NIO

# GISSMO Fracture Modelling with Limited Test Data

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Date 2023-06-08

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NIO ES8

NIO ES6

NIO EC6

NIO ET7

NIO ET5

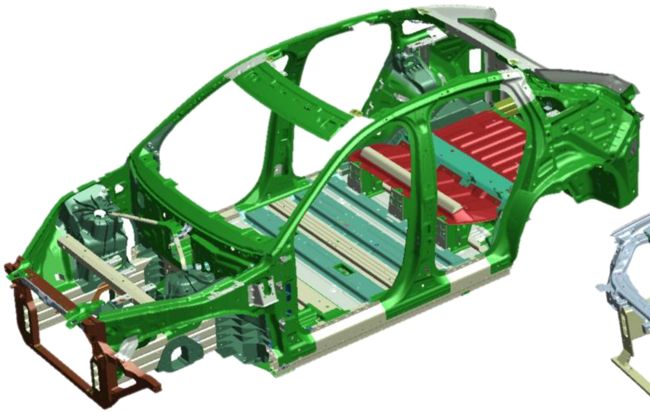
NIO EL7


As of 30. April. 2023, cumulative deliveries have reached 327,255 vehicles.
eT7

# Material Trends in Automotive

EC6 – Aluminium Intensive Car Body

ET7 – Steel Intensive Car Body



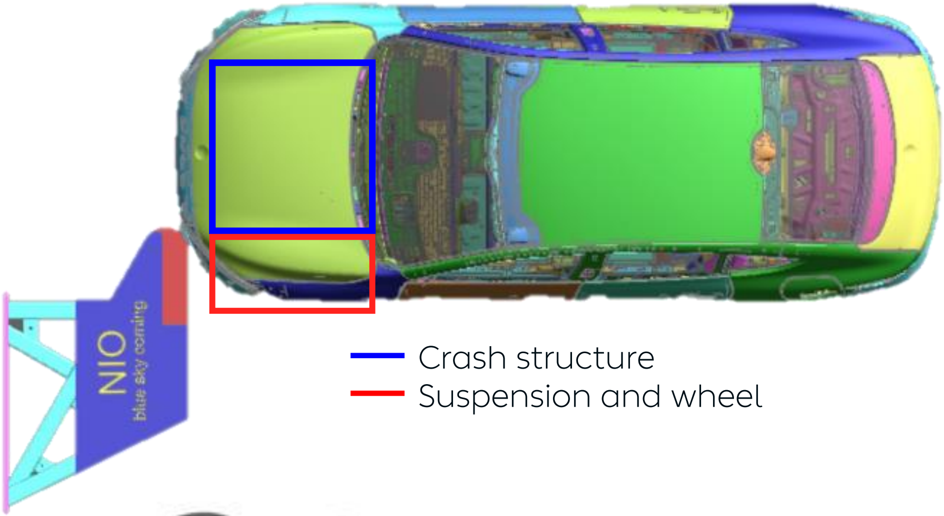
Aluminium Intensive Vehicle Platform

Mixed Material Vehicle Platform

| | |
|---|---|
| Steel | Low Strength Steel |
| | High Strength Steels (HSS) |
| | Advanced High Strength Steels (AHSS) |
| | Austenitic Stainless Steels |
| | Ultra High Strength Steels |
| | Press Hardened Steels |
| | All Steel |
| Aluminium | Aluminium Sheet 7xxx Series |
| | Aluminium Sheet 6xxx Series |
| | Aluminium Sheet 5xxx Series |
| | Aluminium Extrusions 7xxx Series |
| | Aluminium Extrusions 6xxx Series |
| | Aluminium Castings HPDC |
| | Aluminium Castings LPDC |
| | All Aluminium |
| | Magnesium |
| Plastics | Fibre Reinforce Plastics |
| | Duroplastics, including SMC |
| | Thermoplastics |
| | Elastomers |
| | All Plastics |
| | Other Materials |

Automotive materials are moving towards a wider mix of materials and greater use of higher strength steels.
Ways to improve the efficiency of material testing and modelling enables earlier adoption of new material models.

# Brake Disc GISSMO Fracture Study



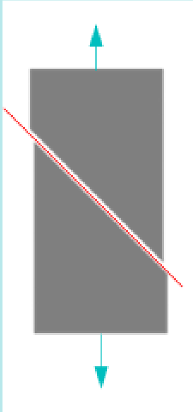

In the SORB impact, parts like the brake disc are directly engaged in the impact and the brake disc fracture plays a role in the load transfer from barrier to vehicle

This study will present a GISSMO Fracture Modelling Approach for the brake disc when only limited test data is available

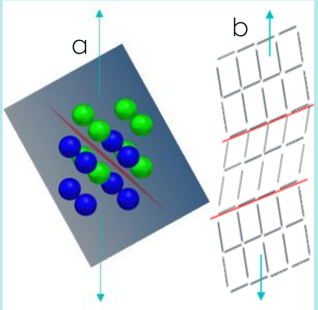
# Some Background to Material Fracture

# Possible Fracture Modes:
# Shear Fracture, Brittle Fracture

## Shear Fracture

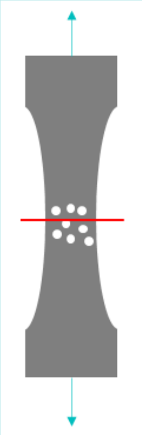


Shear Fracture

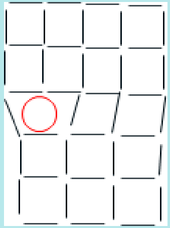



Shearing occurs along slip planes (a) and/or due to twinning (b). Shear fracture occurs on planes at 45° to the direction of the principal stress

## Brittle Fracture



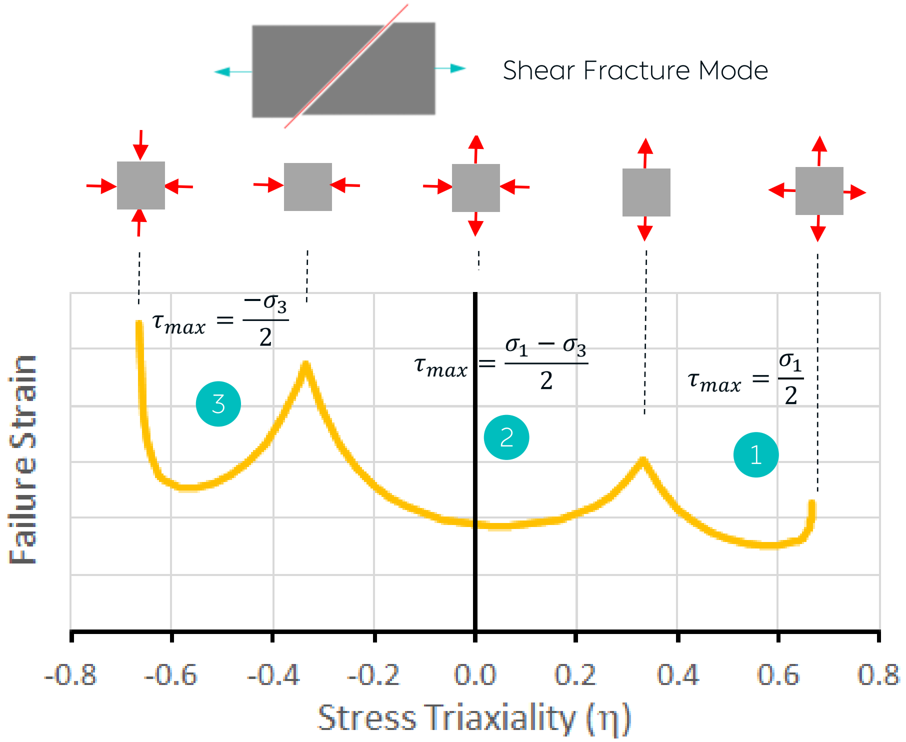
Brittle Fracture



Dislocations are imperfections that give small voids in the micro-structure. At high strains, the voids grow in number and size, and can eventually cause what looks like a brittle fracture on a plane normal to the principal stress

Ductile metals can fail in shear and brittle fracture modes

# Shear Fracture:
# Anatomy of a Shear Fracture Curve (2D Shell Elements)



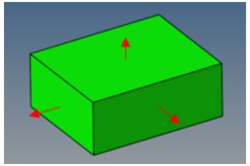

**X-axis:**
$\eta$ is the stress triaxiality, from compression to tension ($-2/3 < \eta < 2/3$)

**Y-axis:**
$\varepsilon_{pl}$ is the plastic strain

**The orange line:**
The fracture limit based on the maximum shear stress

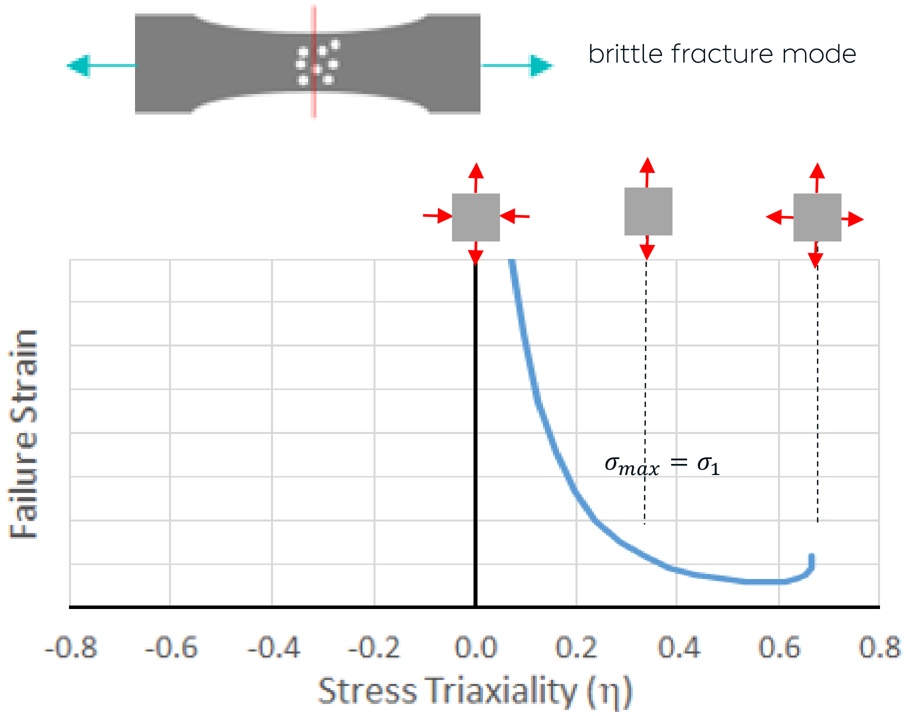
$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2}$$

**Shear Fracture Curve Shape:**
3 partitions
3 principal stresses (one is zero)
3 principal stress planes
3 max shear stress planes



*Ref 1: "Application of extended Mohr–Coulomb criterion to ductile Fracture", Yuanli Bai · Tomasz Wierzbicki, Int J Fract (2010) 161:1–20, 12 November 2009*

# Brittle Fracture:
# Anatomy of a Brittle Fracture Curve (2D Shell Elements):




**X-axis:**
η Is the stress triaxiality, from compression to tension (0 < η < 2/3)

**Y-axis:**
$\varepsilon_{pl}$ is the plastic strain

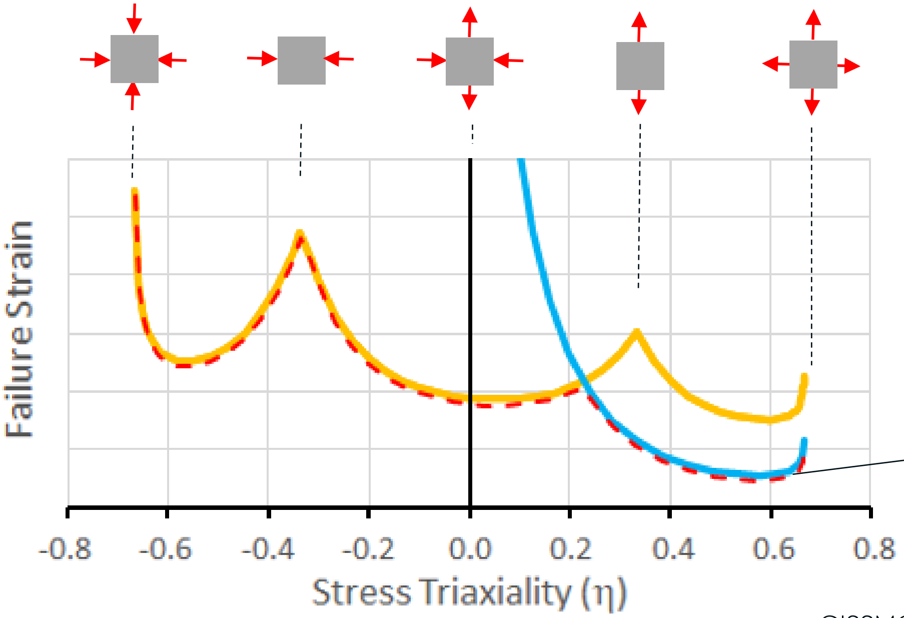
**The blue line:**
The fracture limit based on the maximum principal stress. This type of fracture is normally associated with brittle materials.

**Brittle Fracture Curve Shape:**
A single asymptotic curve in the range 0<η<2/3

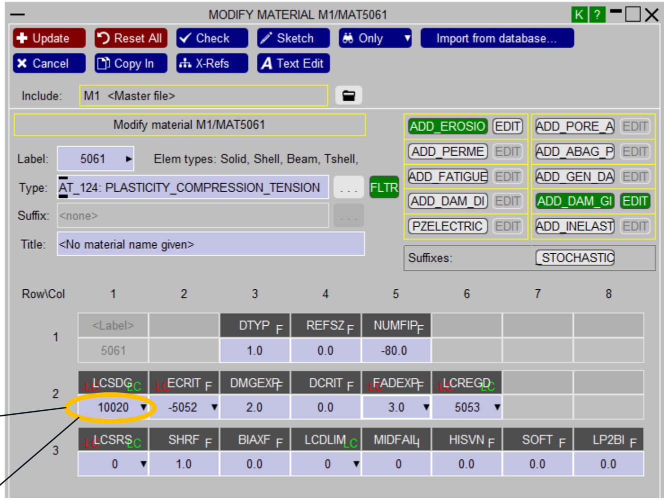
This fracture mode can also be modelled using *MAT_ADD_EROSION with smax or emax.

# Combined Shear and Brittle Fracture Curves (2D Shell Elements)

Combined Shear and Brittle Fracture Curves




GISSMO requires the fracture curves to be combined into a single curve (red dotted line).




GISSMO fracture curve definition

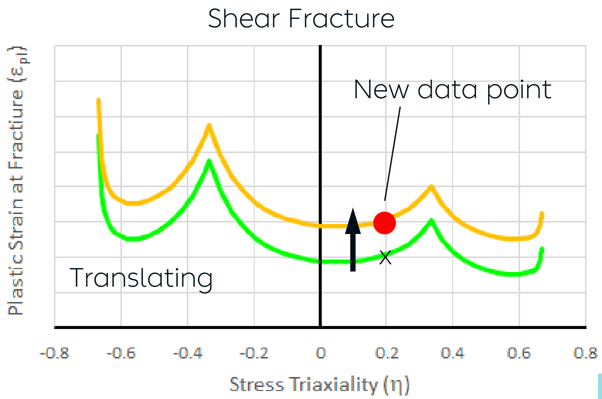
ADD_DAMAGE_GISSMO card

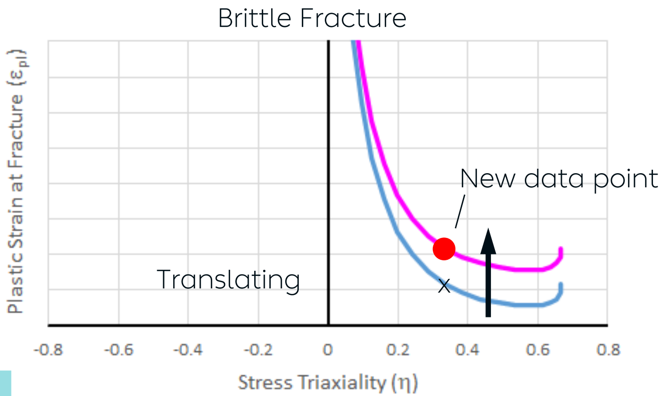
# Method 1: A Graphical Method to derive a GISSMO fracture curve and 3D surface

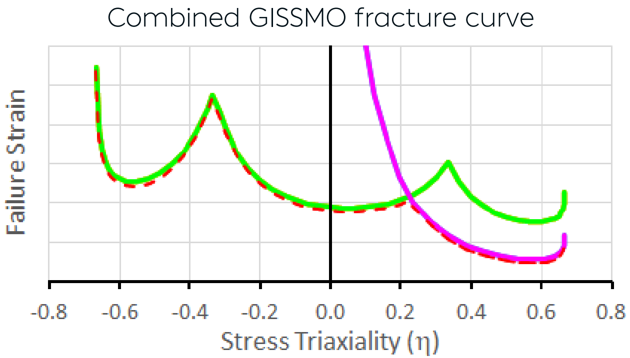
# 2D Curve: Borrowing Data from Another Similar Material (2D Shell Elements)

An approximation to the fracture curve can be made by scaling an existing shear and brittle fracture curve as shown and combining the curves to give one curve

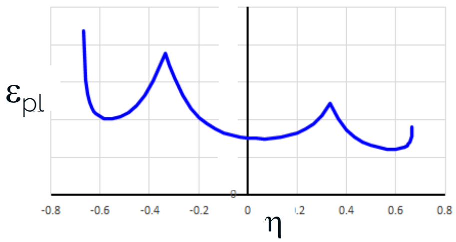
This approach requires only 1 data point for the shear curve and 1 data point for the brittle fracture curve



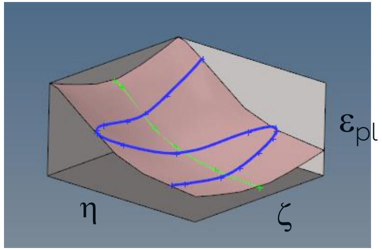



# 3D Fracture Surface for 3D Solids: Projecting Onto a Box

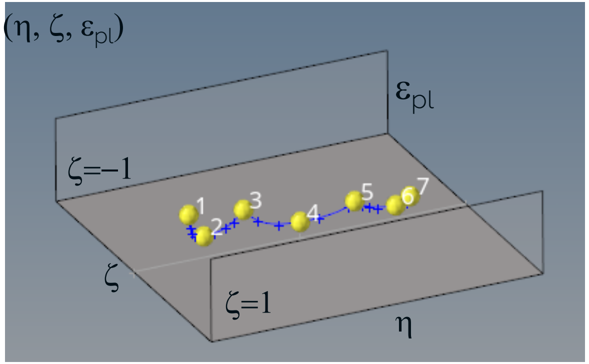


2D shear fracture curve

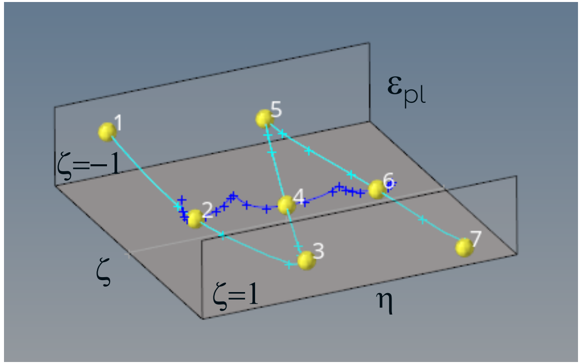


3D shear fracture surface

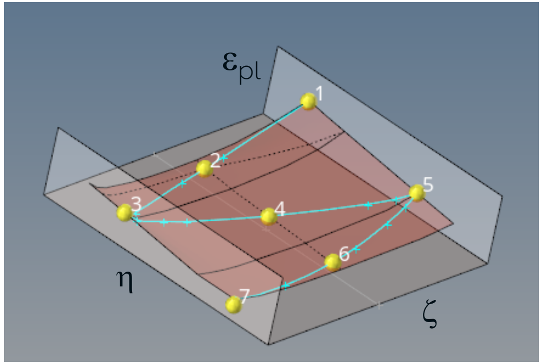
To account for lode angle for 3D elements: x=$\eta$, stress triaxiality ($-2/3<\eta<2/3$)
y=$\zeta$, 3[rd] stress invariant ($-1<\zeta<1$)
z=$\varepsilon_{pl}$, plastic strain ($\varepsilon_{pl}$)



Draw a box, add nodes 1-7 at turning points of the curve



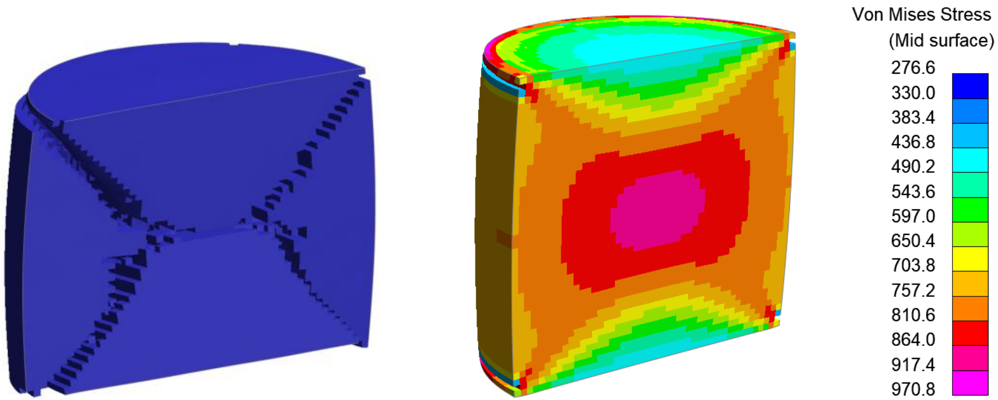
Project points 1, 3, 5, 7 onto walls, draw 3 curves through points shown (cyan)

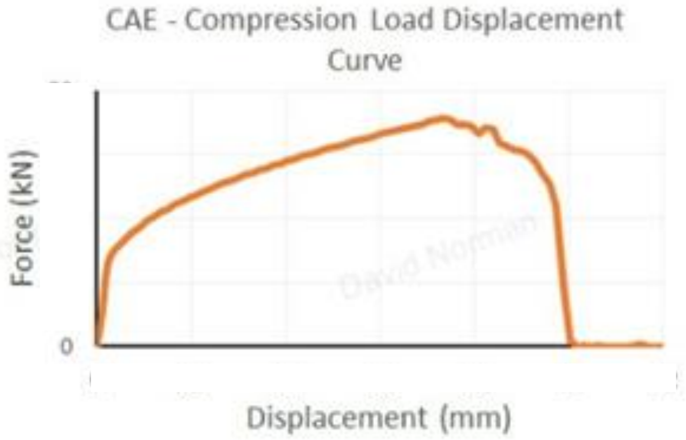


Loft surface over the 3 curves. *DEFINE_TABLE points can be drawn on this surface

# Modelling the Brake Disc

# Uni-Axial Compression - CAE and Test




The cylinder fractures at a compressive stress of 900MPa with a 45° fracture cone

The fracture stress corresponds to the measured maximum compressive stress in the test data (894MPa) and compares well with the maximum compressive stress obtained from literature for ASTM 35B (G3500). The maximum load at fracture is also the same as reported in the uni-axial compression test.

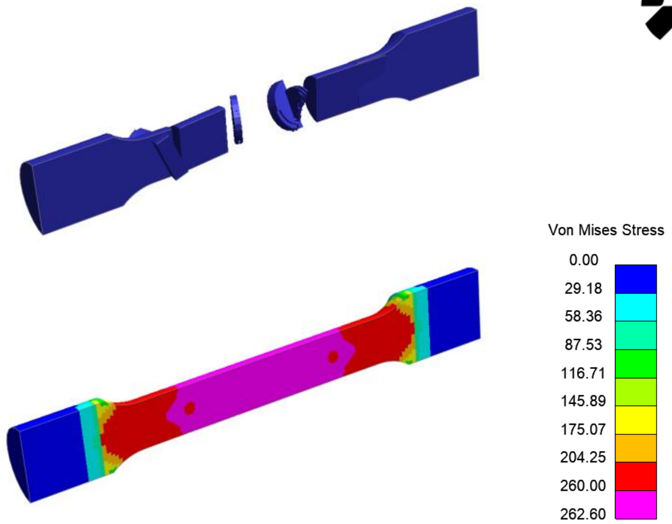
# Uni-Axial Tension - CAE and Test

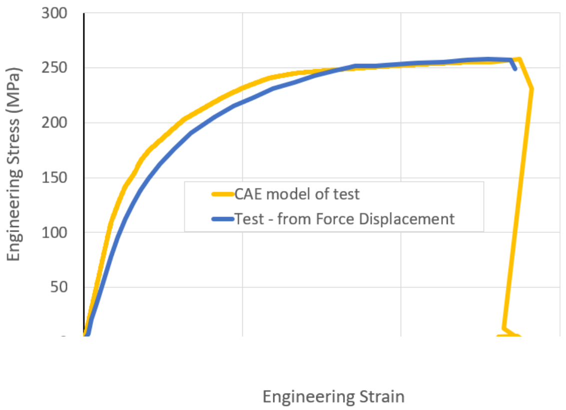
A CAE model of the tensile test is used to verify the cast iron  stress strain curve and fracture strain

There is some discrepancy in the elastic stiffness of the tested material and the CAE model.  This may be due to how the displacement is measured in the test or may be due to an overestimated Young's modulus for cast iron.

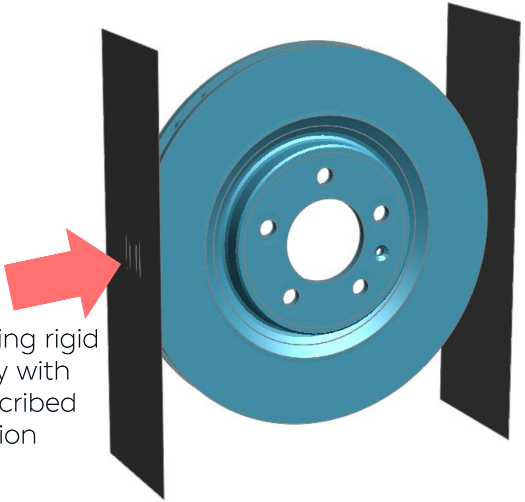
Note the Young's modulus for cast iron is dependent on the porosity of the cast material and may be subject to some variability

Questions remain on how the strain was measured in the tensile tests, which is used to convert to true strain when characterising the stress strain curve.



# Model Set Up – 2 Cases - Shear Fracture and Shear with Brittle Fracture



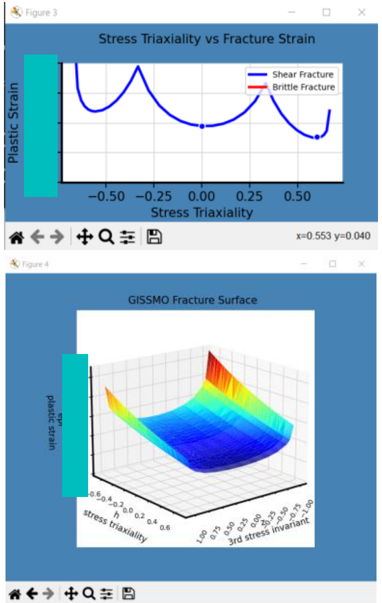
Fixed rigid body

Moving rigid body with prescribed motion

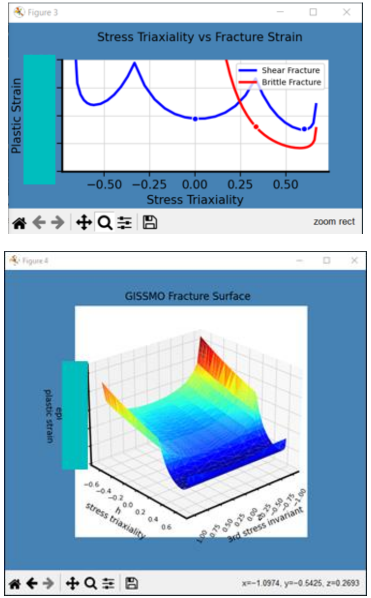
Brake disc is crushed between a moving rigid body and a fixed rigid body. 2 cases run:

1) shear fracture only
2) brittle and shear fracture modelled

Case 1 –Shear Fracture Only




Case 2 – Shear and Brittle Fracture

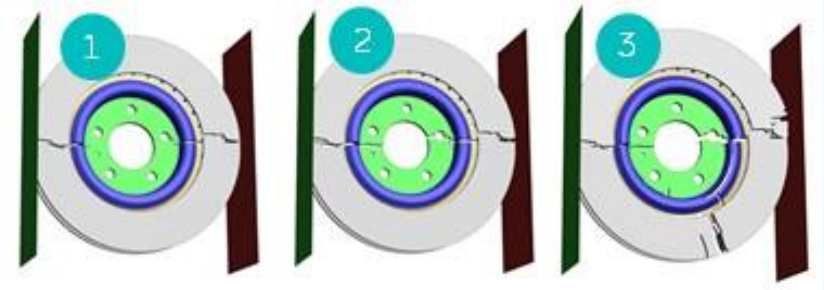



GISSMO fracture surfaces calculated from the paper (Ref 1)

# Brake disc – Shear Failure, Brittle Failure

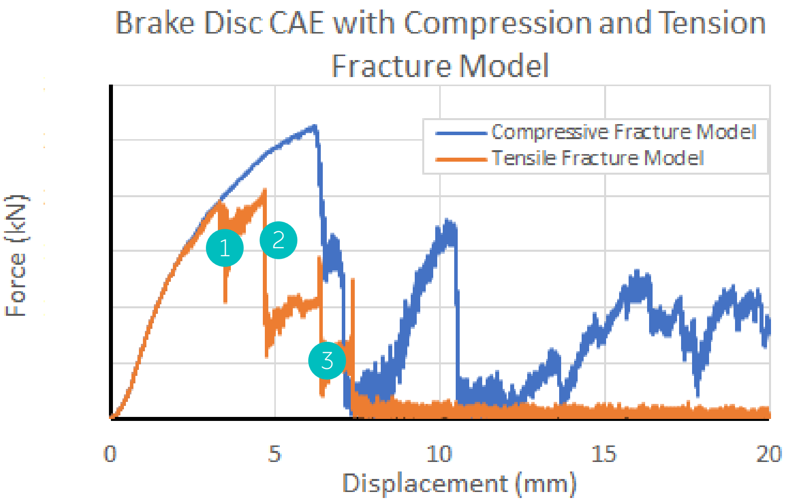
The model with shear fracture shows the impacted region of the brake disc being nibbled away as it is crushed

Case 1: Fracture in shear mode




The model with shear and brittle fracture fractures at a lower load than the shear only fracture, with several fractures occurring in sequence

Case 2: Fracture in brittle mode



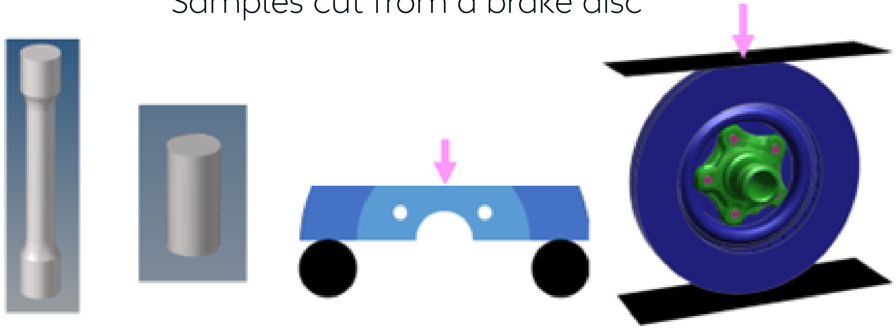

The graphs show the brittle fracture mode occurs before the load is sufficiently large enough to cause a fracture in shear. Thus it is expected the brake disc will fracture in a brittle fracture mode when it is crushed

Results Summary

# Brake Disc Fracture Future Validation Testing Plan

1. Machine a number of standard test coupons from a brake disc.
2. Uniaxial compression and tensile tests with DIC strain measurement system.
3. 3 point bend tests of discs cut into strips. DIC strain measurement system
4. Crush tests of a number of whole brake discs with a bolted hub and wheel centre will be designed and tested.

Samples cut from a brake disc



Tensile, Compression Coupon Tests, Brake Disc 3-Point Bend and Fully Bolted Crush Tests

# Summary Slide

- Generating a GISSMO fracture surface can be achieved by calculation from accepted failure theories or by scaling template shear and brittle fracture curves and projecting onto a 3D box
- By focusing on failure theories to derive the GISSMO fracture curve, fewer tests are needed to derive the GISSMO fracture curve/surface
- In the wheel crush, the brake disc fractures in a brittle fracture mode in tension due to bending
- Further work is ongoing to verify the CAE model findings

# References

# References

Ref 1: “ Application of extended Mohr–Coulomb criterion to ductile Fracture”, Yuanli Bai · Tomasz Wierzbicki, Int J Fract (2010) 161:1–20, 12 November 2009

Ref 2: “Strain Rate and Stress-State Dependence of Gray Cast Iron”, S. A. Brauer, Center for Advanced Vehicular Systems, Mississippi State University, Starkville, MS 39759, Journal of Engineering Materials and Technology, APRIL 2017, Vol. 139 / 021013-1

Ref 3: “A comprehensive failure model for crashworthiness simulation of aluminium extrusions”, H Hooputra1, H Gese2, H Dell2 and H Werner1, 1BMW Group, Forschungs- und Innovationszentrum, Knorrstrasse 147, D-80788 Munich, Germany, 2MATFEM Partnerschaft Dr. Gese & Oberhofer, Nederlingerstrasse 1, D-80638 Munich, Germany, © Woodhead Publishing Ltd doi:10.1533/ijcr.2004.0289

Ref 4: “A Simple Methodology to Determine Fracture Strain of Press-Hardened Steels Under Plane Strain Bending”,Jeff Wang, Dahzen Whu,  Metallurgical and Materials Transactions A · January 2021

# Method 2: A Calculated Method to derive a GISSMO fracture curve and 3D surface

# Shear Fracture Curve and Surface (Mohr-Coulomb Criterion)

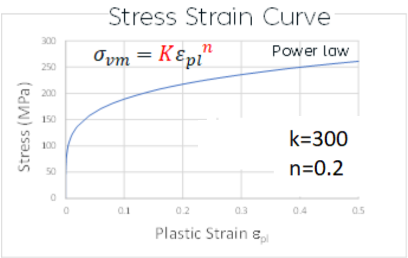
*Ref 1: "Application of extended Mohr–Coulomb criterion to ductile Fracture", Yuanli Bai · Tomasz Wierzbicki, Int J Fract (2010) 161:1–20, 12 November 2009*

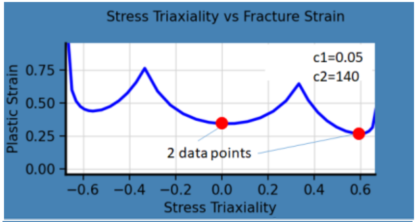
This paper provides the mathematical formulae to calculate the full 3D surface and 2D shear fracture curve

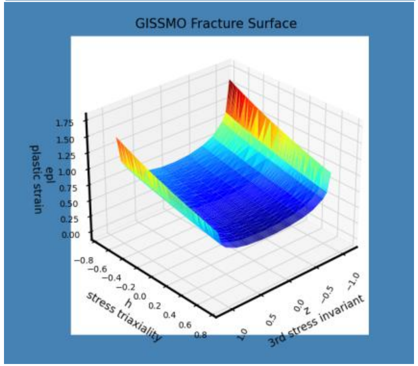
Requirements:
- K = Stress strain power law coefficient
- n = Stress strain power law coefficient
- c2 = Shear stress fracture limit
- c1 = Friction parameter

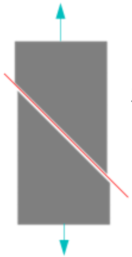
Example material is not a real material, it is a power law curve, K=300, n=0.2 with parameters c1=0.05, c2=140MPa

c1, c2 can be determined from a curve or surface fit with 2 points of stress triaxiality vs plastic strain at fracture ($\eta$, $\varepsilon_{pl}$)



# Brittle Fracture Curve (Maximum Principal Stress Criterion)

Example material is not a real material, it is a power law curve, K=300, n=0.2, fracture stress $\sigma_{fr}$= 210MPa

The maximum principal stress failure criterion can use `*MAT_ADD_EROSION` with smax or emax

An equivalent GISSMO curve ($\eta$, $\varepsilon_{pl}$) for the maximum principal stress failure criterion is shown below

To convert a maximum principal stress criterion to a GISSMO fracture curve...

If you want to convert the maximum principal stress failure criterion into a GISSMO curve you need to convert it to a graph of ($\eta$, $\varepsilon_{pl}$)

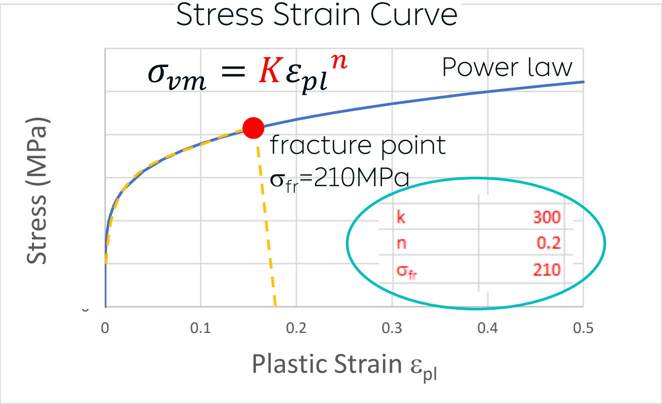
Start with the principal stress ratio $\beta = \frac{\sigma_2}{\sigma_1}$ → $\eta = \frac{1}{3}\frac{(1+\beta)}{\sqrt{1-\beta+\beta^2}}$

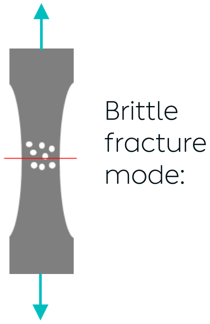
$\sigma_{vm} = \sigma_{fr}\sqrt{1-\beta+\beta^2}$ → $\varepsilon_{pl} = \left(\frac{\sigma_{vm}}{K}\right)^{\left(\frac{1}{n}\right)}$

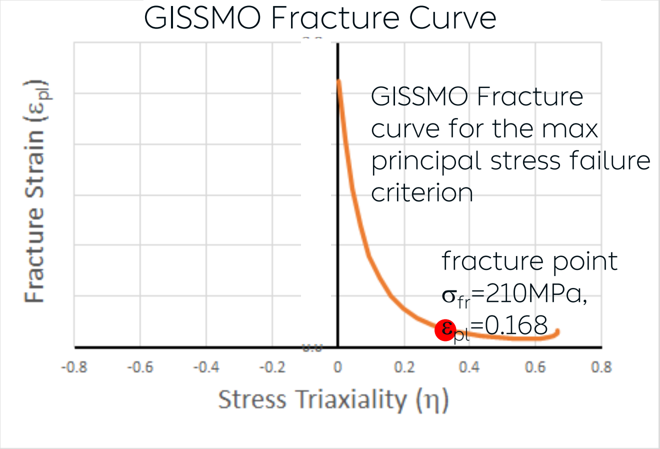
**Steps in EXCEL:**

1. Make a column for $\beta$ from $-1.0<\beta<1.0$ in 0.1 increments
2. Calculate $\eta$, $\sigma_{vm}$, $\varepsilon_{pl}$ in 3 separate columns
3. Plot ($\eta$, $\varepsilon_{pl}$)

| $\beta$ | $\eta$ | $\sigma_{vm}$ | $\varepsilon_{pl}$ |
|---|---|---|---|
| -1 | 0 | 363.7307 | 2.619952 |
| -0.9 | 0.020249 | 345.7036 | 2.031952 |
| -0.8 | 0.042679 | 328.0305 | 1.563021 |
| -0.7 | 0.067574 | 310.7716 | 1.19289 |
| -0.6 | 0.095238 | 294 | 0.903921 |
| -0.5 | 0.125988 | 277.8039 | 0.680903 |
| -0.4 | 0.160128 | 262.2899 | 0.51086 |
| -0.3 | 0.197911 | 247.5863 | 0.382849 |
| -0.2 | 0.239474 | 233.8461 | 0.287769 |
| -0.1 | 0.284747 | 221.2487 | 0.218171 |
| -1.4E-16 | 0.333333 | 210 | 0.16807 |
| 0.1 | 0.384371 | 200.3272 | 0.132768 |
| 0.2 | 0.436436 | 192.4682 | 0.10869 |
| 0.3 | 0.487538 | 186.6521 | 0.09323 |
| 0.4 | 0.535303 | 183.0738 | 0.08463 |
| 0.5 | 0.57735 | 181.8653 | 0.081874 |
| 0.6 | 0.611775 | 183.0738 | 0.08463 |
| 0.7 | 0.63755 | 186.6521 | 0.09323 |
| 0.8 | 0.654654 | 192.4682 | 0.10869 |
| 0.9 | 0.663914 | 200.3272 | 0.132768 |
| 1 | 0.666667 | 210 | 0.16807 |



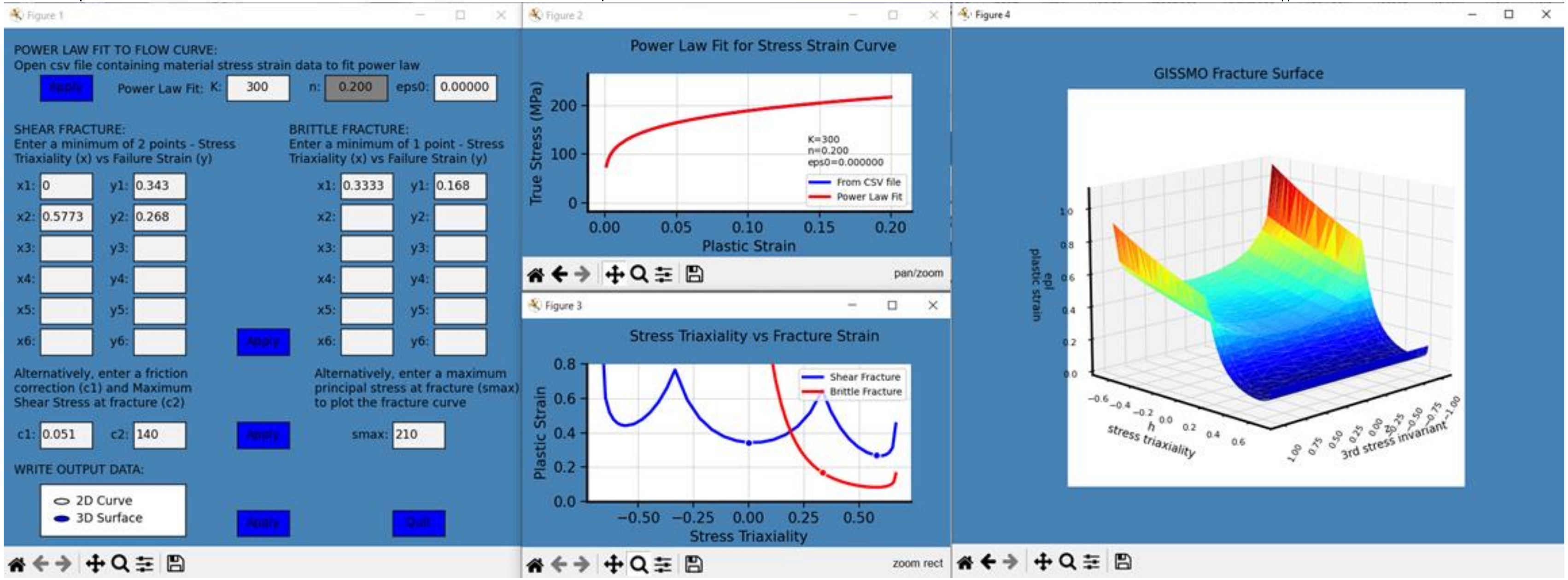




Fracture occurs before necking

# Python Program (Using the Maths)

Example material is not a real material, it is a power law curve, K=300, n=0.2, c1=0.05, c2=140MPa, $\sigma_{fr}$= 210MPa

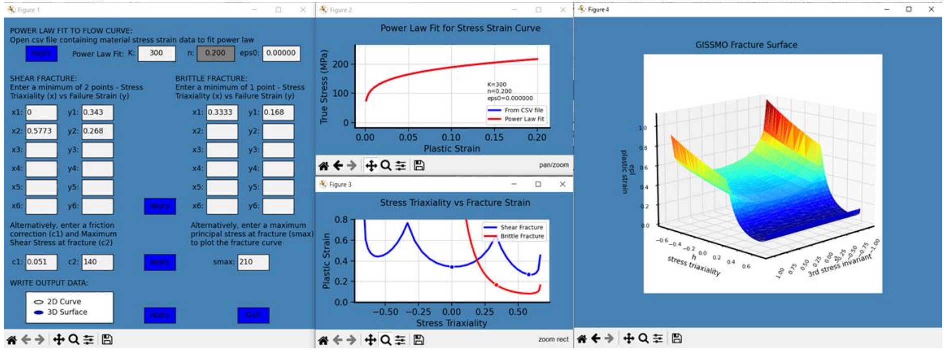


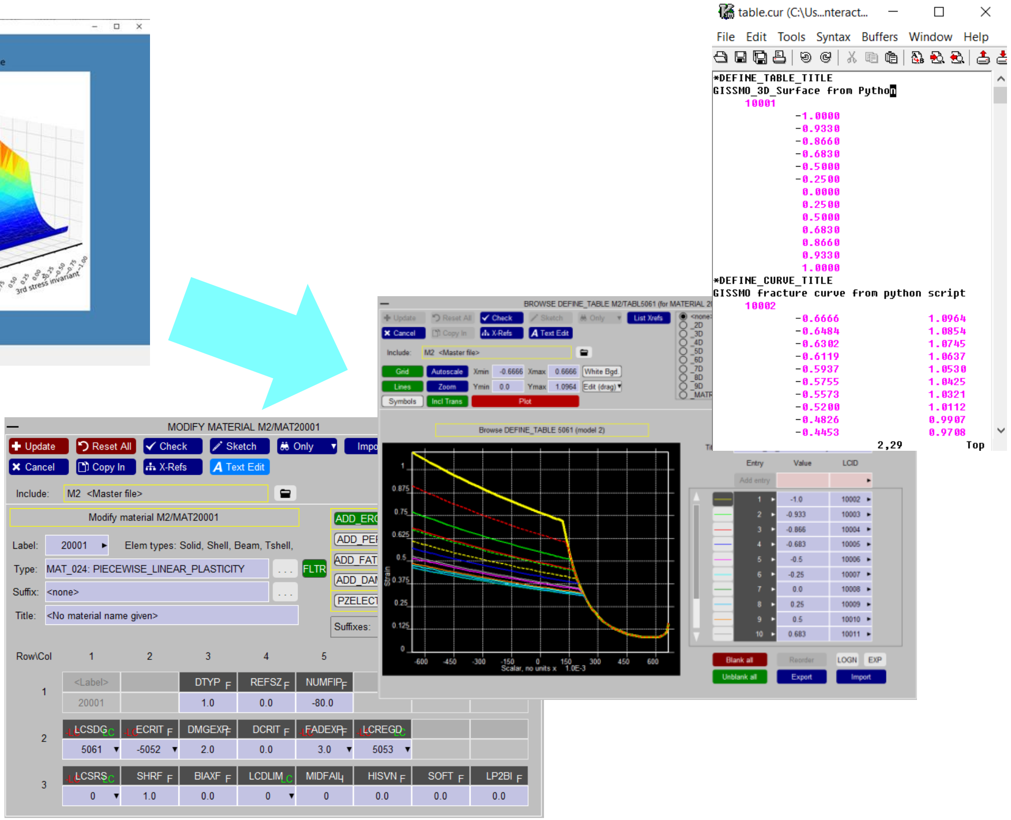

*Ref 1: " Application of extended Mohr–Coulomb criterion to ductile Fracture", Yuanli Bai · Tomasz Wierzbicki, Int J Fract (2010) 161:1–20, 12 November 2009*

Mathematical Function to calculate the fracture surface as a function of $\zeta$ and $\eta$ given in ref shown

# In PRIMER

Example material is not a real material, it is a power law curve, K=300, n=0.2, c1=0.05, c2=140MPa, $\sigma_{fr}$= 210MPa




Output written to text file in keyword format for *DEFINE_TABLE, shown here in PRIMER