Adhesives modeling with LS-DYNA: Recent developments and future work

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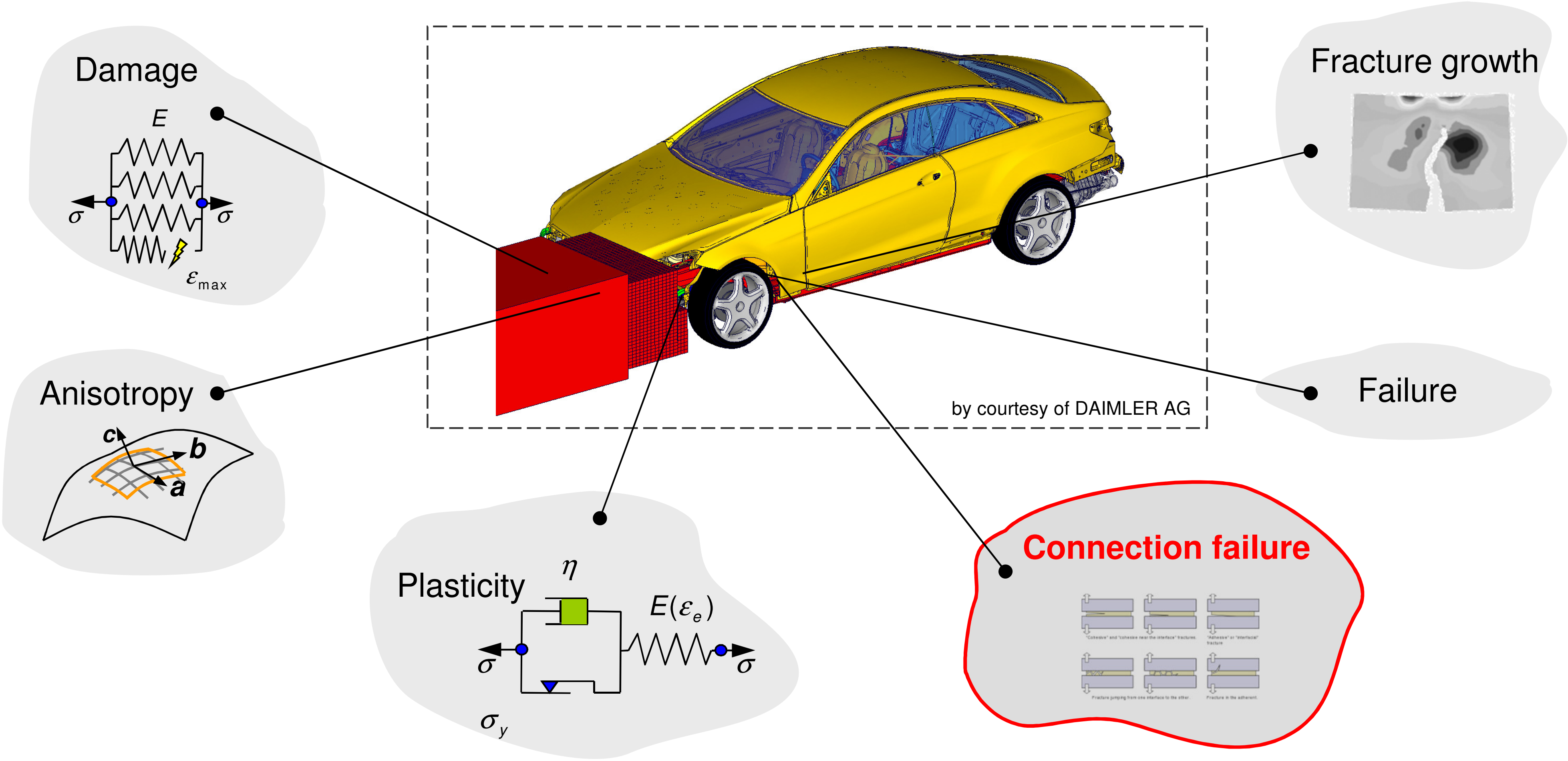
- Preliminary remarks
- Current modeling techniques in LS-DYNA
- Recent trends in LS-DYNA
- Summary

Preliminary remarks

- Current challenges in a full car crash simulation



→ due to a more often usage of high strength steels, the connections become more and more the weak points in crash

Preliminary remarks

- Failure forces
  - main focus of connection modeling in crash lies on the correct prediction of the respective failure forces
  - one has to distinguish between two totally different connection categories:

Failure forces depend on the **connected** materials

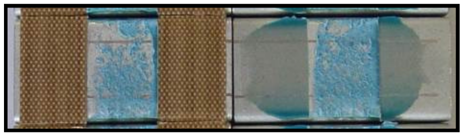
- e. g., spot welding
- material parameters have to be identified for every individual material combination
- **idea:** Find relation to predict failure forces based on the material parameters of the sheet materials and geo. information

→ a lot of experiments are necessary

Failure forces depend on the **connection** material

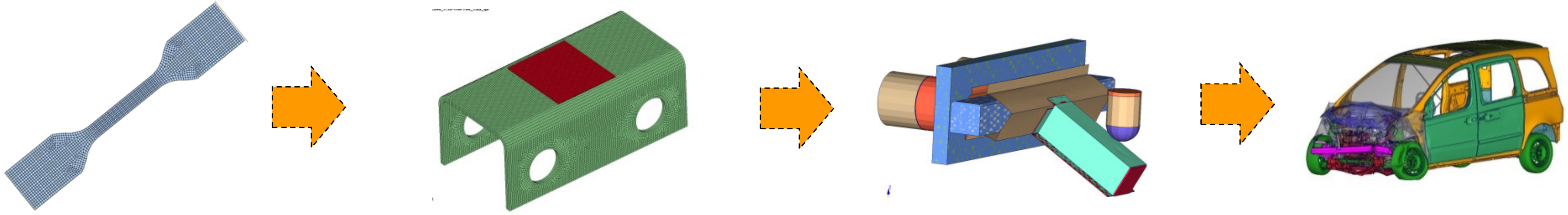
- e. g., adhesive bonding
- identify material parameters using a certain material combination
- **idea:** The material model can be applied to any other material combination

→ fewer experiments are necessary



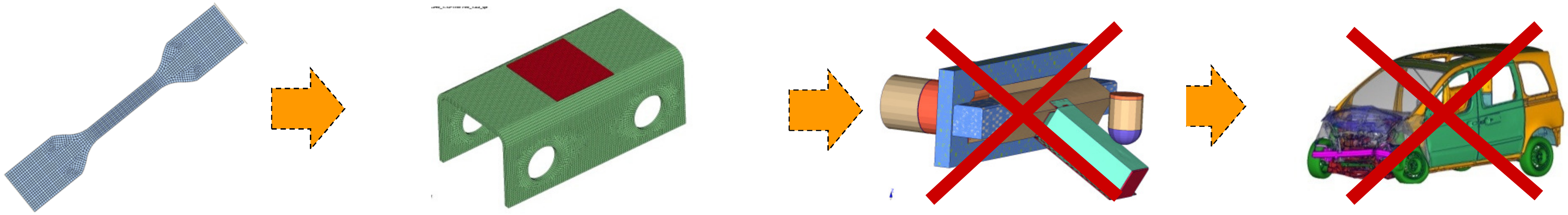
Preliminary remarks

- Verification and validation process
  - **problem I:** Element size and explicit time integration
    - ideal procedure: A detailed model with physical material parameters can be used on every scale of interest



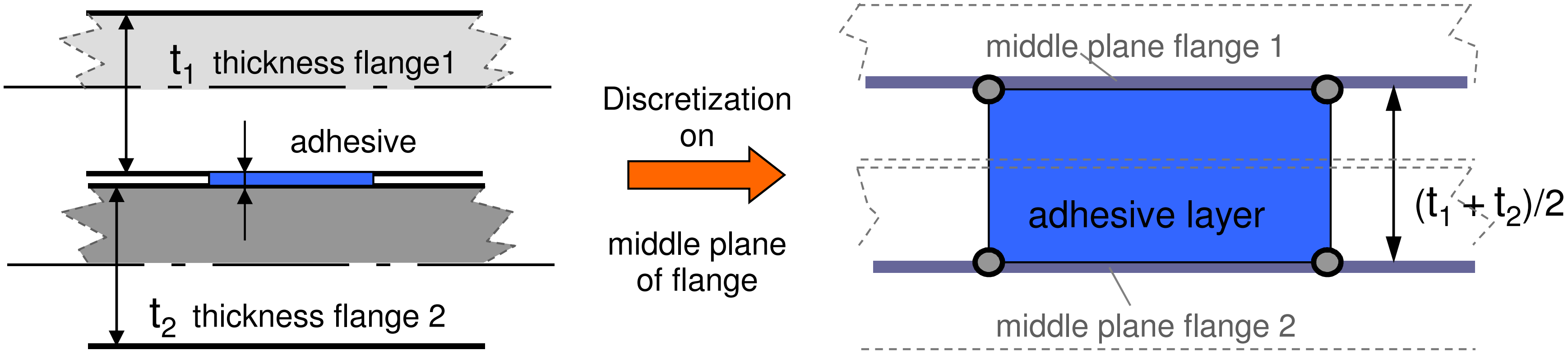
→ verification is done on the smallest scale
→ validation can be done on KS-II and component scale

    - the spatial discretization of the connection has to be very fine compared to the element size usually used on the component and full car scale
    - explicit time integration → decreasing of time step or increasing of additional mass
    - because of limited CPU-power, the highest scale for the usage of a detailed model is currently the scale of the KS-II specimen

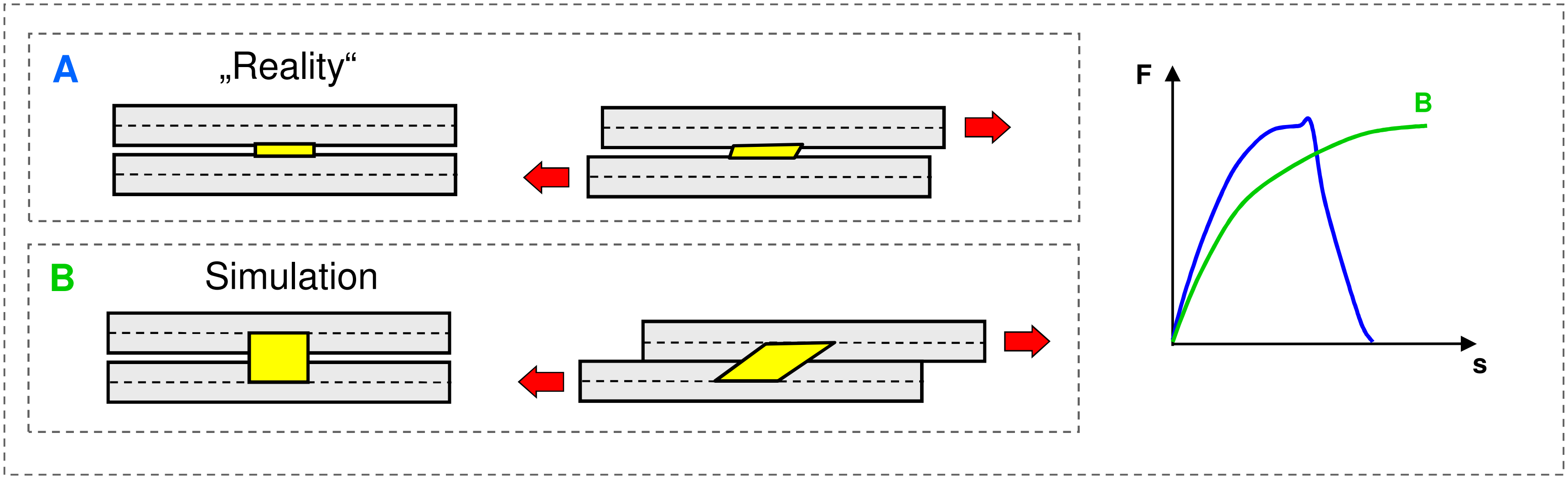


Preliminary remarks

- **problem II:** Discretization issue
  - flange materials are currently discretized with shell elements

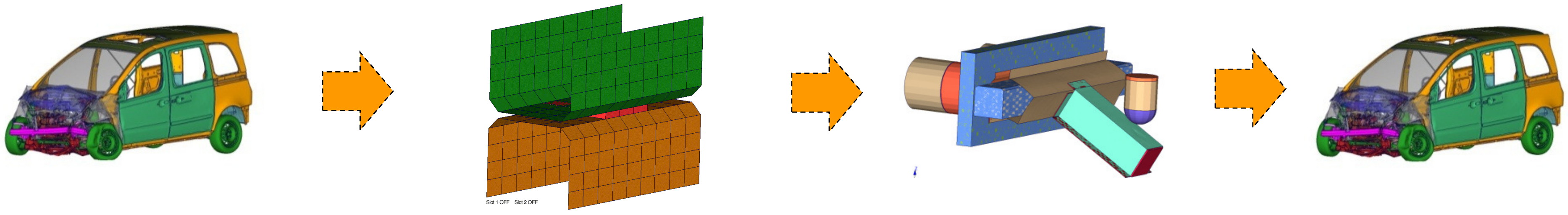


  - **consequence:** Material behavior is too flexible using physical material parameters



Preliminary remarks

- **requirement:** The spatial discretization and the respective material model of the connection has to be chosen in such a way that the performance and the validity of the full car simulation is not negatively affected.

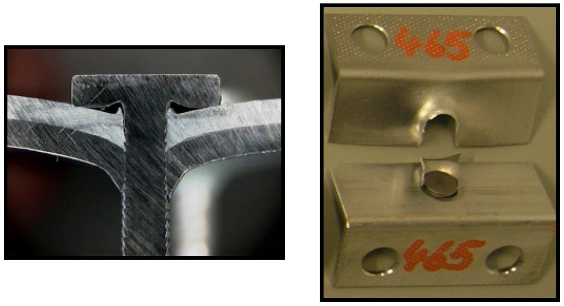


→ **The only applicable procedure for connection modeling is the usage of so-called substitute models with artificial material parameters**

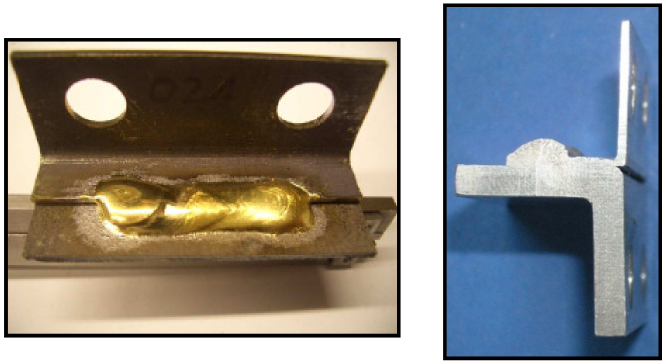
- currently used robust element types and corresponding material models
  - hexahedron elements in combination with 3-d material models, e. g.,
    - *MAT_SPOTWELD (*MAT_100),
    - *MAT_SPOTWELD_DAIMLERCHRYSLER,
    - *MAT_ARUP_ADHESIVE (*MAT_169),
    - *MAT_FU_CHANG_FOAM (*MAT_083), …

Preliminary remarks

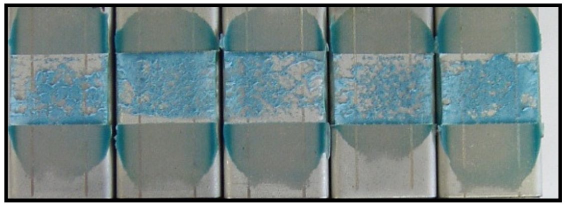
- Different joining techniques and the corresponding material models
  - punctiform
    - spot welding, RIVTAC, …
    - currently used robust material models: *MAT_SPOTWELD_{DAMAGE_FAILURE}, *MAT_SPOTWELD_DAIMLERCHRYSLER + *DEFINE_CONNECTION_PROPERTIES, …



  - line-shaped
    - MIG welding, MIG soldering, …
    - currently used robust material model: *MAT_ARUP_ADHESIVE, …

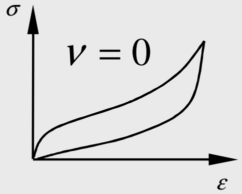
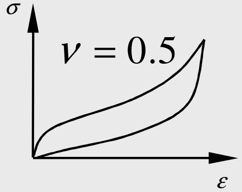
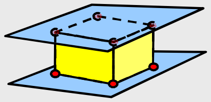
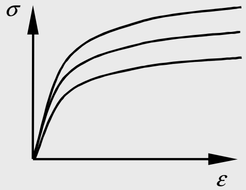


  - area-shaped
    - adhesive bonding: Structural adhesive, hood adhesive, PU windshield, …
    - currently used robust material models: *MAT_ARUP_ADHESIVE, *MAT_FU_CHANG_FOAM, …



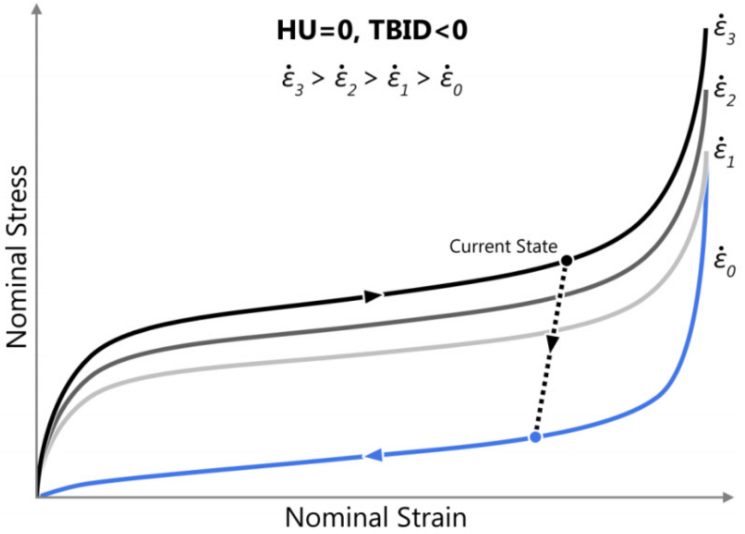
Current modeling techniques in LS-DYNA

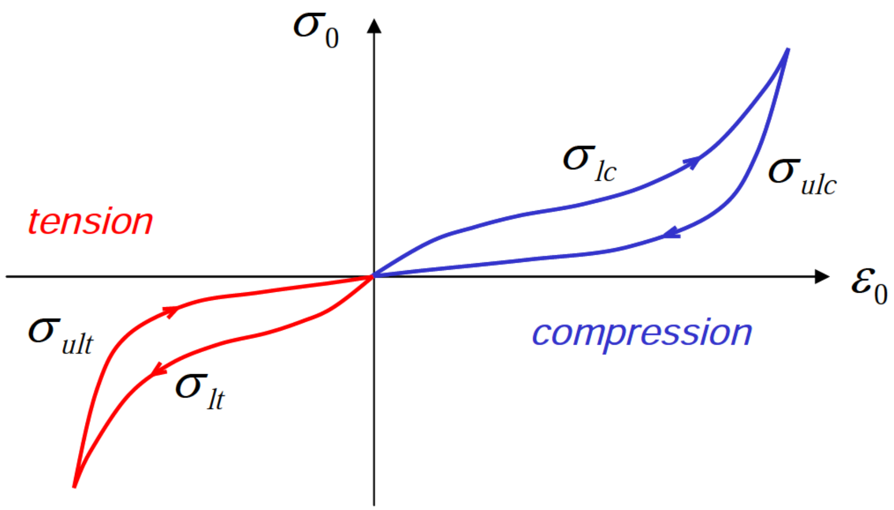
- Mechanical behavior of the different bonding materials

Material behavior		Choice of material model
▪ hood adhesive → foam-like, → viscoelastic		▪ hyperelastic and foam-like, strain rate dependent → ***MAT_FU_CHANG_FOAM**
▪ PU windshield → rubber-like, → viscoelastic		▪ hyperelastic and rubber-like, strain rate dependent → *MAT_SIMPLIFIED_RUBBER_{}, ν=0.499 (*OGDEN*) → using substitute model with one element attached with tied contact results in ν=0 for the element → extremely high in plane stress values → use ***MAT_FU_CHANG_FOAM** 
▪ structural adhesive → elasto-viscoplastic		▪ elastoplastic, strain rate dependent, failure → ***MAT_ARUP_ADHESIVE**

Current modeling techniques in LS-DYNA

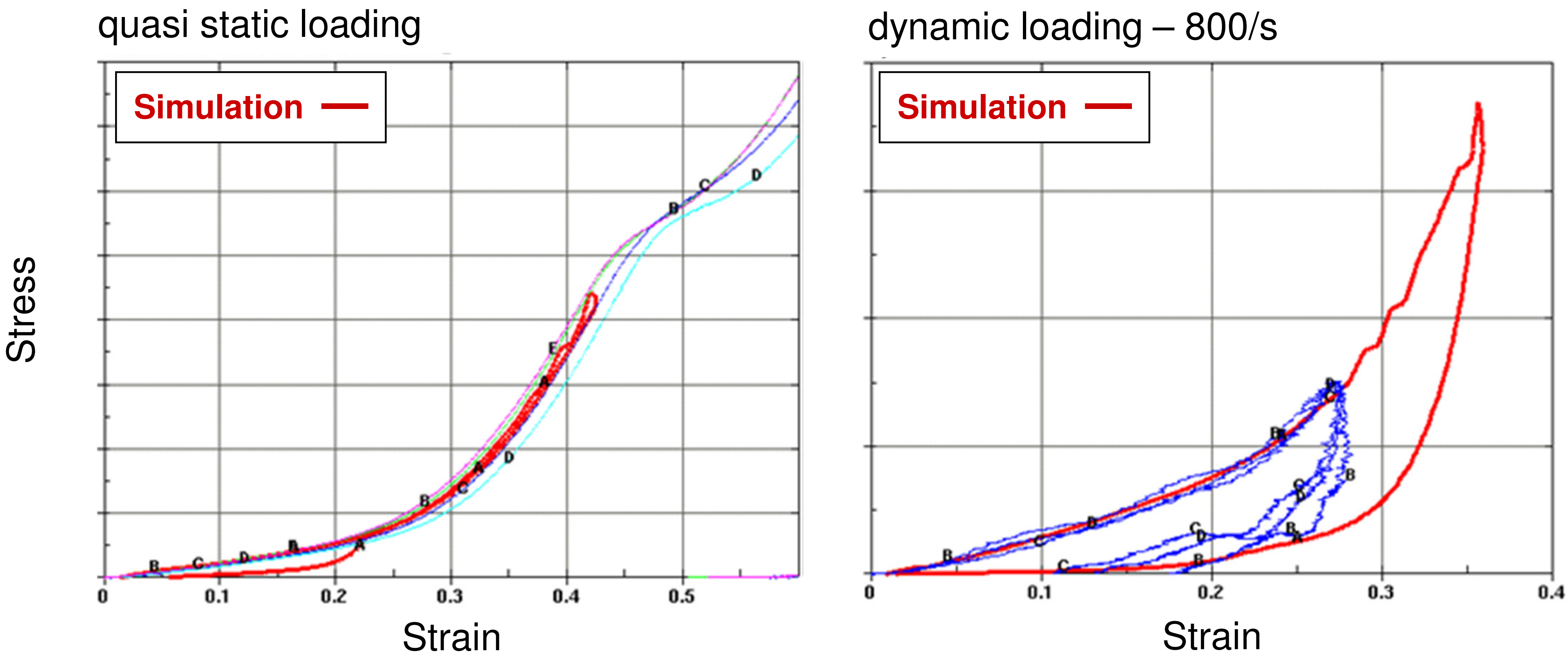
- *MAT_FU_CHANG_FOAM (*MAT_083)
  - used for modeling hood adhesive and PU windshield
  - viscoelastic material model
  - input of engineering stress versus engineering strain curves
  - incorporation of rate effects via table definition
  - by default linear in tension, but load curves can be defined in tension as well (TFLAG=1)





Current modeling techniques in LS-DYNA

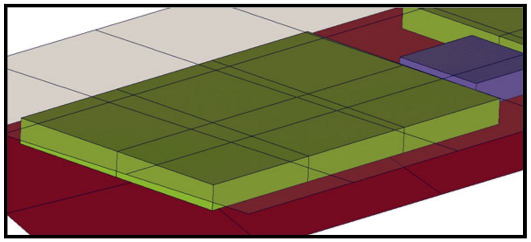
- example: Hood adhesive – quasi static and dynamic loading



Material model is suitable to describe loading and unloading of hood adhesive under quasi static and dynamic conditions.

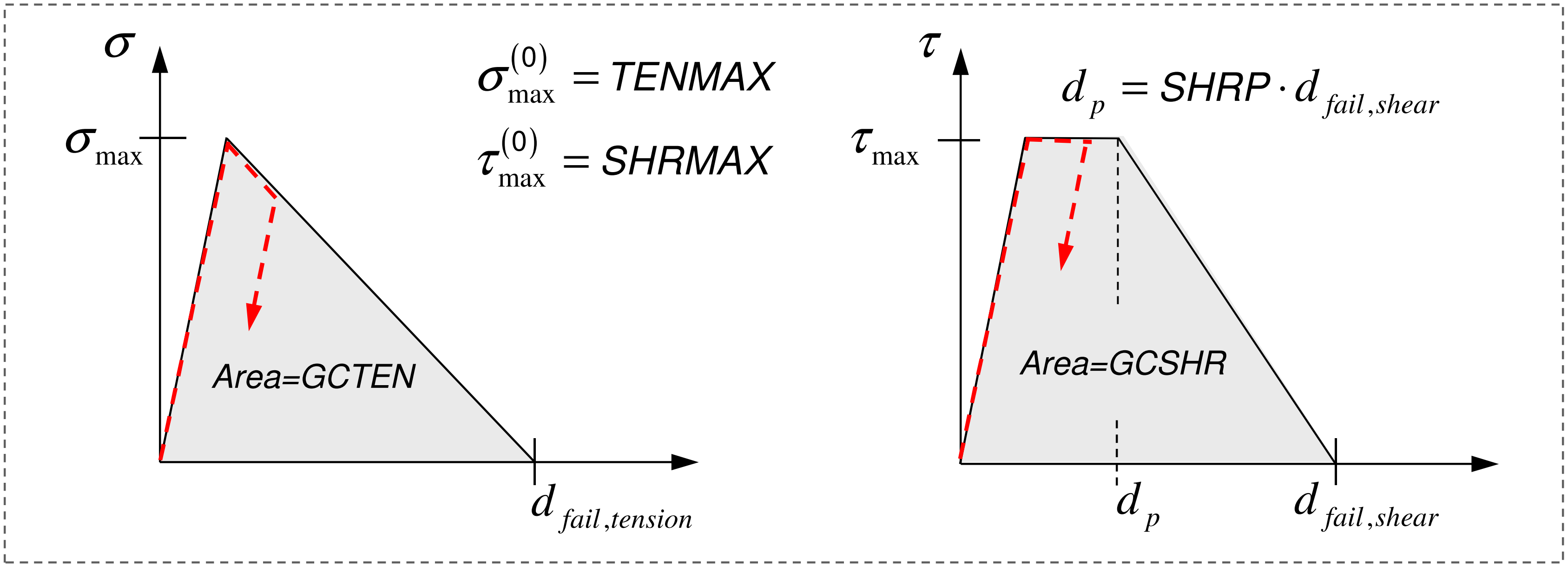
Current modeling techniques in LS-DYNA

- *MAT_ARUP_ADHESIVE (*MAT_169)
  - used for modeling of structural adhesive
  - material behavior can be defined individually for the normal and shear direction → correct definition of the thickness direction is extremely important
  - elastoplastic material model with the following yield surface:



$$\left(\frac{\sigma(\dot{\varepsilon})}{\sigma_{\max}(\dot{\varepsilon})}\right)^{PWRT}+\left(\frac{\tau(\dot{\varepsilon})}{\tau_{\max}(\dot{\varepsilon})-SHL\_SL\cdot\sigma(\dot{\varepsilon})}\right)^{PWRS}-1.0=0$$

  - material is characterized via maximum stresses (yield stresses) and energies



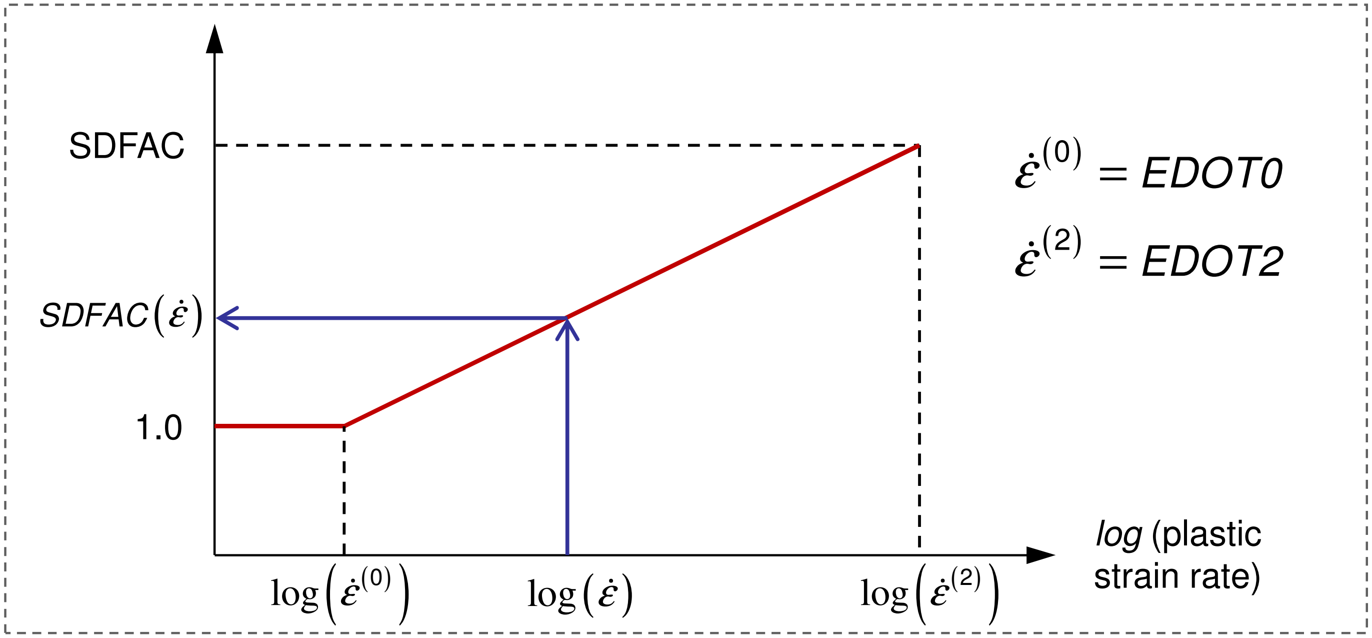
$$\sigma_{\max}^{(0)}=TENMAX$$

$$\tau_{\max}^{(0)}=SHRMAX$$

$$d_p=SHRP\cdot d_{fail,shear}$$

Current modeling techniques in LS-DYNA

- possibility to account for strain rate effects:
  → strengths and fracture energies are scaled linearly in the log-scale of the plastic strain rate



$$\sigma_{\max}(\dot{\varepsilon}) = SDFAC(\dot{\varepsilon}) \cdot \sigma_{\max}^{(0)}$$

$$\tau_{\max}(\dot{\varepsilon}) = SDFAC(\dot{\varepsilon}) \cdot \tau_{\max}^{(0)}$$

$$GCTEN(\dot{\varepsilon}) = SGFAC(\dot{\varepsilon}) \cdot GCTEN$$

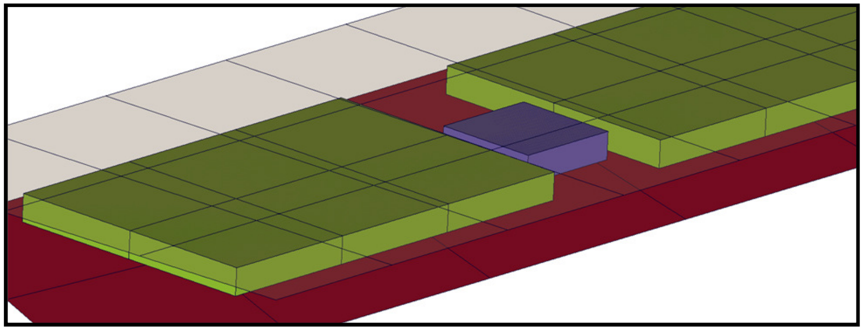
$$GCSHR(\dot{\varepsilon}) = SGFAC(\dot{\varepsilon}) \cdot GCSHR$$

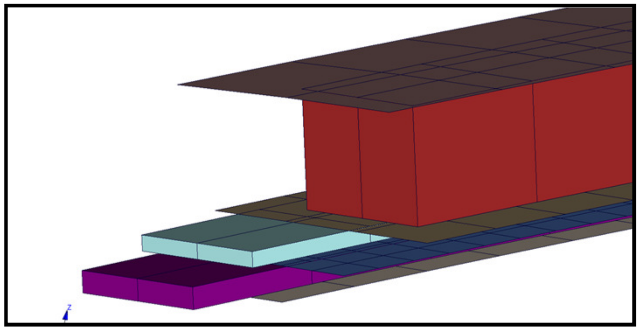
- additionally output can be activated via OUTFAIL

```
1808 t 9.9979E-01 dt 5.53E-04 write d3plot file            04/11/14 13:56:15
    mat_arup element 13 (IP= 1) had damage initiated at time 1.0468E+00
      axial term of failure function ... 0.00000
      shear term of failure function ... 1.00044
      resultant axial force ............ 2.9562E-04
      resultant shear force ............ 2.8676E+00
```

Current modeling techniques in LS-DYNA

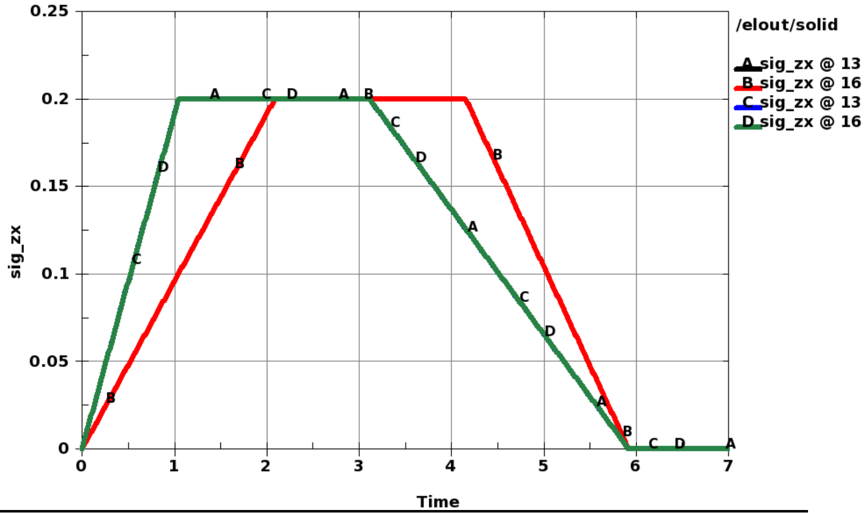
- thickness direction can be defined via
  smallest element side (default) or node numbering (THKDIR)

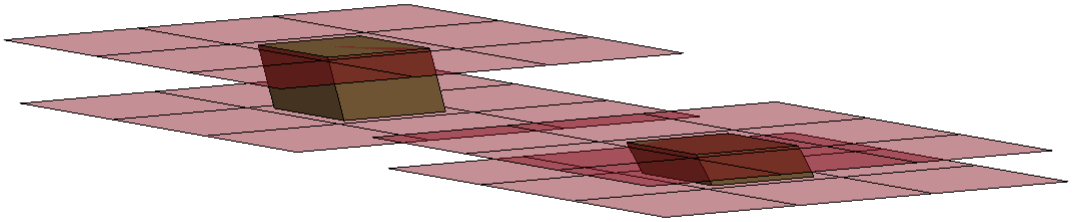




future work: Thickness direction is calculated based on tied contact information

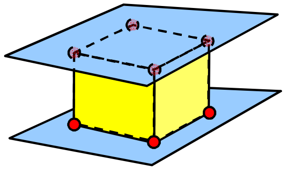
- bond thickness can be defined individually (BTHK)
  → material behavior independent of element height
  → reduce errors due to an incorrect spatial discretization in the full car crash model
  → negative value: BTHK is bond thickness
  but critical time step is not affected
  (can affect stability!!!)



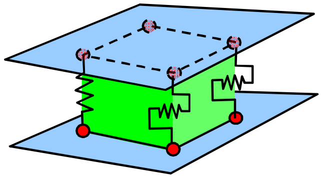


Recent trends in LS-DYNA

- Element types and corresponding material models
  - volume elements and 3-d material models, e.g.,
    *MAT_SPOTWELD (*MAT_100),
    *MAT_ARUP_ADHESIVE (*MAT_169)



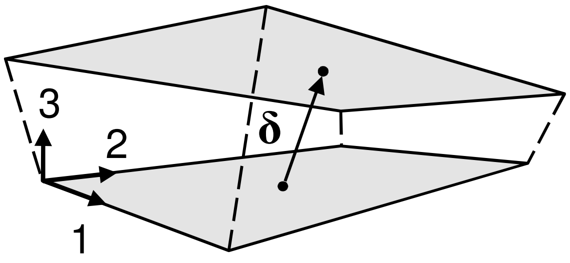
    - **material law**: Stress vs. strain
      → critical time step **depends** on thickness
    - **disadvantage:** If element height tends to zero, e.g., switching from a shell disc. of the flanges to a discretization with solids, the critical time step tends to zero as well
      → impossible to use standard element formulations and corresponding material models
  - cohesive elements and corresponding material models,
    e. g., *MAT_COHESIVE_...



    - **material law**: Stress vs. displacement
      → critical time step is **independent** of thickness
    - **advantage:** Elements with zero height can be used without running into troubles regarding the critical time step

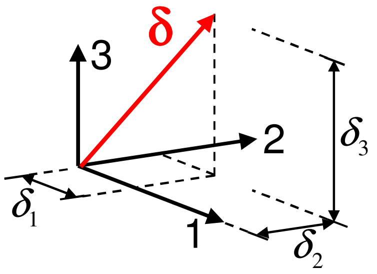
Recent trends in LS-DYNA

- Cohesive elements and material modeling
  - material behavior can be defined individually for the normal and shear direction
    → correct definition of the thickness direction is extremely important
  - cohesive material laws are displacement driven:
    → local relative displacements at integration points
    → local (interface) stresses



$$\begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix} = \begin{bmatrix} E_T & 0 & 0 \\ 0 & E_T & 0 \\ 0 & 0 & E_N \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{bmatrix} \quad \left[N/mm^2 \right] = \left[N/mm^3 \right] \cdot \left[mm \right]$$

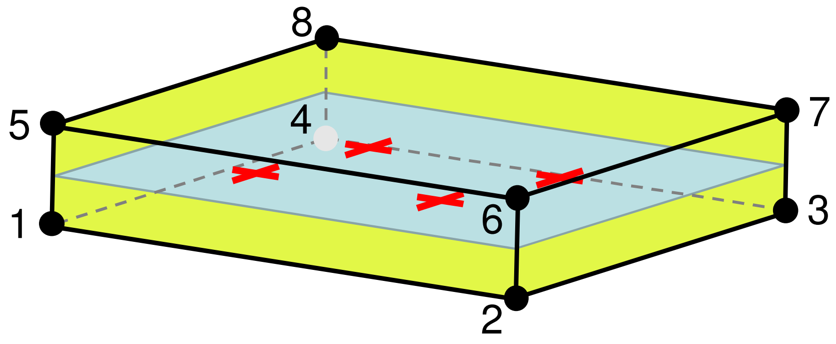
Interface stiffness is not the same
as *classical* stiffness



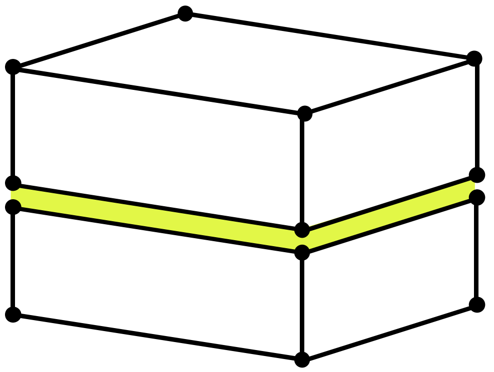
  - density can be specified per unit volume or per unit area
    → handling of elements with an initial volume of zero
  - LS-DYNA provides “special" volume elements:
    Account for orientation (element numbering),
    special treatment of thickness (critical time step)

Recent trends in LS-DYNA

- Cohesive elements
  - attached via coincident nodes or tied contact
  - in plane integration: 2x2 Gauss
  - element numbering defines thickness direction. **Future work:** Thickness direction calculated based on tied contact information



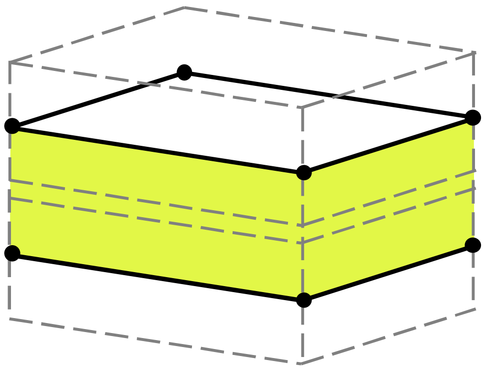
tie volume elements



ELFORM=19

- moments have not to be transferred
- "null" thickness (→ ROFLG) → calculation of mass based on area

tie shell elements



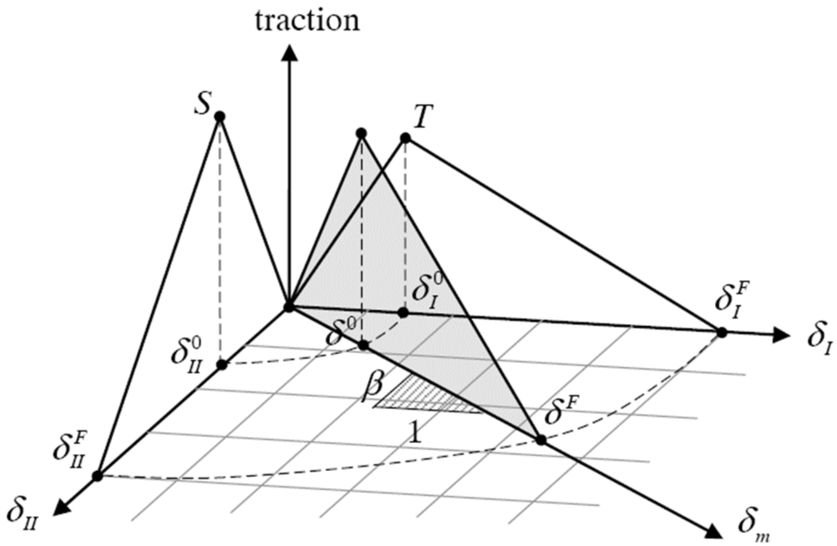
ELFORM=20

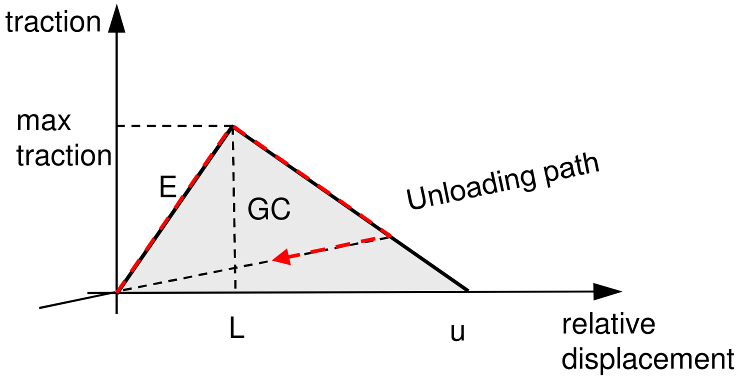
- moments are transferred
- cohesive element with „offset"
- moments = forces · offset

Recent trends in LS-DYNA

- *MAT_COHESIVE_MIXED_MODE (*MAT_138)
  - purely elastic cohesive zone model with damage (no plasticity!!!)
  - bi-linear traction-separation law with a quadratic mixed-mode delamination criterion and damage formulation (as well available in tiebreak contact OPTION=9/11)
  - elastic stiffness, maximum stress and total energy can be specified in tension as well as shear
  - number of integration points required for the element to be deleted can be specified (INTFAIL)
  - total mixed-mode relative displacement

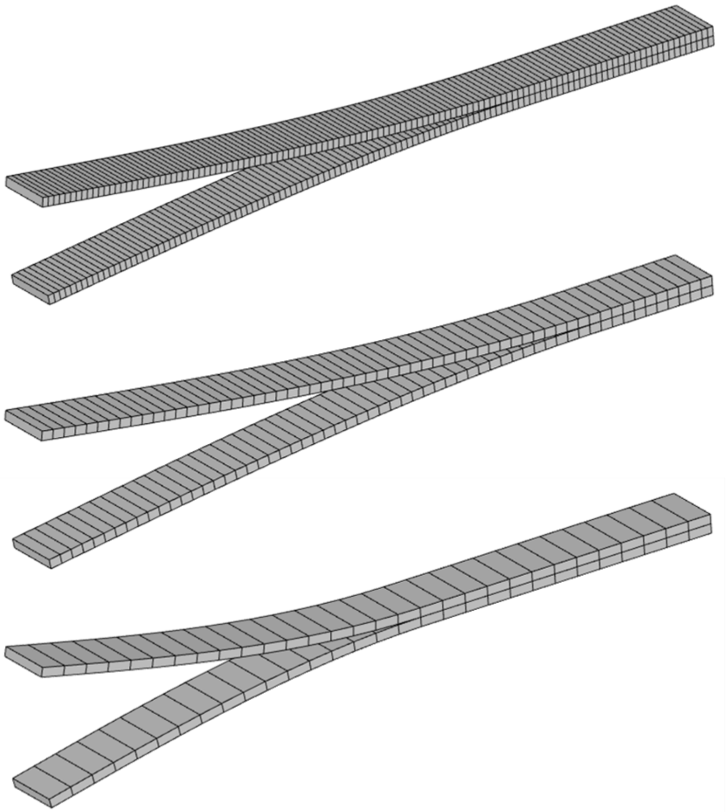
$$\delta_I = \delta_3 \;\; ; \;\; \delta_{II} = \sqrt{\delta_1^2 + \delta_2^2} \;\; ; \;\; \delta_m = \sqrt{\delta_I^2 + \delta_{II}^2}$$

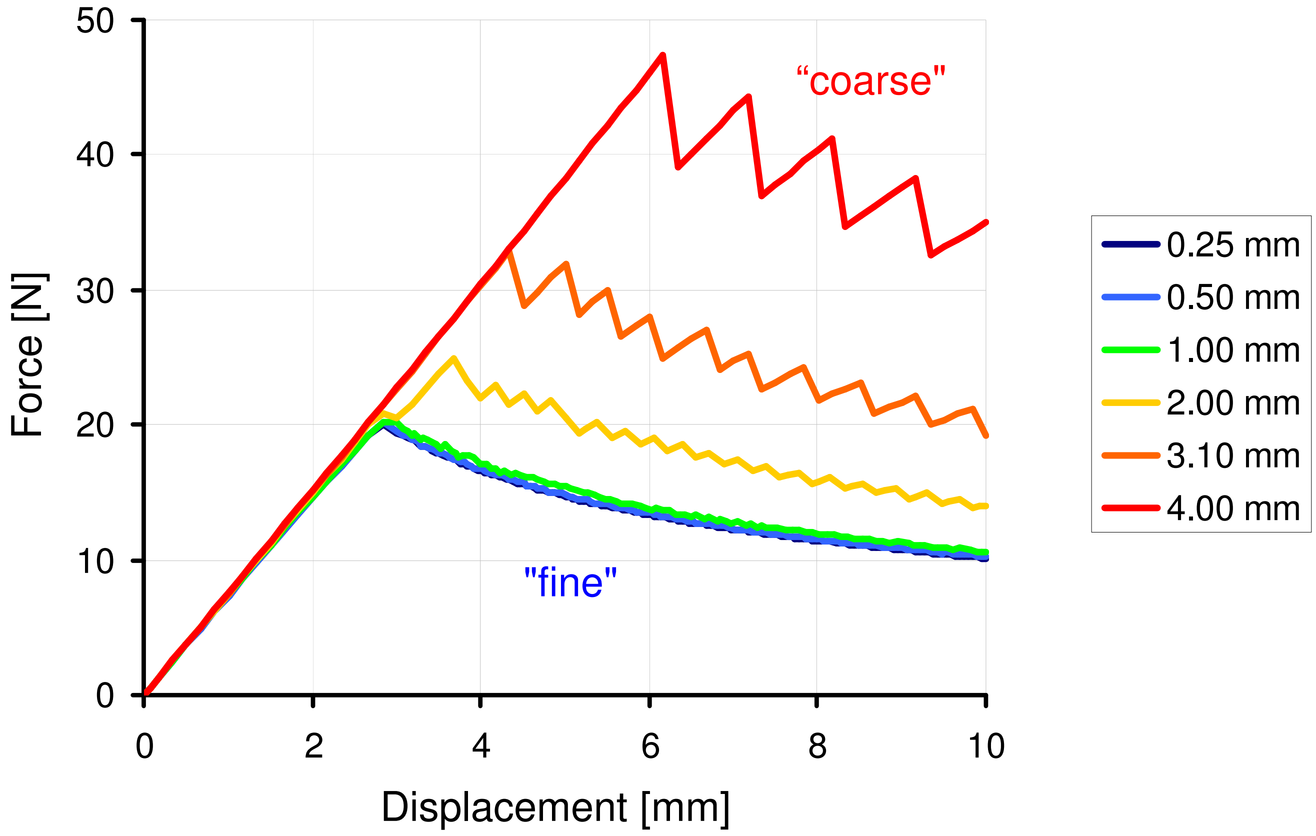




Recent trends in LS-DYNA

- example: Fracture mode I – opening, mesh dependency

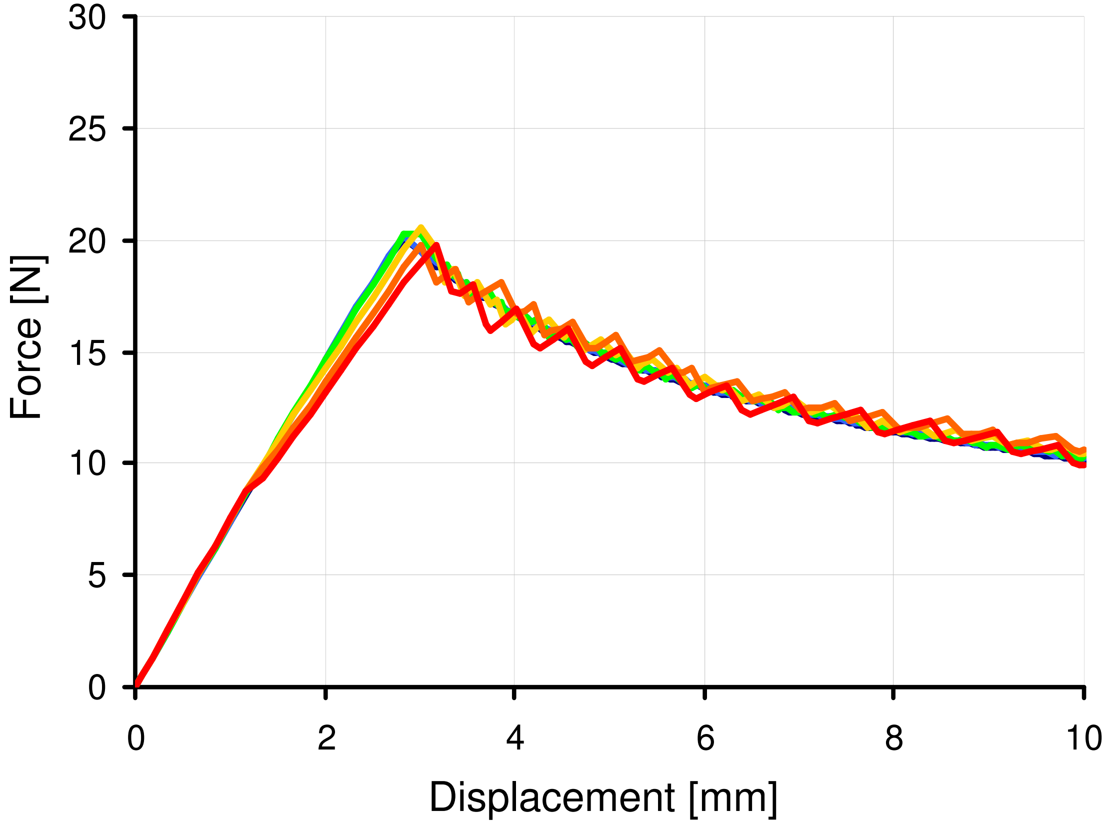


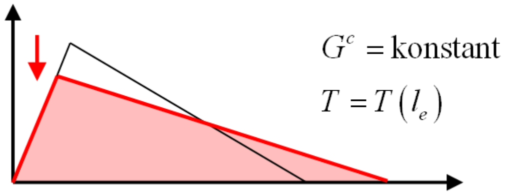


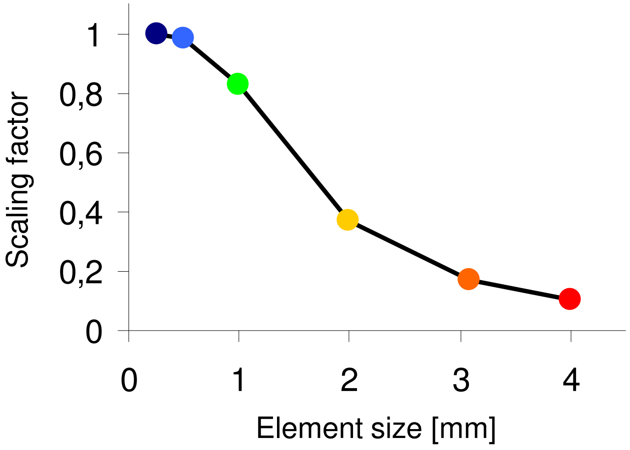
If the discretization is too coarse, the crack process zone is not resolved sufficiently.

Recent trends in LS-DYNA

- example: Fracture mode I – opening, mesh dependency
  - idea: Maximum stress is element size dependent: $T = T\left(l_e\right)$
  - fracture energy is kept constant
  - scaling / fitting is done by trial end error
  - load curve (stress vs. element size) can be referenced in material definition

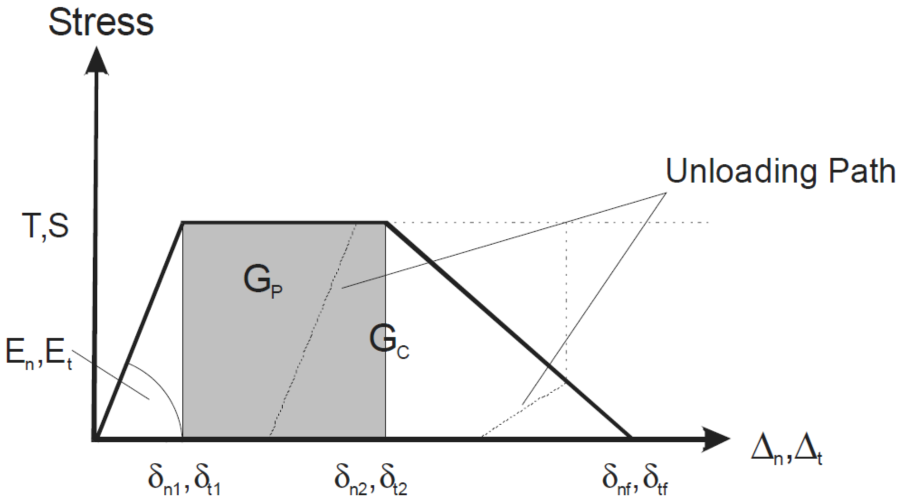


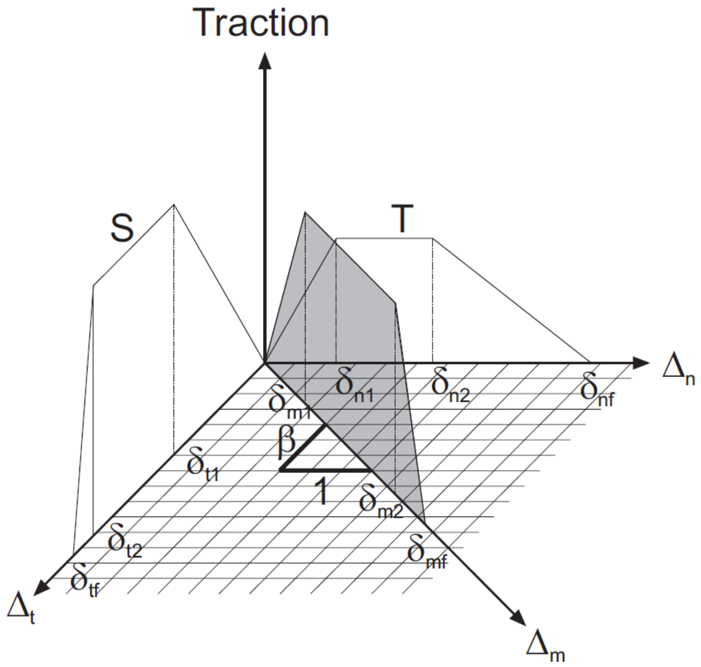




Recent trends in LS-DYNA

- *MAT_COHESIVE_MIXED_MODE_ELASTOPLASTIC_RATE (*MAT_240)
  - elastic-ideally plastic cohesive zone model with damage
  - rate-dependent
  - tri-linear traction-separation law
  - alternative for *MAT_ARUP_ADHESIVE
  - quadratic yield and damage criterion in mixed-mode loading
  - number of integration points required for the element to be deleted can be specified (INTFAIL)
  - maximum stress, total energy and a further factor describing the traction-separation law can be specified in tension as well as shear

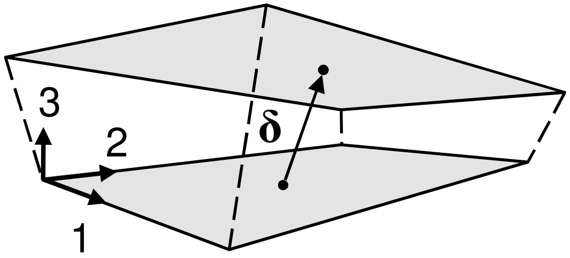




Recent trends in LS-DYNA

- 3-d models in conjunction with cohesive elements – *MAT_ADD_COHESIVE
  - using this keyword, it is possible to combine currently the following material models with cohesive elements (ELFORM=19, 20):
    *MAT_{1, 3, 4, 6, 15, 24, 41-50, 81, 82, 89, 96, 98, 103-107, 115, 120,
    123, 124, 141, 168, 173, 187, 188, 193, 224, 225, 252 and 255}
    assumption: No lateral expansion and no in-plane shearing

$$\begin{bmatrix}\delta_1\\\delta_2\\\delta_3\end{bmatrix} \rightarrow \begin{bmatrix}\dot{\varepsilon}_{xx}\\\dot{\varepsilon}_{yy}\\\dot{\varepsilon}_{zz}\\\dot{\varepsilon}_{xy}\\\dot{\varepsilon}_{yz}\\\dot{\varepsilon}_{zx}\end{bmatrix} = \begin{bmatrix}0\\0\\\dot{\delta}_3/(t+\delta_3)\\0\\\dot{\delta}_2/(t+\delta_3)\\\dot{\delta}_1/(t+\delta_3)\end{bmatrix} \qquad \begin{bmatrix}\sigma_{xx}\\\sigma_{yy}\\\sigma_{zz}\\\sigma_{xy}\\\sigma_{yz}\\\sigma_{zx}\end{bmatrix} \rightarrow \begin{bmatrix}t_1\\t_2\\t_3\end{bmatrix} = \begin{bmatrix}\sigma_{zx}\\\sigma_{yz}\\\sigma_{zz}\end{bmatrix}$$



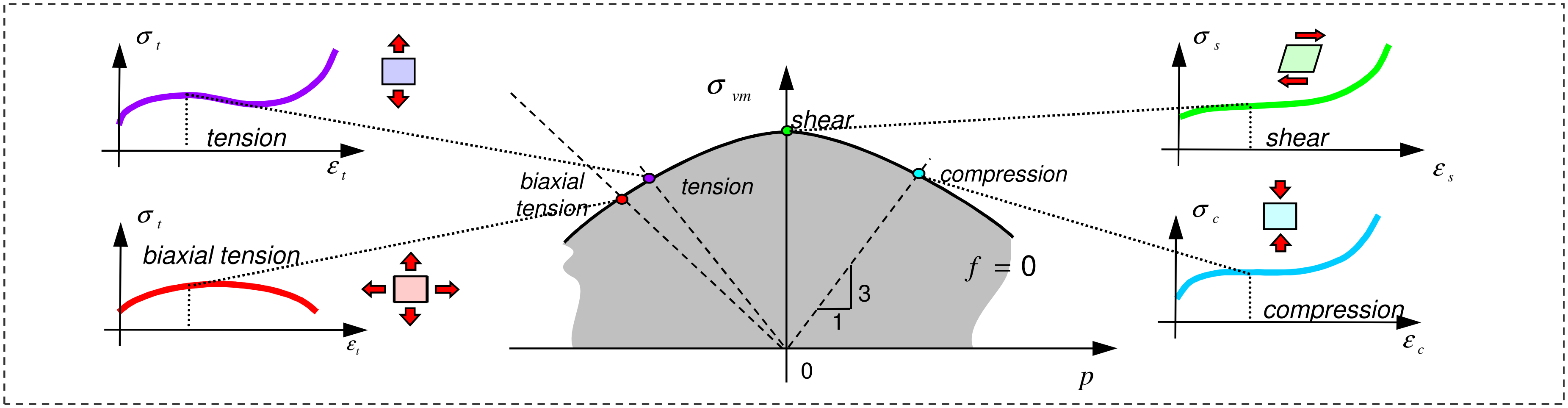
  - keyword definition

```
*MAT_ADD_COHESIVE
$       PID      ROFLG    INTFAIL      THICK
$         I          F          F          F
```

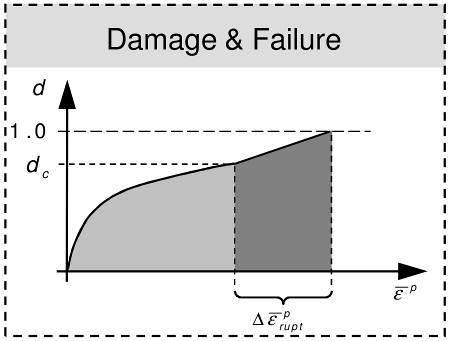
  - density can be specified per unit volume or per unit area
    → handling of elements with an initial volume of zero
  - number of integration points required for the element to be deleted can be specified

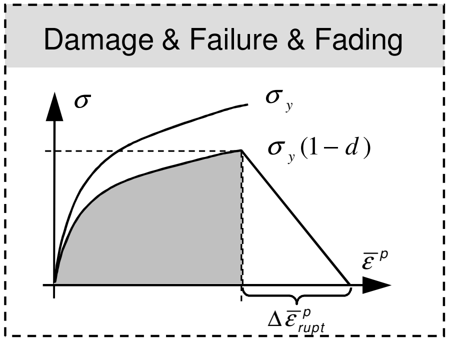
Recent trends in LS-DYNA

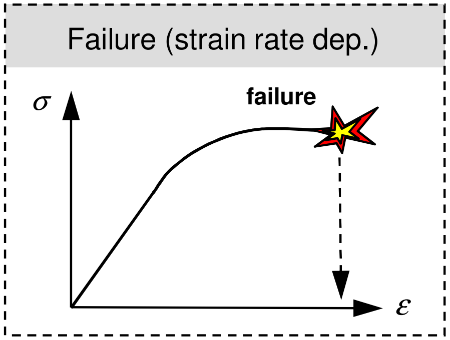
- Interesting combination: *MAT_ADD_COHESIVE and *MAT_SAMP-1 (*MAT_187)
  - plasticity can be defined individually for tension, shear and compression



  - strain rate dependent failure with fading can be defined


Damage & Failure


Damage & Failure & Fading


Failure (strain rate dep.)

Summary

- Preliminary remarks
  - joining techniques can be classified in three categories: punctiform, line-shaped and area-shaped joining techniques
  - substitute models with artificial material parameters are currently the only practicable way to model connection materials in full car crash simulations
- Current modeling techniques in LS-DYNA
  - PU windshield, hood adhesives: *MAT_FU_CHANG_FOAM (*MAT_083)
  - structural adhesives: *MAT_ARUP_ADHESIVE (*MAT_169)
- Recent trends in LS-DYNA
  - cohesive element formulations and corresponding material models:
    - *MAT_COHESIVE_MIXED_MODE (*MAT_138)
    - *MAT_COHESIVE_MIXED_MODE_ELASTOPLASTIC_RATE (*MAT_240)
  - coupling of 3-d continuum mechanical material models with cohesive element formulation: *MAT_ADD_COHESIVE