Material Modeling Summary Inconel-718 V1.0, with new Adiabatic Shear Band Capability

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SUMMARY

- Inconel 718 modeling challenge
- Problem review
- 2D Simulations
- Analytical approach
- Single elements verification
- 2D Verification
- Ballistic limit validation 0.2mm mesh
- Ballistic limit regularization
- Ballistic limit validation full model
- Development version

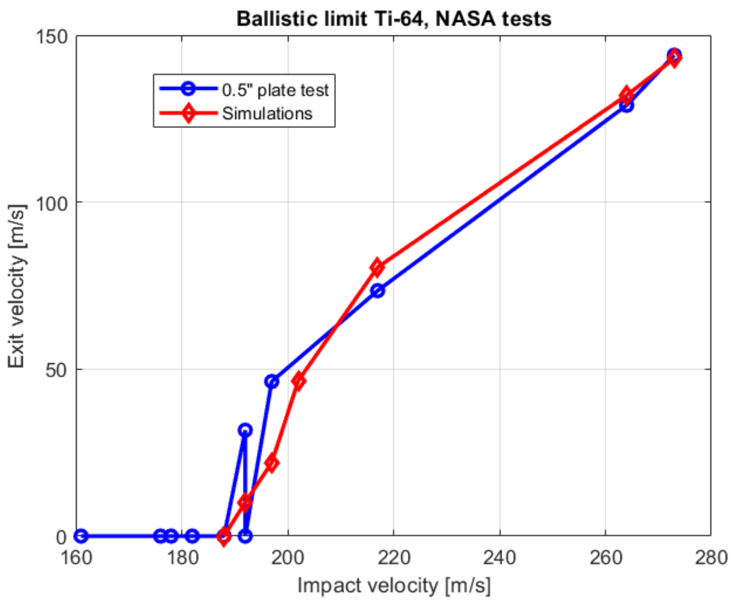
- Material set insuring model accuracy for other applications
  - Updated Failure Surface:
    - Material failure test simulations
    - Failure surface strain rate scaling function
  - Ballistic limit sim repeated

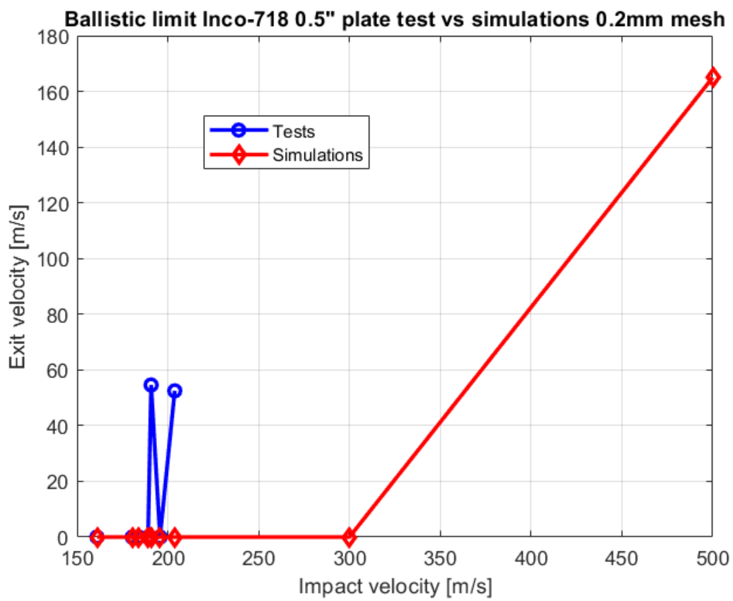
In-718 Modeling Challenge Review

- The approach of using stress-state dependent plastic strain to failure has not been successful in high strain rate simulations
- The source of analytical challenge had been identified
  - In-718 gets brittle as elevated temperatures
  - At these temperatures, adiabatic shear bands easily form
  - Adiabatic shear bands in In-718 are very narrow (**1-5 µm!)**
    - Not practical to use this size of elements in general analysis

Problem Review

- Ballistic impact tests were performed at NASA using cylindrical projectiles impacting 0.5" (P4) plates on both In-718 and Ti-64
- In-718 has a larger elastic modulus (210GPa) than Ti-64 (110GPa)
- At our highest tested strain rate, In-718 has a larger yield stress (~1500MPa) than Ti-64 (~1300MPa)
- At the same high rate, In-718 true strain at rupture is (~.22) higher than Ti-64 (~.15)
- Despite In-718's greater stress and strain**, the ballistic limits are about the same - WHY?**





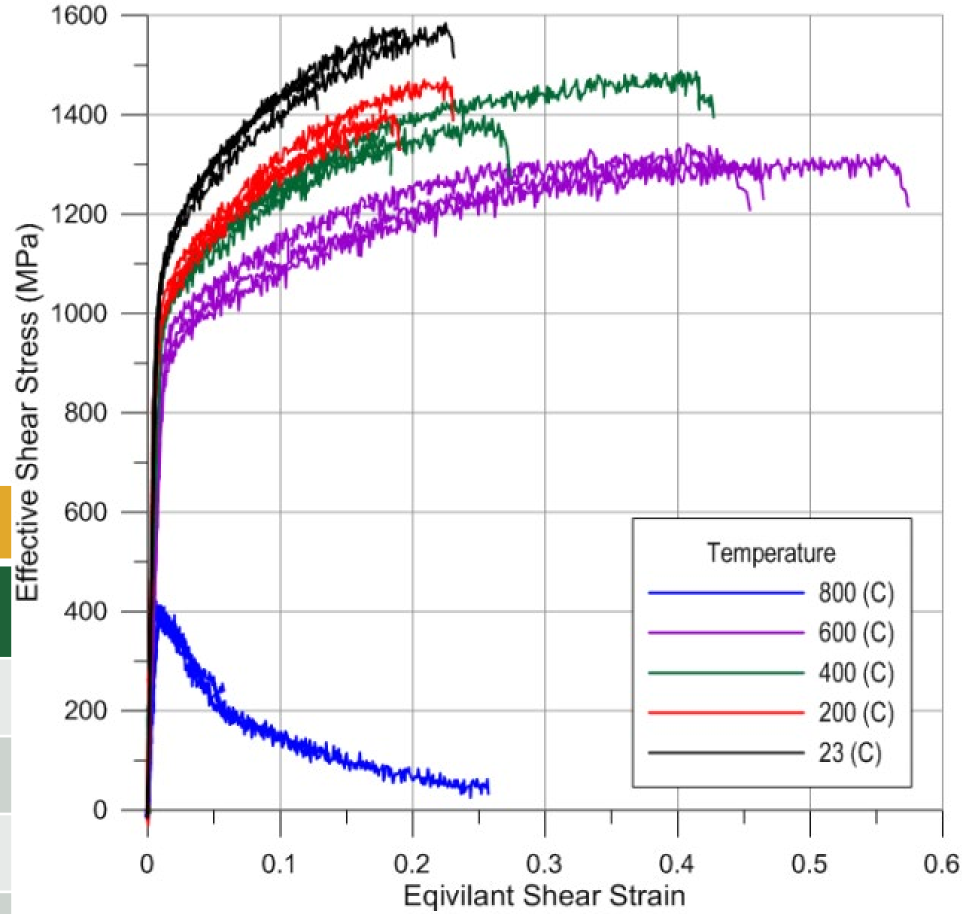
Problem Review

- Temperature sensitivity Inconel ≠ Ti.
- Inconel becomes very brittle at T>700˚C
- **This neutralizes the advantage In-718 has in yield stress and failure strain over Ti-64, at room temperature**

Titanium 6Al 4V		
T(K)	ε_p^f	**Scale**
293	0.541	1
473	0.809	1.95
673	0.789	1.95
873	1.150	2.95
1877		2.95

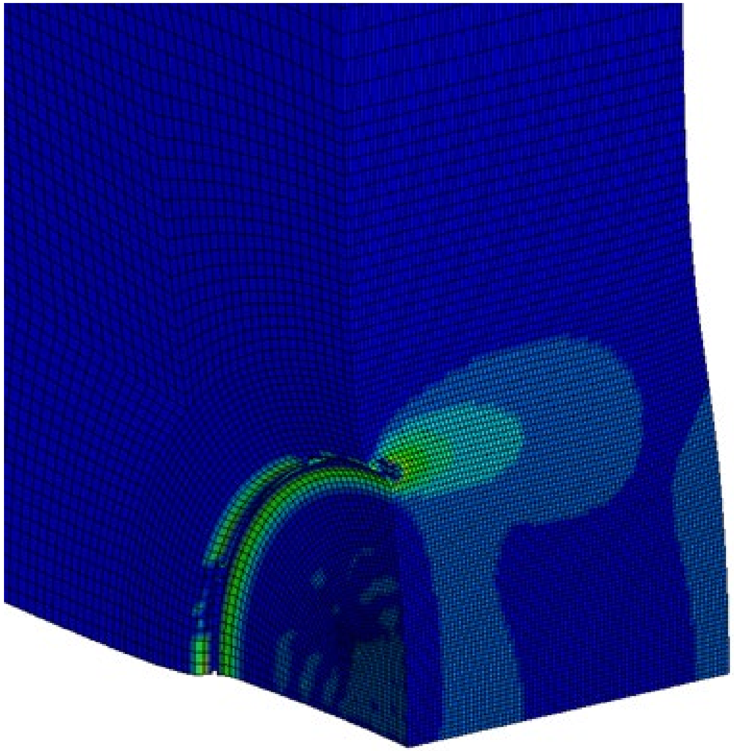
Inconel 718		
T(K)	ε_p^f	**Scale**
300	0.39	1
473	0.35	1
673	0.47	1
873	0.39	1
1073	0.03	0.1

Inconel 718



Problem Review

- High temperature brittleness allow Adiabatic Shear Bands (ASB) to easily form in In-718
  - Almost perfect In-718 plugs result from cylindrical projectile
- Approximate shear band width for our metals
  - Al-2024 -.05 mm to .3 mm
  - Ti-64 - ~.02 mm
  - In-718 - .001 to .005 mm
- Current MAT224 is unable to simulate In-718 ballistic impact producing ASB using practical “industrial size mesh”



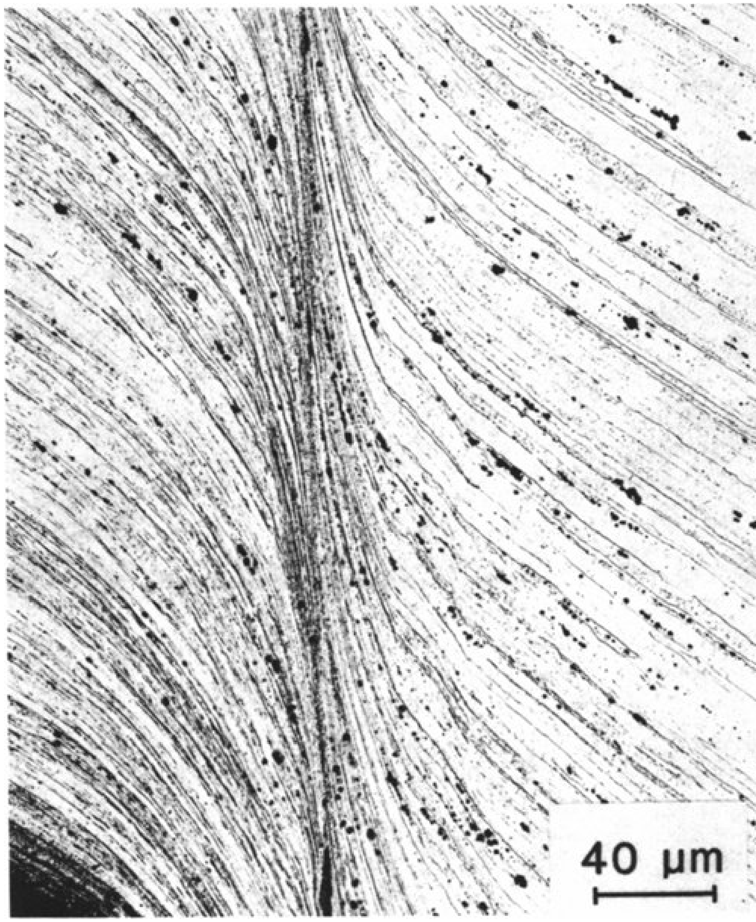
- ***Full scale 3D analysis -> ASB not propagating***
- ***Temperatures do not reach brittle level***

Problem Review

ADIABATIC SHEAR BAND (ASB)

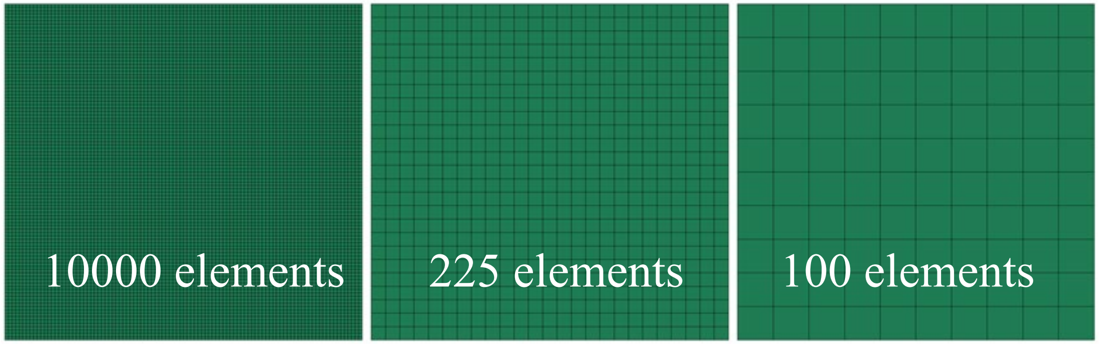
ASB is a failure mechanism that can result in an unpredicted catastrophic failure due to a concentrated shear deformation mode. It is generally considered a material or structural instability.

- Thermodynamic phenomena occurring at high strain rates
- Large deformations in a narrow band (typically 1-500µm), consisting of very highly sheared material
- "Adiabatic" absence of heat transfer
    - Heat produced is retained
- Common in machine chips, forging, and ballistic impact
- Causes the material to lose its load carrying and energy dissipation capacity
- Precursor to failure



- In-718 is more prone to fail with an ASB than Ti-64 or Al-2024
    - ASB do form in Ti-64 ballistic impact and compression mechanical property tests

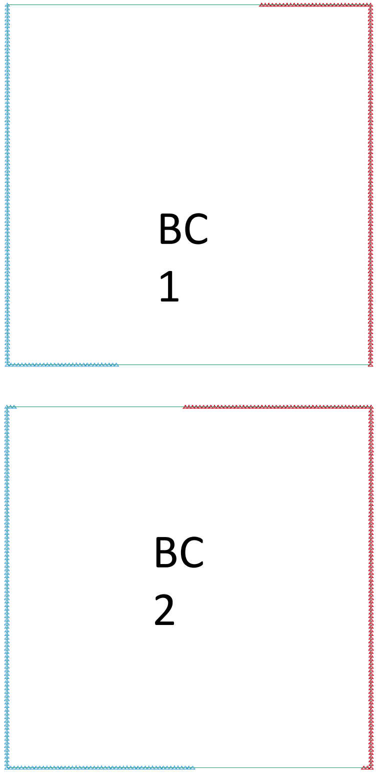
Simulations using Ultrafine Mesh in 2D



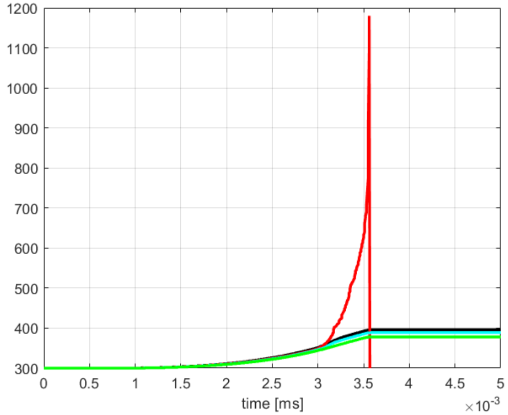
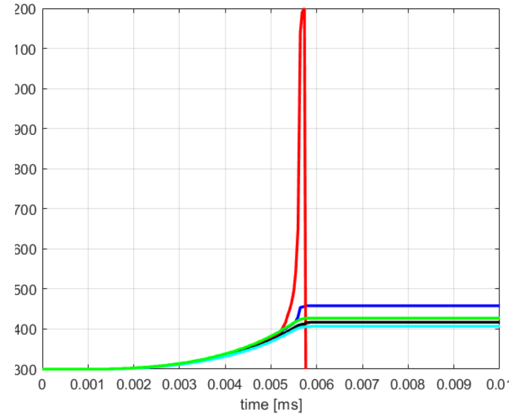
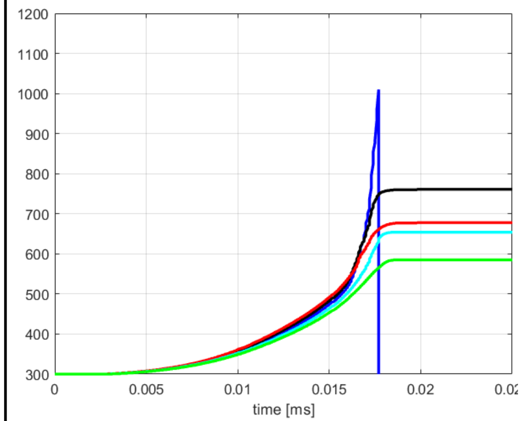
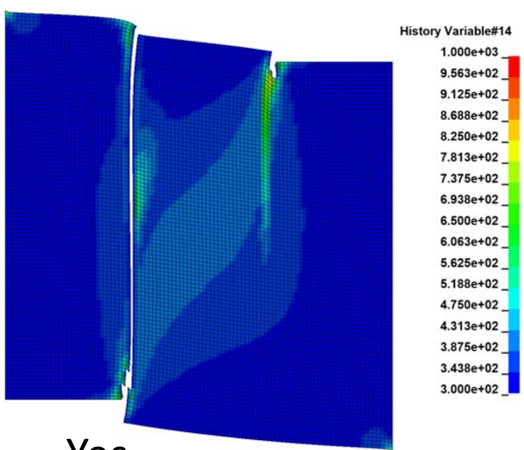
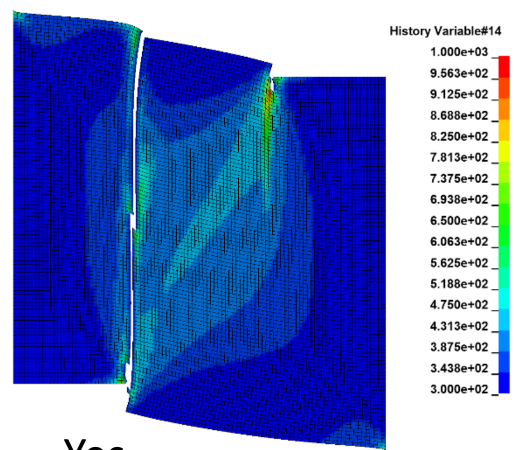
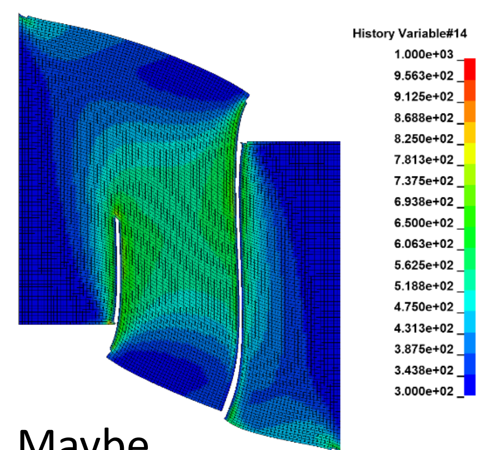
A series of 2D simulations was performed to verify capability to predict ASBs

Shown on next two pages

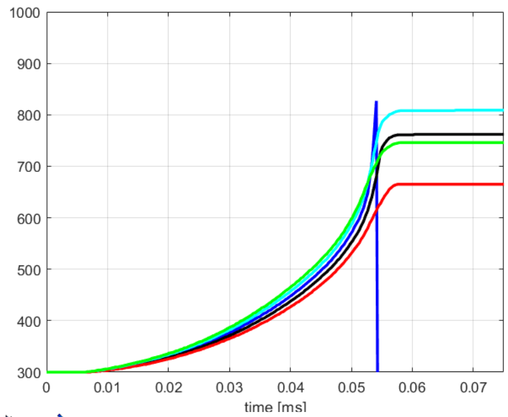
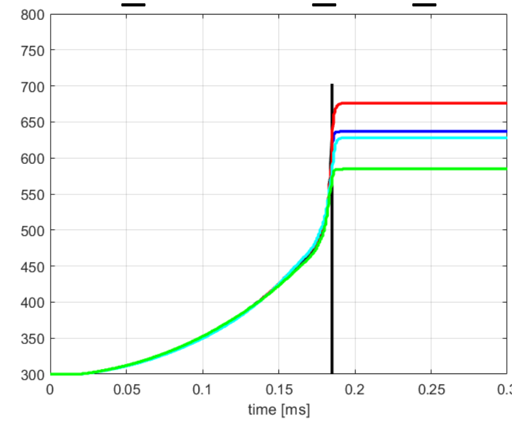
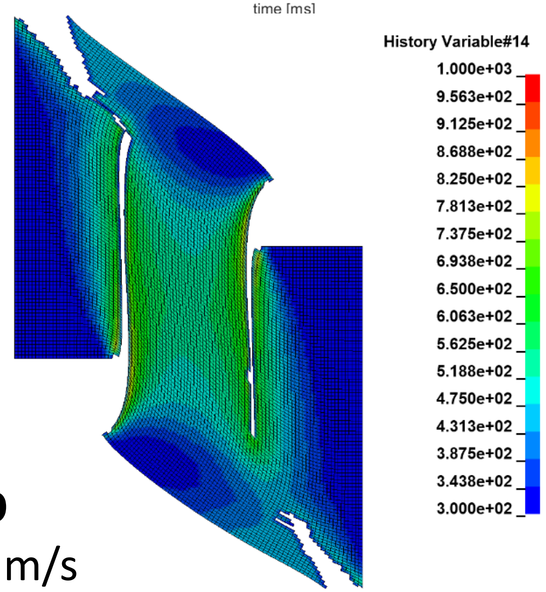
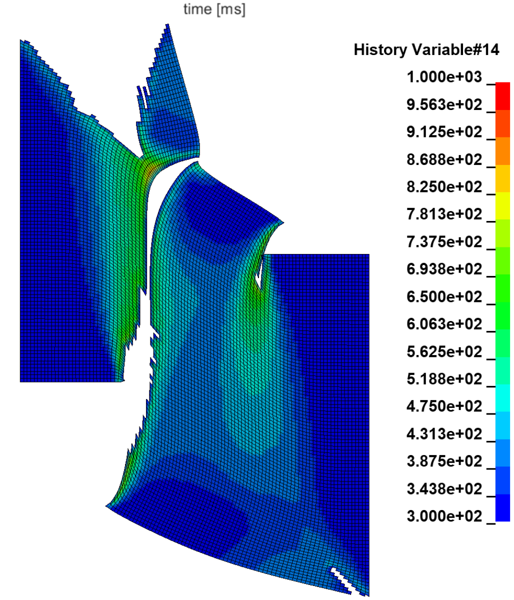
Simulation Name	# of Elements	Elements Size [µm]	Boundary Conditions type	Overall Edge Size [µm]
Inco_100x100_BC1_05	10000	0.5	1	50
Inco_100x100_BC1_1	10000	1	1	100
Inco_100x100_BC1_4	10000	4	1	400
Inco_100x100_BC1_20	10000	20	1	2000
Inco_100x100_BC1_200	10000	200	1	20000
Inco_100x100_BC2_05	10000	0.5	2	50
Inco_100x100_BC2_1	10000	1	2	100
Inco_100x100_BC2_4	10000	4	2	400
Inco_100x100_BC2_20	10000	20	2	2000
Inco_100_4_BC1	225	4	1	100
Inco_100_4_BC2	225	4	2	100
Inco_100_10_BC1	100	10	1	100
Inco_100_10_BC2	100	10	2	100



2D Simulations BC1

<table>
<tr><td>Simulation</td><td>Inco_100x100_BC1_05</td><td>Inco_100x100_BC1_1</td><td>Inco_100x100_BC1_4</td></tr>
<tr><td>T[K]
across SB</td><td></td><td></td><td></td></tr>
<tr><td>T[K]
contours</td><td></td><td></td><td></td></tr>
<tr><td>ASB ?
Crack vel</td><td>Yes
761 m/s</td><td>Yes
351 m/s</td><td>Maybe
98 m/s</td></tr>
</table>

2D Simulations BC1

Simulation	Inco_100x100_BC1_20	Inco_100x100_BC1_200
T[K] across SB		
T[K] contours		
ASB ?	**NO**	**NO**
Crack velocity	68 m/s	N/A

PRELIMINARY RESULTS

MESH SENSITIVITY

Remarks

- Ultrafine 2D mesh allows generation of ASB (with proper Boundary Conditions and Loading Conditions)
  - Element sizes of .0005 mm and .001 mm produce ASBs in In-718
  - Temperatures in the ASB increases suddenly and reaches the brittle temperature of Inconel
  - The shear band propagates extremely fast
  - The width of the ASB in Inconel 718 was shown to be approximately 1 μm

- GOAL is to get an ASB with practical element size
  - We want to see localization of plastic strain and subsequent erosion of elements along a perfectly cylindrical and very narrow band
  - This localization will be in a 1 element wide zone

Analytical Approach for New Capability

- The element size needed for the simulation of an ASB in In-718 is industrially not acceptable with “standard” analysis
- Idea: ‘Thermal Regularization’
  - How ASB work: inside a narrow shear band extreme increase of temperature
  - Thus, we need to bring the temperature up ‘high enough’ in a zone that is 1 or a few elements wide
  - Solution is to make the Taylor Quinney Coefficient (BETA) dependent by mesh size, strain rate and state of stress
- Goal: Reach the same temperature in a zone with an .2 mm element width as would occur within a .0005 mm width ASB
  - 40 times larger element size

Current MAT_224 implementation

- Taylor Quinney Coefficient (TQC) is called BETA (***β***) in MAT_224
- BETA (***β***) is the differential TQC: part of plastic power converted into temperature rise
- As opposed to the integral TQC which would be the part of the total plastic work converted into temperature rise
- Since both are variable, they are not the same
- Using the integral beta is possible in a material law like 224, but we would lose all flexibility wrt Room Temperature being interpreted as the initial temperature of the model
- BETA (***β***) can also be used as an effective value; for when using the mechanical solver only
- The differential BETA implemented in MAT_224 already has many functional dependencies
  - Mesh size dependency is not currently available
- For any given integration point, LS-DYNA will solve this nonlinear equation system:

$$w_p^{n+1} = w_p^n + \left[\frac{\sigma_y^{n+1} + \sigma_y^n}{2}\right]\Delta\varepsilon_p$$

$$\beta_{diff} = g\left(\varepsilon_p^{n+1}, T^{n+1}, \frac{\Delta\varepsilon_p}{\Delta t}, \frac{p}{\sigma_{vm}}\right)$$

$$T^{n+1} = T^n + \beta_{diff}\left[\frac{w_p^{n+1} - w_p^n}{\rho C_p}\right]$$

$$\varepsilon_p^{n+1} = \varepsilon_p^n + \Delta\varepsilon_p$$

$$\sigma_y^{n+1} = f\left(\varepsilon_p^{n+1}, T^{n+1}, \frac{\Delta\varepsilon_p}{\Delta t}\right)$$

$$\sigma_{vm}^{n+1} = \sigma_y^{n+1}$$

$$\sigma_{vm}^{n+1} = \sigma_{vm}^e - 3G\Delta\varepsilon_p$$

Enhanced MAT_224 ASB Implementation

- Identify regions of high plastic strain rate
- Identify regions with high plastic shear deformation
  - The metric used is the maximum plastic shear strain, γ
- In these regions, make the differential BETA dependent upon the mesh size
  - Increase BETA sufficiently to allow ASB to occur in practical sized, coarse meshes
  - Some BETA values will be greater than 1.0
- We use the initial mesh size l_0, for the regularization, consistently with other regularization models in MAT_224
- Note that this method is NOT adding energy into the system
- Rather it can be interpreted as locally decreasing the specific heat of the material thus allowing a small amount of plastic work per volume to generate important increases in temperature

$$w_p^{n+1} = w_p^n + \left[\frac{\sigma_y^{n+1} + \sigma_y^n}{2}\right]\Delta\varepsilon_p$$

$$\beta_{diff} = g\left(\gamma_p^{n+1}, \frac{\Delta\varepsilon_p}{\Delta t}, l_0\right)$$

$$T^{n+1} = T^n + \beta_{diff}\left[\frac{w_p^{n+1} - w_p^n}{\rho C_p}\right]$$

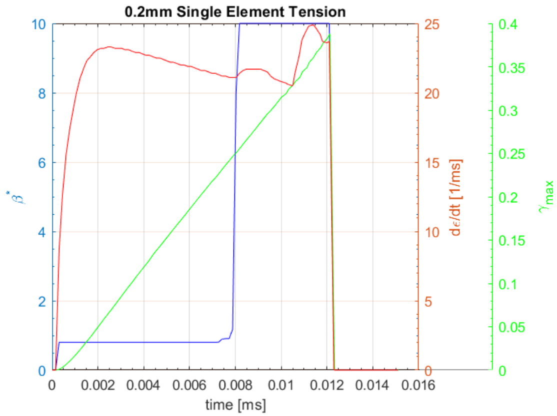
$$\varepsilon_p^{n+1} = \varepsilon_p^n + \Delta\varepsilon_p$$

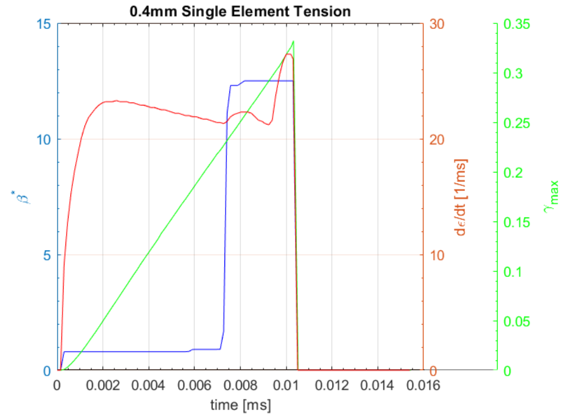
$$\sigma_y^{n+1} = f\left(\varepsilon_p^{n+1}, T^{n+1}, \frac{\Delta\varepsilon_p}{\Delta t}\right)$$

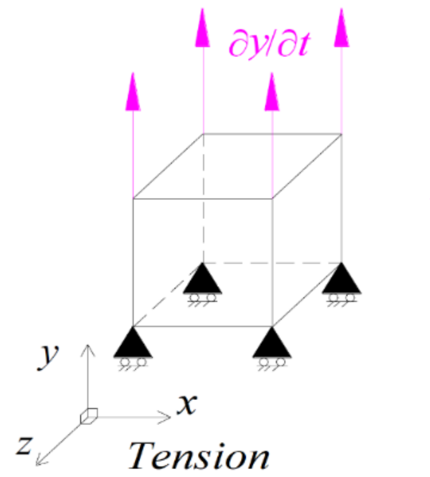
$$\sigma_{vm}^{n+1} = \sigma_y^{n+1}$$

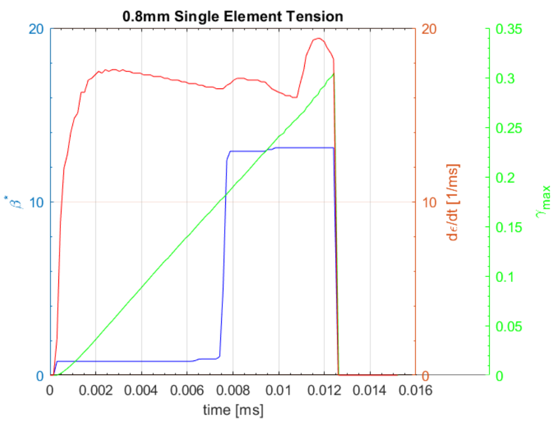
$$\sigma_{vm}^{n+1} = \sigma_{vm}^e - 3G\Delta\varepsilon_p$$

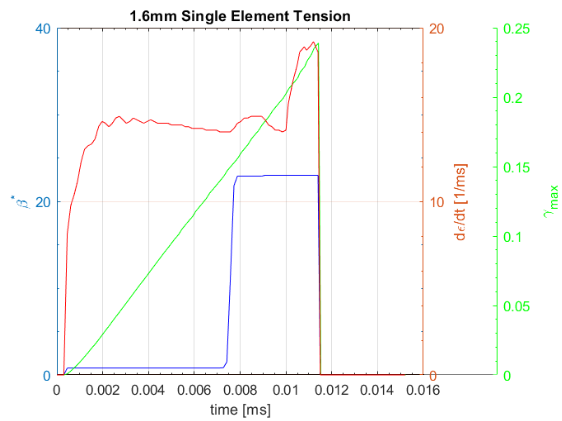
Single Element Verification





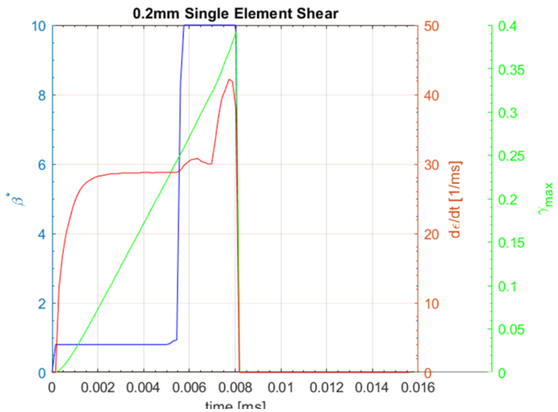


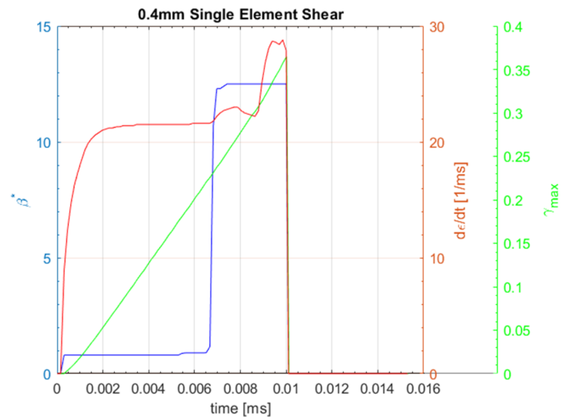


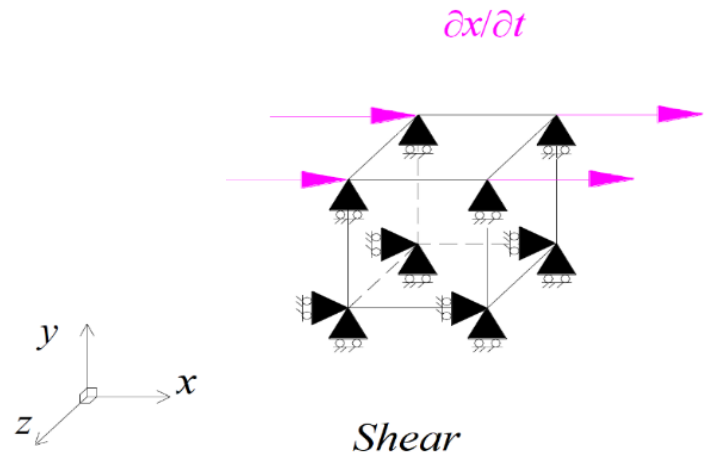


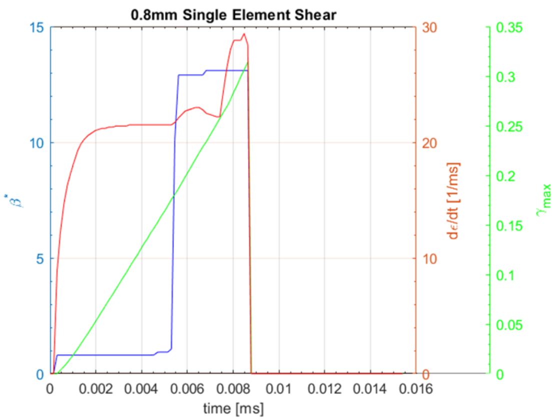
Mesh [mm]	γ_{max}	$\dot{\varepsilon}_p[s^{-1}]$	β^*_{max}
0.2	0.25	8000	10
0.4	0.23	8000	12.5
0.8	0.18	8000	13
1.6	0.15	8000	23

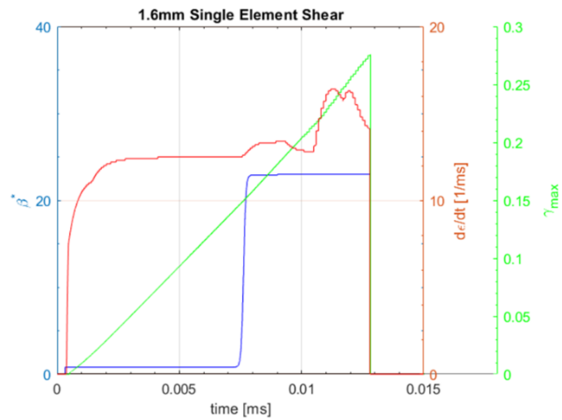
Single Element Verification











Mesh [mm]	γ_{max}	$\dot{\varepsilon}_p[s^{-1}]$	β^*_{max}
0.2	0.25	8000	10
0.4	0.23	8000	12.5
0.8	0.18	8000	13
1.6	0.15	8000	23

2D Verification Inco_100x100_BC1_200

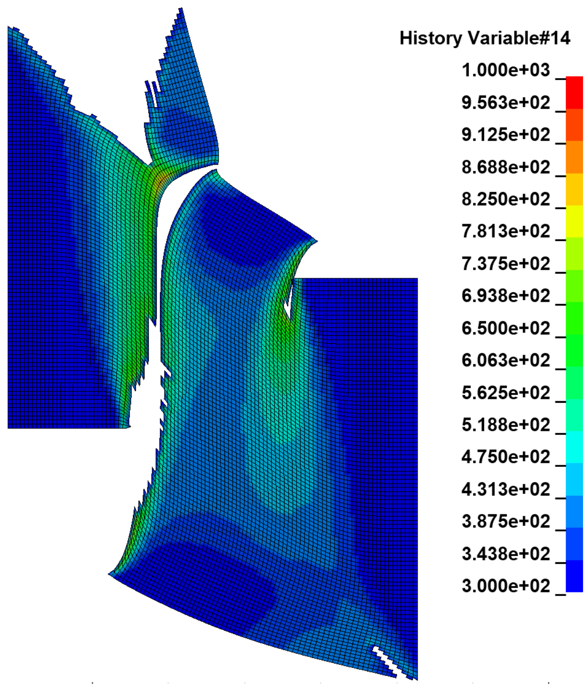
Simulation

T[K] contours

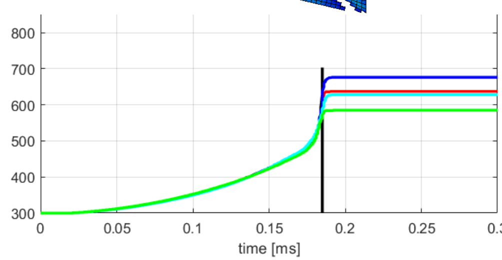
T[K] across SB

ASB ?
Crack velocity

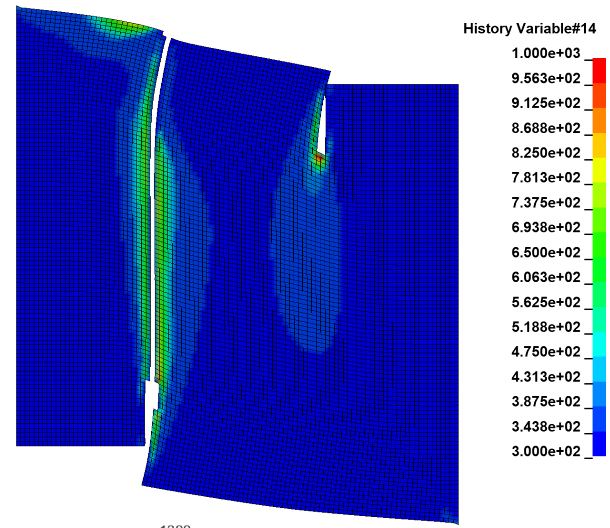
ORIGINAL *MAT_224



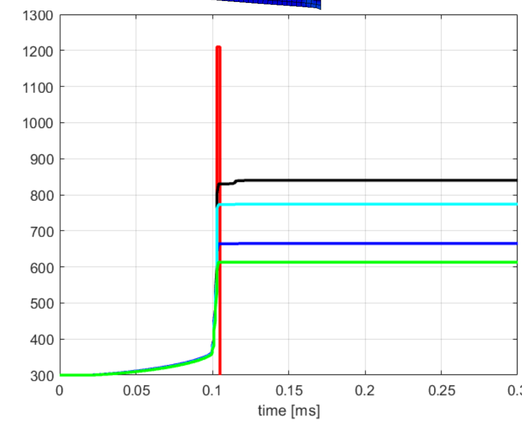
No
N/A



MODIFIED *MAT_224



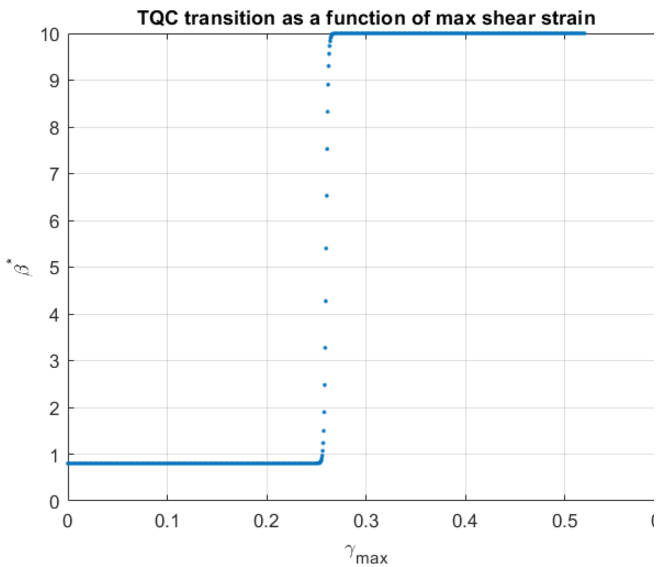
YES!
404 m/s

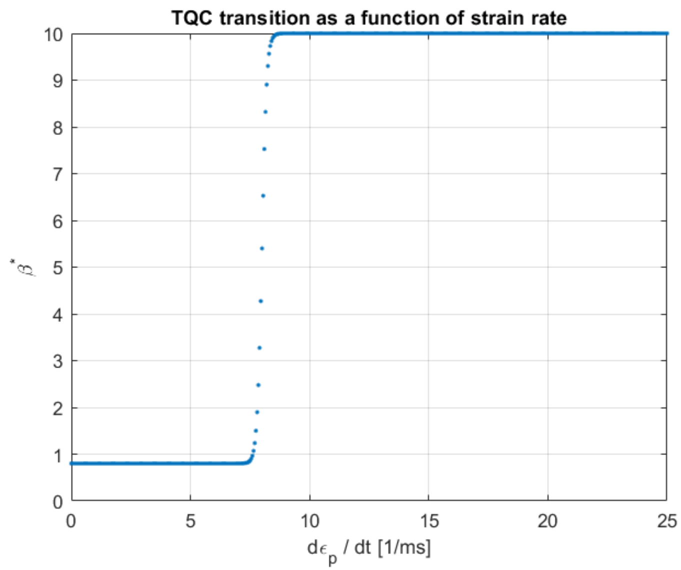


Ballistic Impacts Validation

Tabulated TQC generation

MESH [mm]	Tabulated input	γ_{max} @ transition	$\dot{\varepsilon}_p$ @ transition [1/s]	β^*_{min}	β^*_{max}
0.2	$\beta^*_{TAB,02}$	0.26	8000	0.8	10





ASBs were found to occur when the shear strain is greater than 26%, and the strain is greater than 8000 1/sec for .2 mm element size

The Tabulated TQC was developed using a hyperbolic tangent function for the transition between $\boldsymbol{\beta^*_{min}}$ outside the ASB and $\boldsymbol{\beta^*_{max}}$ in the ASB

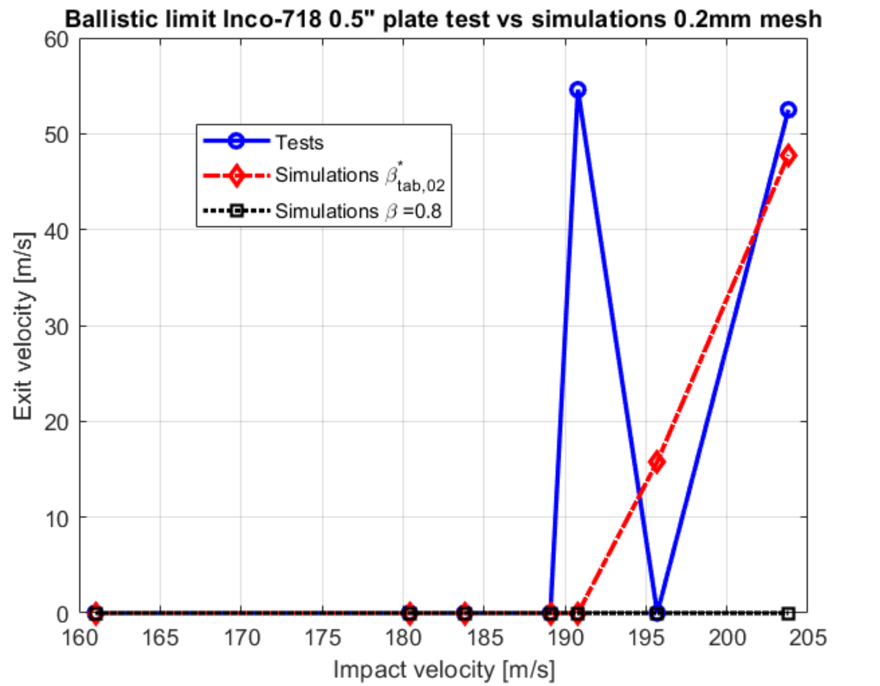
Ballistic Impacts Validation with 0.2 mm Mesh

Test	DB266		DB267		DB268		DB269		DB270		DB271		DB272	
Impact/exit velocity [m/s]	203.8/52.5		161.0/0		190.8/54.6		180.4/0		183.8/0		189.1/0		195.7/0	
TQC	β	$\beta^*_{TAB,0.2}$	β	$\beta^*_{TAB,0.2}$	β	$\beta^*_{TAB,0.2}$	β	$\beta^*_{TAB,0.2}$	β	$\beta^*_{TAB,0.2}$	β	$\beta^*_{TAB,0.2}$	β	$\beta^*_{TAB,0.2}$
Simulation Exit velocity	0	47.8	0	0	0	(0) Full plug	0	0	0	0	0	0	0	15.8

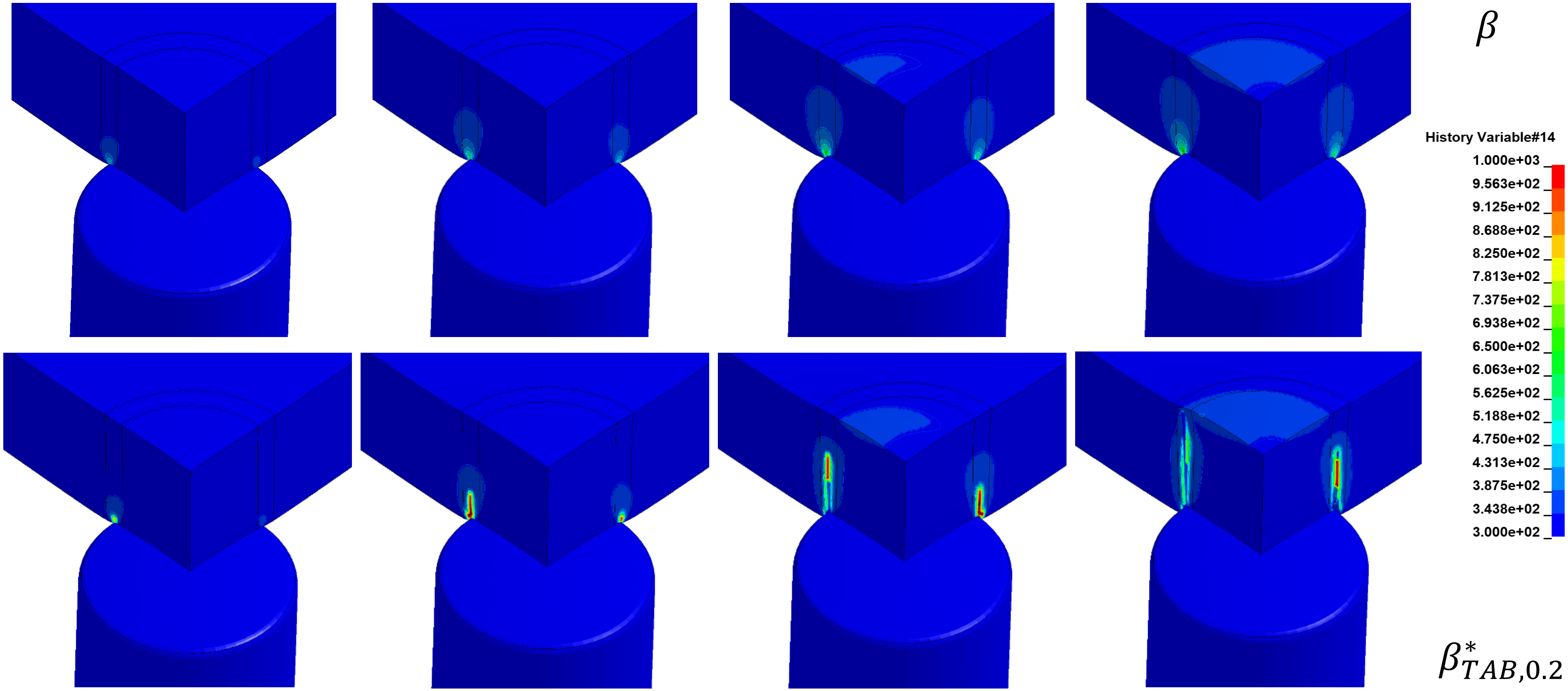
All the ballistic tests performed by NASA were simulated with the enhanced and original material law using a 0.2 mm mesh

The modified material law with tabulated beta gives a good match of exit velocities for ballistic tests close to the ballistic limit

The original material law with constant beta value (BETA = 0.8) incorrectly always predicted an exit velocity = 0.0 (No penetration), which is the original problem!



Ballistic Impacts Validation DB266



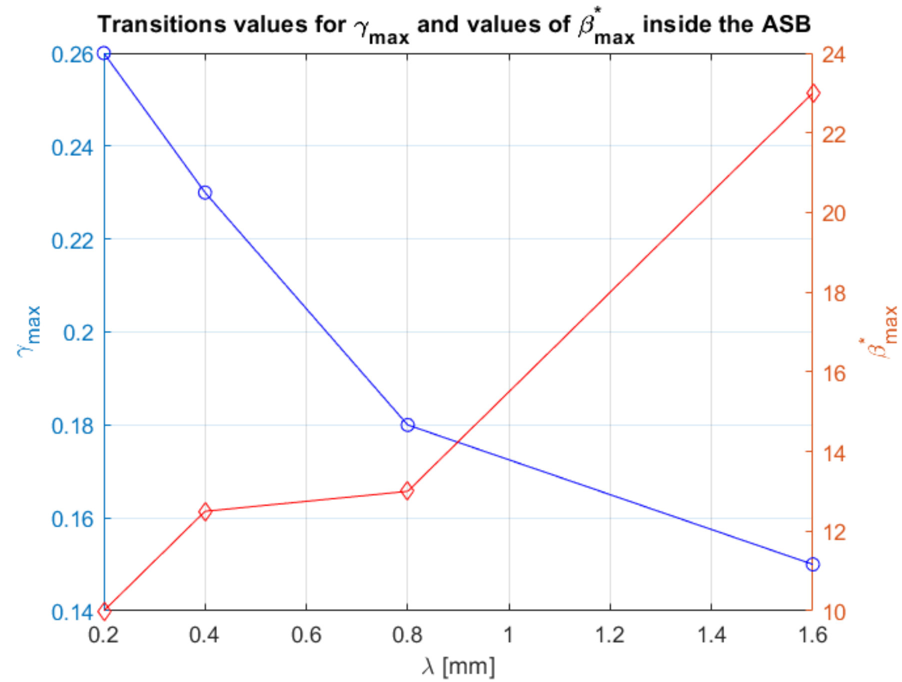
Time 0.015ms **Time 0.02ms** **Time 0.025ms** **Time 0.03ms**

The overall average speed of crack propagation through the thickness was about 1200 m/s.
The propagation speed in the ASB itself is about 4000 m/s.

Regularization with Multiple Mesh Sizes

Mesh [mm]	γ_{max}	$\dot{\varepsilon}_p$[1/s]	β^*_{max}
0.2	0.26	8000	10
0.4	0.23	8000	12.5
0.8	0.18	8000	13
1.6	0.15	8000	23

Test		DB266	DB268	DB272
Impact velocity [m/s]		203	191	189
Exit velocity [m/s]		52	54	0
Mesh [mm]	TQC name	Simulation exit velocity [m/s]		
0.2	$\beta^*_{TAB,0.2}$	47.8	Full plug	0
0.4	$\beta^*_{TAB,0.4}$	47.8	Full plug	0
0.8	$\beta^*_{TAB,0.8}$	52.0	Full plug	0
1.6	$\beta^*_{TAB,1.6}$	51.5	partial plug	0

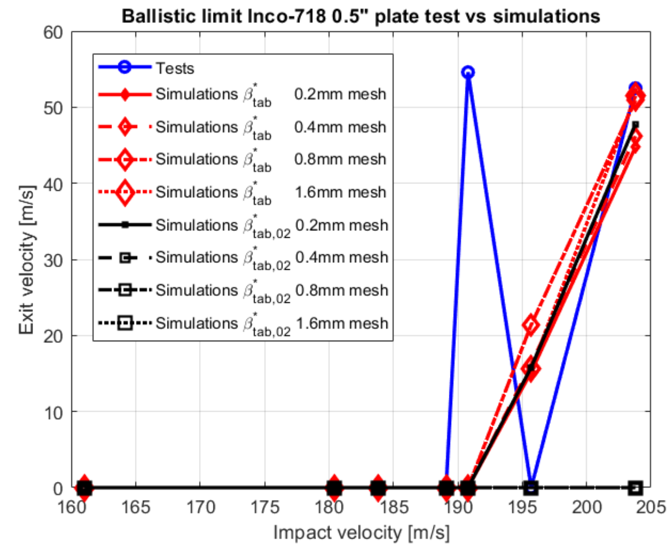


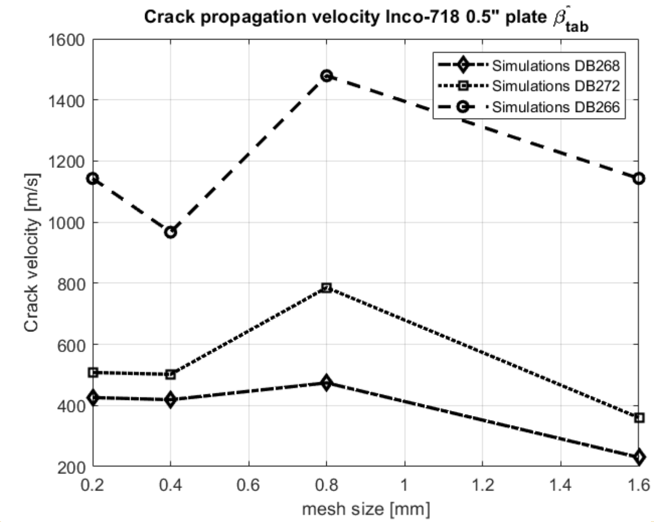
The regularized Tabulated TQC was developed on 3 tests. For each mesh a tabulated TQC was created, the various tabulated TQC were then merged in $\boldsymbol{\beta^*_{TAB}}$

Validation of Final Regularization Table

Test simulation	DB268		DB272		DB266	
Impact/exit velocity [m/s]	190.8/54.6		195.7/0		203.8/52.5	
Mesh [mm]	$\beta^*_{TAB,0.2}$	β^*_{TAB}	$\beta^*_{TAB,0.2}$	β^*_{TAB}	$\beta^*_{TAB,0.2}$	β^*_{TAB}
0.2	(0) Full plug	(0) Full plug	15.8	15.2	47.8	44.8
0.4	0	(0) Full plug	0	16.2	(0) Partial plug	46.2
0.8	0	(0) Full plug	0	21.4	0	50.9
1.6	0	(0) Partial plug	0	15.6	0	51.5

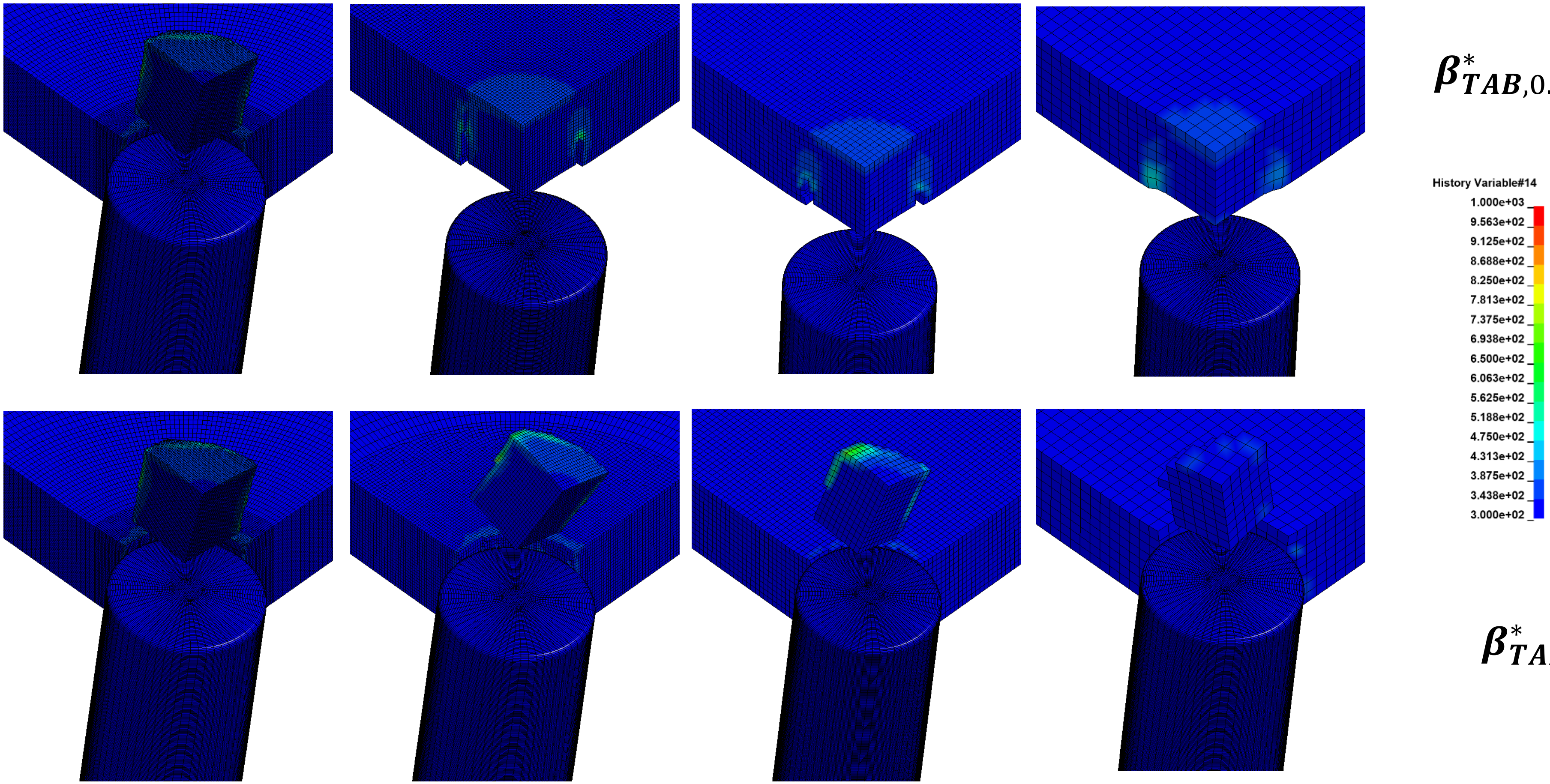
Test simulation (β^*_{TAB})	DB268		DB272	DB266	
Impact/exit velocity [m/s]	190.8/54.6		195.7/0	203.8/52.5	
Mesh [mm]	Crack [m/s]	ASB [m/s]	Crack [m/s]	Crack [m/s]	ASB [m/s]
0.2	426	2717	508	1143	3299
0.4	419	1128	502	967	2095
0.8	474		786	1479	
1.6	230		360	1143	





Ballistic Impacts Validation DB272

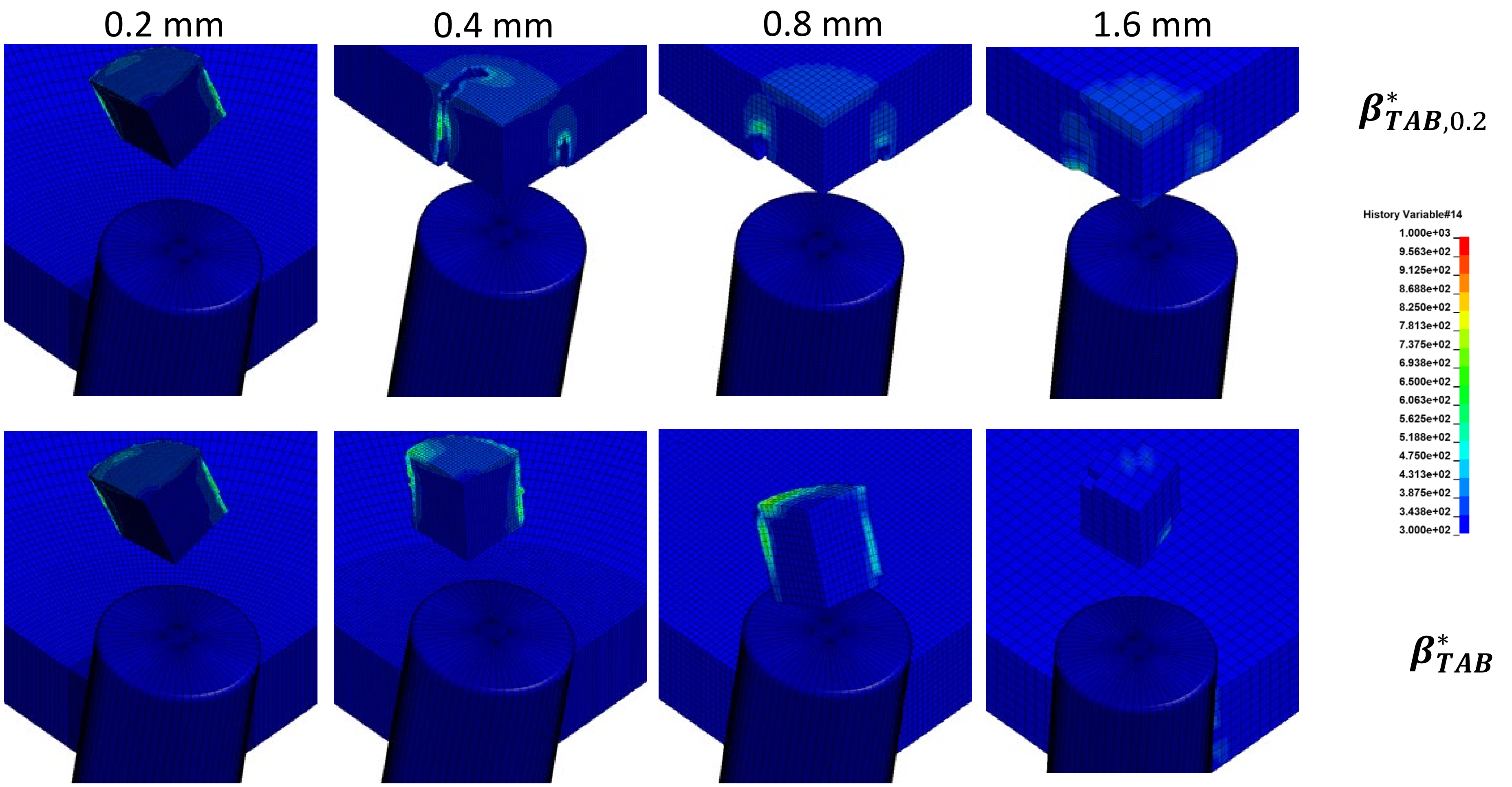
0.2 mm | 0.4 mm | 0.8 mm | 1.6 mm



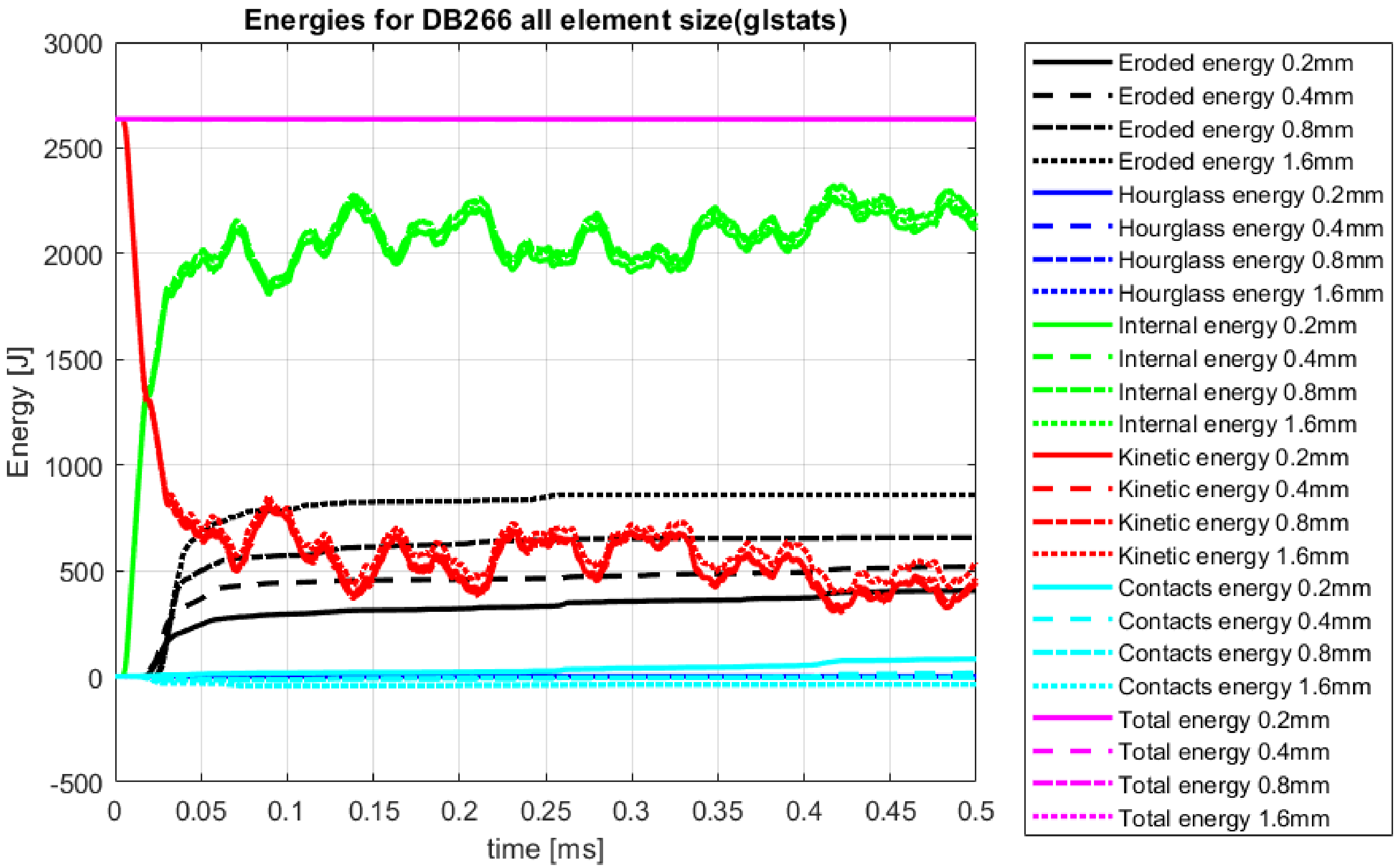
$\boldsymbol{\beta}^*_{TAB,0.2}$

$\boldsymbol{\beta}^*_{TAB}$

Ballistic Impacts Validation DB266



Ballistic Impacts Validation Energies DB266

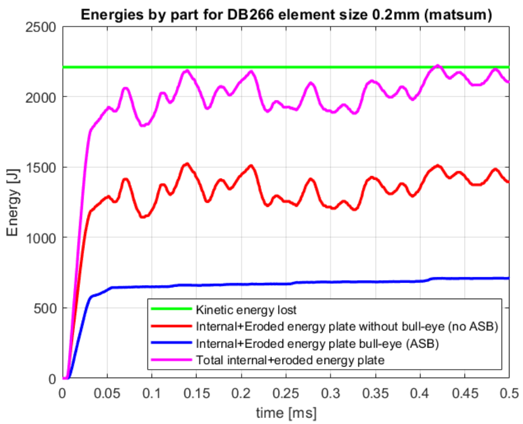


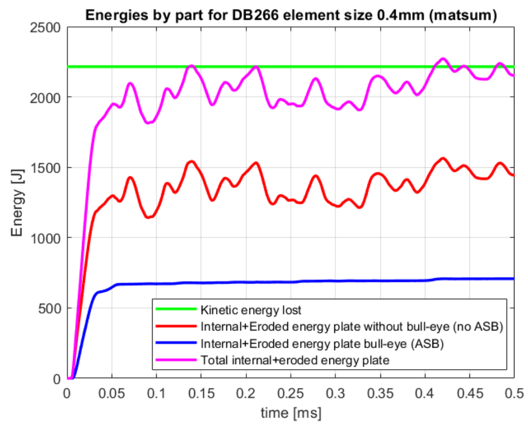
The simulations seem reliable:

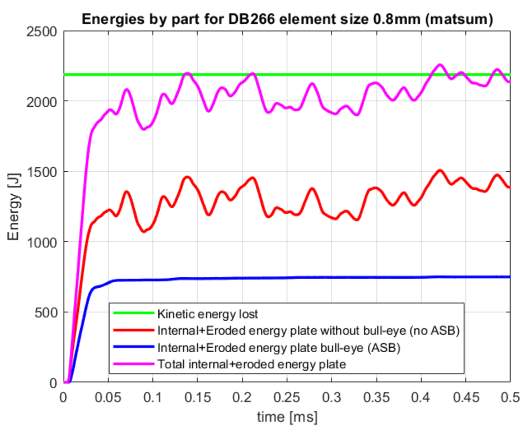
- Constant total energy
- No hourglass
- Reasonable contact energy
- Good match to the tests

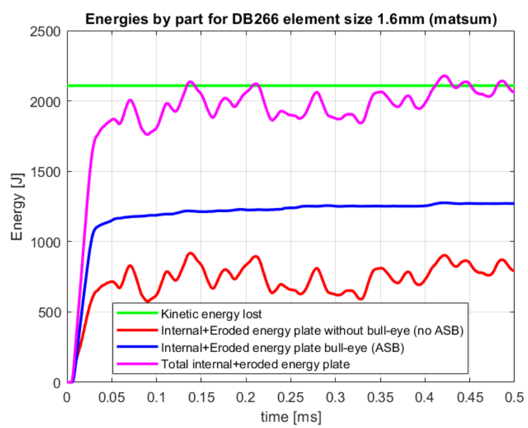
Eroded energy increases with the mesh size which is expected

Ballistic Impacts Validation Energies DB266









Common assumption:
Total energy ASB = kinetic energy lost projectile - kinetic energy plug

We found that is not true:
Not all the kinetic energy of the projectile goes in the ASB.

Plate part outside ASB absorbed 2/3 of the energy.

Eroded energy increases with the mesh size which is expected

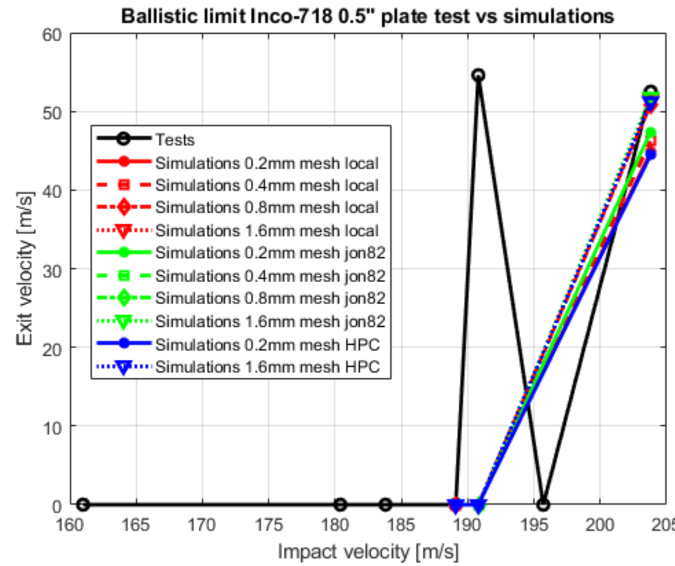
Ballistic Impact Validation and Regularization

CONCLUSIONS

- This research was the subject of Stefano Dolci's PhD dissertation: https://www.proquest.com/docview/2573003826/fulltextPDF/A2557B05375F44B4PQ/1?accountid=14541
- The enhanced MAT_224 material model creates an accurate prediction of the impact physics and the ballistic limit
  - For the higher impact velocities, the temperature inside the ASB reached values where the Inconel becomes brittle
  - The width of the ASB was ~1 element
- With the tabulated regularized TQC (BETA), the enhanced MAT_224 maintains its predictive capability across element sizes ranging from 0.2mm to 1.6 mm
  - This corresponds to 200 times and 1600 times the ASB width!
  - Crack propagation speed across various meshes is fairly consistent for all simulations
  - Temperature reached in the ASB goes above 1200K in all test simulations with plugs
  - BETA was raised to values between 10 and 23, dependent on mesh size
- Not all the kinetic energy of the projectile goes into the ASB
  - The part of the plate not subjected to the ASB deformation absorbed most of the impact energy

DEV-86797

- The enhanced material model was implemented in FORTRAN and developed in a local LS-DYNA environment; it was later included in LS-DYNA's development versions after (DEV-86797)
- The DEV version was tested on different machines and compared to the local version to check for reliability



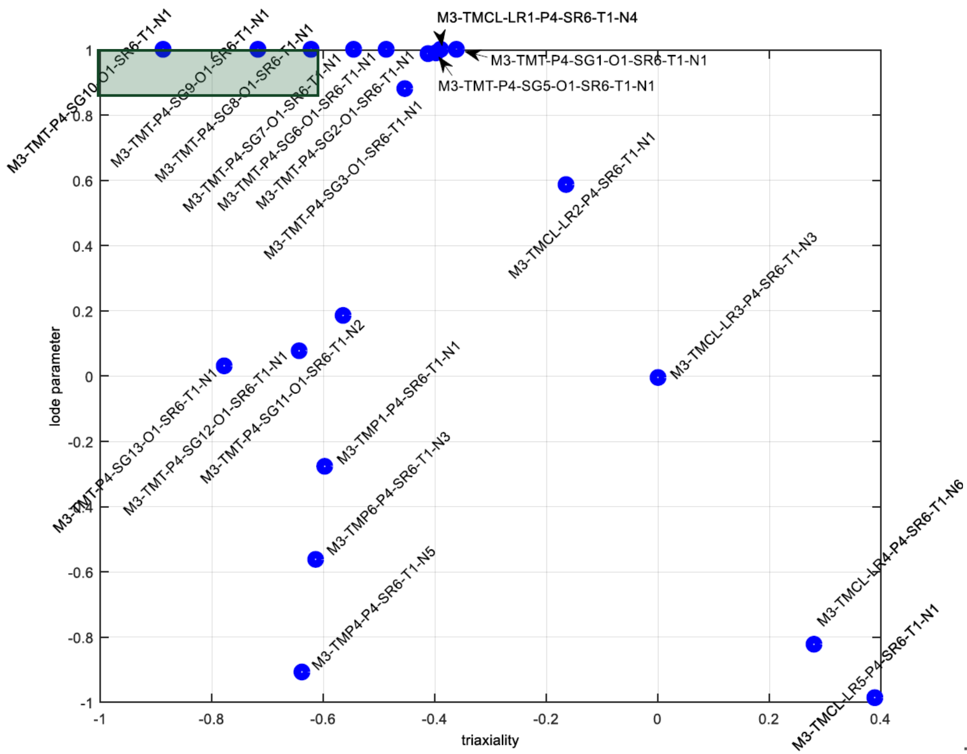
Test/ simulation	DB266			DB268			DB271		
Impact/exit vel.	203.8/52.5 [m/s] Highest vel.			190.8/54.6 [m/s] Ballistic limit.			189.1/0 [m/s] Highest vel. No penetration		
Mesh [mm]	Local CCSA jon	DEV FAA-HPC	DEV CCSA-jon82	Local CCSA jon	DEV FAA-HPC	DEV CCSA-jon82	Local CCSA jon	DEV FAA-HPC	DEV CCSA-jon82
0.2	44.8	44.5	47.4	0(full plug)	0(full plug)	0(full plug)	0	0	0 (1/4 plug)
0.4	46.2			0(full plug)		0(full plug)	0 (<1/4 plug)		
0.8	50.9			0(full plug)		0(full plug)	0		
1.6	51.5	51.2	51.8	0(¾ plug)	0(¾ plug)	0(¾ plug)	0	0	0

Material set In-718 SI1 V1.0

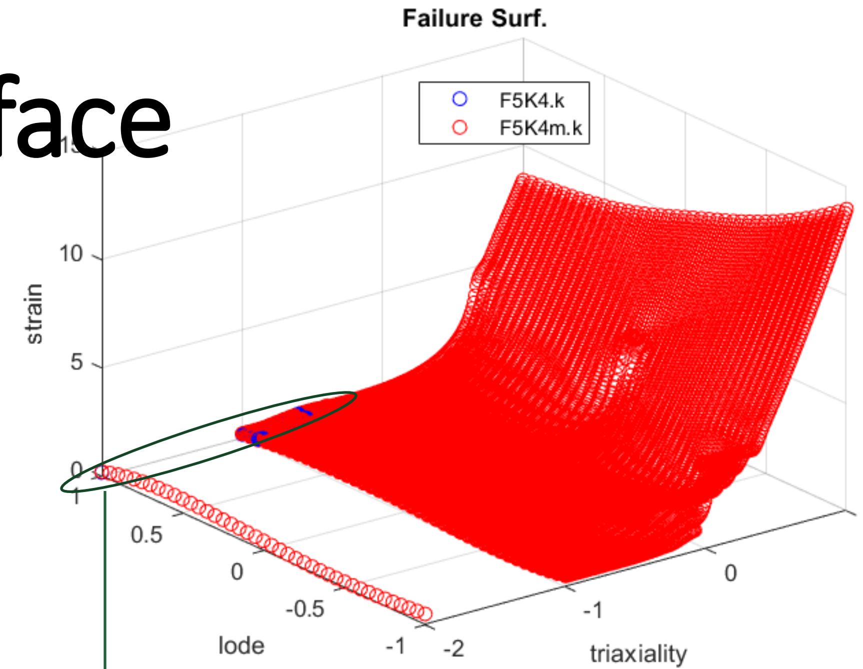
- End to end check using simulations of all mechanical and validation tests were conducted using this development version and presented in the next slides:
  - The Failure Surface was updated
  - All the mechanical failure test re-simulated
  - The Strain Rate regularization curve was re-analysed
  - The Ballistic limit simulation were repeated
- WARNING: THE ASB FEATURE WORKS ONLY WITH DEV-86797 or later development versions:
  - bflg needs to be set =1, beta needs to be a negative ID 3D table in order to activate ASB

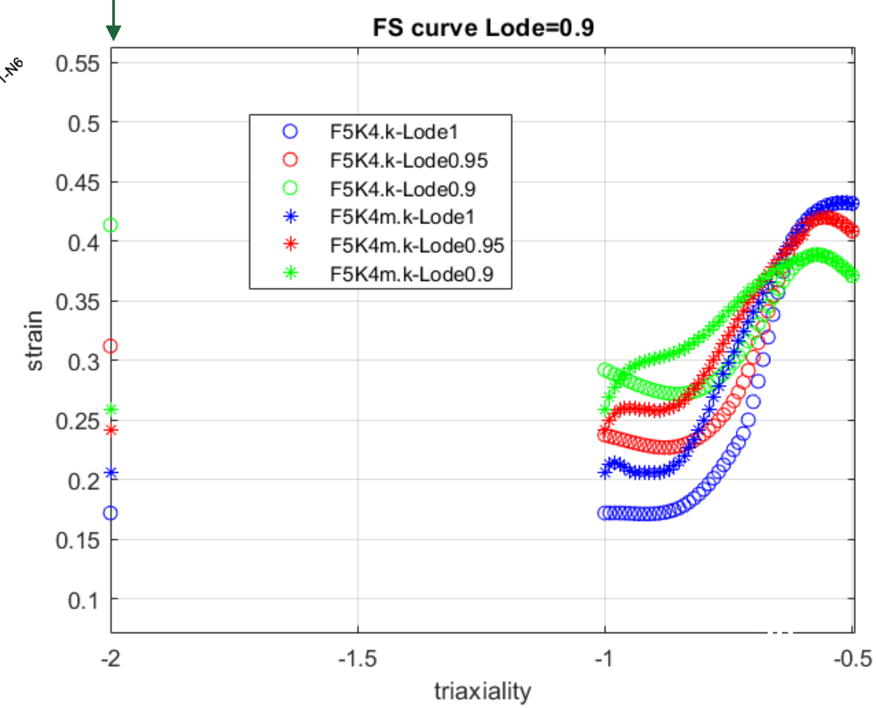
```
*MAT_TABULATED_JOHNSON_COOK_TITLE
MAT_224_Inco718_ASB
$      mid        ro         e        pr        cp        tr      beta    numint
       100  8.190E-6     210.0      0.29     435.0     300.0     -6701       1.0
$     lck1      lckt       lcf       lcg       lch       lci      bflg
         1         2       500       600       700       900         1
```

Updated Failure Surface

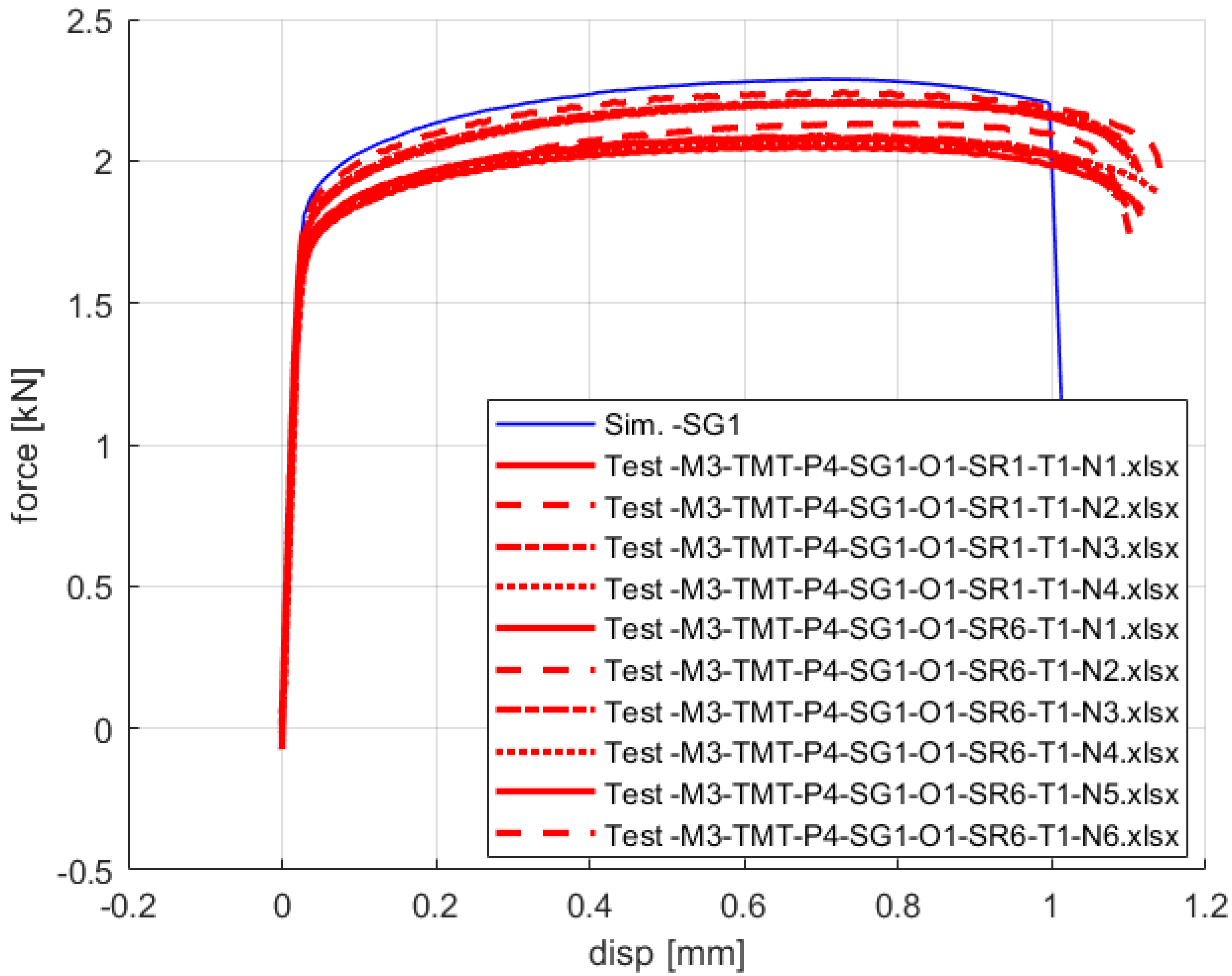


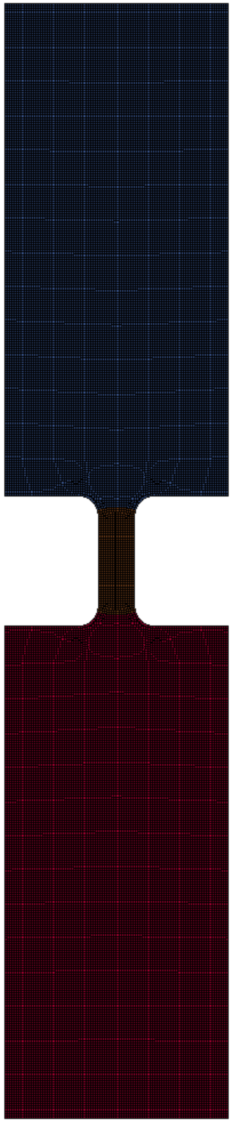
Modified Region



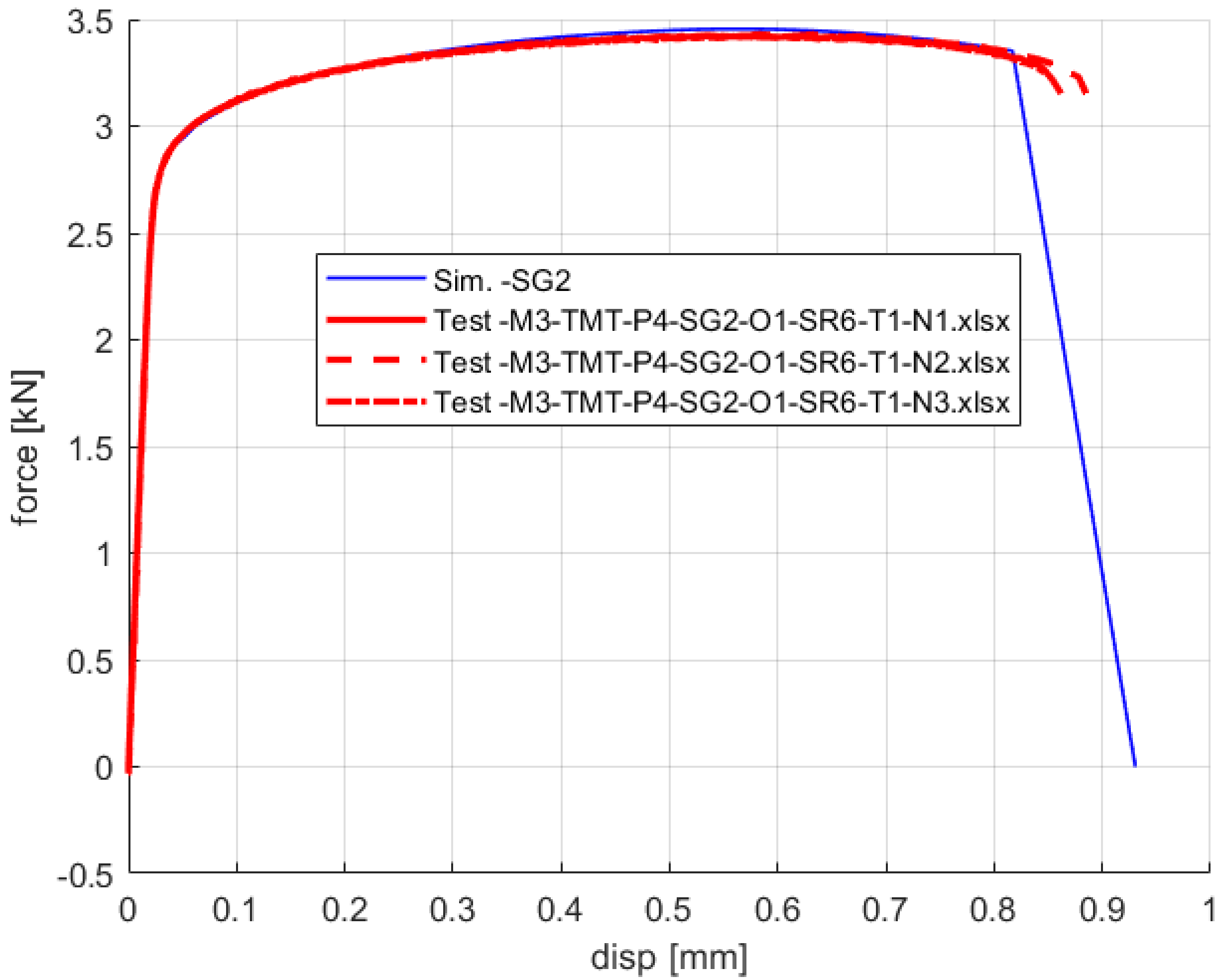


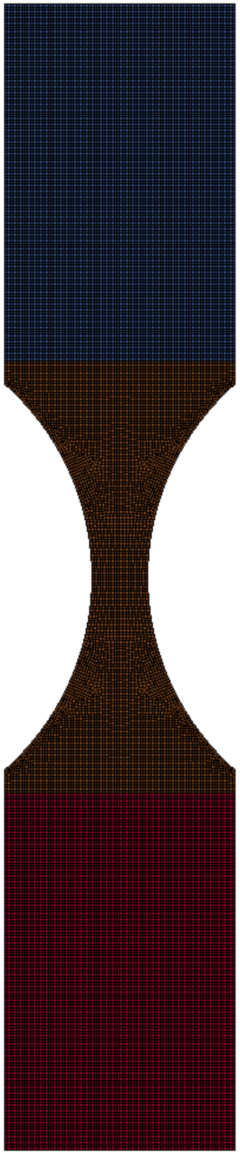
SG1 (triax = -0.36, lode = 0.99)



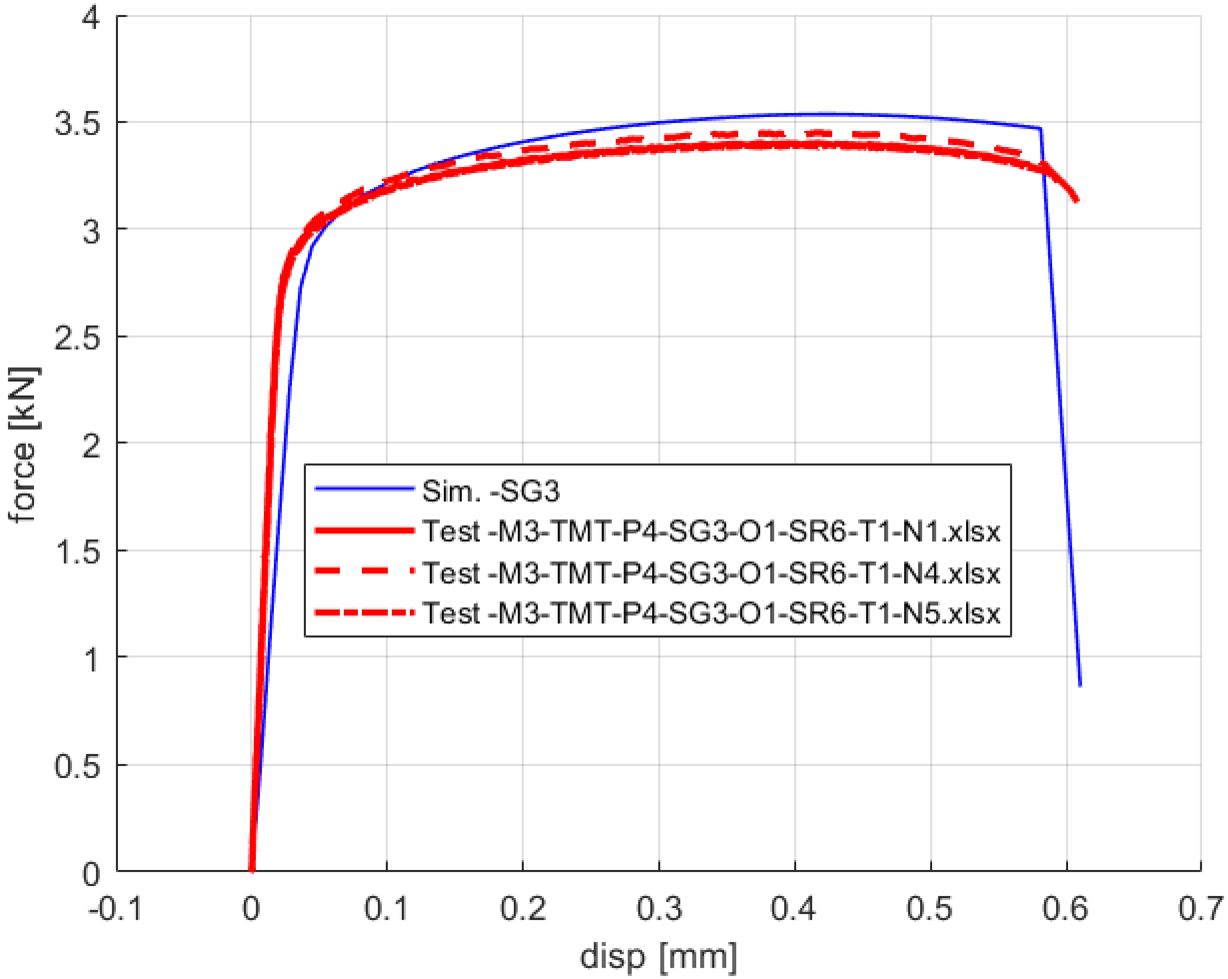


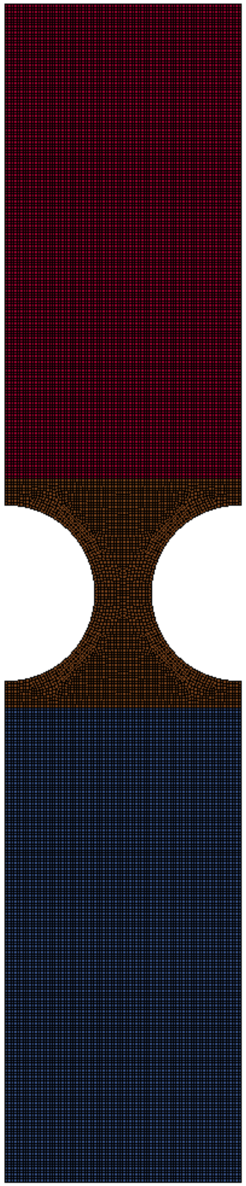
SG2 (triax = -0.41, lode = 0.98)



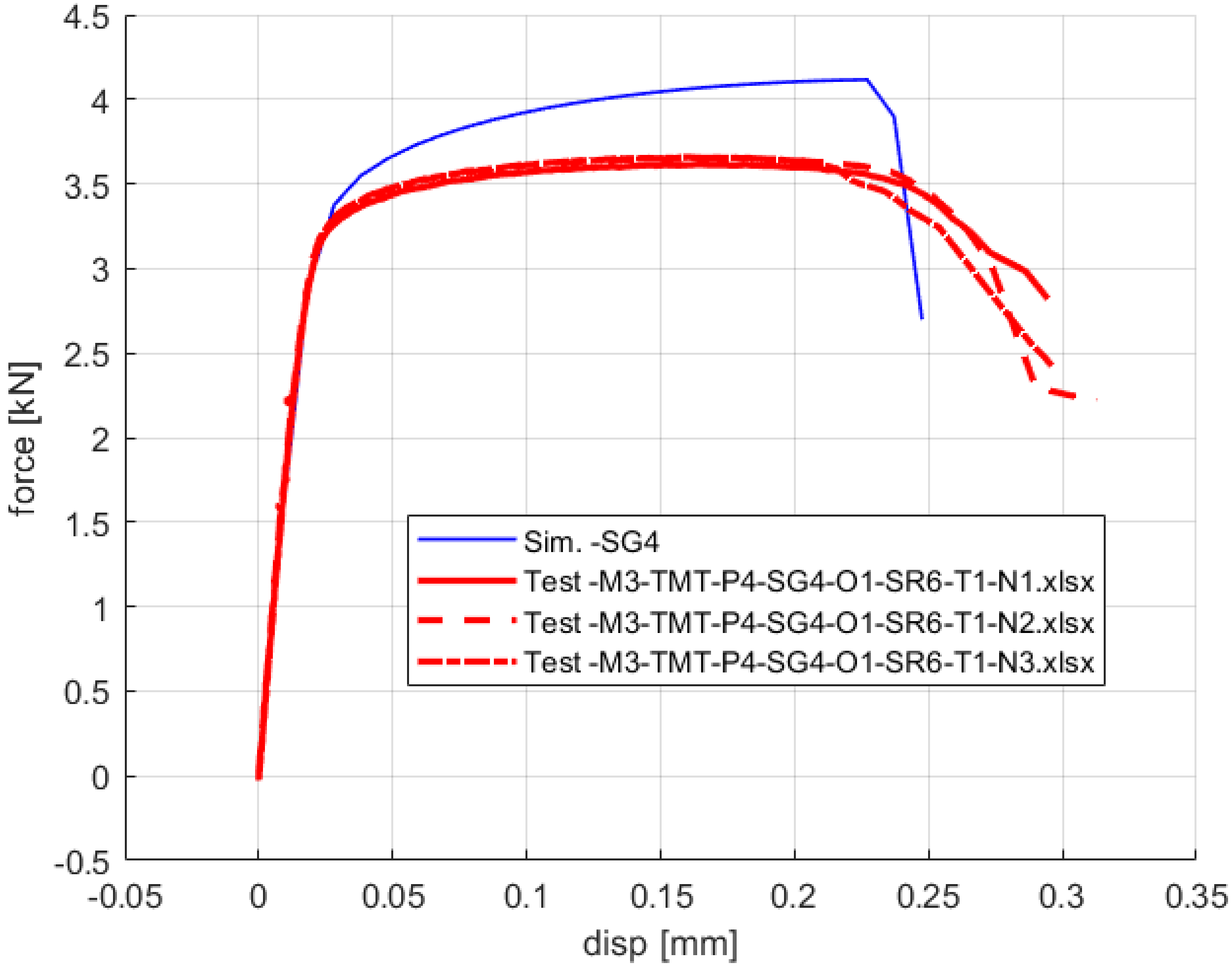


SG3 (triax = -0.45, lode = 0.87)

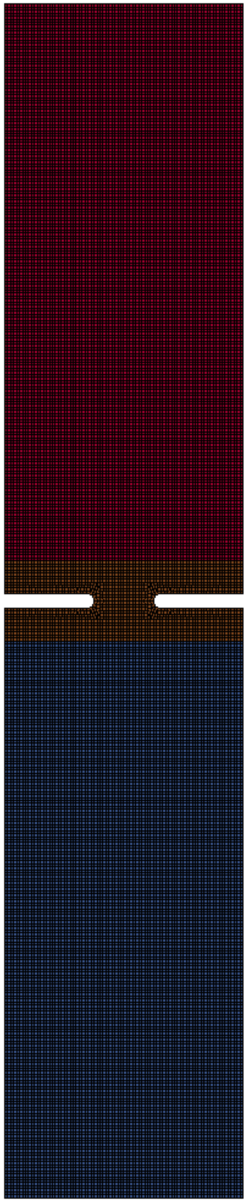




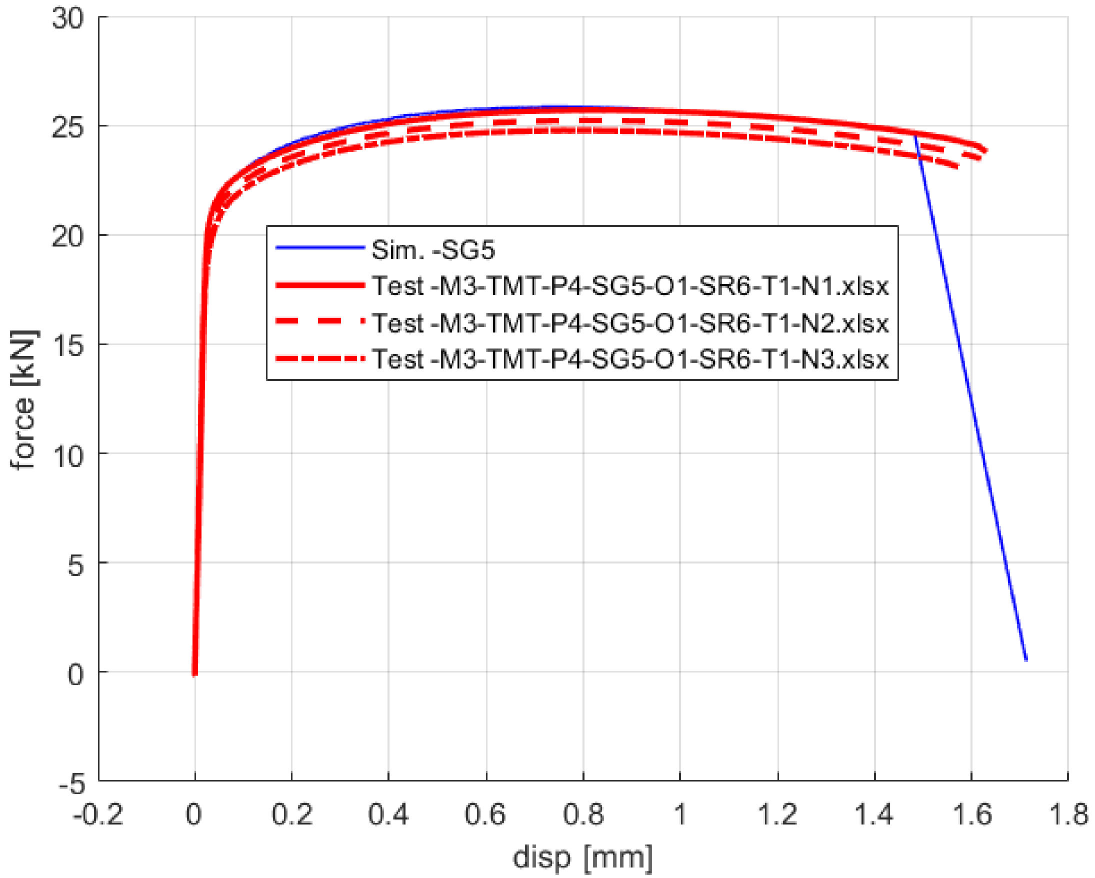
SG4 (N/A)

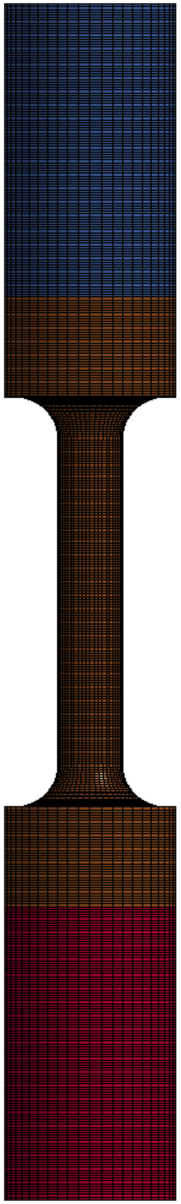


4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
force [kN]
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
disp [mm]
Sim. -SG4
Test -M3-TMT-P4-SG4-O1-SR6-T1-N1.xlsx
Test -M3-TMT-P4-SG4-O1-SR6-T1-N2.xlsx
Test -M3-TMT-P4-SG4-O1-SR6-T1-N3.xlsx

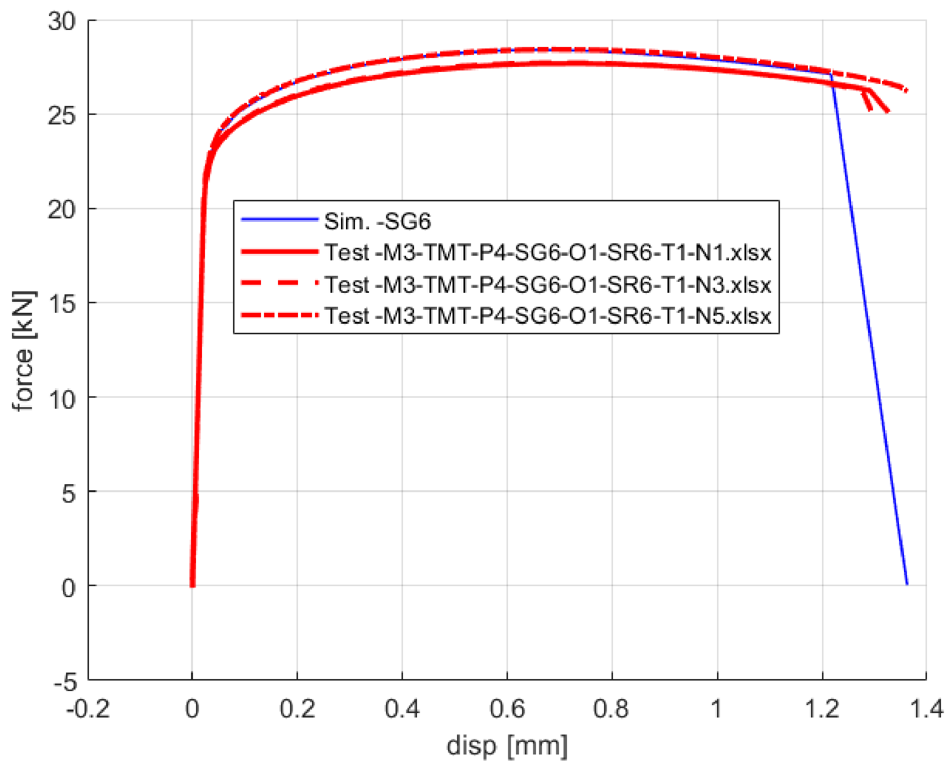


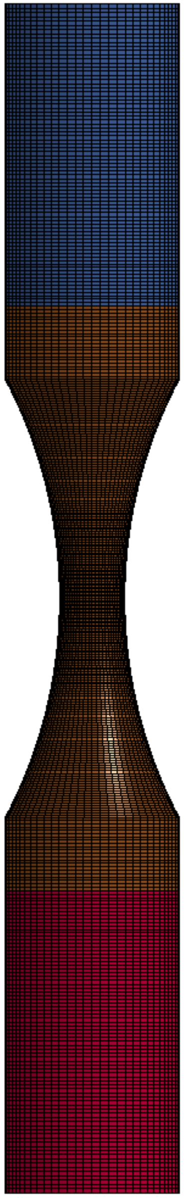
SG5 (triax = -0.38, lode = 1.00)



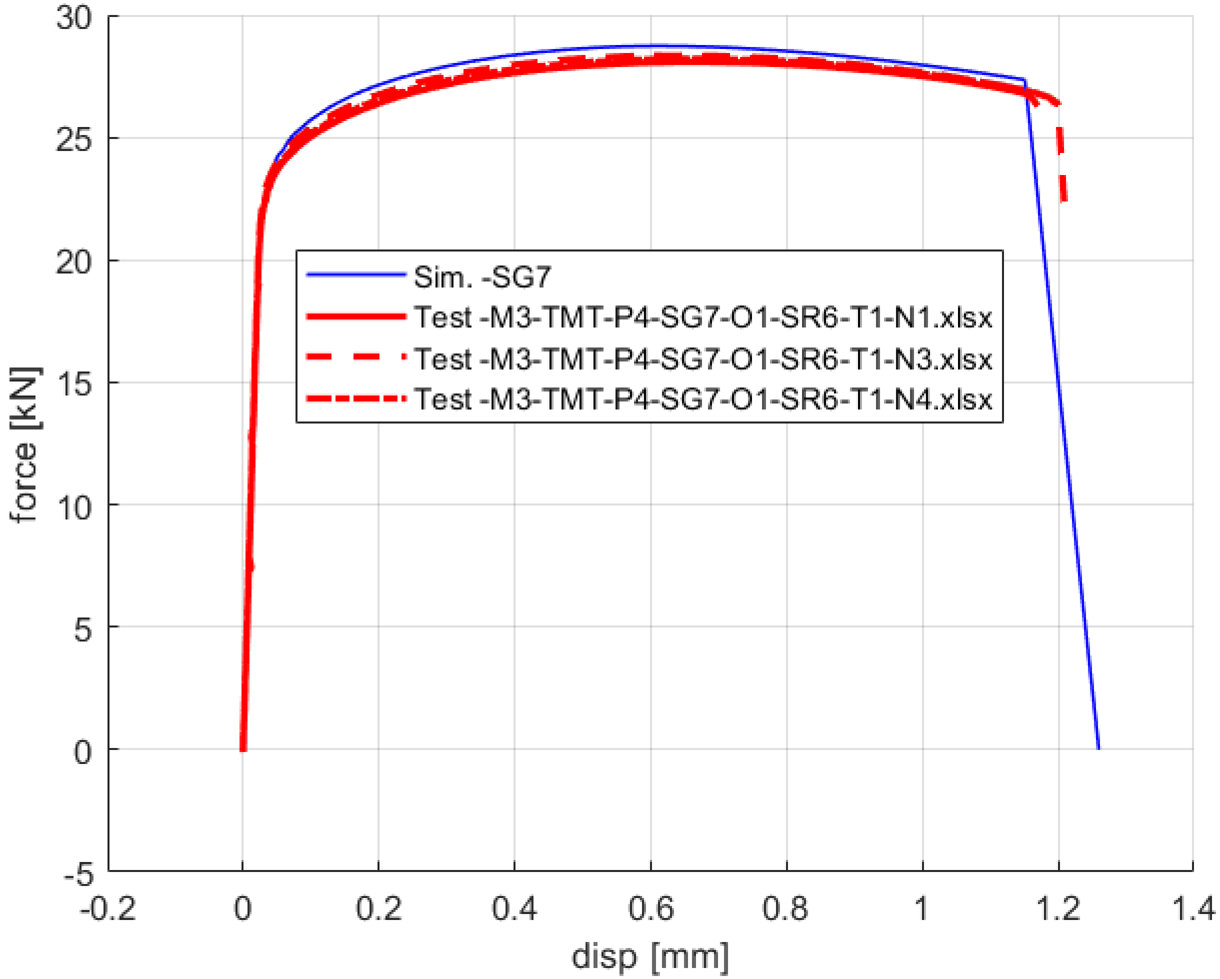


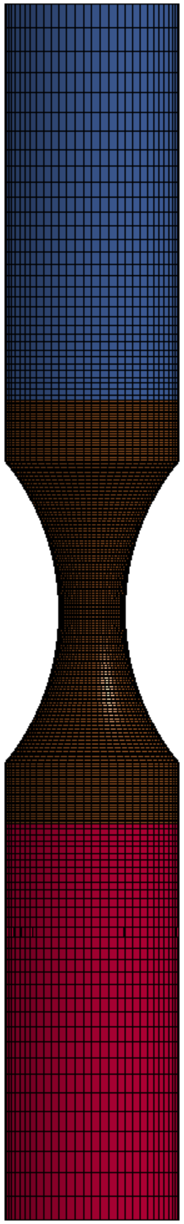
SG6 (triax = -0.48, lode = 1.00)



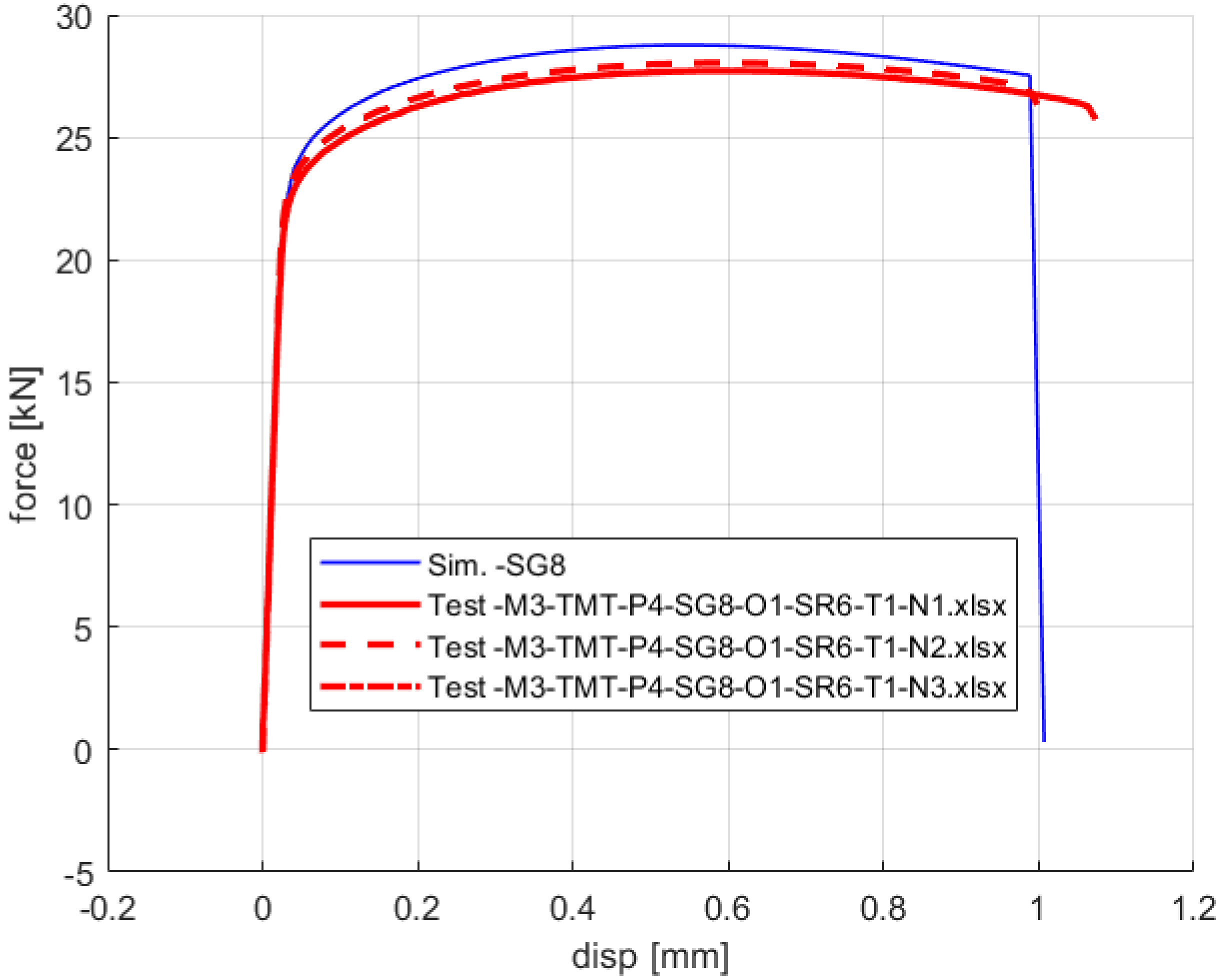


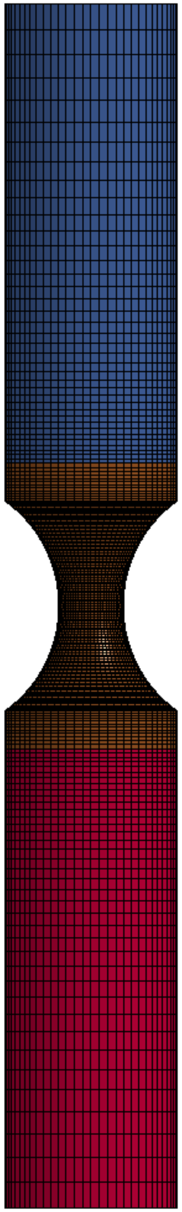
SG7 (triax = -0.54, lode = 0.99)



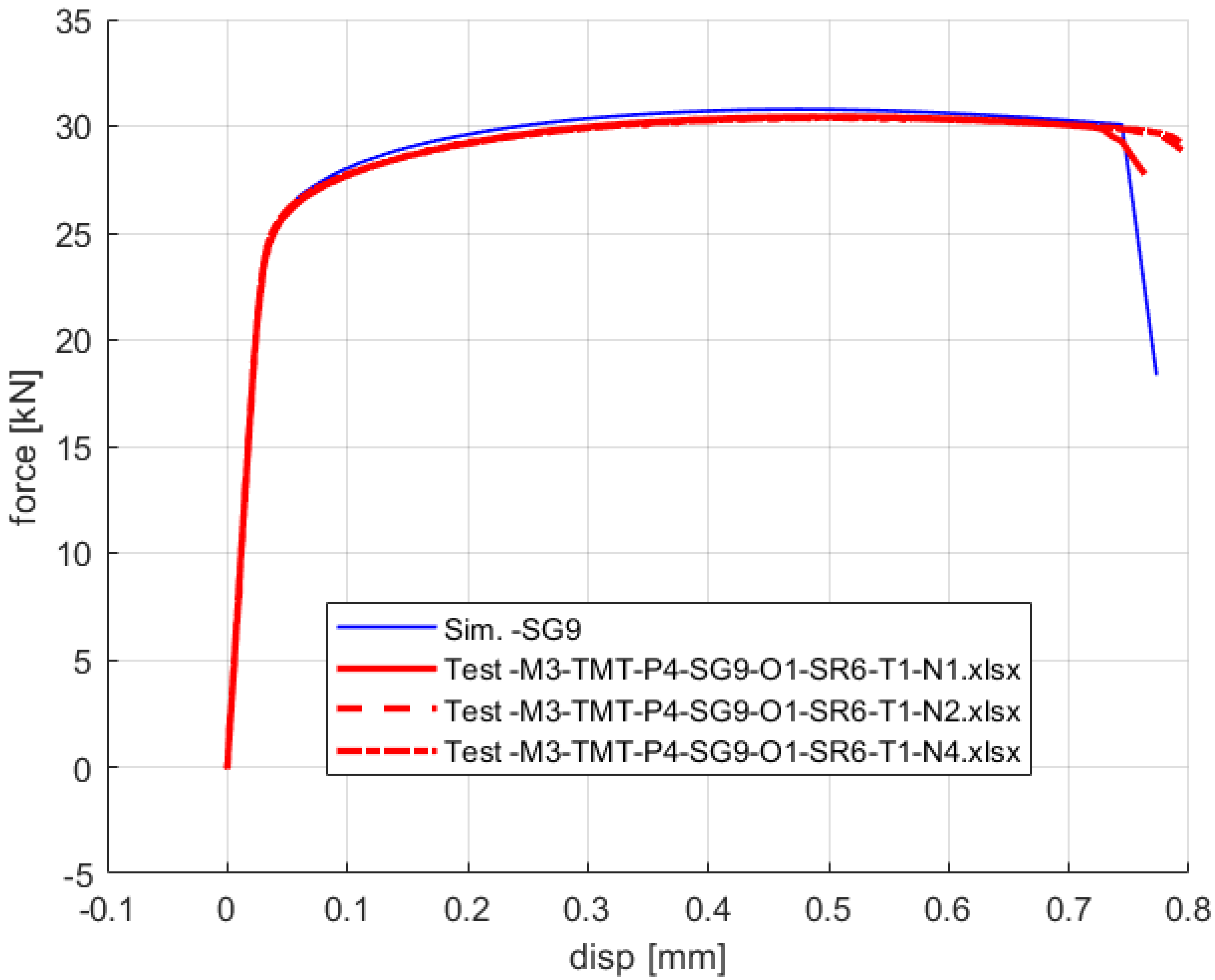


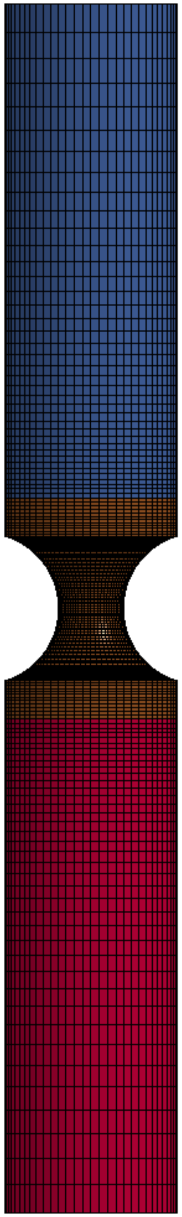
SG8 (triax = -0.62, lode = 0.99)



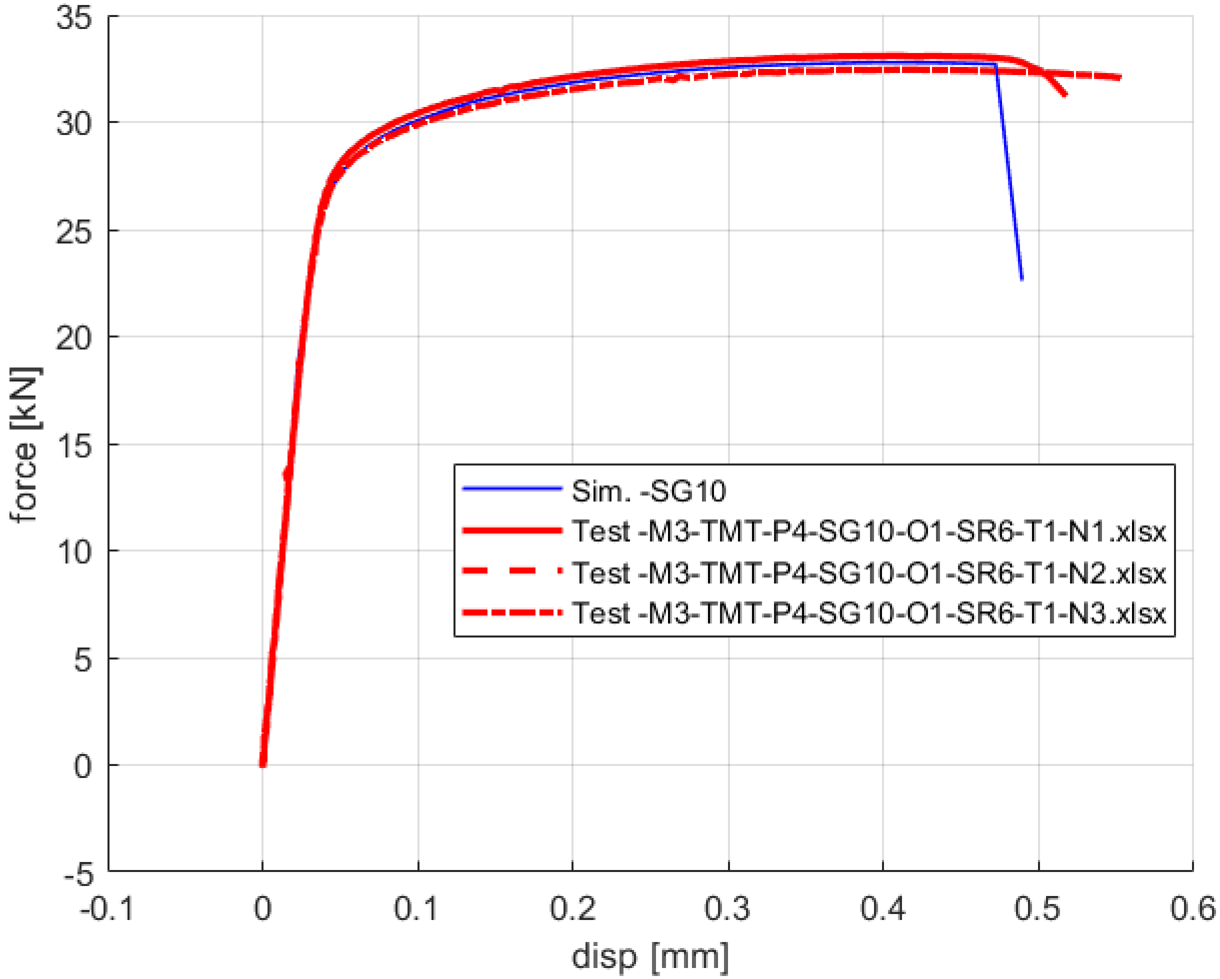


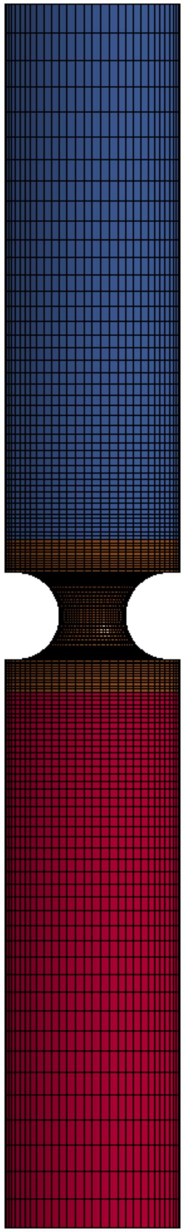
SG9 (triax = -0.71, lode = 0.99)



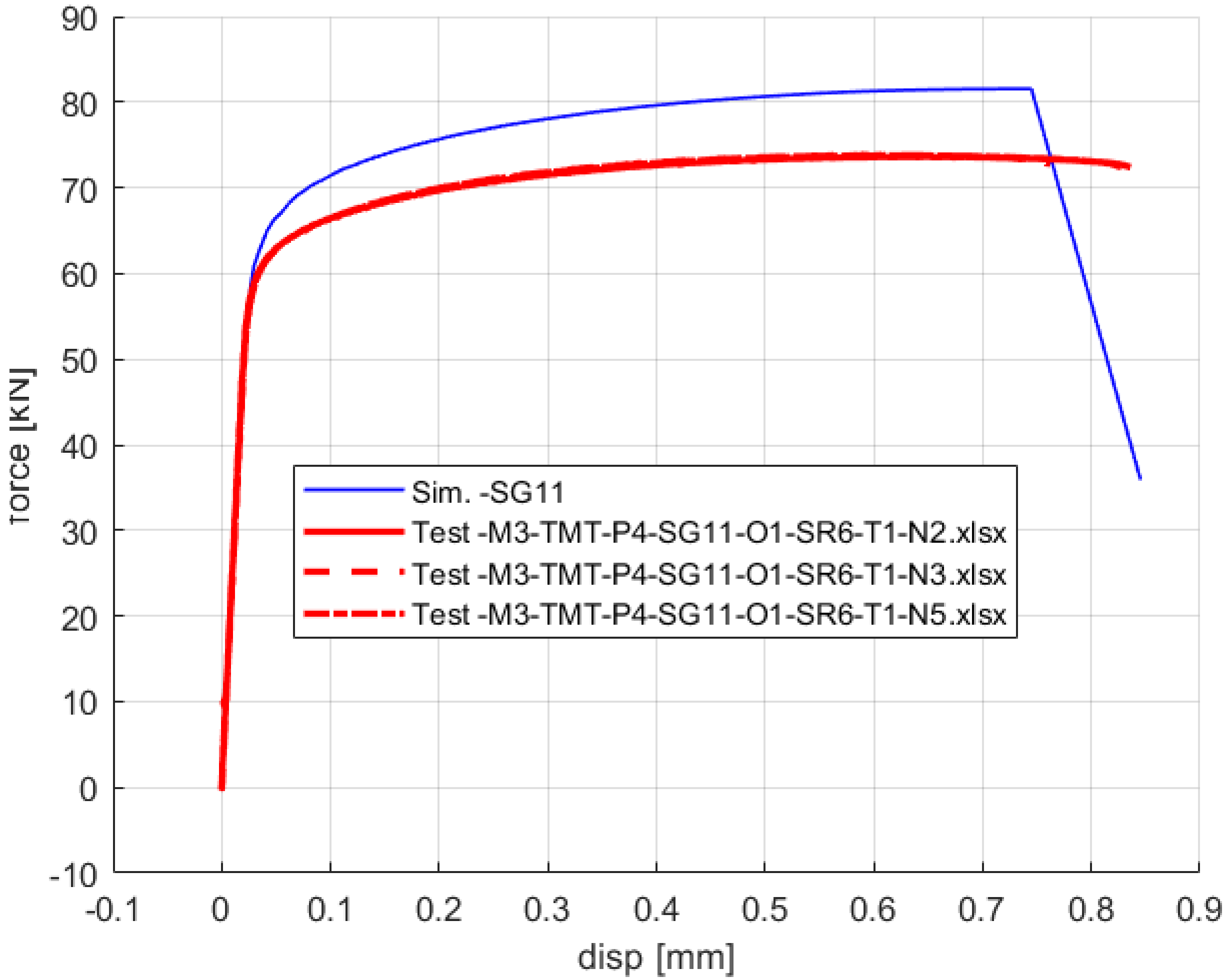


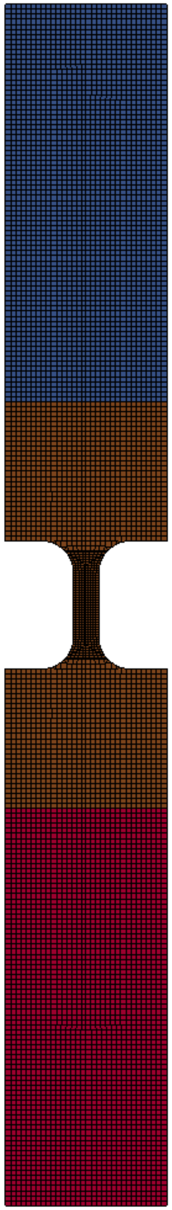
SG10 (triax = -0.88, lode = 0.99)



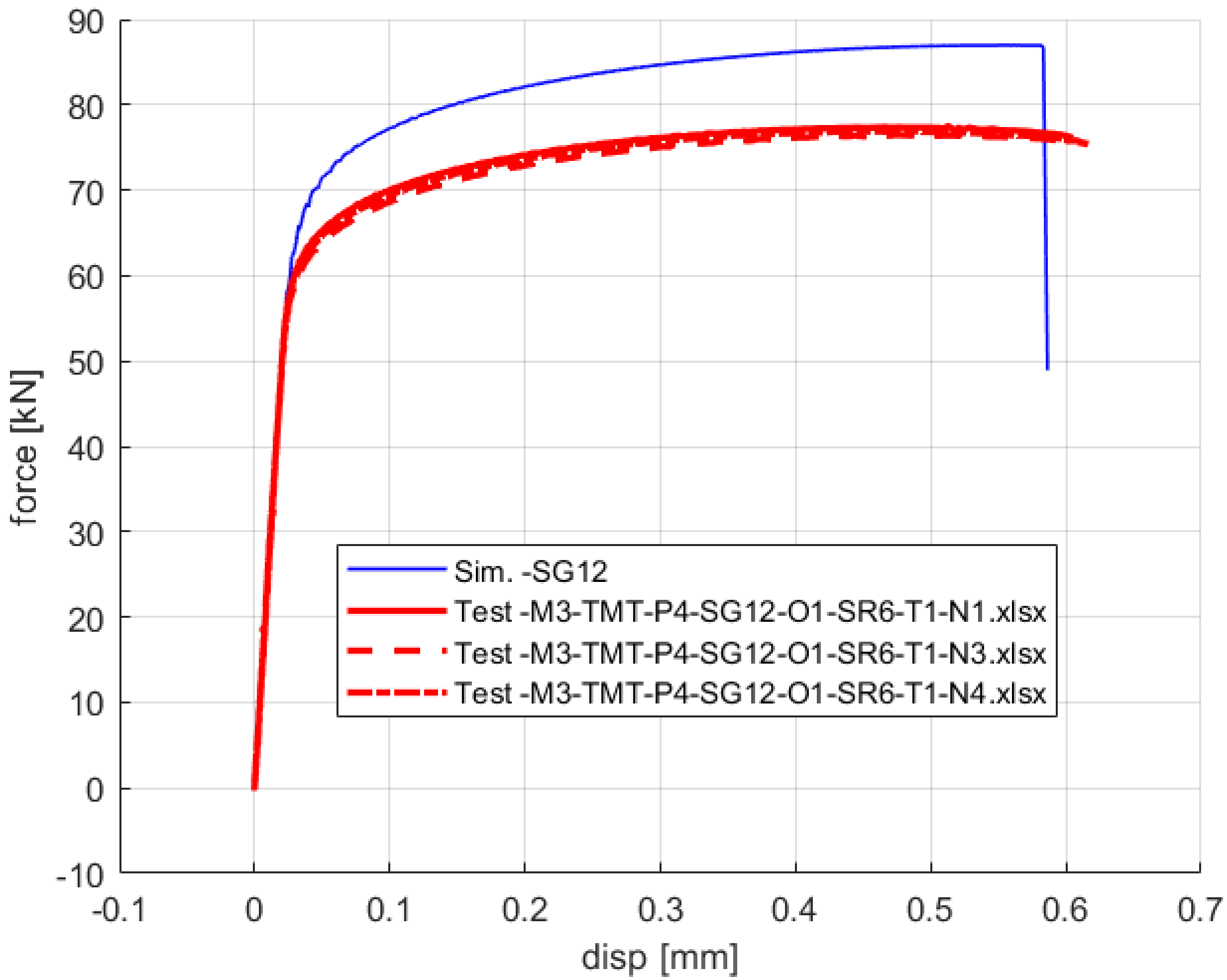


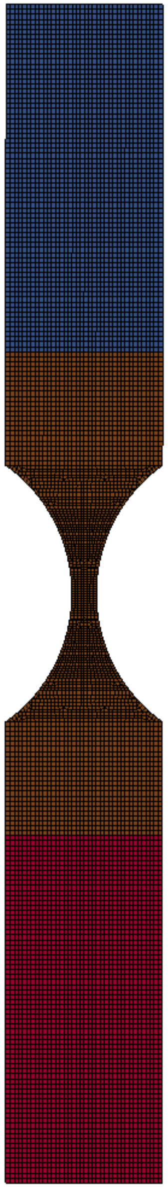
SG11 (triax = -0.56, lode = 0.18)



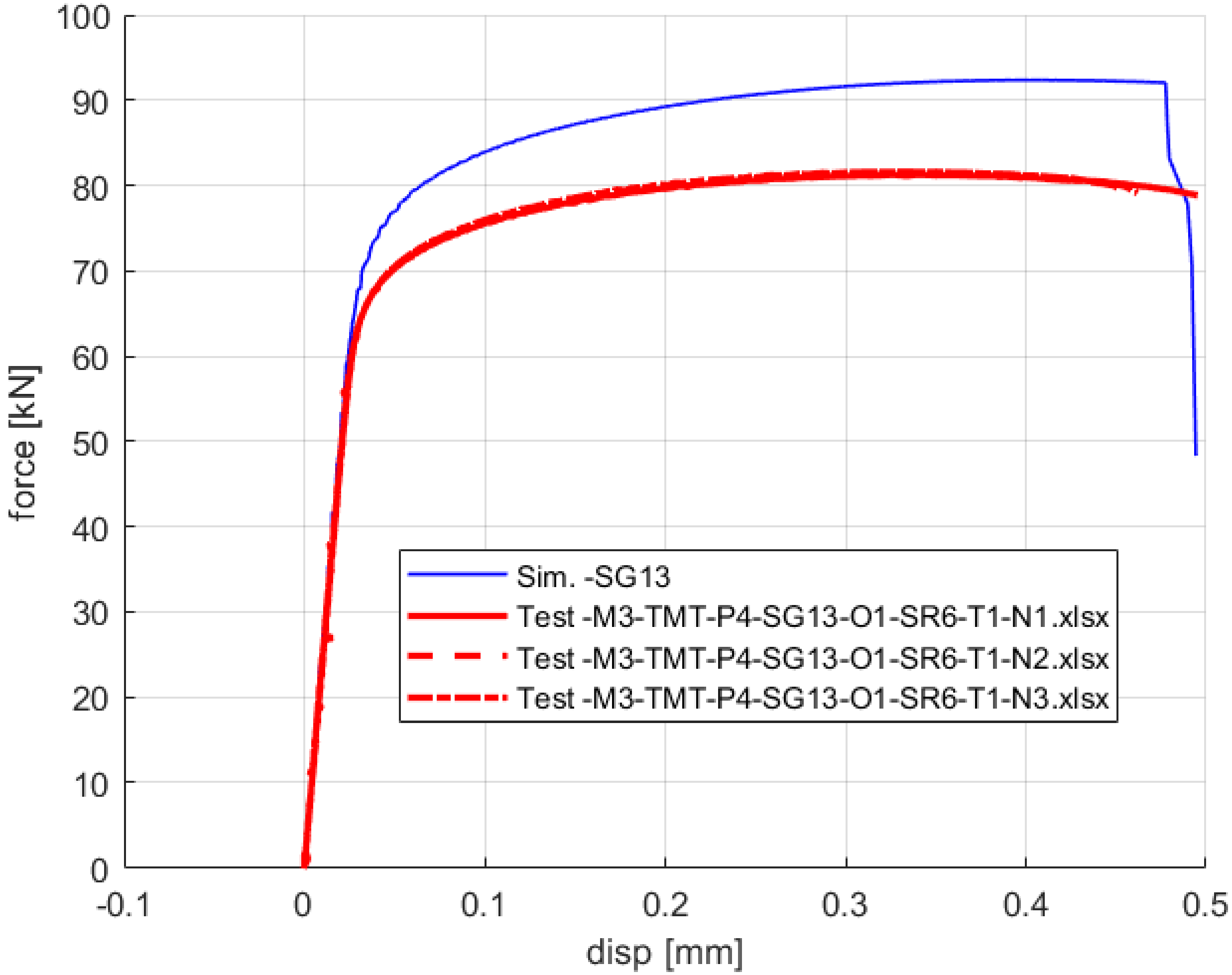


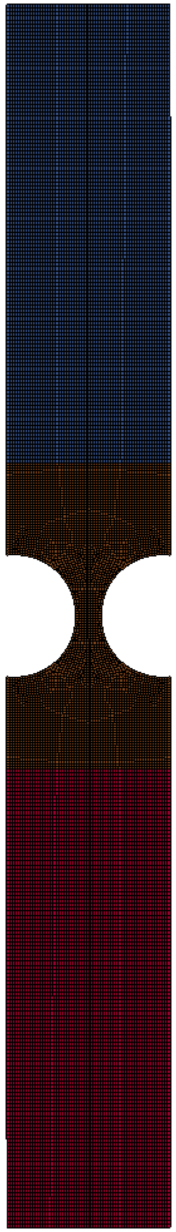
SG12 (triax = -0.64, lode = 0.07)



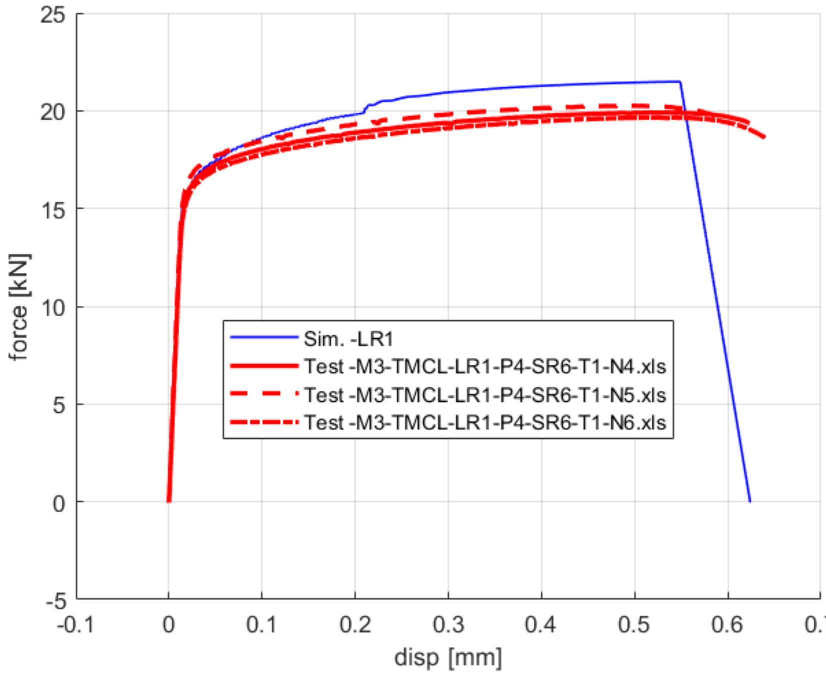


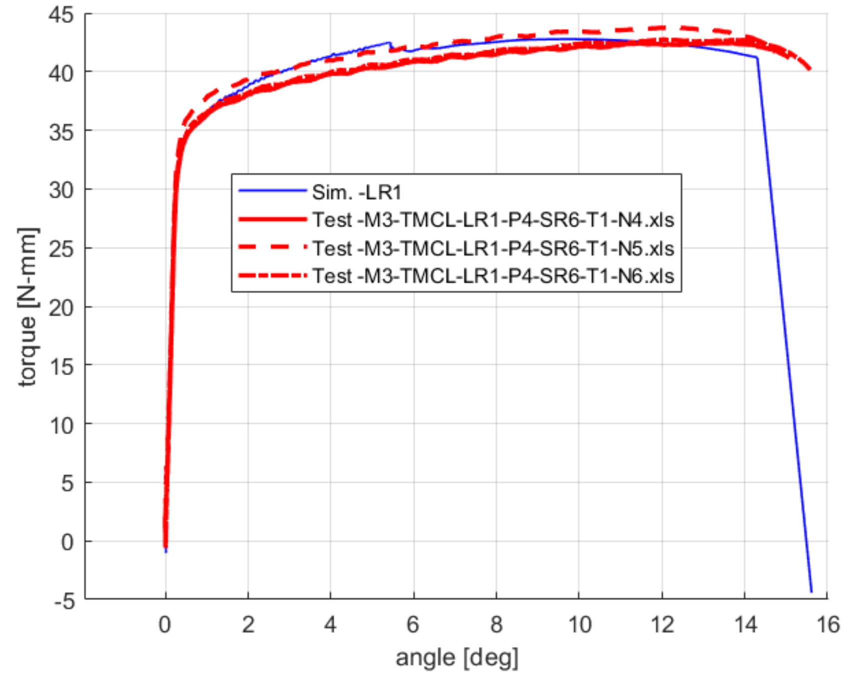
SG13 (triax = -0.78, lode = 0.03)



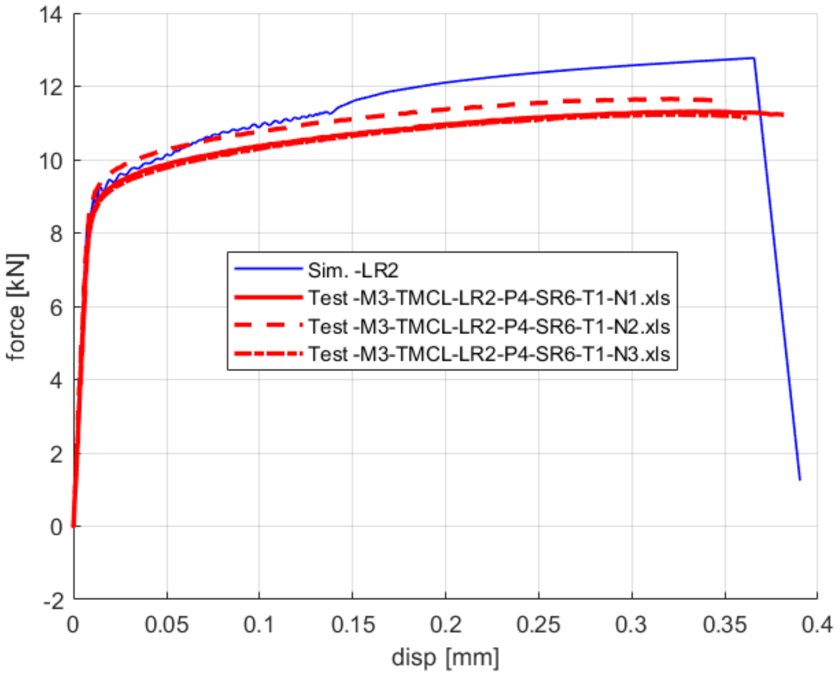


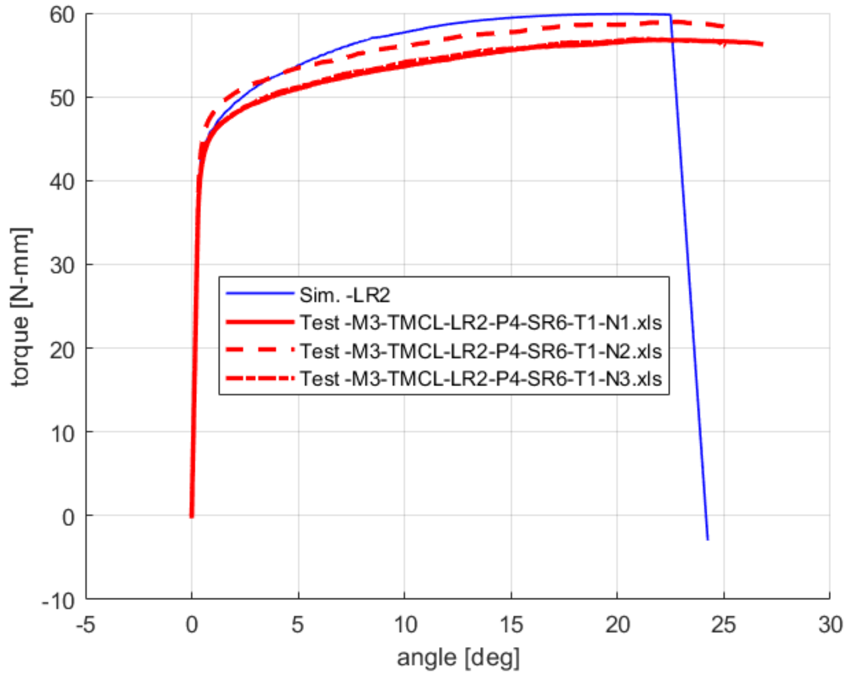
LR1 – Combined axial tension and torsion load (triax = -0.39, lode = 0.99)



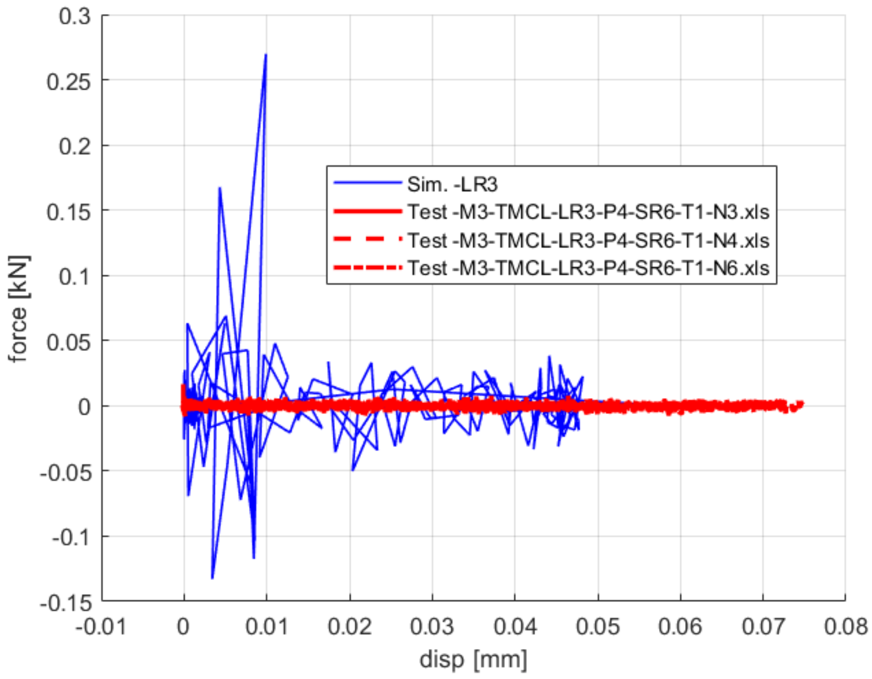


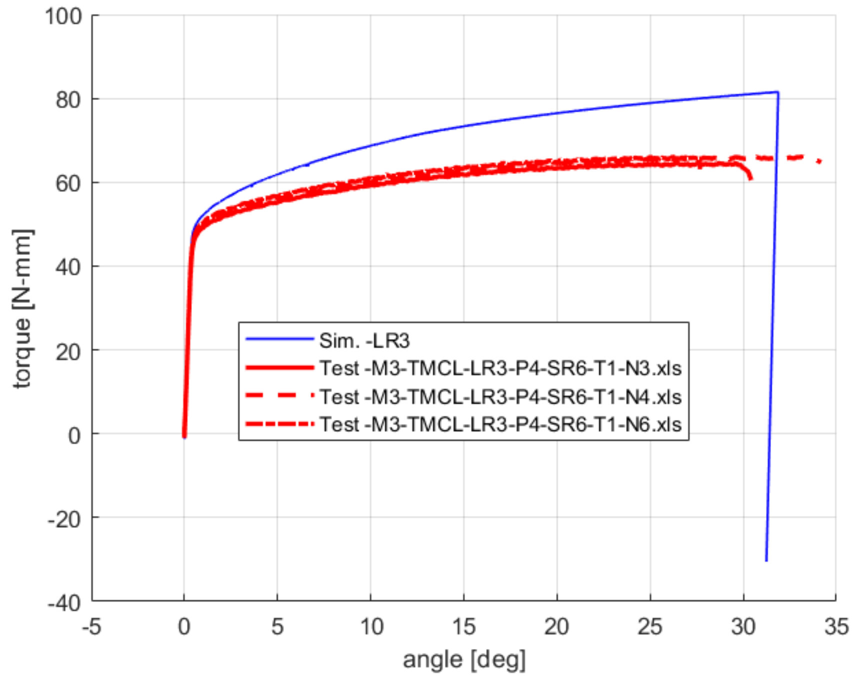
LR2 – Combined axial tension and torsion load (triax = -0.16, lode = 0.58)



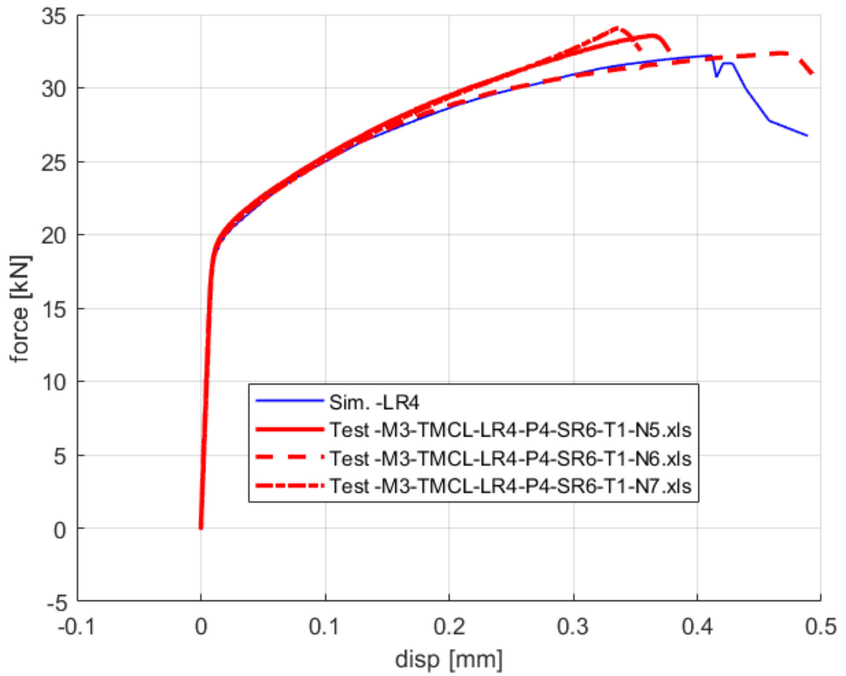


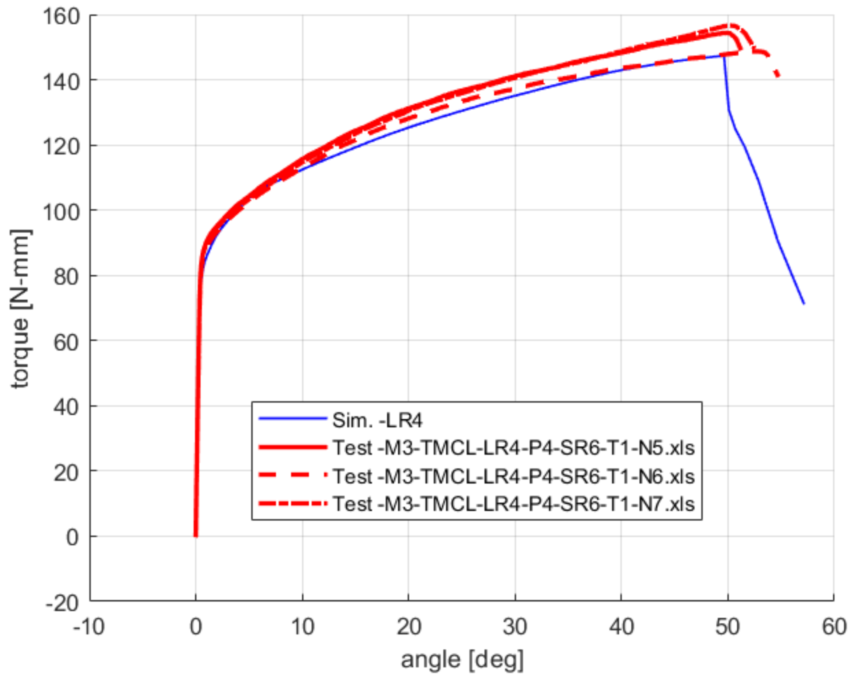
LR3 – Only torsion load (triax = 0.01, lode = -0.006)



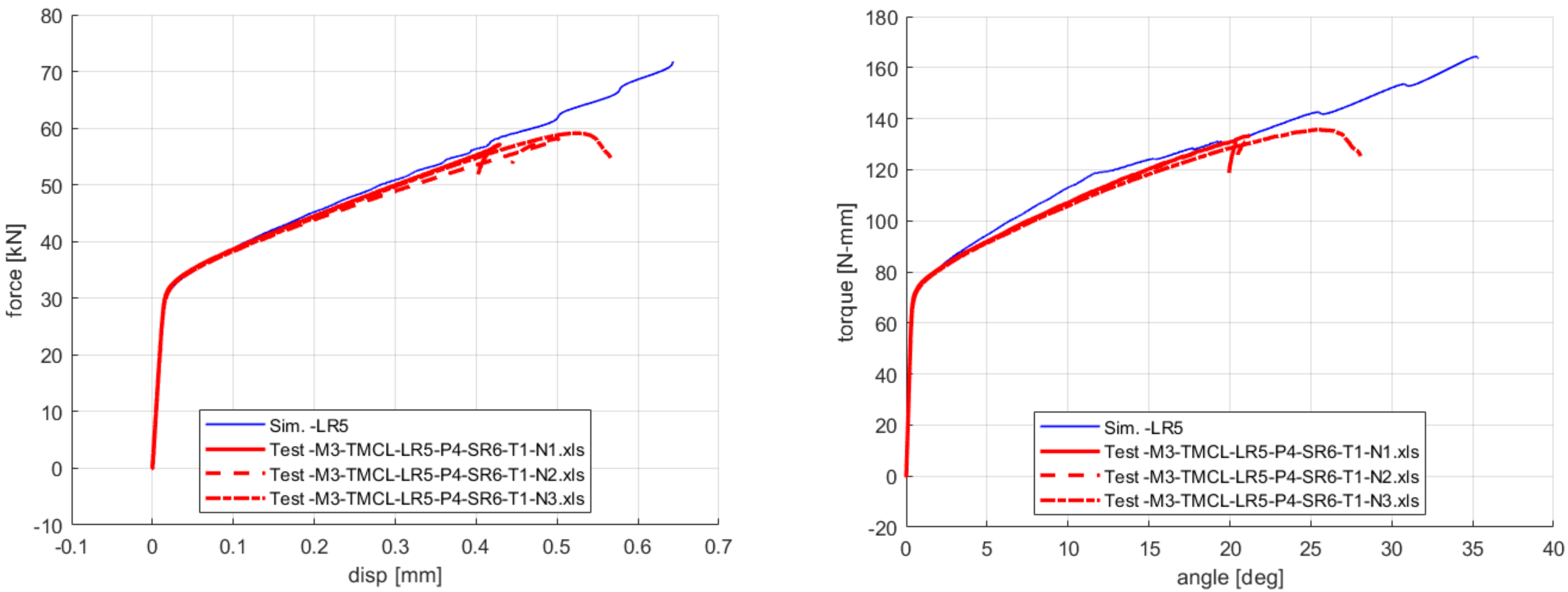


LR4 – Combined axial compression and torsion load (triax = 0.22, lode = -0.77)

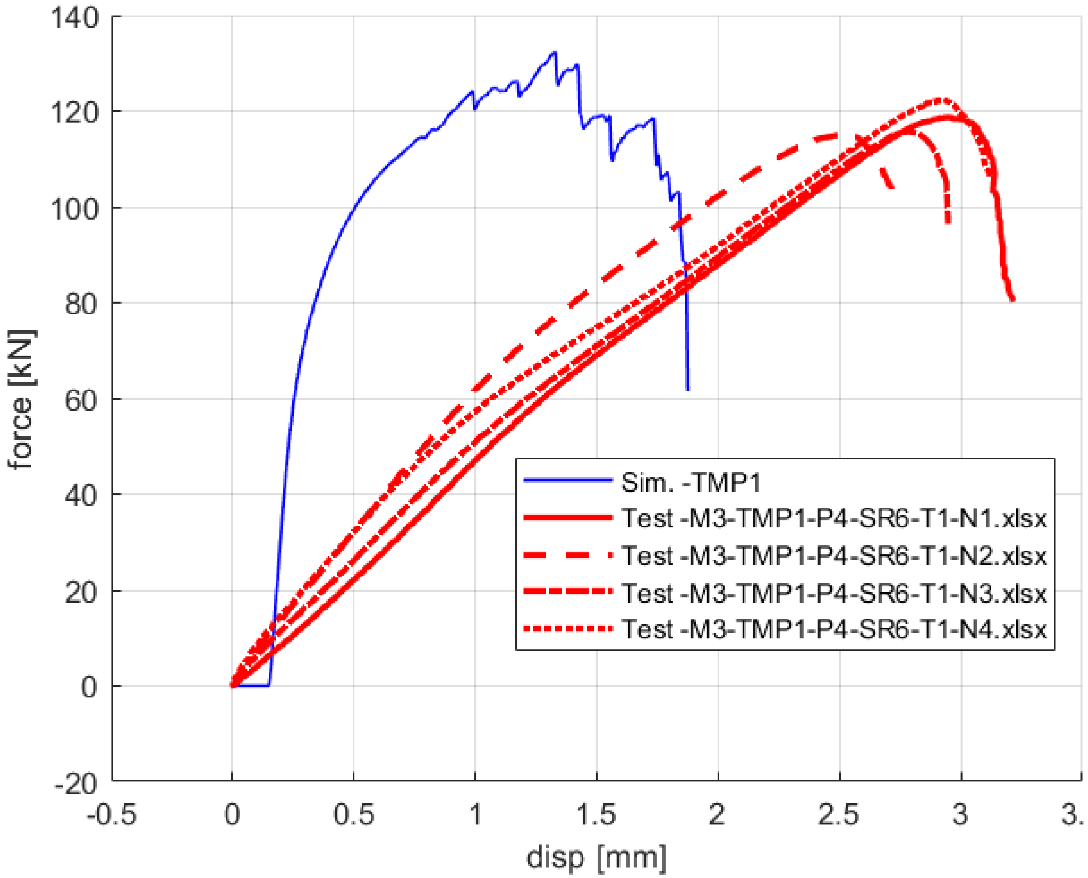


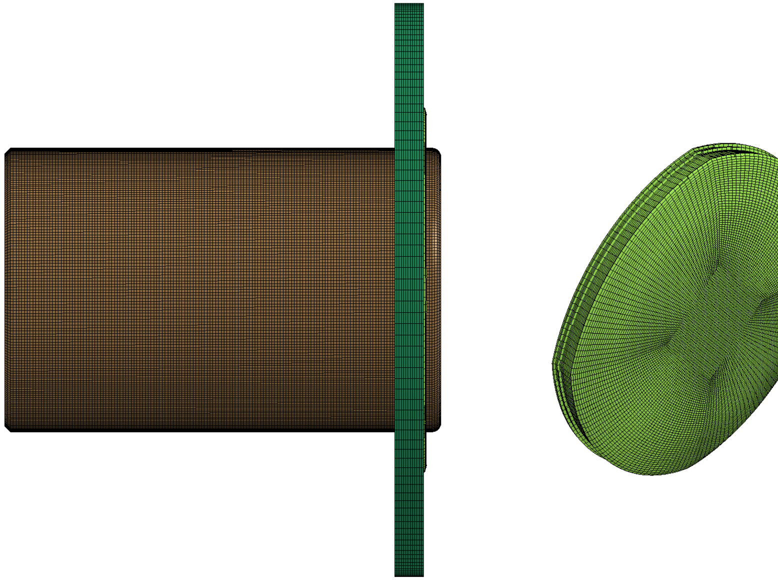


LR5 – Combined axial compression and torsion load (N/A)

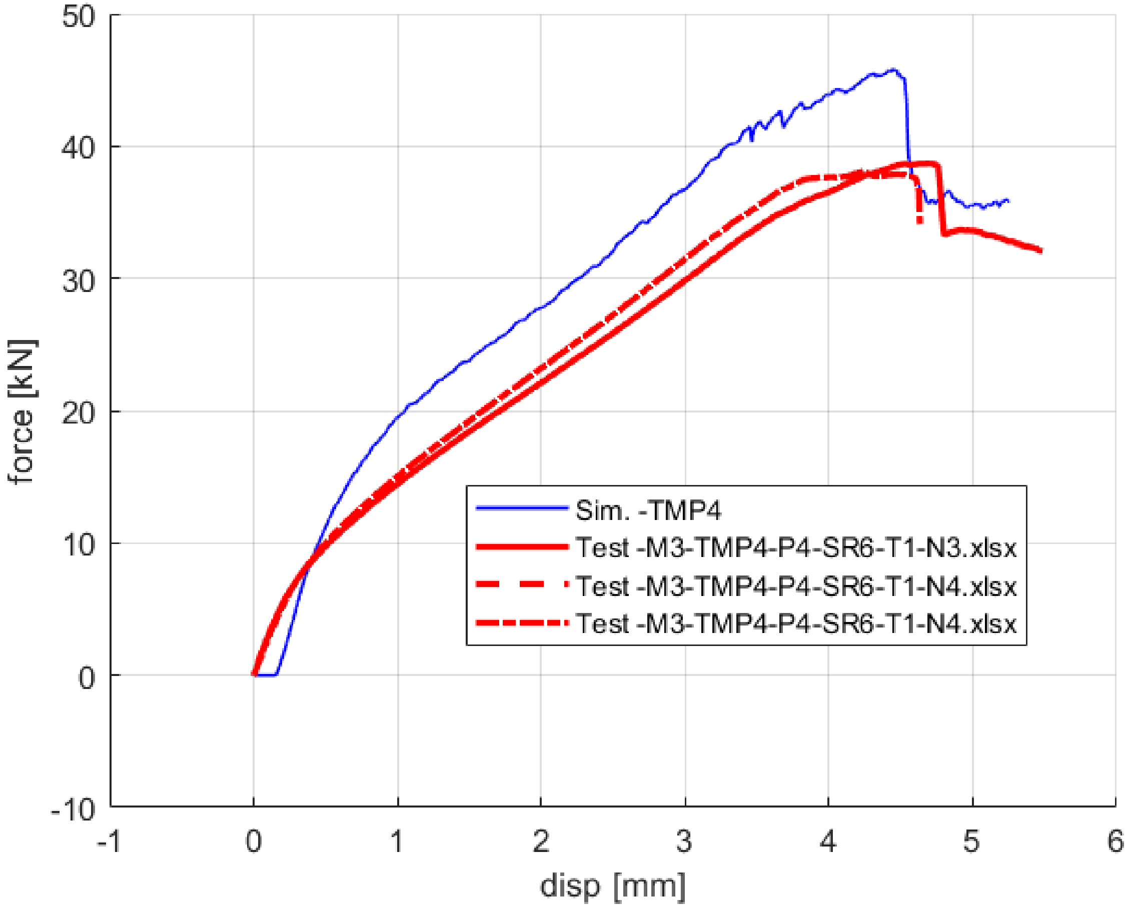


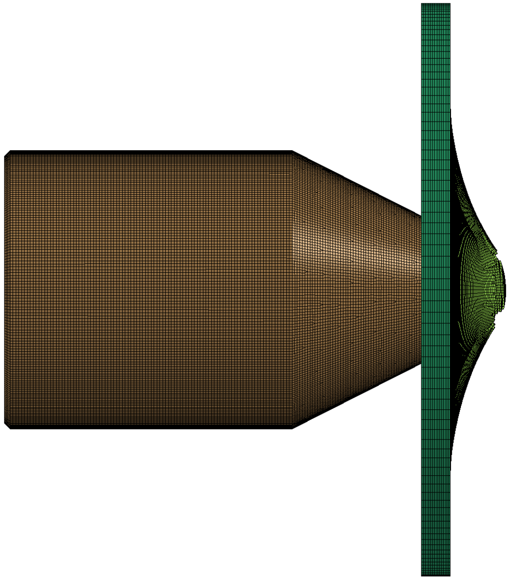
TMP1 - Punch (triax=-0.59,lode = -0.28)



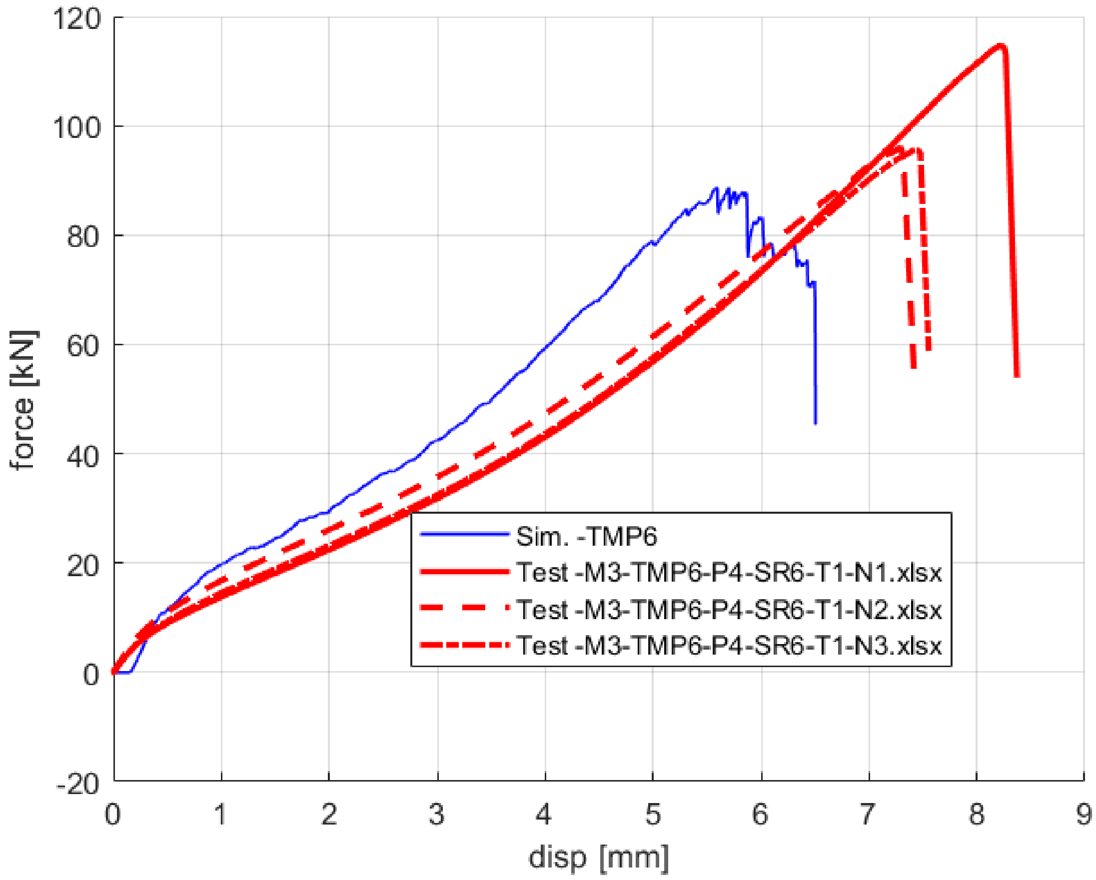


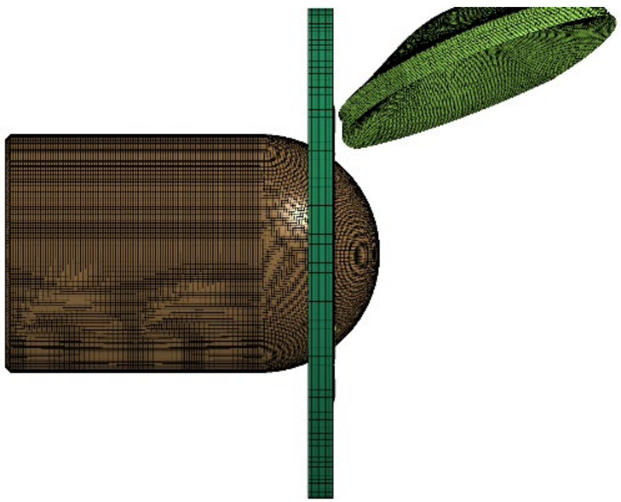
TMP4 - Punch (triax=-0.64,lode=-0.91)



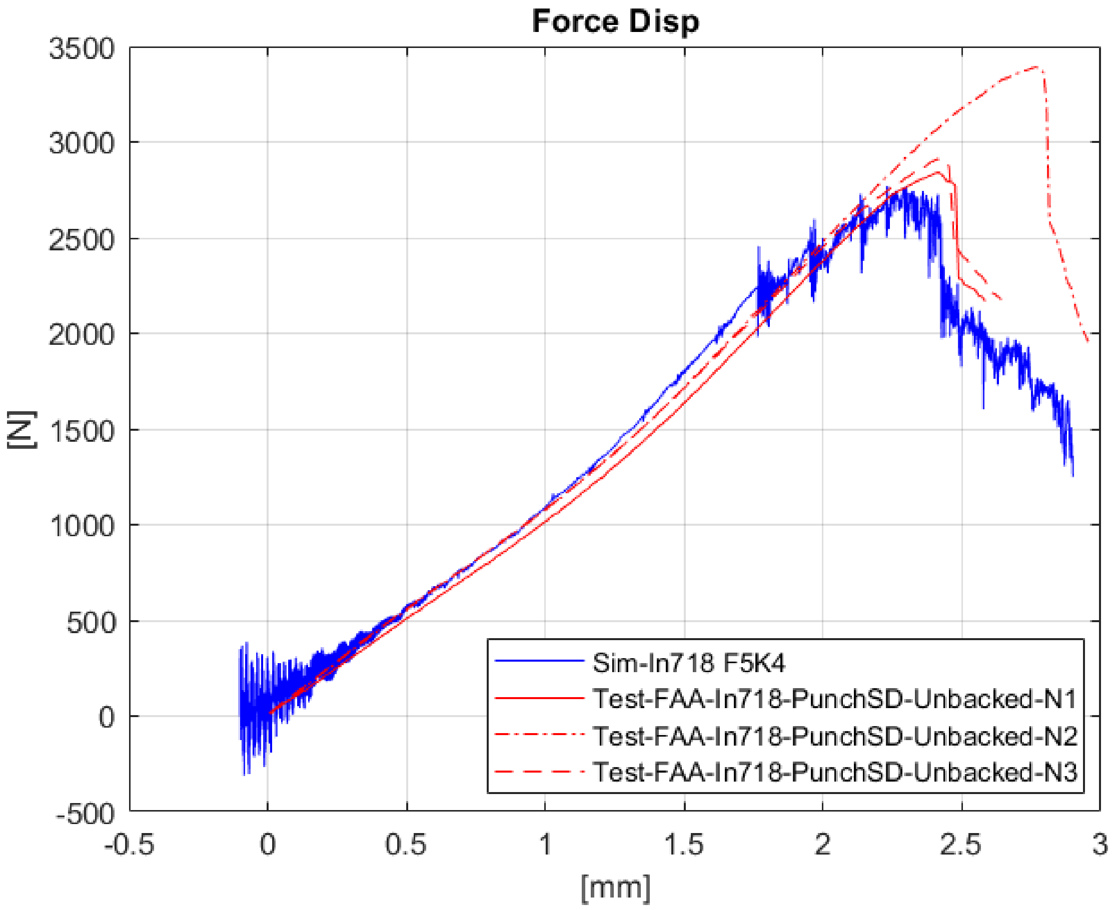


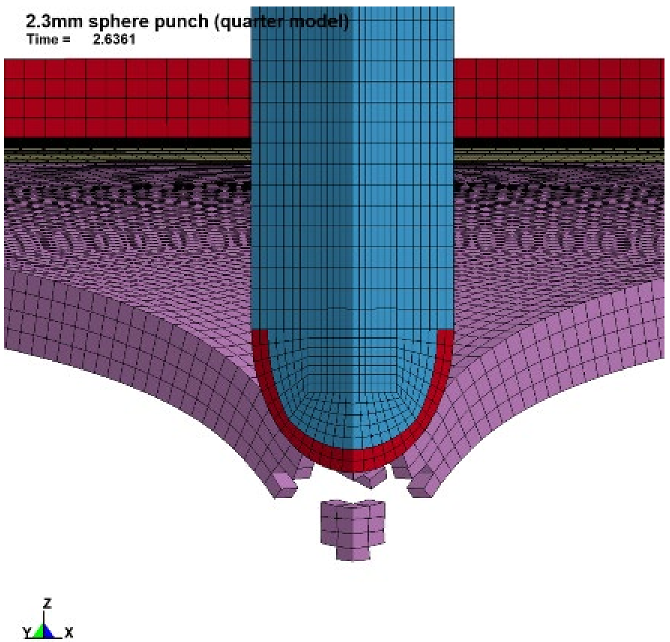
TMP6 – Punch (triax=-0.61,lode=-0.56)



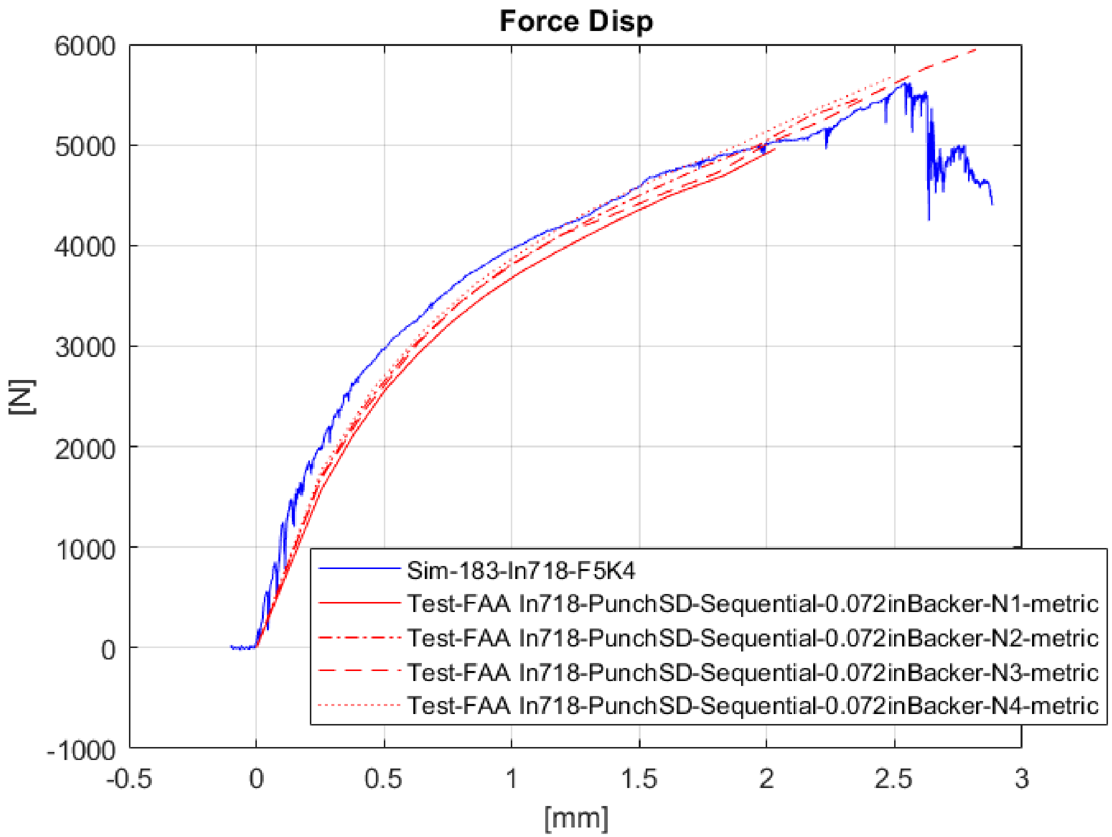


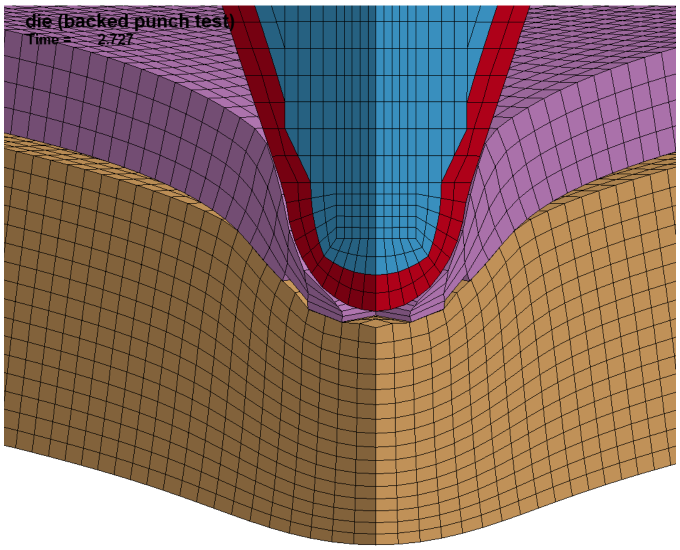
PUNCH UNBACKED (triax = -0.60, lode = -0.99)



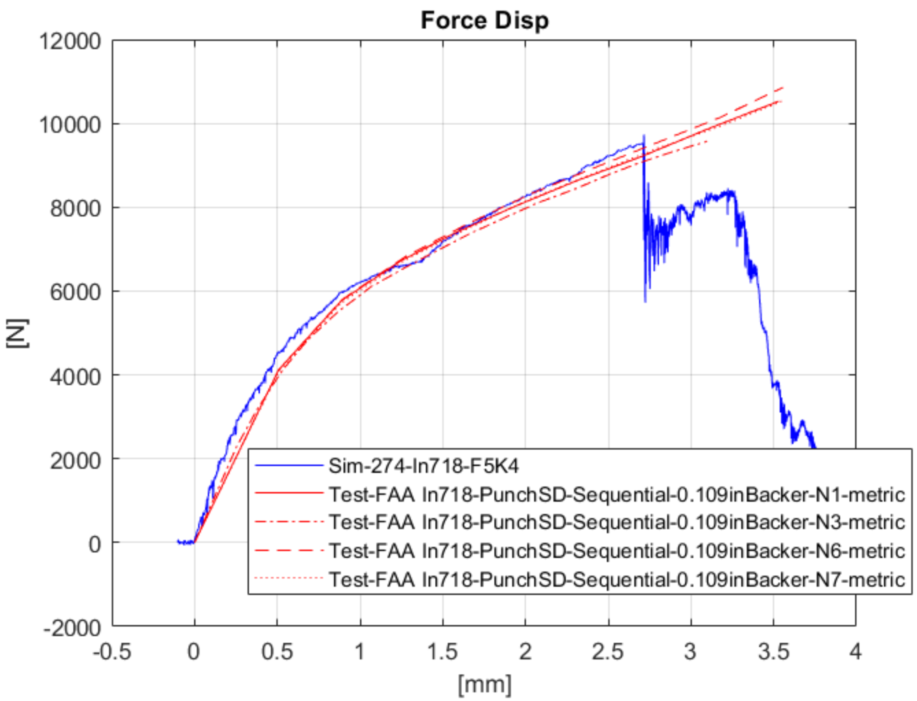


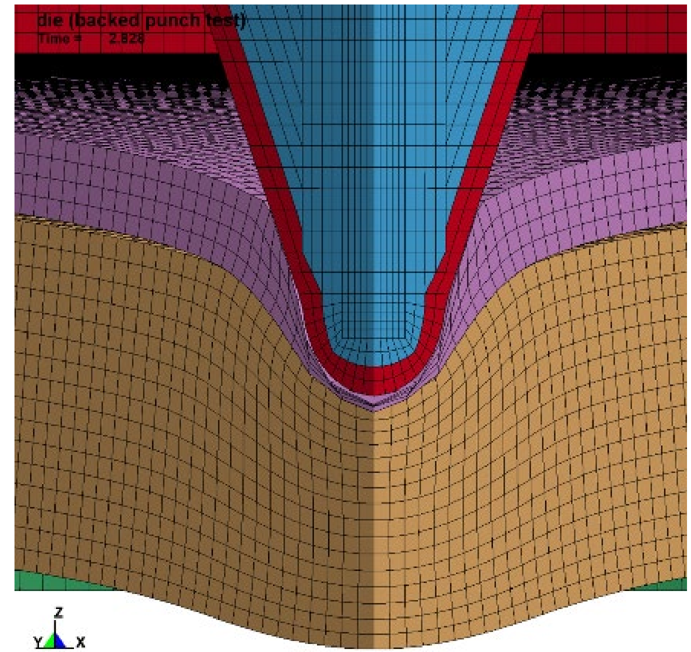
PUNCH - THIN BACKED (1.83 mm, triax = 0.00, lode = -1.00)





PUNCH - THICK BACKED (2.74 mm, triax = 0.15, lode = -1.00)





The failure strain in the test was so high that the analysis couldn't match it because of extreme element distortion and mesh entanglement. Since the failure strain is so high matching to get the exact value isn’t vital, since elements don’t typically fail in this failure surface region, in a real-life application.

LCG – Rate Sensitivity of Failure Strain

$\dot{\varepsilon}$	Scaling factor
1E-4	1
3000	1
8000	1
50000	1

- Rate sensitivity of FS of Inconel it is very different from Ti. This has a large effects on ballistic impact

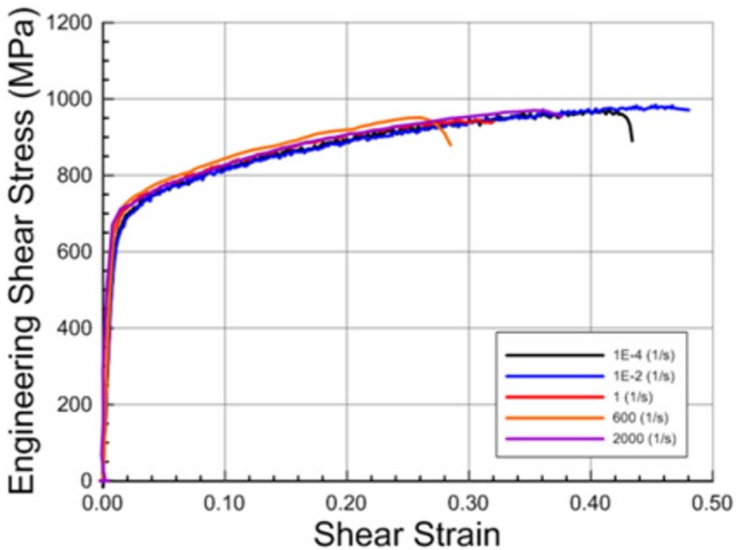
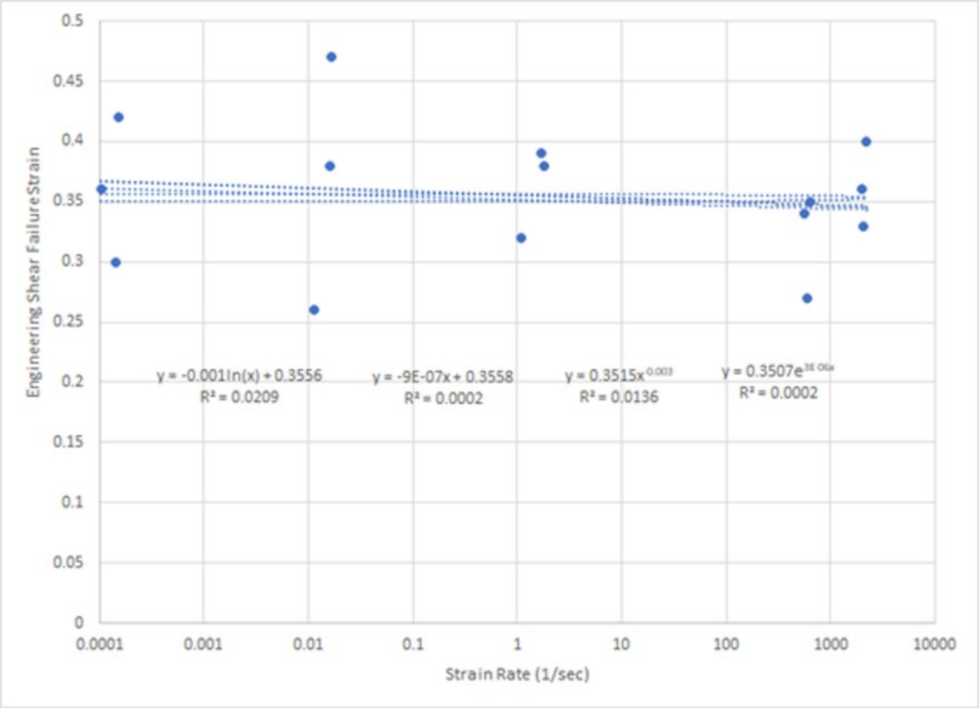
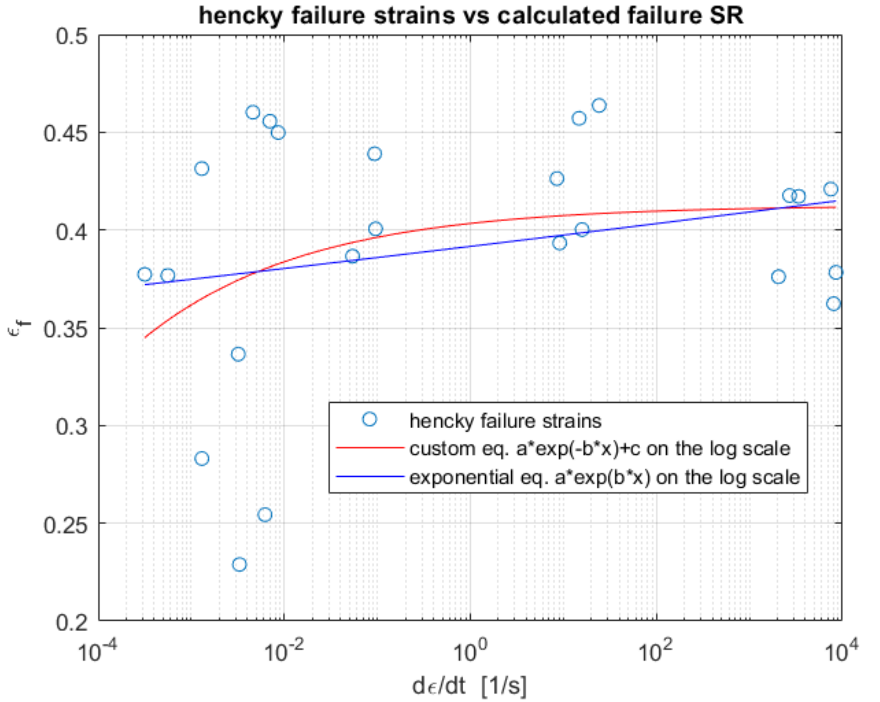
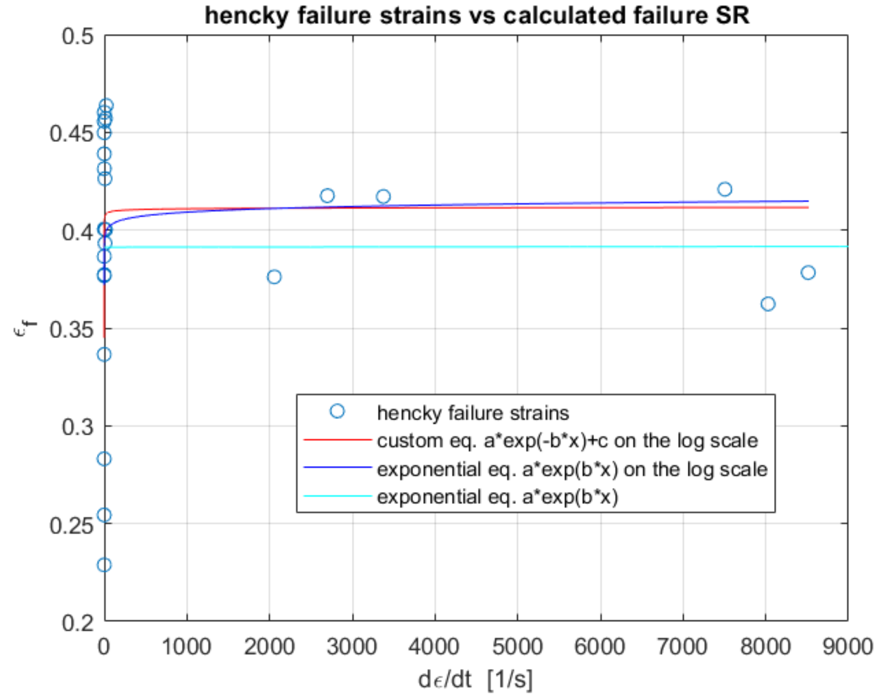


Figure 30. Representative engineering shear stress versus engineering strain curves at each strain rate examined.

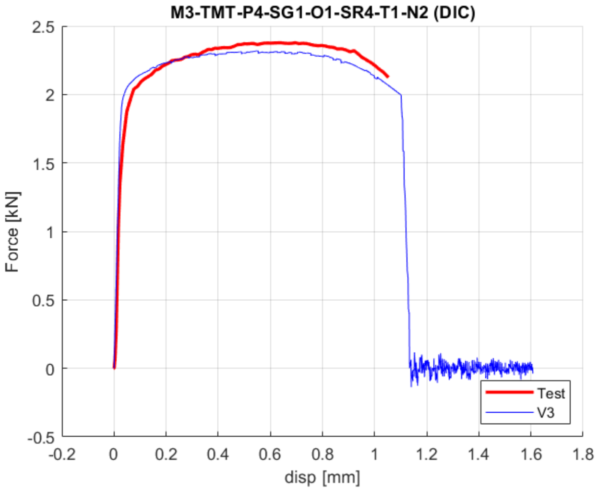


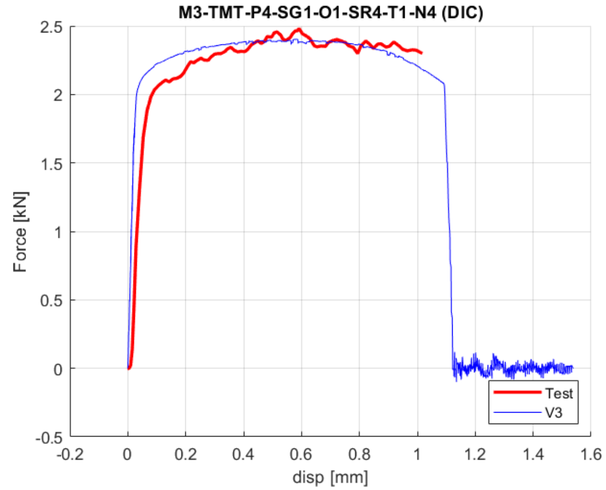
LCG – Calculated Rate Sens. Failure Strain Tension

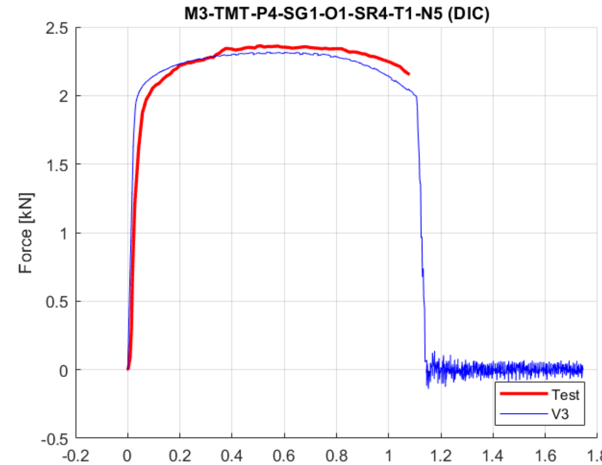


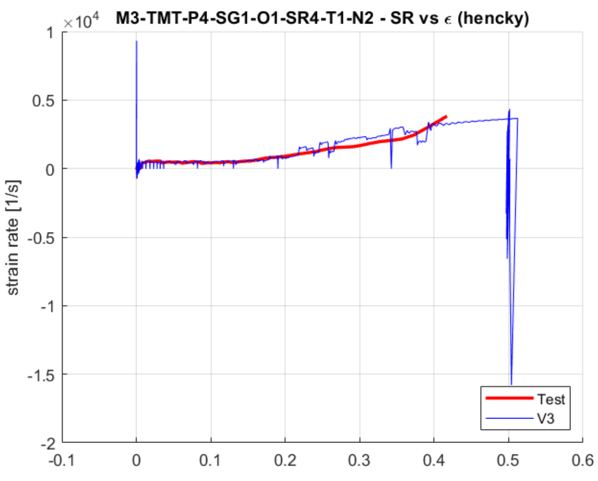


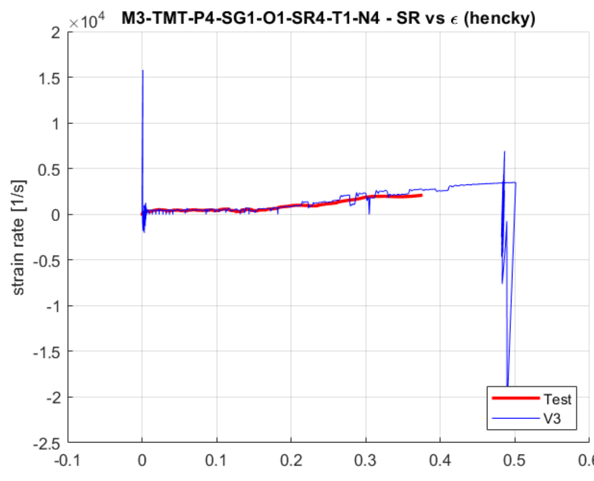
LCG SR4

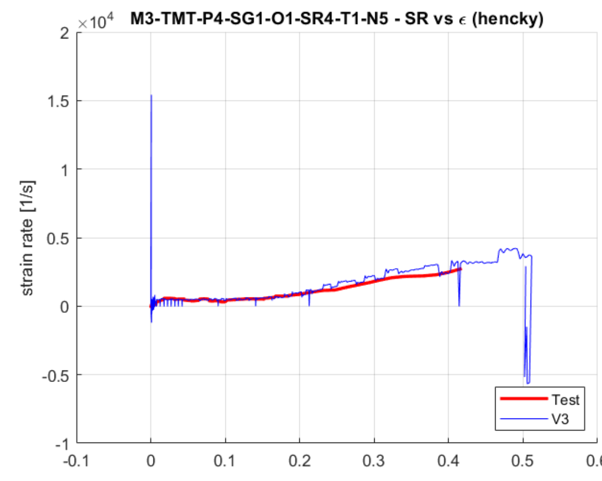

M3-TMT-P4-SG1-O1-SR4-T1-N2 (DIC)
Force [kN]
disp [mm]
Test
V3


M3-TMT-P4-SG1-O1-SR4-T1-N4 (DIC)
Force [kN]
disp [mm]
Test
V3

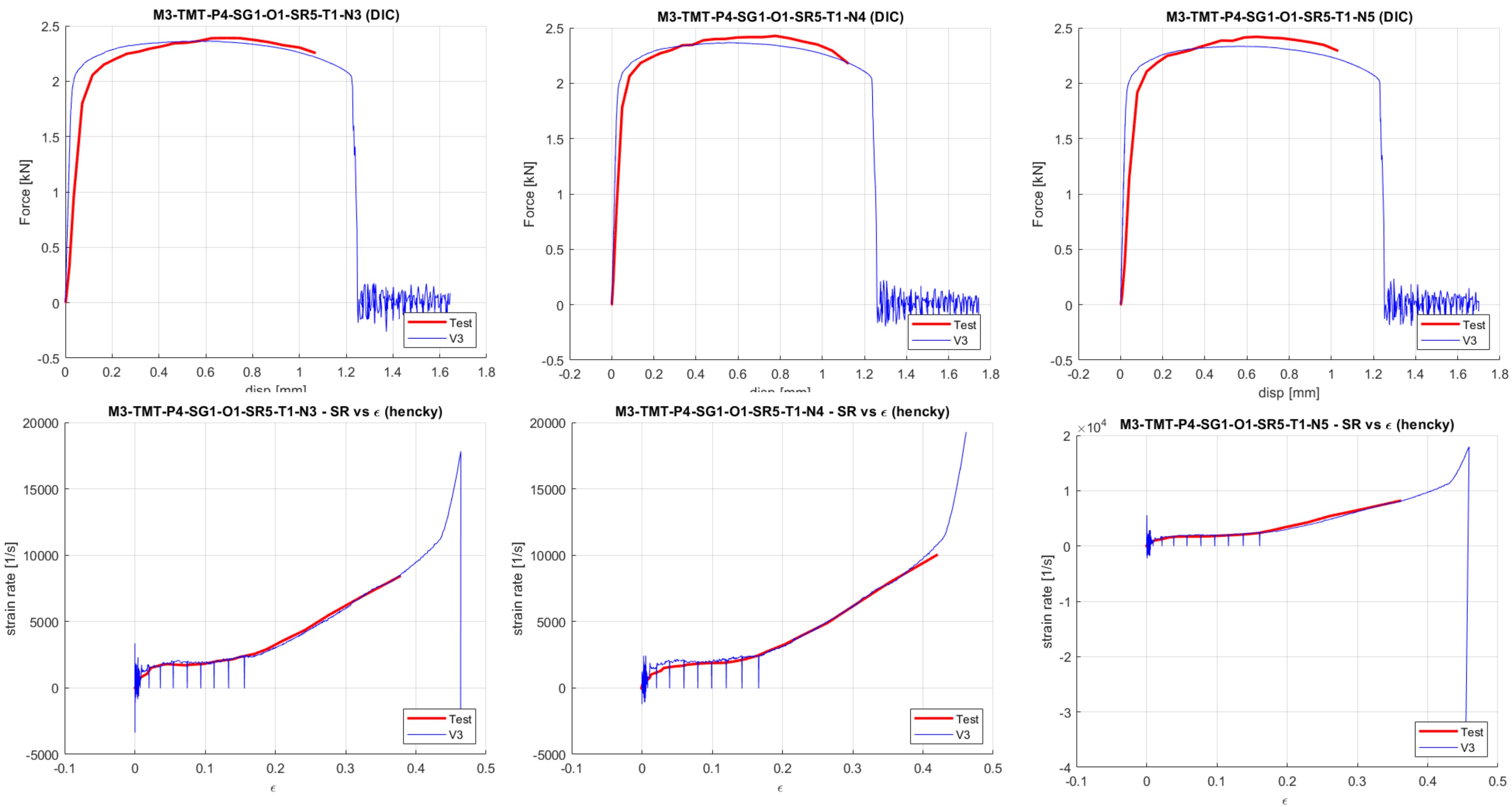

M3-TMT-P4-SG1-O1-SR4-T1-N5 (DIC)
Force [kN]
Test
V3


M3-TMT-P4-SG1-O1-SR4-T1-N2 - SR vs ϵ (hencky)
×10^4
strain rate [1/s]
ϵ
Test
V3


M3-TMT-P4-SG1-O1-SR4-T1-N4 - SR vs ϵ (hencky)
×10^4
strain rate [1/s]
ϵ
Test
V3


M3-TMT-P4-SG1-O1-SR4-T1-N5 - SR vs ϵ (hencky)
×10^4
strain rate [1/s]
ϵ
Test
V3

LCG SR5


M3-TMT-P4-SG1-O1-SR5-T1-N3 (DIC)
M3-TMT-P4-SG1-O1-SR5-T1-N4 (DIC)
M3-TMT-P4-SG1-O1-SR5-T1-N5 (DIC)
Force [kN]
disp [mm]
Test
V3
M3-TMT-P4-SG1-O1-SR5-T1-N3 - SR vs ϵ (hencky)
M3-TMT-P4-SG1-O1-SR5-T1-N4 - SR vs ϵ (hencky)
M3-TMT-P4-SG1-O1-SR5-T1-N5 - SR vs ϵ (hencky)
strain rate [1/s]
ϵ
×10^4

Final version (V1.0) Ballistic impact

Test/ simulation	DB266		DB268		DB271	
Impact/exit vel.	203.8/52.5 [m/s] Highest vel.		190.8/54.6 [m/s] Ballistic limit.		189.1/0 [m/s] Highest vel. No penetration	
Mesh [mm]	CCSA jon82 $\beta^*_{TAB,0.2}$	CCSA jon82 V1.0	CCSA jon82 $\beta^*_{TAB,0.2}$	CCSA jon82 V1.0	CCSA jon82 $\beta^*_{TAB,0.2}$	CCSA jon82 V1.0
0.2	47.4	46.9	0(full plug)	0(full plug)	0 (1/4 plug)	0
1.6	51.8	52.2	0(¾ plug)	0(¾ plug)	0	0

Current Release Version (V1.0) Summary

- Delivered model can simulate ballistic tests, where ASBs develop
- Delivered model can also simulate other loading events with differing states of stress, rates, and temperatures, where ASB is not the failure mode
- The Range of applicable elements sizes to use with the material set is between 0.2 and 1.6 mm
- Three versions of model, in different units, available on AWG website
- FAA report is in the process of being written