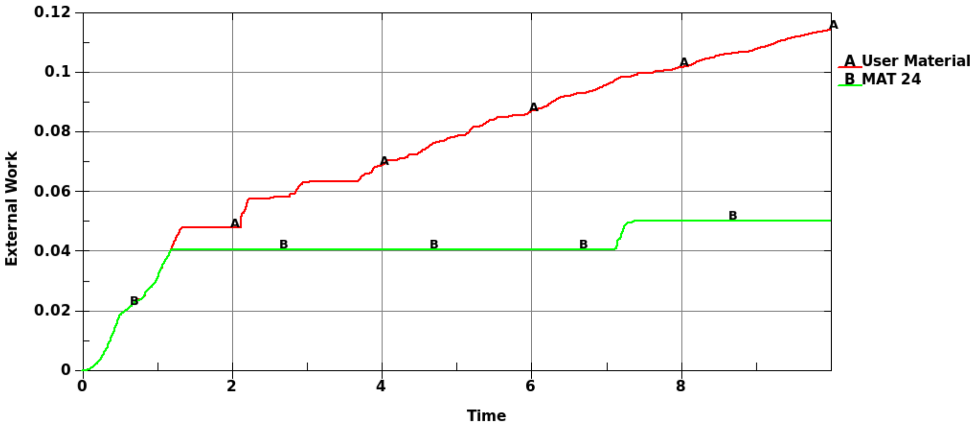
- Stress responses:



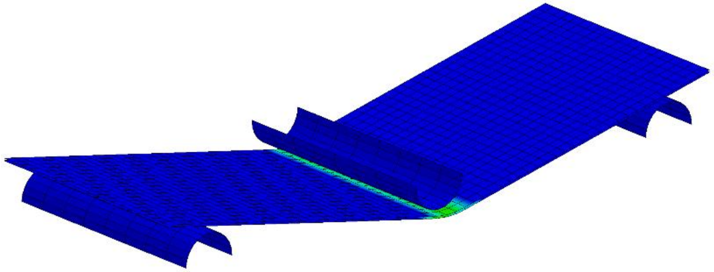


3-Point-Bending





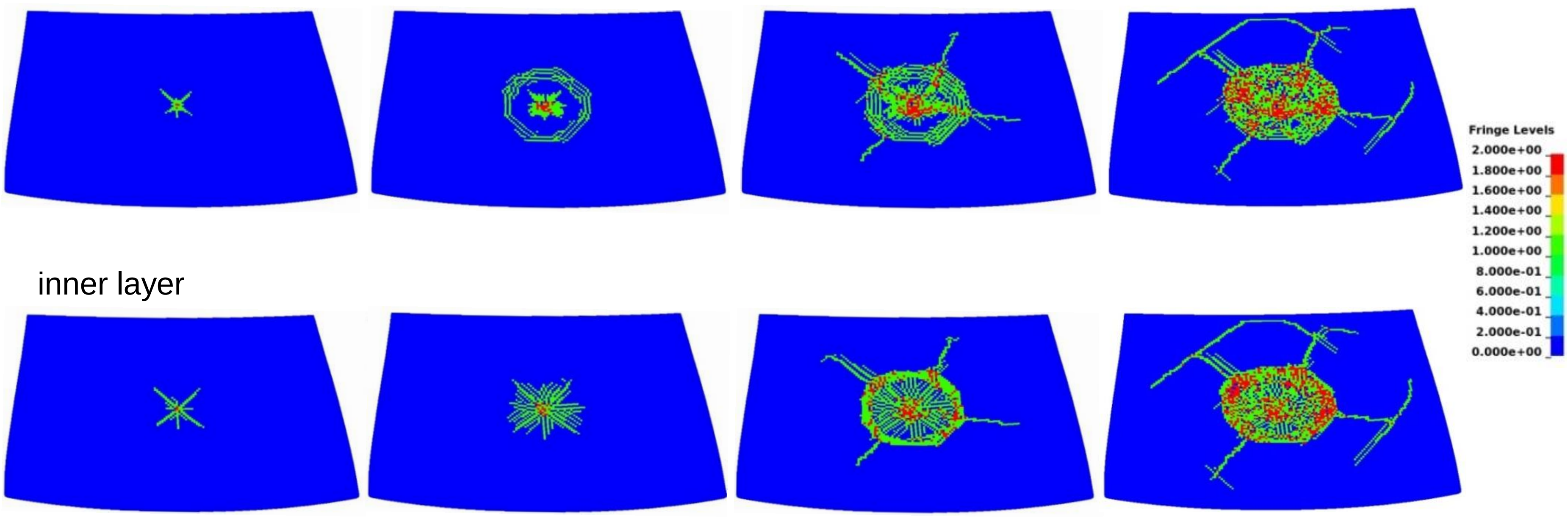
- Comparison: MAT_280 vs. MAT24+ADD_EROSION
- Different post breakage behaviour
- Energy consumption is higher after failure when using MAT_280



Windshield Head Impact

- Head impactor on a windshield using *MAT_280 and regular mesh (grid)

outer layer



t = 2.5 ms | t = 5 ms | t = 7.5 ms | t = 20 ms

- Cracks forming independendly from mesh

Conclusion

- New Approach for treatment of laminated glass
- Implemented in LS-DYNA release R9.0
- First test simulations done
- To come: use in larger models, experimental results, …

Fin