Detroit, November 16th, 2023

Status and Strategies of Glass Modelling with MAT_GLASS (MAT_280)

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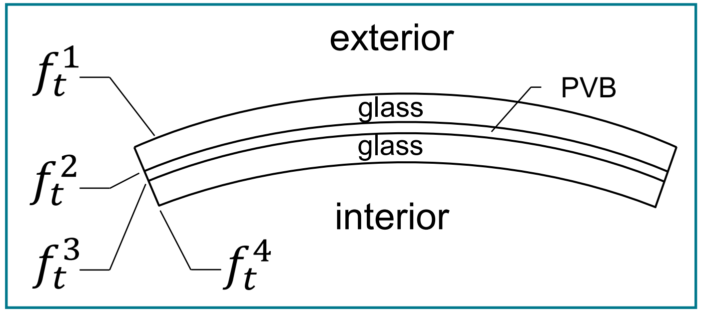
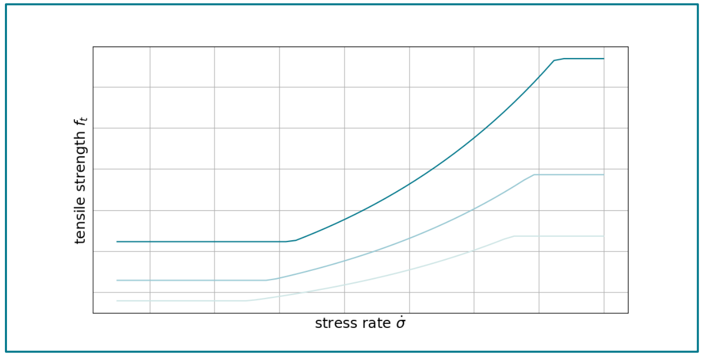
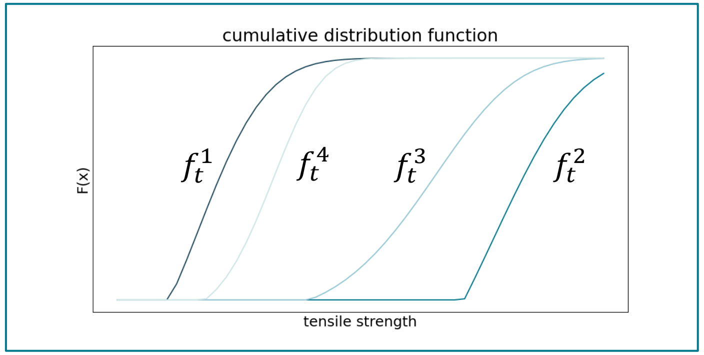
Motivation

- Keynote given by Stefan Kolling at LS-Dyna Forum 2022 in Bamberg "Notes on Simulating Head Impact on Windshields"
  - Glass material model (user material) which allows for
    - different strengths over thickness
    - strength reduction near cracked elements
    - rate dependent tensile strengths
    - stochastic variation of strengths
    - …
- This presentation
  - How to use *MAT_GLASS/*MAT_280 to get similar features as the user material described by Stefan Kolling

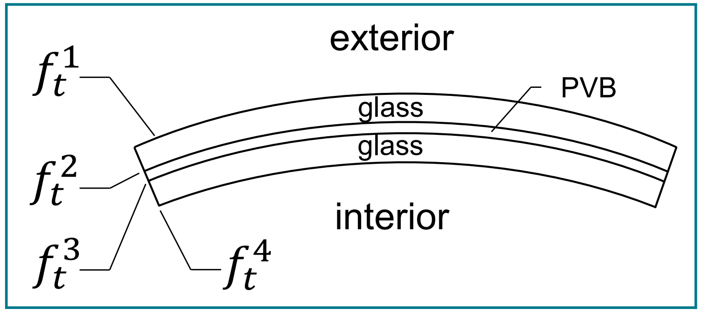


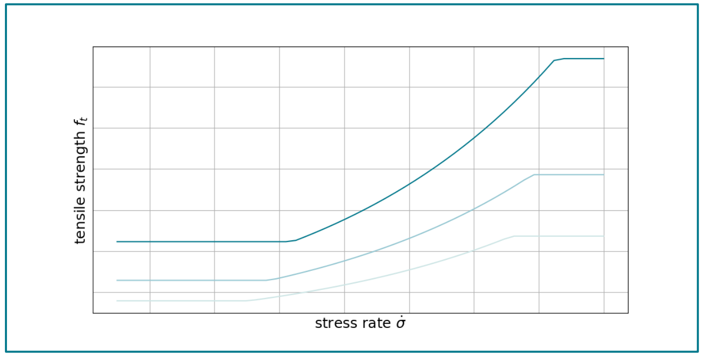


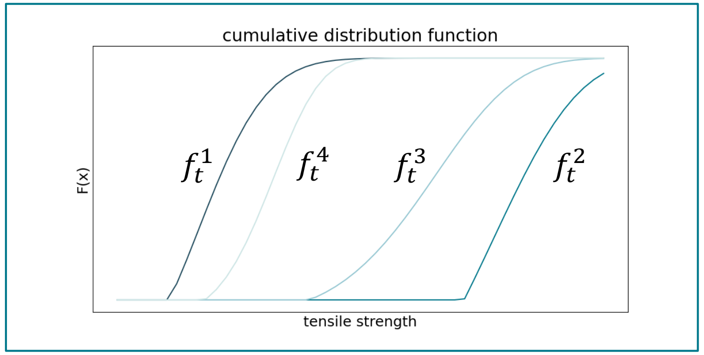


Outline

- Motivation
- Introduction to MAT_GLASS
- A Model for Laminated Glass
- MAT_GLASS Features
  - Strength Reduction
  - Strain Rate Dependency
  - Stochastic Variation
  - Position-Based Tensile Strength
- Application
- Summary





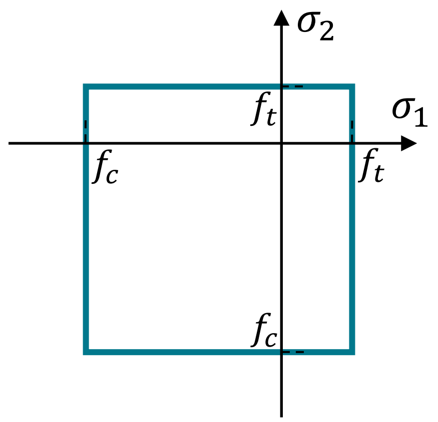


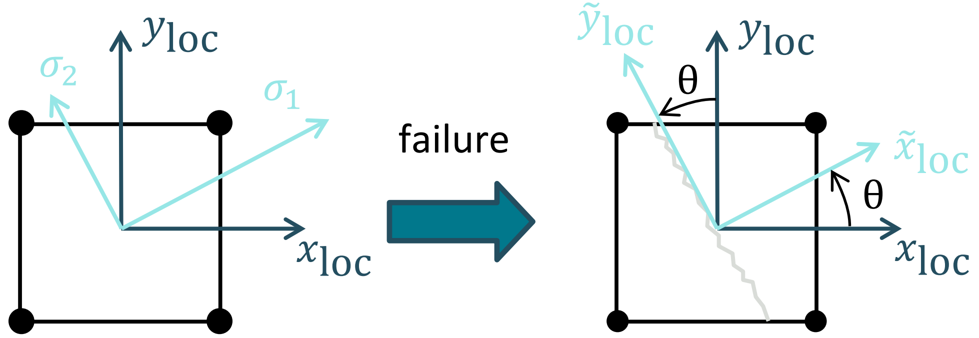
Introduction to MAT_GLASS

Introduction to MAT_GLASS

Theoretical Background

- Linear elastic until failure
- Stress based failure criteria: **Rankine**, Mohr-Coulomb, Drucker-Prager
- Compressive failure
  - Material is ‘crumbled‘
- Tensile failure
  - Single Cracks
  - Crack direction perpendicular to the 1st principal stress
  - Local crack coordinate systems
  - 2nd crack can occur orthogonal to the 1st crack
  - Cracks can open and close independently

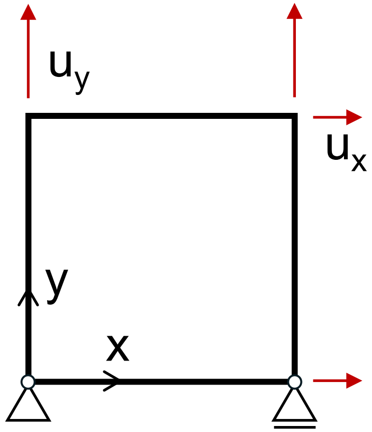


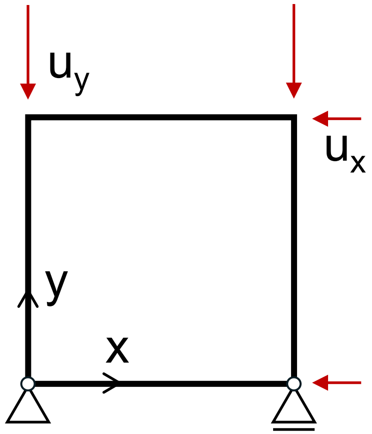


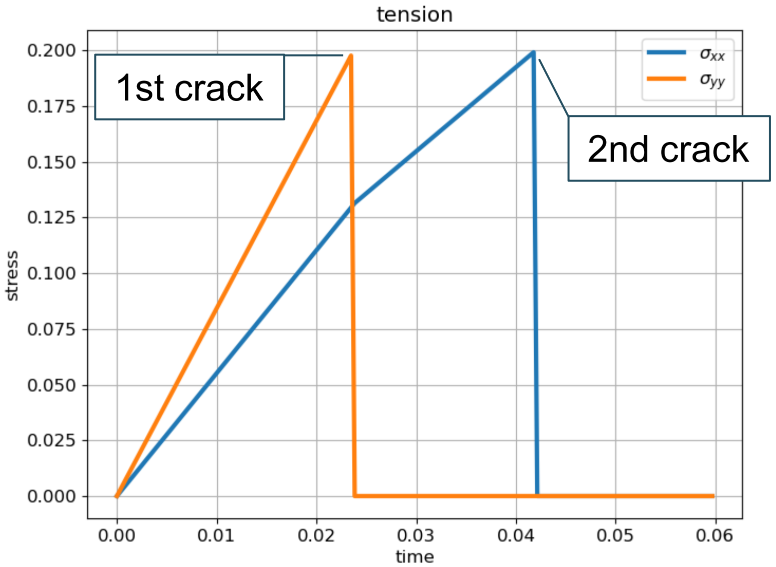
Introduction to MAT_GLASS

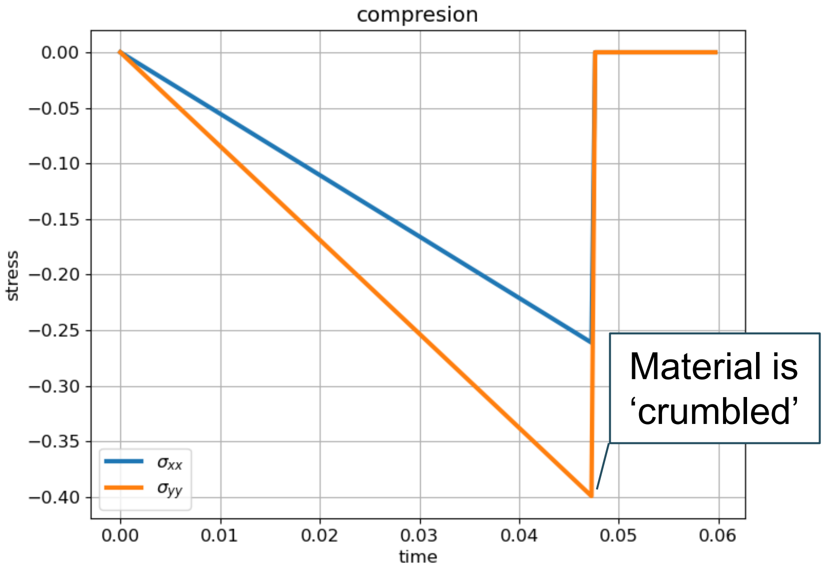
Single element test

- Material properties
  - Tensile strength $f_t = 0.2$
  - Compressive strength $f_c = 0.4$









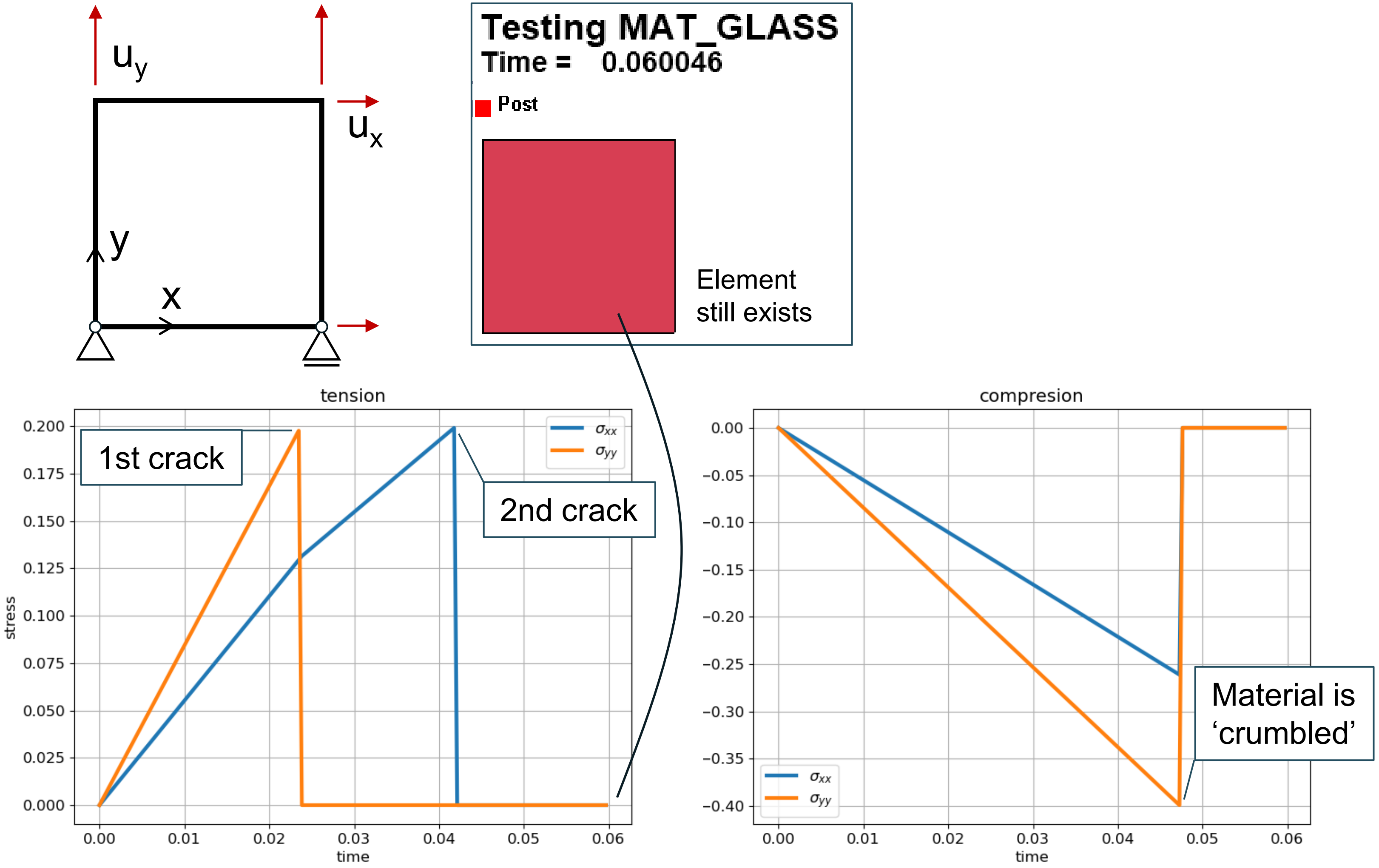
Introduction to MAT_GLASS

Element deletion

- Material properties
  - Tensile strength $f_t = 0.2$
  - Compressive strength $f_c = 0.4$
- MAT_GLASS elements will not be deleted when f_t or f_c is reached
- To avoid highly distorted elements use
  - EPSCR (MAT_GLASS)
  - MAT_ADD_EROSION

HINT

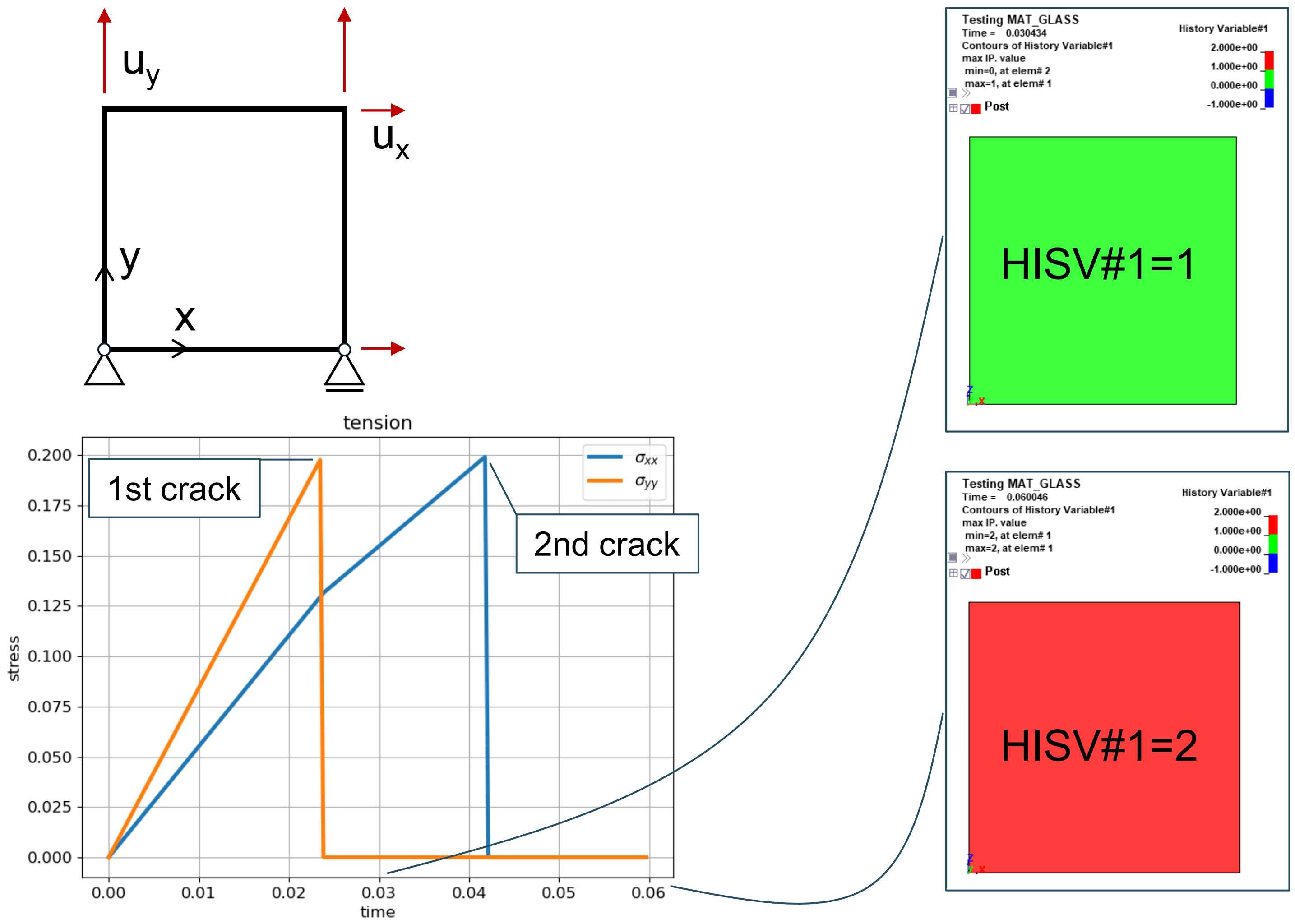
Make sure the element erosion criterion is not taking effect prior to tensile or compressive strength



Introduction to MAT_GLASS

Crack visualization – Option I

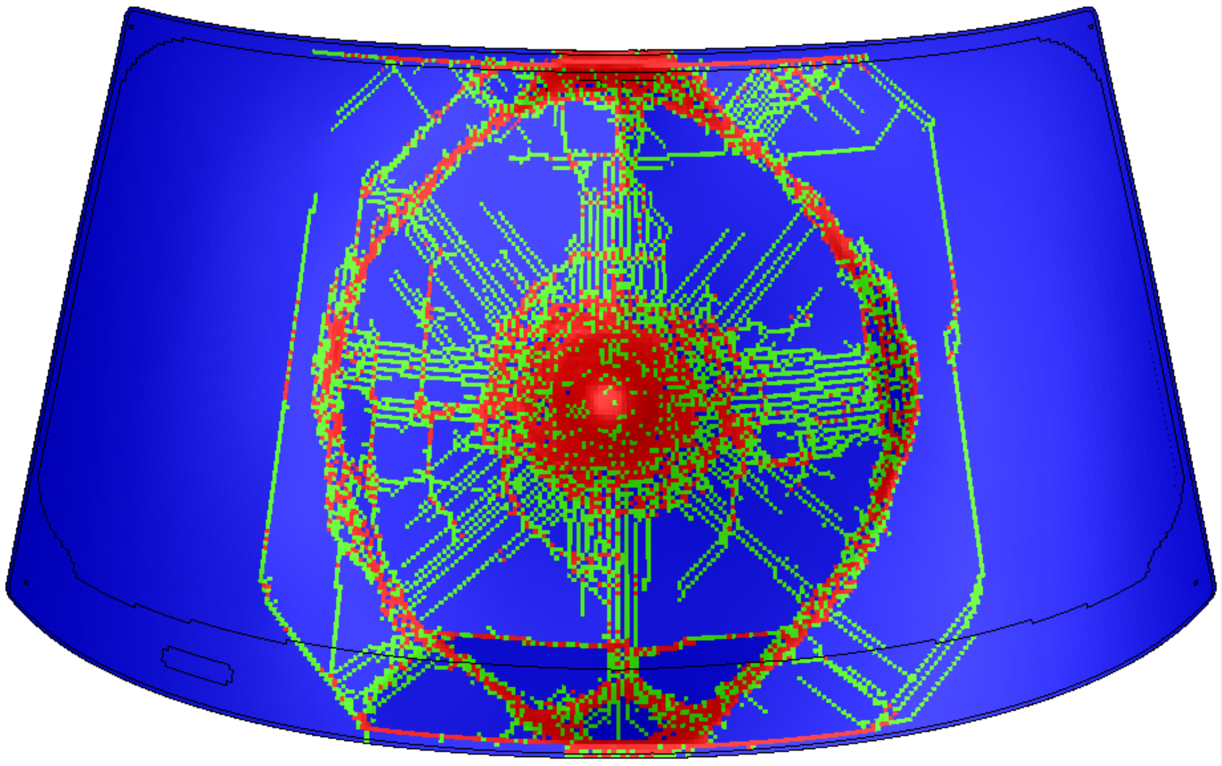
- Material properties
  - Tensile strength $f_t = 0.2$
  - Compressive strength $f_c = 0.4$
- Cracks can be visualized by history variable #1 of MAT_GLASS
  - -1: compressive failure
  - 0: no failure
  - 1: one crack
  - 2: two cracks



Introduction to MAT_GLASS

Crack visualization – Option I

- Head impact on windshield

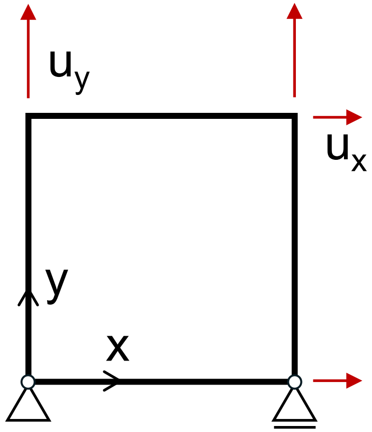


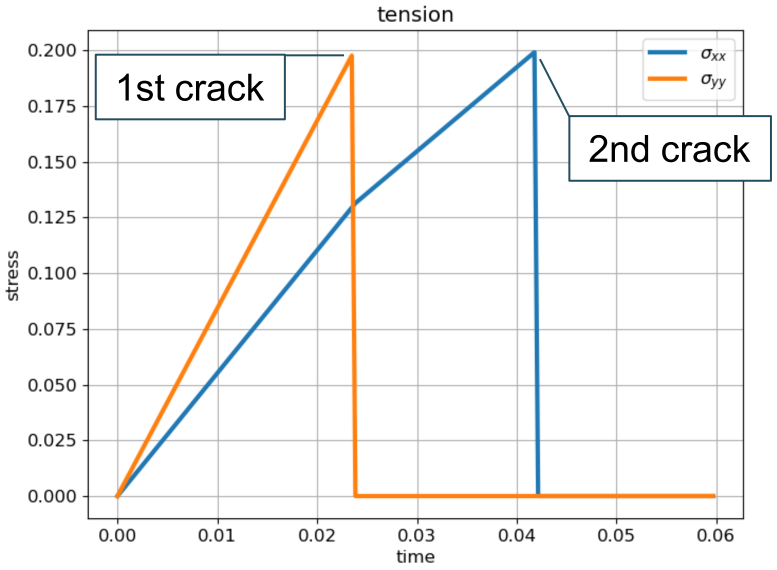
- Cracks can be visualized by history variable #1 of MAT_GLASS
  - -1: compressive failure
  - 0: no failure
  - 1: one crack
  - 2: two cracks

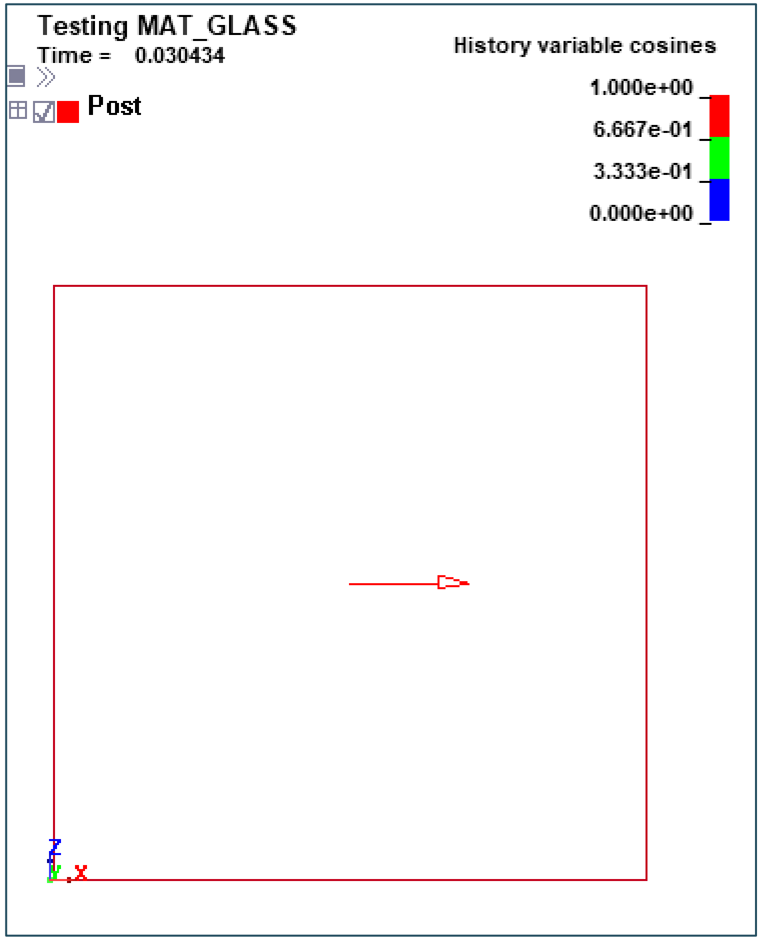
Introduction to MAT_GLASS

Crack visualization – Option II

- Material properties
  - Tensile strength $f_t = 0.2$
  - Compressive strength $f_c = 0.4$
- Cracks can be visualized as a vector plot using history variables #15, #16, and #17
  - Crack direction is shown
  - So far only shows 1st crack
  - So far only available in current DEV versions (→ R15)







IMPORTANT

NIPS ≥ 17 in *DATABASE_EXTENT_BINARY

Introduction to MAT_GLASS

Crack visualization – Option II

- Head impact on windshield

- Cracks can be visualized as a vector plot using history variables #15, #16, and #17
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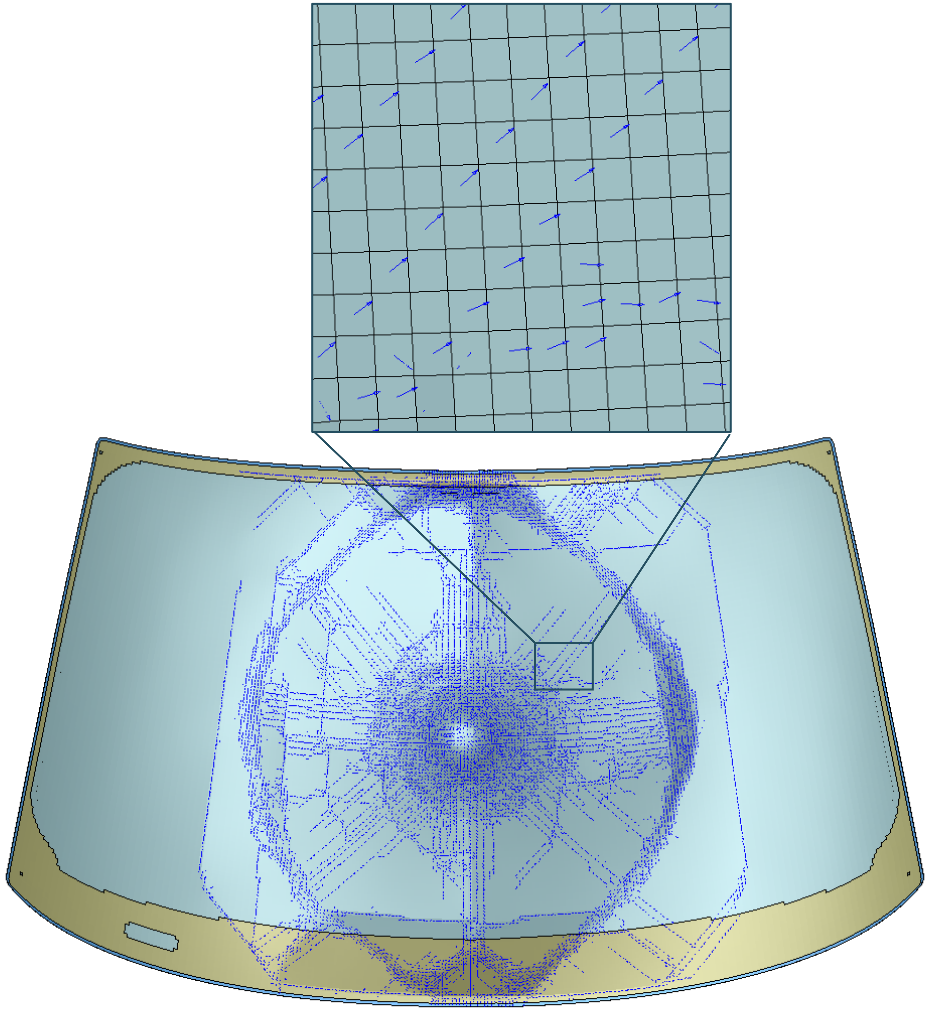
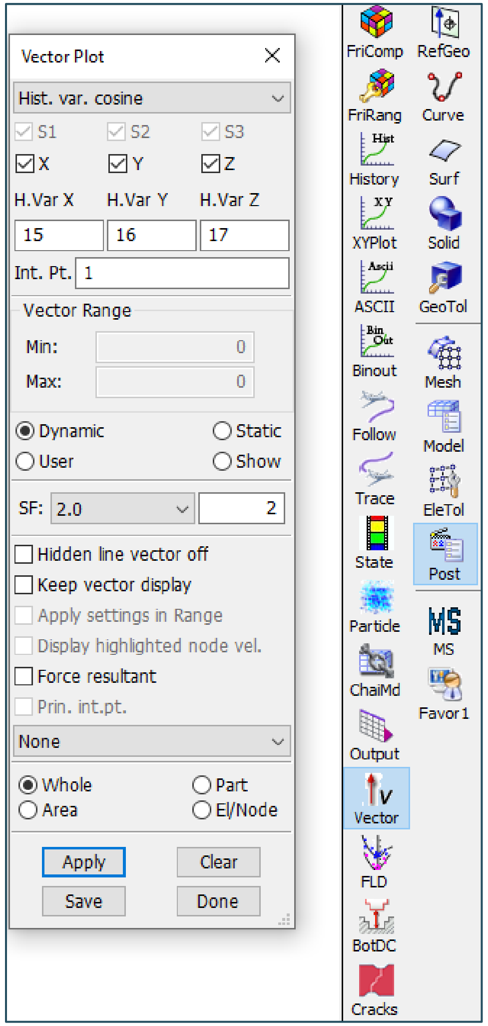
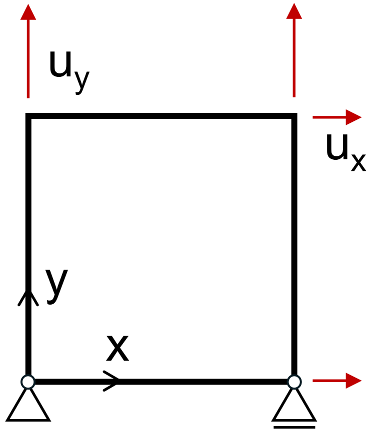




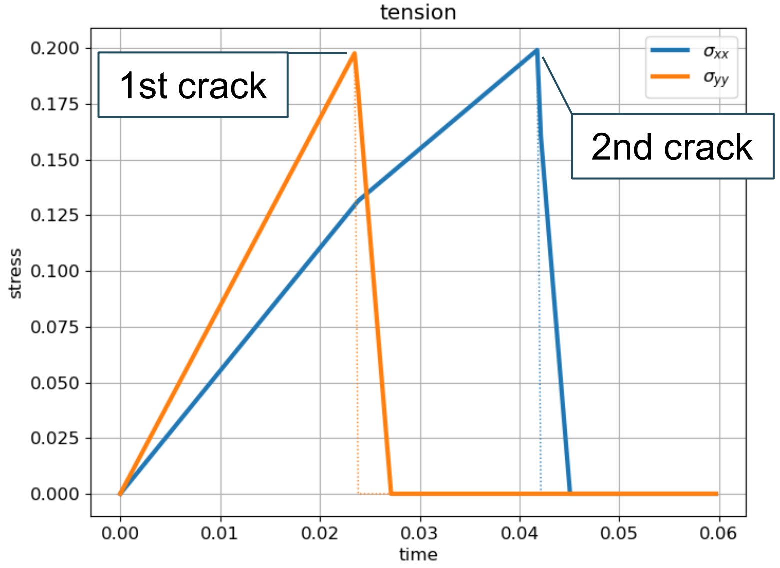
Introduction to MAT_GLASS

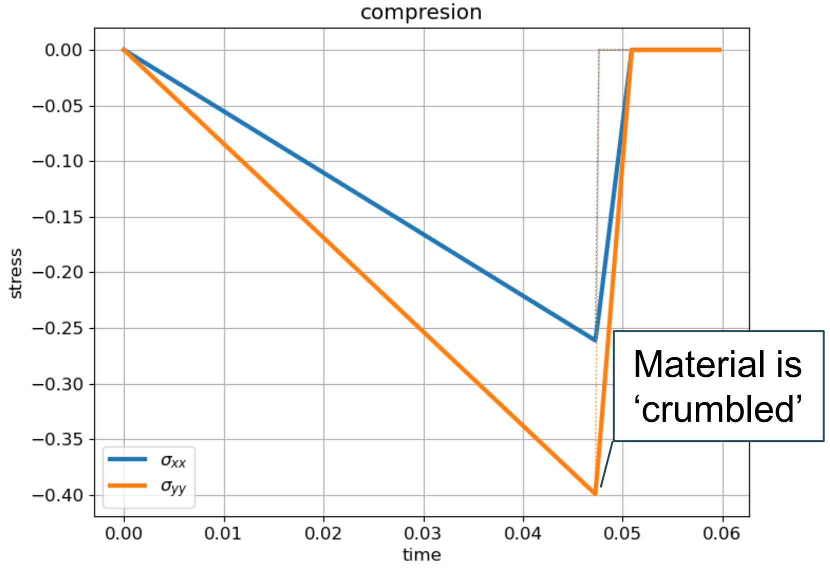
Softening/damage

- Material properties
  - Tensile strength $f_t\ =\ 0.2$
  - Compressive strength $f_c = 0.4$
- Without modifications after cracking the stress is relieved to zero within one cycle
- The post-cracking behavior can be controlled by the following variables
  - NCYCR, FRACEN, SFSTI, SFSTR, IMOD (AT, BT, AC, BC)

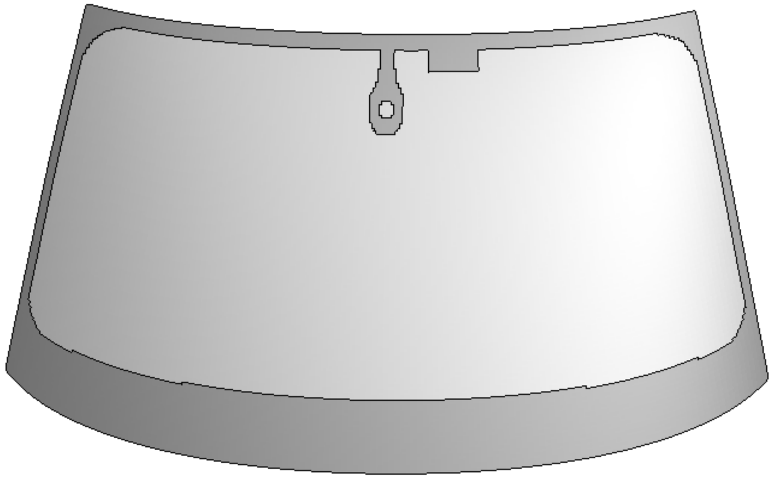


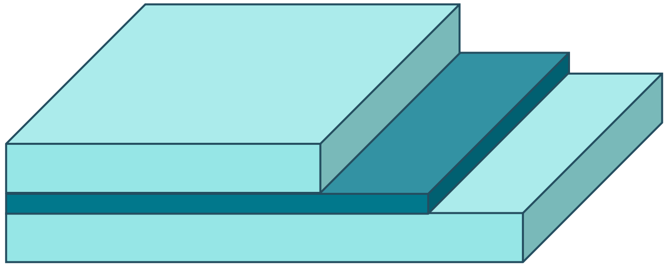
- Example
  - $\mathrm{NCYCR}\ =\ 10$
  - Stress is relieved within 10 cycles





A Model for Laminated Glass

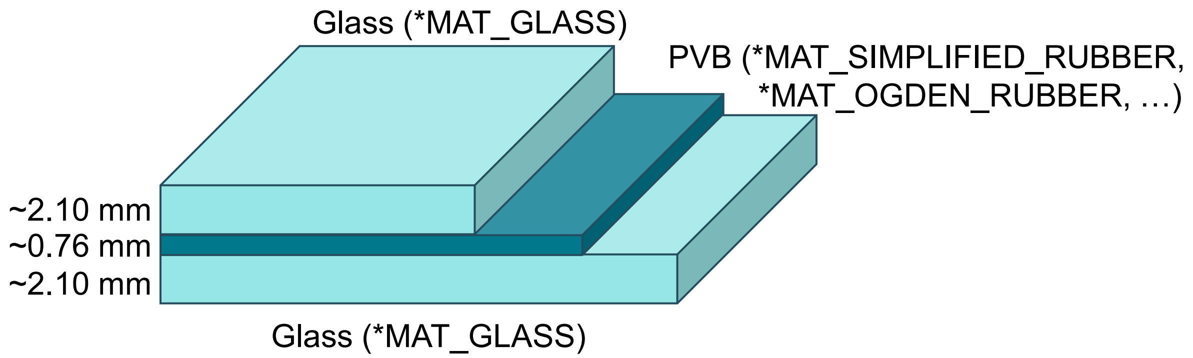




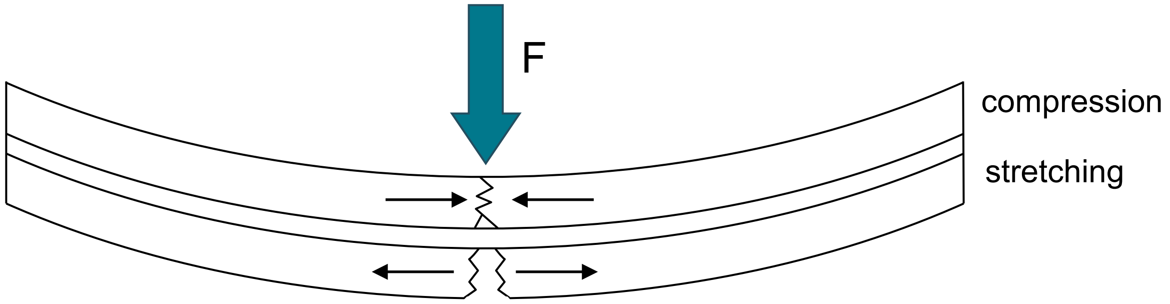
A Model for Laminated Glass

Overview

- Laminated glass consists of at least 3 layers
  - 2 glass panes
  - PVB interlayer



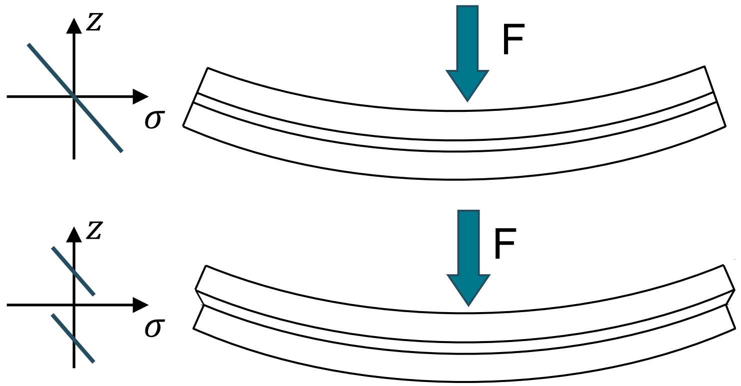
- Glass fragments are bonded
  - Difficult mechanical behavior

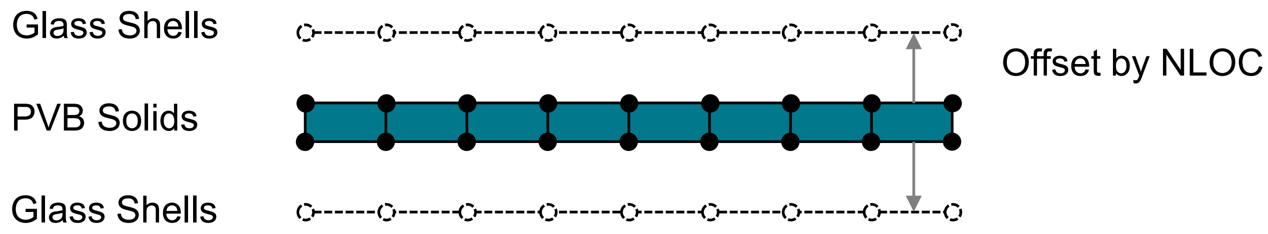


A Model for Laminated Glass

Discretization

- Elements
  - PVB: transverse shear deformation important
    → **solid elements**
  - Glass: shell elements
- Contact between layers: Shared nodes
- Offset the glass layers by NLOC parameter (SECTION_SHELL)

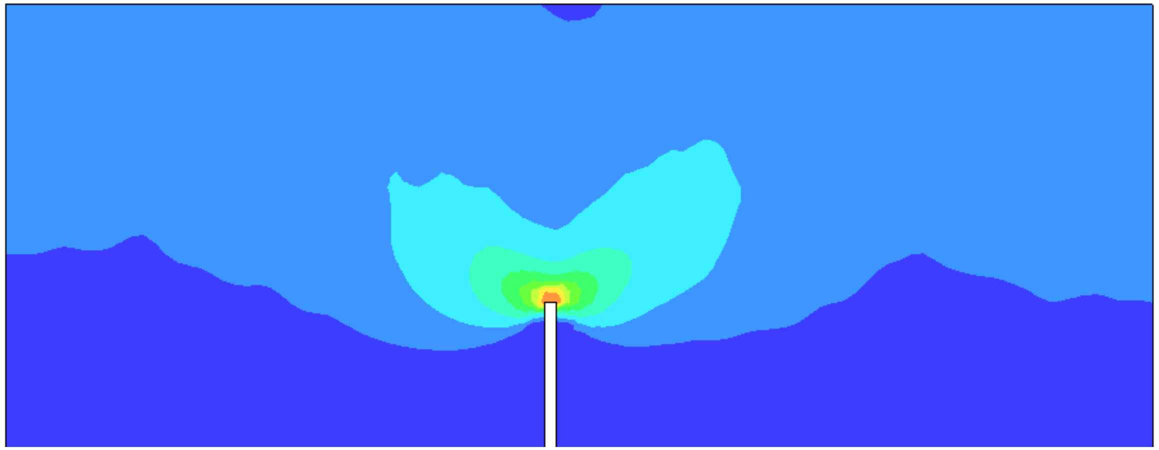





```
*SECTION_SHELL
$     SECID    ELFORM      SHRF       NIP     PROPT   QR/IRID     ICOMP     SETYP
        100         2     0.833         5       1.0         0         0         0
$        T1        T2        T3        T4      NLOC     MAREA
        2.1       2.1       2.1       2.1        -1
```

MAT_GLASS Features

Strength Reduction



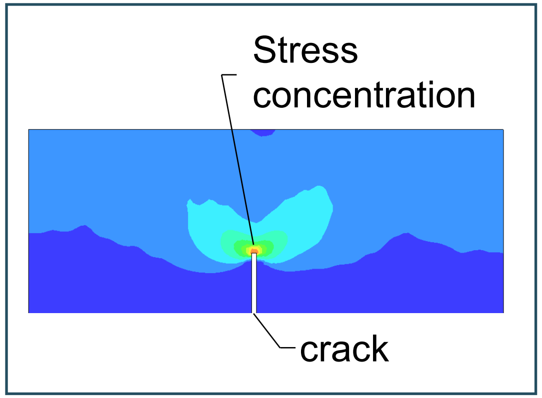
Strength Reduction

General Remarks

- Stress concentration in tip of crack
  - Cannot be resolved by coarse FE-mesh
  - To consider this effect in MAT_280 the tensile strength can be reduced after the first crack
- Variables affecting strength reduction

```
*MAT_GLASS_{STOCHASTIC}
$      MID        RO         E        PR                           IMOD      ILAW
         1    2.5E-6        70      0.23
$     FMOD        FT        FC        AT        BT        AC        BC     FTSCL
                 0.2                                                           1
$    SFSTI     SFSTR      CRIN     ECRCL     NCYCR      NIPF

$    EPSCR    ENGCRT    RADCRT    RATENL    RFILTF    FRACEN

```

- Combination of variables determines the way the strength reduction works



Strength Reduction

Type 1

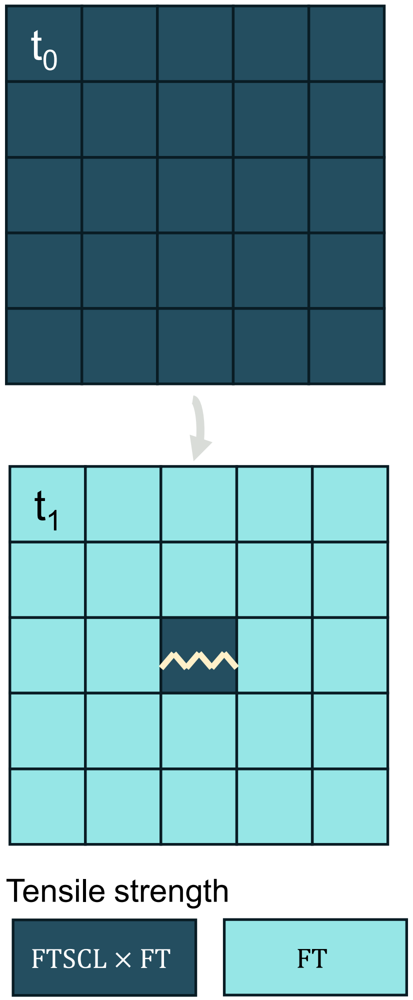
- FT and FTSCL are defined

```
*MAT_GLASS
…
$       FMOD        FT        FC        AT        BT        AC        BC     FTSCL
                   0.2                                                       1.5
```

- Initially all elements have the tensile strength

$$FT_{mod} = FTSCL \times FT$$

- After the first crack **all elements of the part** get the tensile strength FT



Strength Reduction

Type II

- FT, FTSCL and RATENL are defined

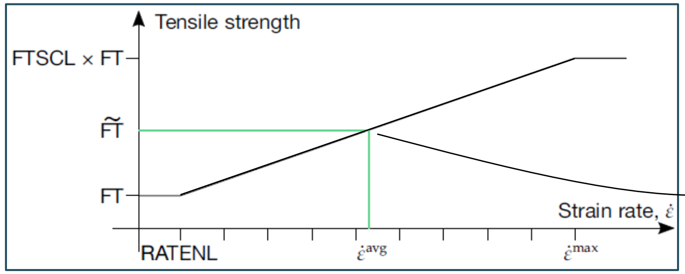
```
*MAT_GLASS
…
$      FMOD        FT        FC        AT        BT        AC        BC     FTSCL
                  0.2                                                          1.5
…
$     EPSCR    ENGCRT    RADCRT    RATENL    RFILTF    FRACEN
                                      1.5      0.95
```

- Initially all elements have the tensile strength

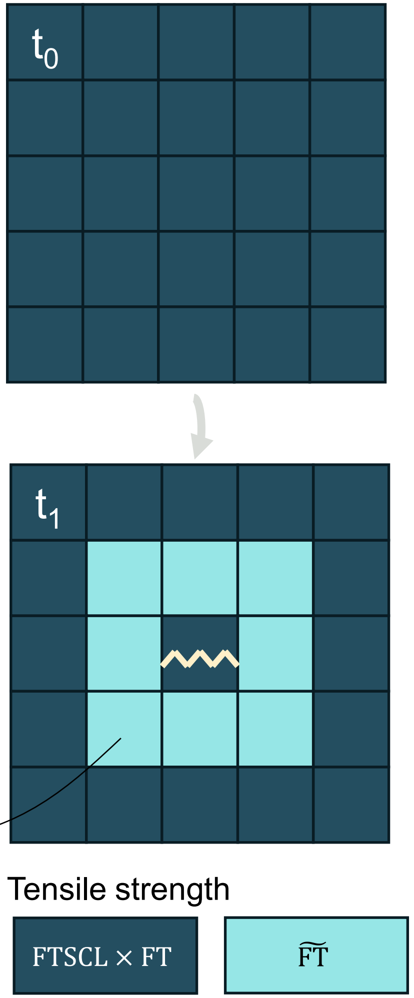
$$\mathrm{FT}_{\mathrm{mod}} = \mathrm{FTSCL} \times \mathrm{FT}$$

- After a crack, all **elements adjacent to cracked elements** get a tensile strength $\widetilde{\mathrm{FT}}$ depending on their current strain rate
- The strain rate should be filtered by RFILTF

LS-DYNA manual



$$\dot{\varepsilon}_{\mathrm{max}} = 10^9 \times \mathrm{RATENL}$$



Strength Reduction

Type II

- FT, FTSCL and RATENL are defined

```
*MAT_GLASS
…
$      FMOD        FT        FC        AT        BT        AC        BC     FTSCL
                  0.2                                                         1.5
…
$     EPSCR    ENGCRT    RADCRT    RATENL    RFILTF    FRACEN
                                      1.5      0.95
```

- Initially all elements have the tensile strength

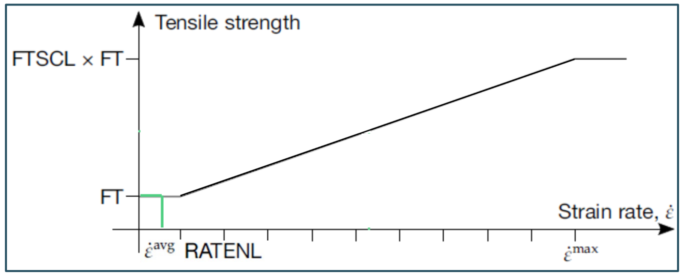
$$\mathrm{FT_{mod}} = \mathrm{FTSCL} \times \mathrm{FT}$$

- After a crack, all **elements adjacent to cracked elements** get a tensile strength $\widetilde{\mathrm{FT}}$ depending on their current strain rate
- The strain rate should be filtered by RFILTF

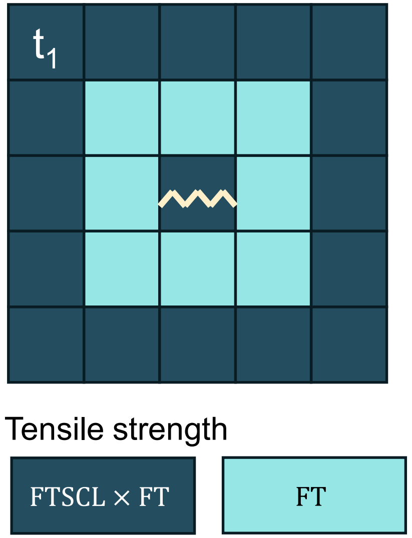
HINT

Setting RATENL to a high value e.g., 1E9 practically removes the rate dependency: $\widetilde{\mathrm{FT}} = \mathrm{FT}$

LS-DYNA manual



$$\dot{\varepsilon}_{max} = 10^9 \times \mathrm{RATENL}$$

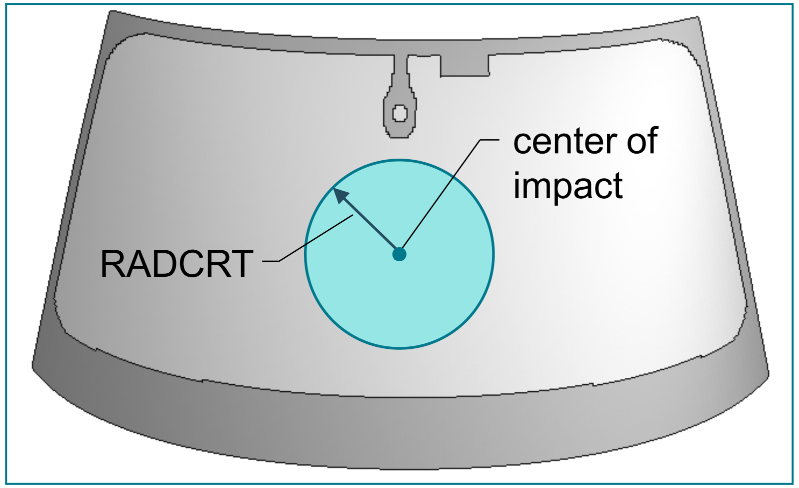


Strength Reduction

Delayed Crack Initiation

- ENGCRT and RADCRT are defined

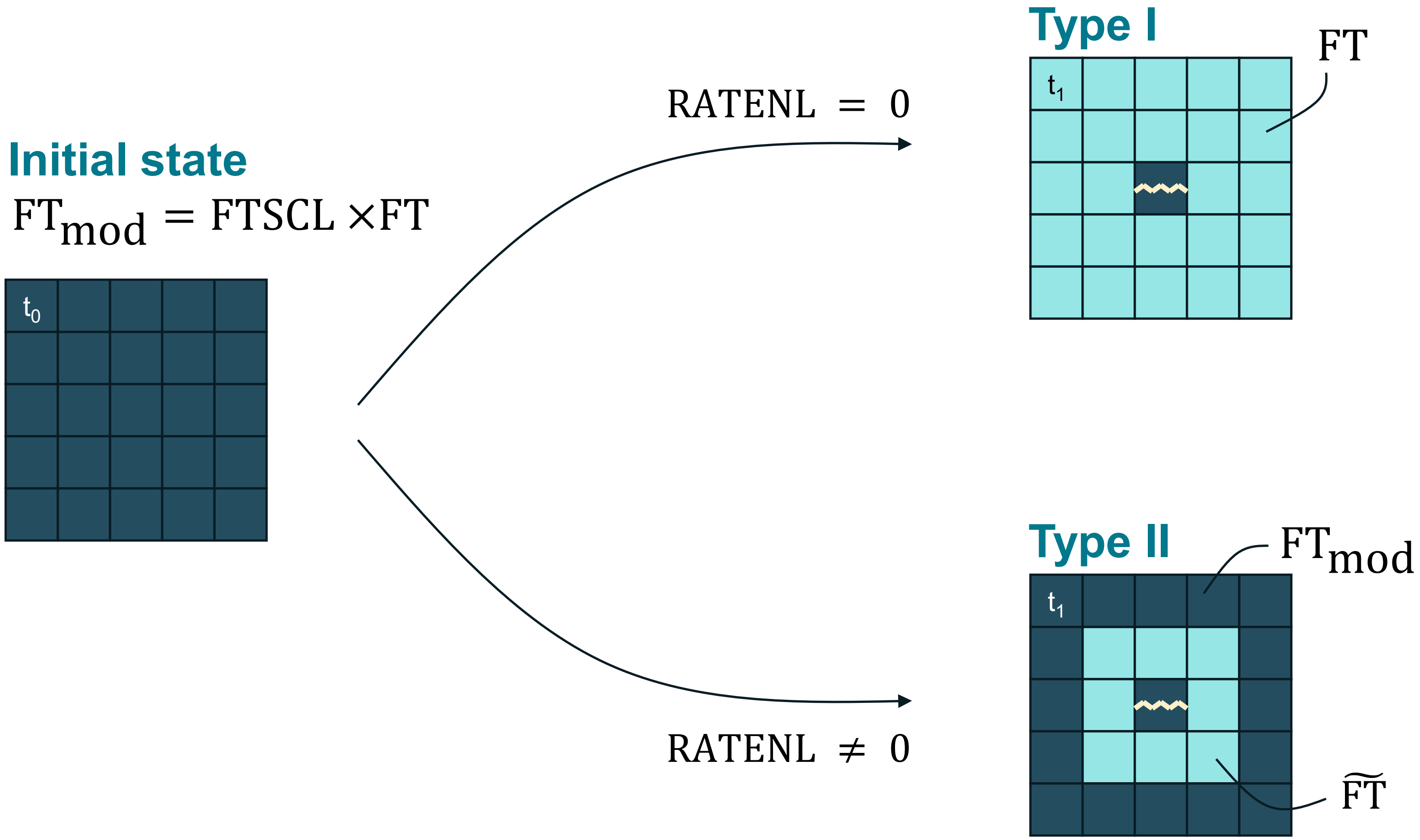
```
*MAT_GLASS
$      MID        RO         E        PR                                  IMOD      ILAW
         1    2.5E-6        70      0.23
$     FMOD        FT        FC        AT        BT        AC        BC     FTSCL
               0.2                                                            1
$    SFSTI     SFSTR      CRIN     ECRCL     NCYCR      NIPF

$    EPSCR    ENGCRT    RADCRT    RATENL    RFILTF    FRACEN

```



- Activates a failure model described by Pytell/Liebertz (2011)
- Initially deactivates failure/cracks
- 1st element with $\sigma_1 > \mathrm{FT} \times \mathrm{FTSCL}$ defines center of impact
- Internal energy of part within radius RADCRT is monitored
- When internal energy reaches ENGCRT failure as activated
- Strength reduction according to type I or II depending on the variables defined

Strength Reduction

Overview

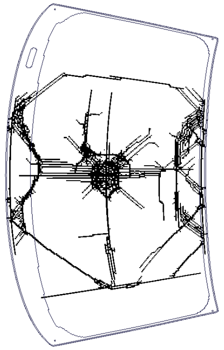
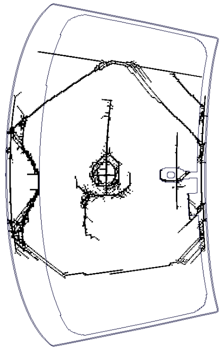
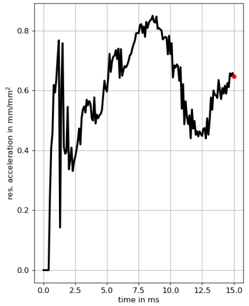
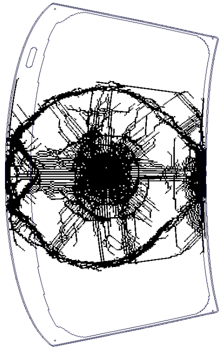
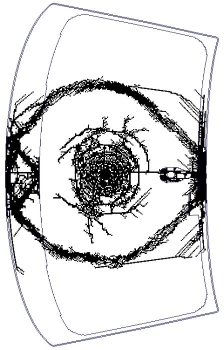
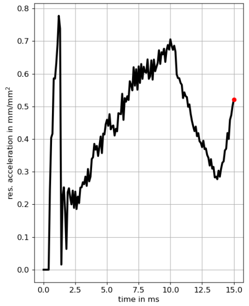


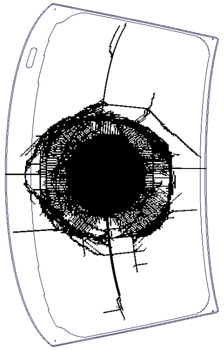
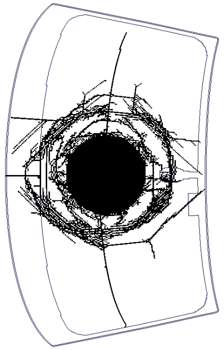
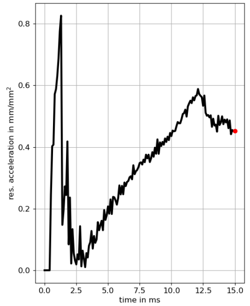
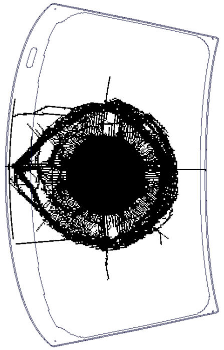
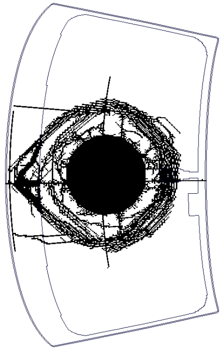
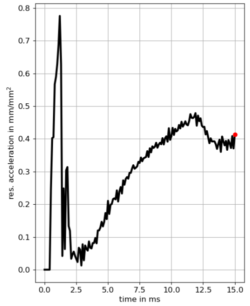
- After the first crack the tensile strength **in the entire part** is reduced to FT
- After a crack, all **elements adjacent to cracked elements** get the tensile strength $\widetilde{FT}$

Strength Reduction

Parameter Study

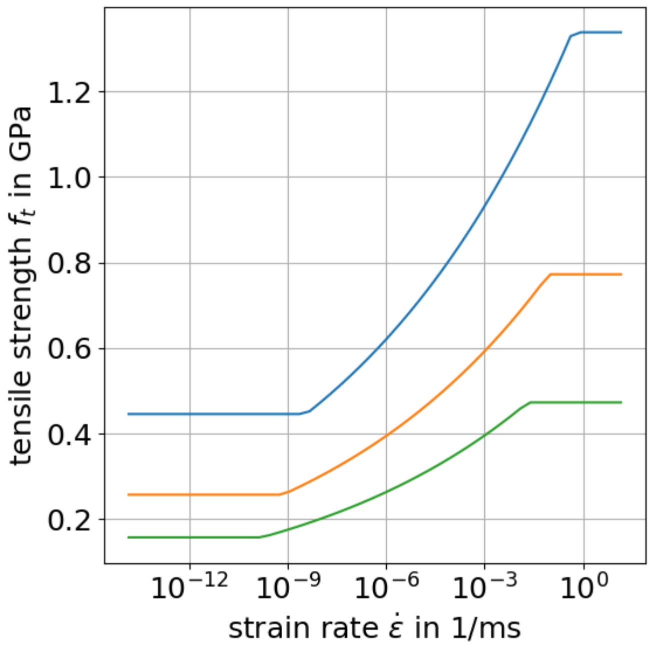
- Head impact on windshield
- Type II – FT, FTSCL and RATENL are defined → strength reduction in adjacent elements

FTSCL	inner glass	outer glass	acc. vs time
1.0			
2.0			

FTSCL	inner glass	outer glass	acc. vs time
3.0			
3.5			

MAT_GLASS Features

Strain Rate Dependency



Strain Rate Dependency

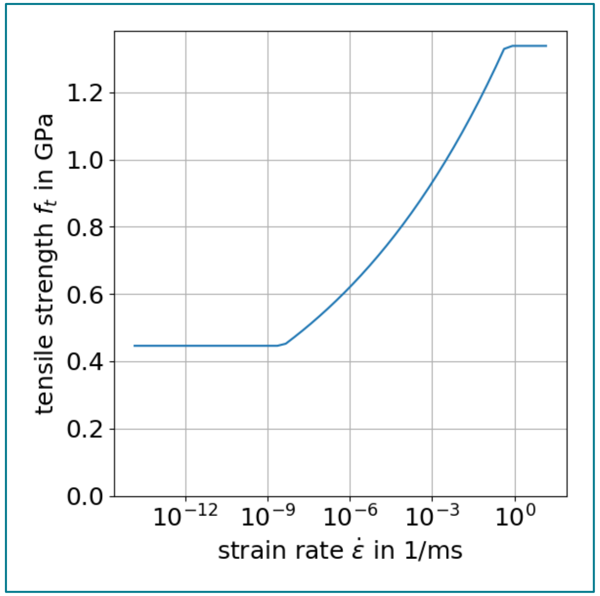
General Remarks

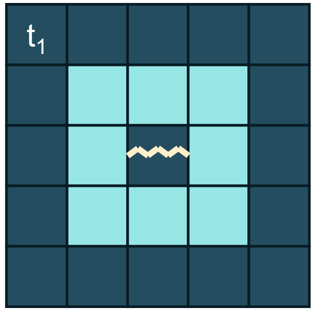
- Strain rate dependent tensile strength from literature, e.g.,

$$f_t = \left(\frac{2(n+1) K_{Ic}^n}{v_0 (n-1) (Y\sqrt{\pi})^n a_i^{\frac{n-1}{2}}} \right)^{1/(1+n)} \dot{\sigma}^{1/(1+n)}$$

Alter, Kolling, Schneider 2017

- To be flexible LS-DYNA allows to define FT as a curve
  - Abscissa: strain rate $\dot{\varepsilon} = |d\varepsilon_1|/\Delta t$
    with $d\varepsilon_1$: increment of 1st principal strain
    - If first value is negative, LS-DYNA expects logarithmic values $\ln(\dot{\varepsilon})$
    - Use $\ln(\dot{\varepsilon})$ when the lowest strain rate and highest strain rate differ by several orders of magnitude
  - Ordinate: tensile strength f_t
- Approximation to get strain rate from stress rate: $\dot{\varepsilon} \approx \dot{\sigma}/E$
- Strength reduction only in adjacent elements, Type II
- Strain rate should be filtered using RFILTF





+ rate dependency

Strain Rate Dependency

Example

- Strain rate dependent tensile strength from literature, e.g.,

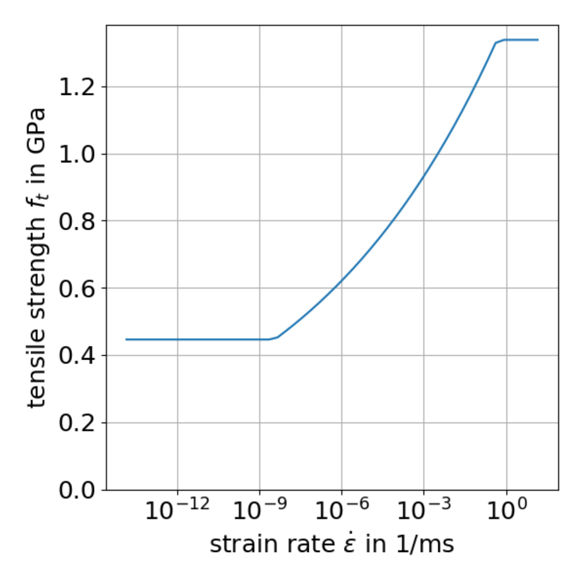
$$f_t = \left(\frac{2(n+1)K_{Ic}^n}{v_0(n-1)\left(Y\sqrt{\pi}\right)^n a_i^{\frac{n-1}{2}}}\right)^{1/(1+n)} \dot{\sigma}^{1/(1+n)}$$

Alter, Kolling, Schneider 2017

- To be flexible LS-DYNA allows to define FT as a curve

```
*MAT_GLASS
$      MID        RO         E        PR                          IMOD      ILAW
         1    2.5E-6        70      0.23
$     FMOD        FT        FC        AT        BT        AC        BC     FTSCL
                -100                                                          1
$    SFSTI     SFSTR      CRIN     ECRCL     NCYCR      NIPF

$    EPSCR    ENGCRT    RADCRT    RATENL    RFILTF    FRACEN
                                              0.95

*DEFINE_CURVE
$     LCID      SIDR       SFA       SFO      OFFA      OFFO    DATTYP     LCINT
       100
$        ln(epsdot)                   ft
           -31.187                 0.158
…
           2.65926                 0.473
```

$\dot{\varepsilon} = e^{2.65926} = 14.3/\text{ms}$

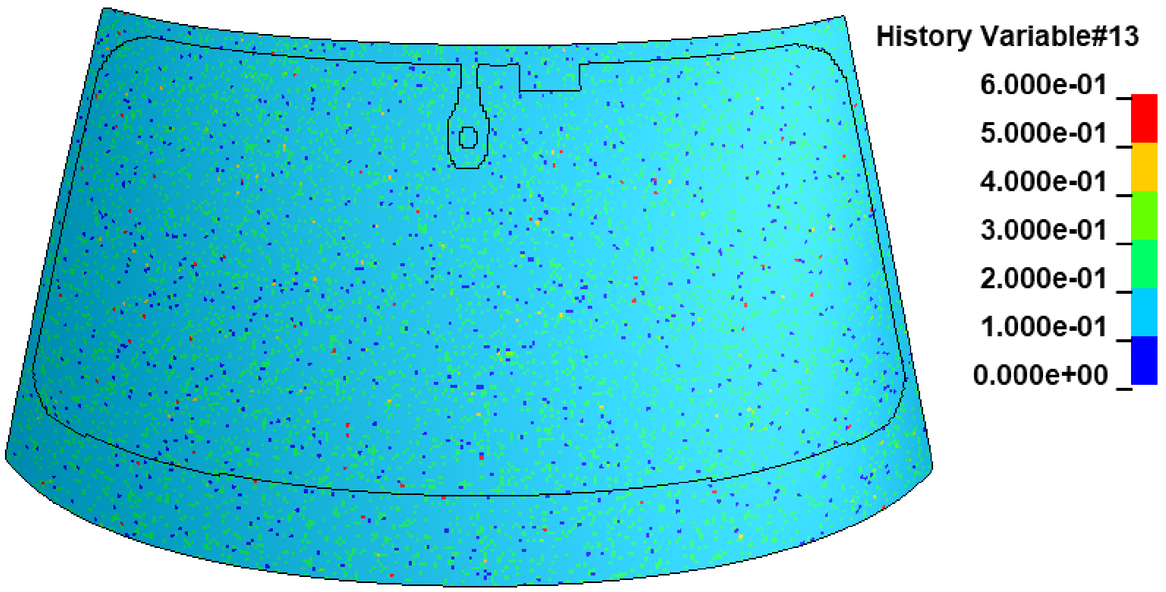


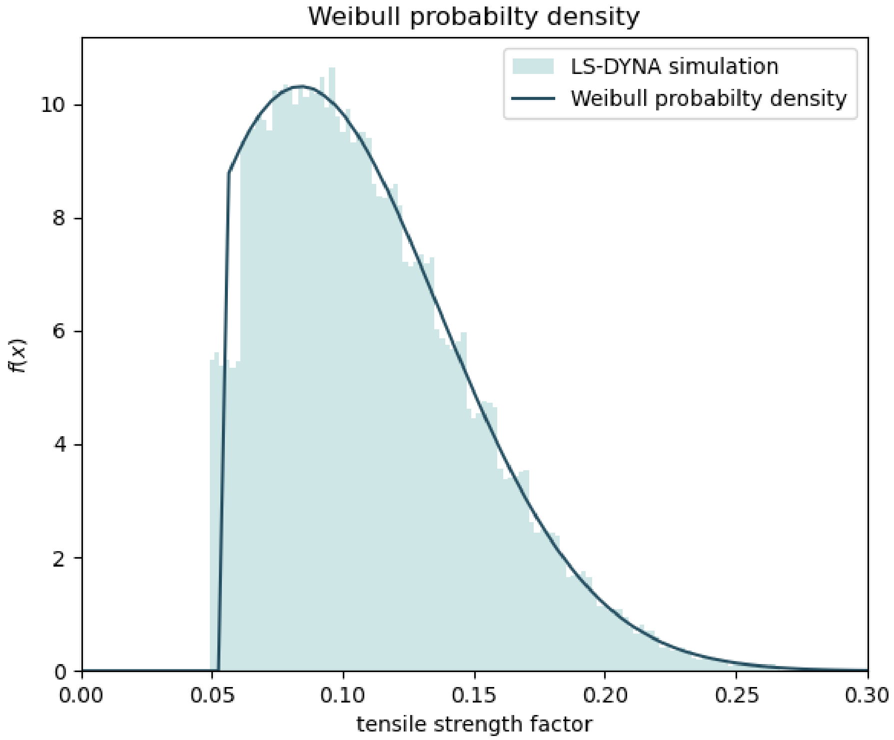
HINT

Use LS-DYNA versions ≥ R12 and newer than August 2023

MAT_GLASS Features

Stochastic Variation





Stochastic Variation

How to define

- Stochastically distributed tensile strength due to microcracks
- *MAT_280_STOCHASTIC + *DEFINE_STOCHASTIC_VARIATION
  → stochastically distributed factor for tensile strength
- Kind of distribution is given by VAR_S
  - 1: Uniform random distribution
  - 2: Normal distribution
  - 3: User defined probability distribution
  - 4: User defined cumulative distribution
- History variable #13 shows factor

```
*PART
Glass
$      PID     SECID       MID     EOSID      HGID      GRAV    ADPOPT
       100       100       100         0         0         0         0
*MAT_GLASS_STOCHASTIC
$      MID        RO         E        PR                          IMOD
       100    2.5E-6        70      0.23
$     FMOD        FT        FC        AT        BT        AC        BC
                   1
$    SFSTI     SFSTR      CRIN     ECRCL     NCYCR      NIPF

$    EPSCR    ENGCRT    RADCRT    RATENL    RFILTF    FRACEN

*DEFINE_STOCHASTIC_VARIATION
$    ID_SV       PID   PID_TYP      ICOR     VAR_S     VAR_F      IRNG
       100       100                             4                   1
$     LCID
       200
$       R1        R2        R3

*DEFINE_CURVE_TITLE
Weibull cumulative distribution
$     LCID      SIDR       SFA       SFO      OFFA      OFFO    DATTYP
       200
$                  A                   O
            0.048980            0.000000
```

Stochastic Variation

Example

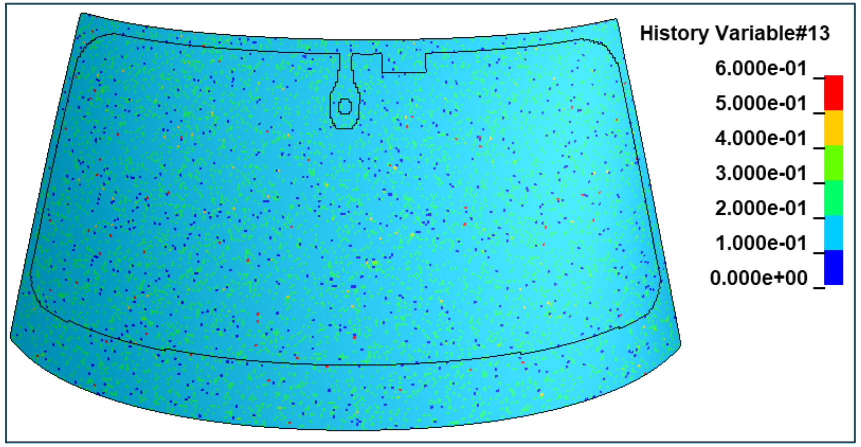
- Stochastic variation given by left truncated Weibull distribution
  - Left truncated Weibull probability density function

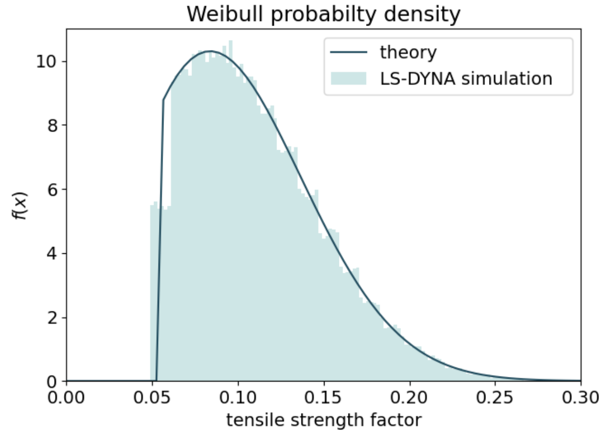
$$f(x) = \begin{cases} \left(\frac{k}{\lambda}\right)\left(\frac{x}{\lambda}\right)^{k-1} e^{\left(\left({}^{\tau}/_{\lambda}\right)^{k} - \left({}^{x}/_{\lambda}\right)^{k}\right)} & , x \geq \tau \\ 0 & , x < \tau \end{cases}$$

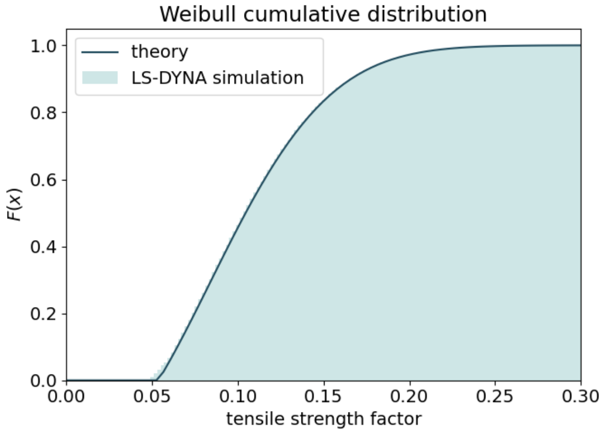
  - Left truncated Weibull cumulative distribution function

$$F(x) = 1 - e^{\left(\left({}^{\tau}/_{\lambda}\right)^{k} - \left({}^{x}/_{\lambda}\right)^{k}\right)}$$

- Parameters Kolling, Schneider, FAT-Schriftenreihe 339
  - Scale parameter $\lambda = 0.11\ \mathrm{GPa}$
  - Shape parameter $k = 2.22$
  - Truncation point $\tau = 0.054\ \mathrm{GPa}$

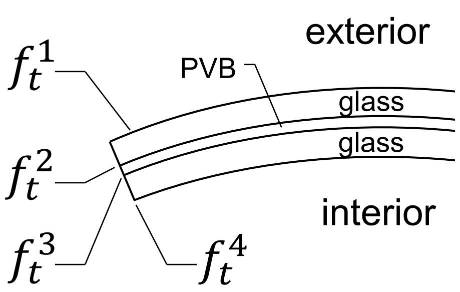


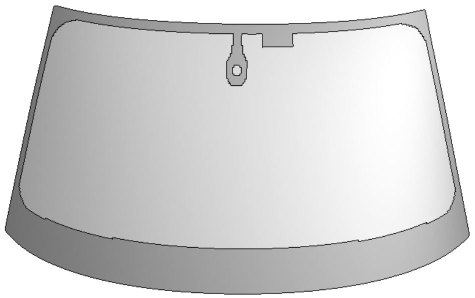




MAT_GLASS Features

Position-Based Tensile Strength

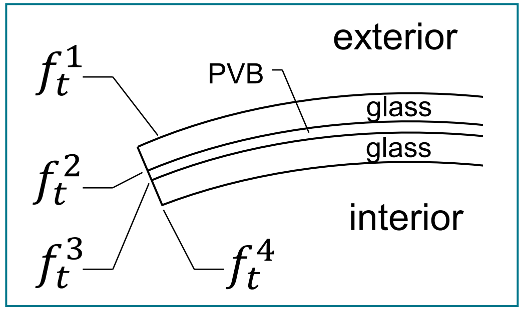


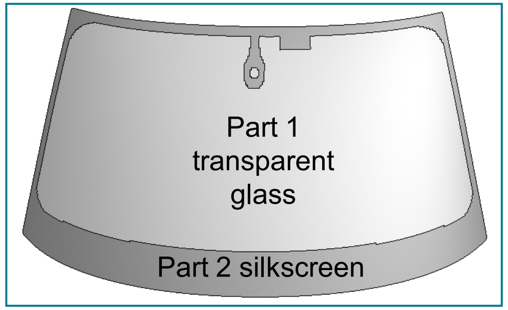


Position-Based Tensile Strength

Ways to define

- Laminated glass
  - tensile strength varies over thickness
- Options to consider effect in LS-DYNA
  - INTEGRATION_SHELL
  - PART_COMPOSITE
- INTEGRATION_SHELL is more flexible
  - Integration rule can be defined
  - For each ply, an individual stochastic variation can be defined

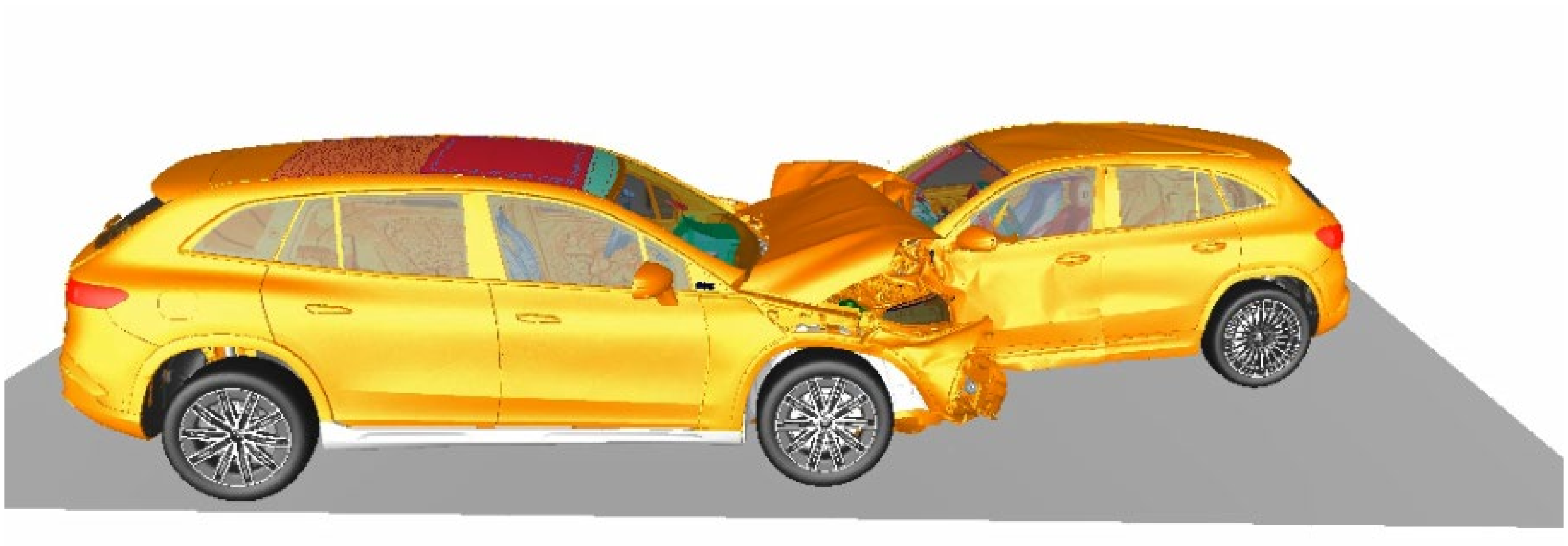





```
*PART
Glass outer pane
$       PID     SECID       MID     EOSID      HGID      GRAV    ADPOPT
        100       100       100         0         0         0         0
*SECTION_SHELL
$     SECID    ELFORM      SHRF       NIP     PROPT QR / IRID     ICOMP
        100         2     0.833         3       1.0      -100         0
…
*INTEGRATION_SHELL
$ Gauss-Lobatto integration 3 IPs
$      IRID       NIP      ESOP   FAILOPT
        100         3
$         S        WF       PID
  -1.00000 0.3333333       101
   0.00000 1.3333333       101
   1.00000 0.3333333       102
*PART
DUMMY PART - Glass outer pane - air side - position 1
$       PID     SECID       MID     EOSID      HGID      GRAV    ADPOPT
        102       100       102         0         0         0         0
*MAT_GLASS
$       MID        RO         E        PR                          IMOD
        102    2.5E-6        70      0.23
…
```

Application

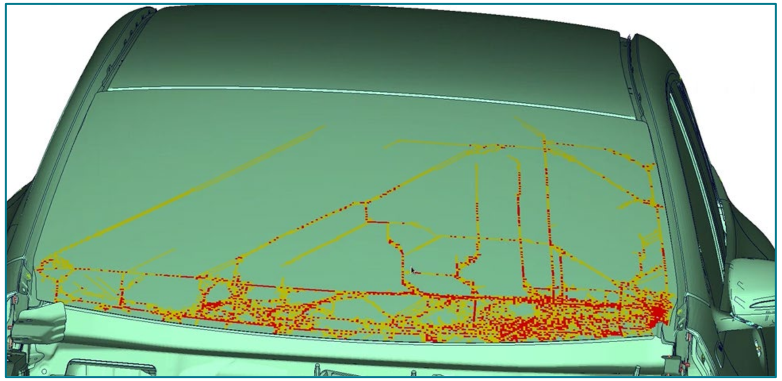
Car-to-Car Crash

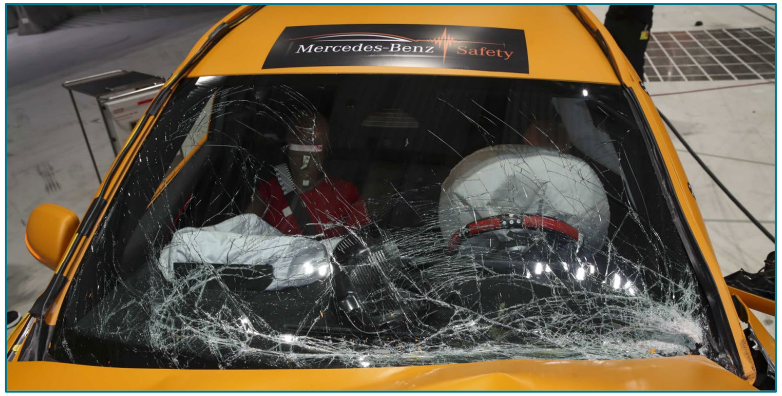


Application

Car-to-Car Crash

- Model presented this morning “Key success factors for digital vehicle development at Mercedes-Benz” by Markus Hermle, Markus Feucht
- Windshields modelled with MAT_GLASS
  - Shell-solid-shell discretization
  - Material card used is a work status coming from a different car model and crash scenario
    - Strength reduction
    - Strain rate dependency

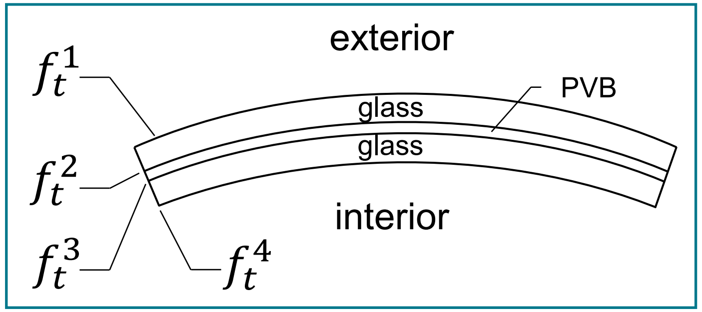


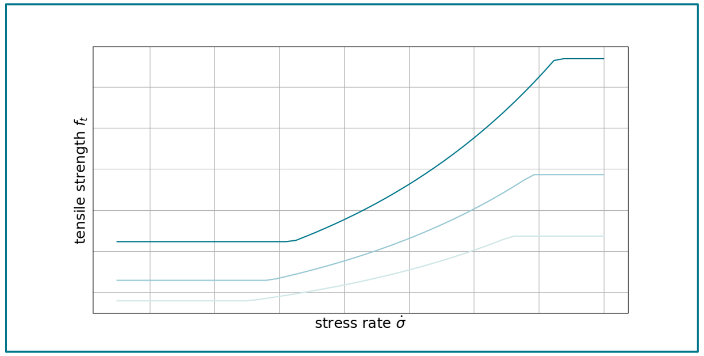


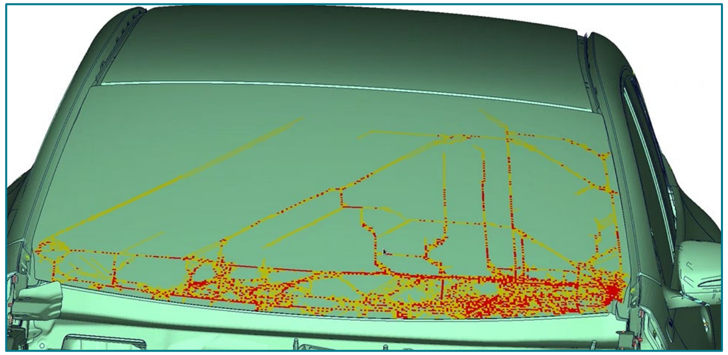
Summary

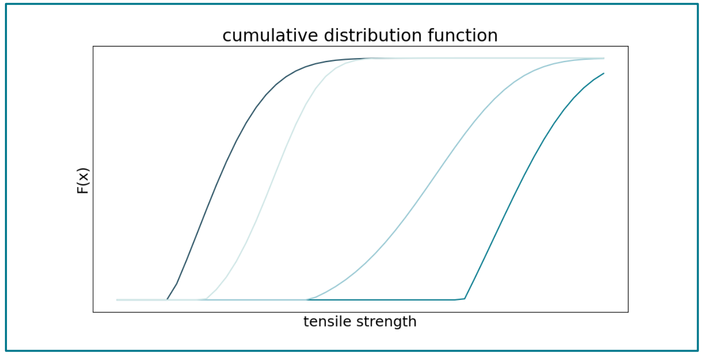
Summary

- Now, we can define MAT_GLASS to use the following features
  - Strength reduction
  - Strain rate dependency
  - Stochastic variation
  - Position-based tensile strength
- MAT_GLASS can be used in full car models









Thank You

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