GREAT DESIGNS IN STEEL

THE DIC REVOLUTION IN METAL PROPERTY CHARACTERIZATION

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GM Global R&D Center, GM Tech Fellow

MOTIVATION

1) Why is a revolution in material testing needed?

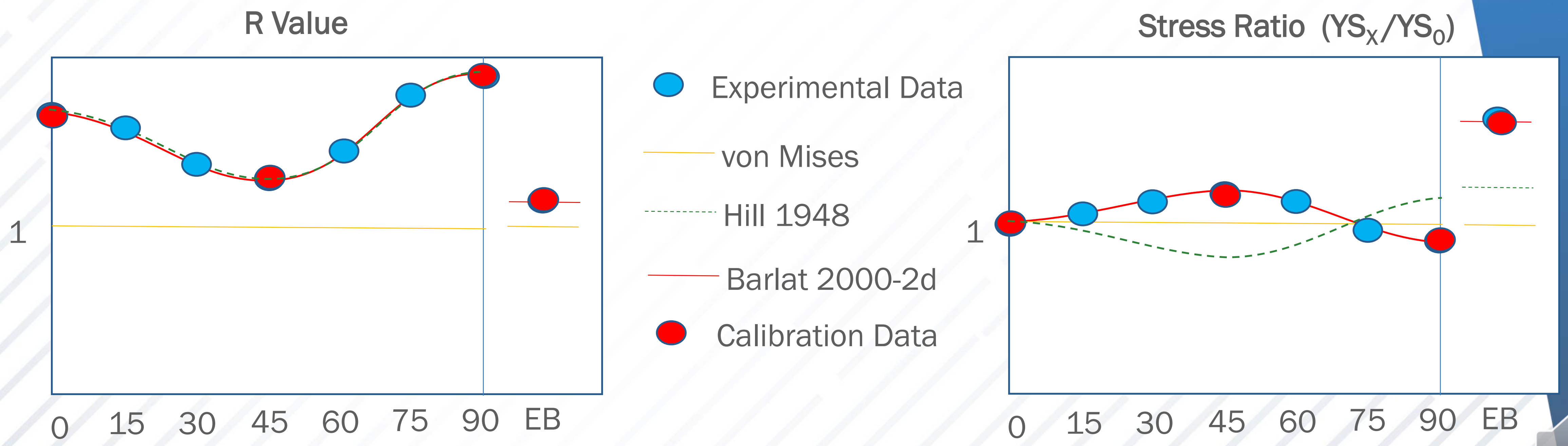
2) What is revolutionary about Digital Image Correlation?

3) What is the potential of a SINGLE Uniaxial Tension Test?

   - Example of DP 980

HISTORY OF CONSTITUTIVE MODELS

1) Von Mises Yield Model (1913) ← Requires only a single hardening law
2) Hill 1948 Fully Anisotropy Model ← … also requires R_0, R_{45}, R_{90}
3) Barlat 2000-2d Model ← … also requires YS_0, YS_{45}, YS_{90} and YS_{EB}, and R_{EB}



TRADITIONAL UNIAXIAL TENSION TEST

GDIS

Standard Results

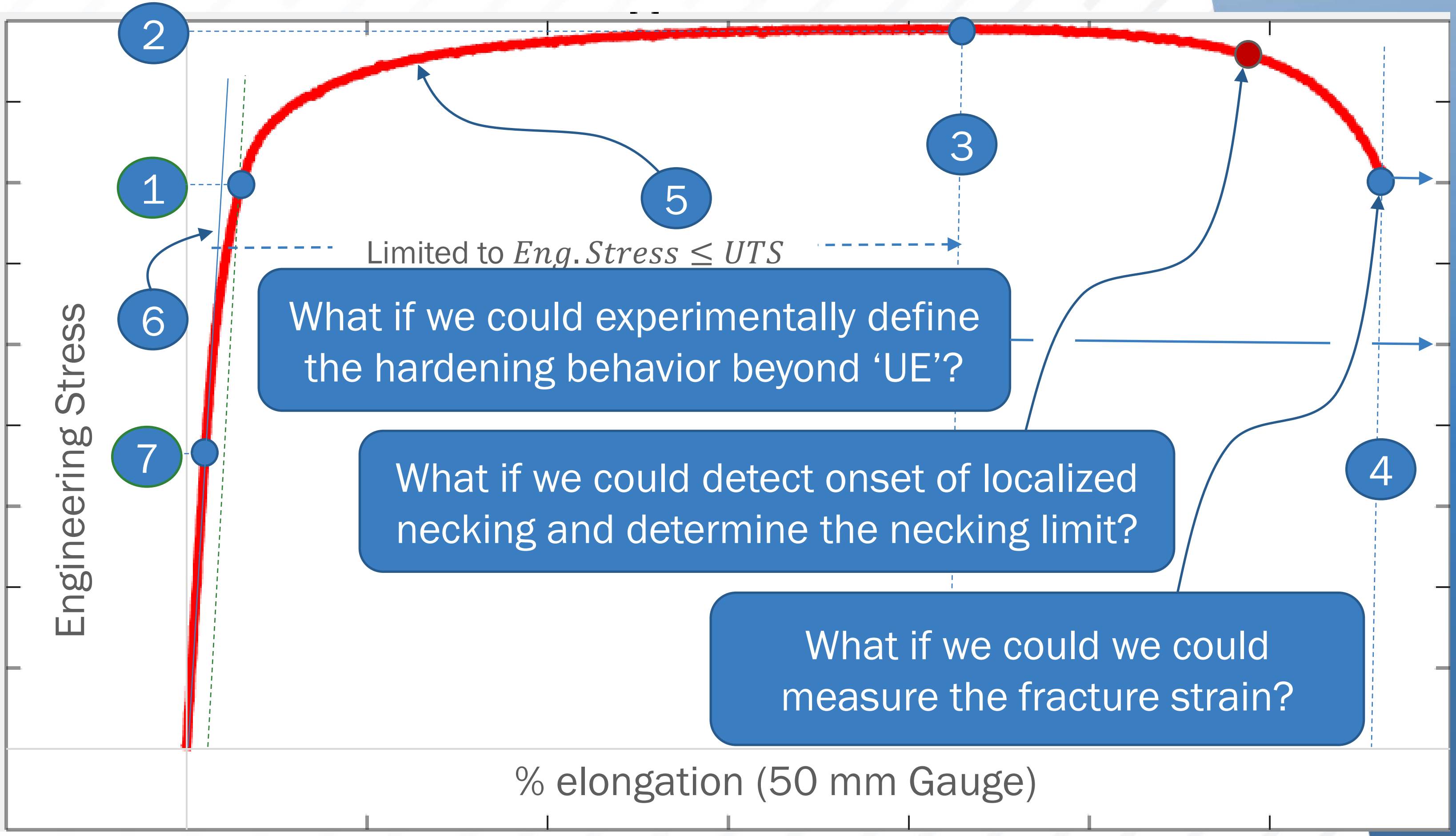
1) 0.2% Offset Yield Stress
2) Ultimate Tensile Strength
3) Uniform Elongation
4) Total Elongation
5) Hardening Behavior
6) Elastic Modulus
7) Proportional Limit

Add a Width Strain Gauge

8) R Value
9) Poisson Ratio

Additional Needs

10) m Value (jump tests)
11) YM degradation (load/unload)
12) Property variation (repeats)



Additional Tension Tests

What if we could get a handle on this from a SINGLE Uniaxial Tension Test?

HOW TO BEST USE DIC

Standard Results

Multiple Points

1) Young's Modulus
2) Ultimate Tensile Strength
3) Uniform Elongation
4) Hardening Behavior
5) Total Elongation

Includes Width Strain Gauge

6) R Value
7) Poisson Ratio

Implicitly Includes Multiple Loading Conditions

8) m Value (jump tests)
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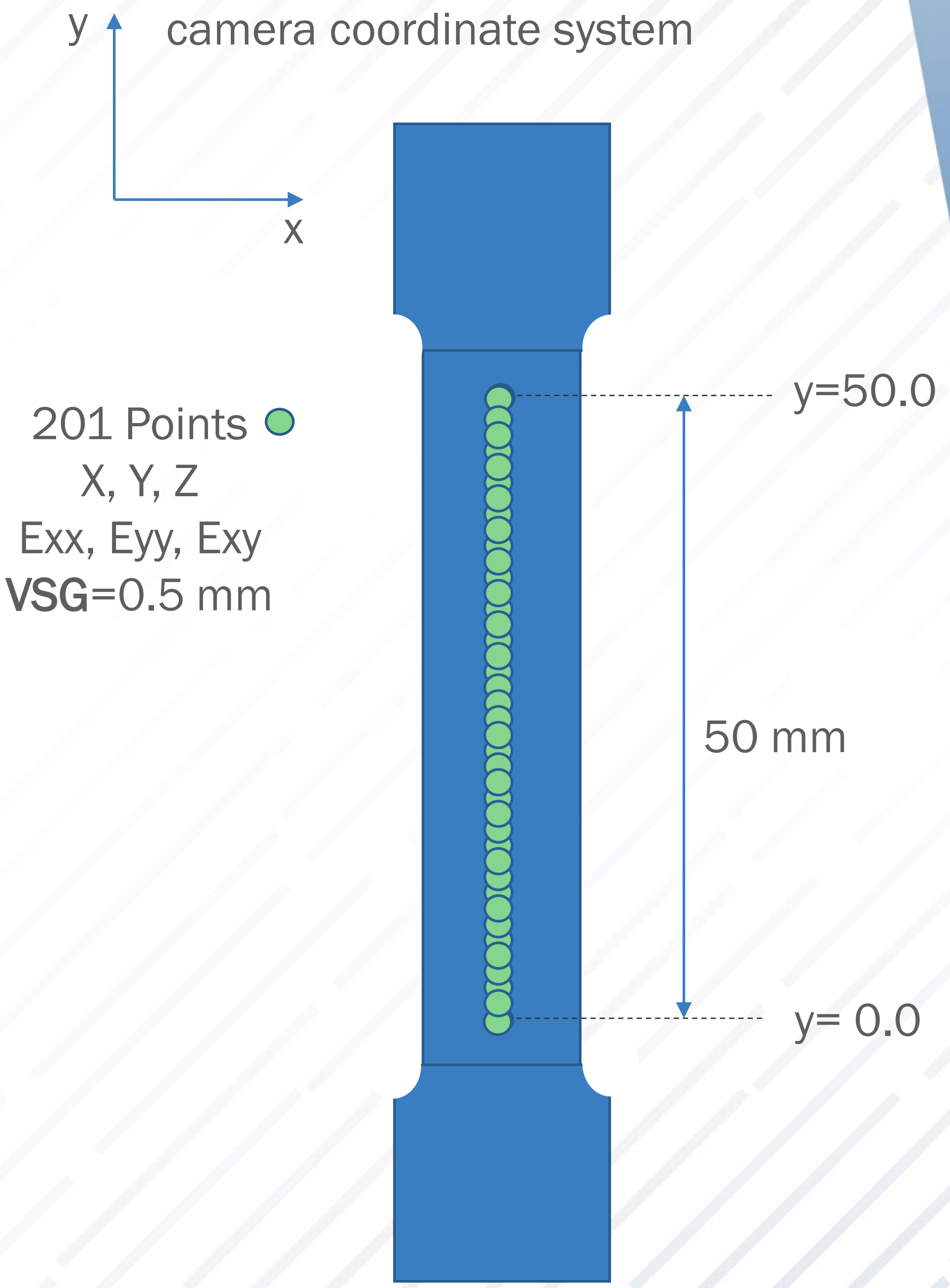
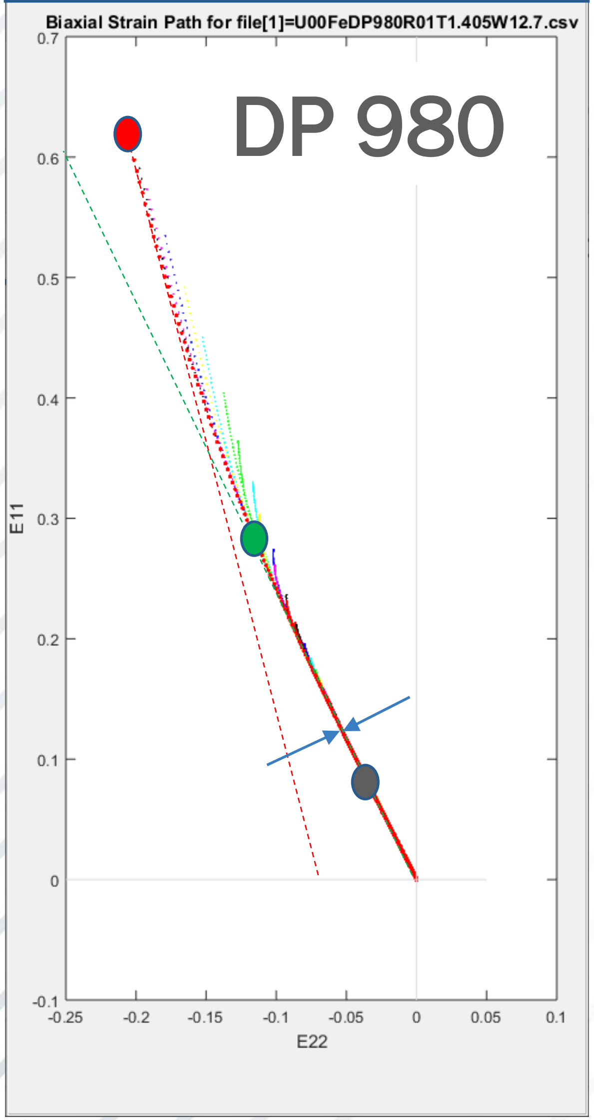
10) Property variation (repeats)



R VALUE MEASUREMENT

201 Strain Paths



Benefits of DIC

1) R Value can be defined properly, in of ratios of plastic strain rates

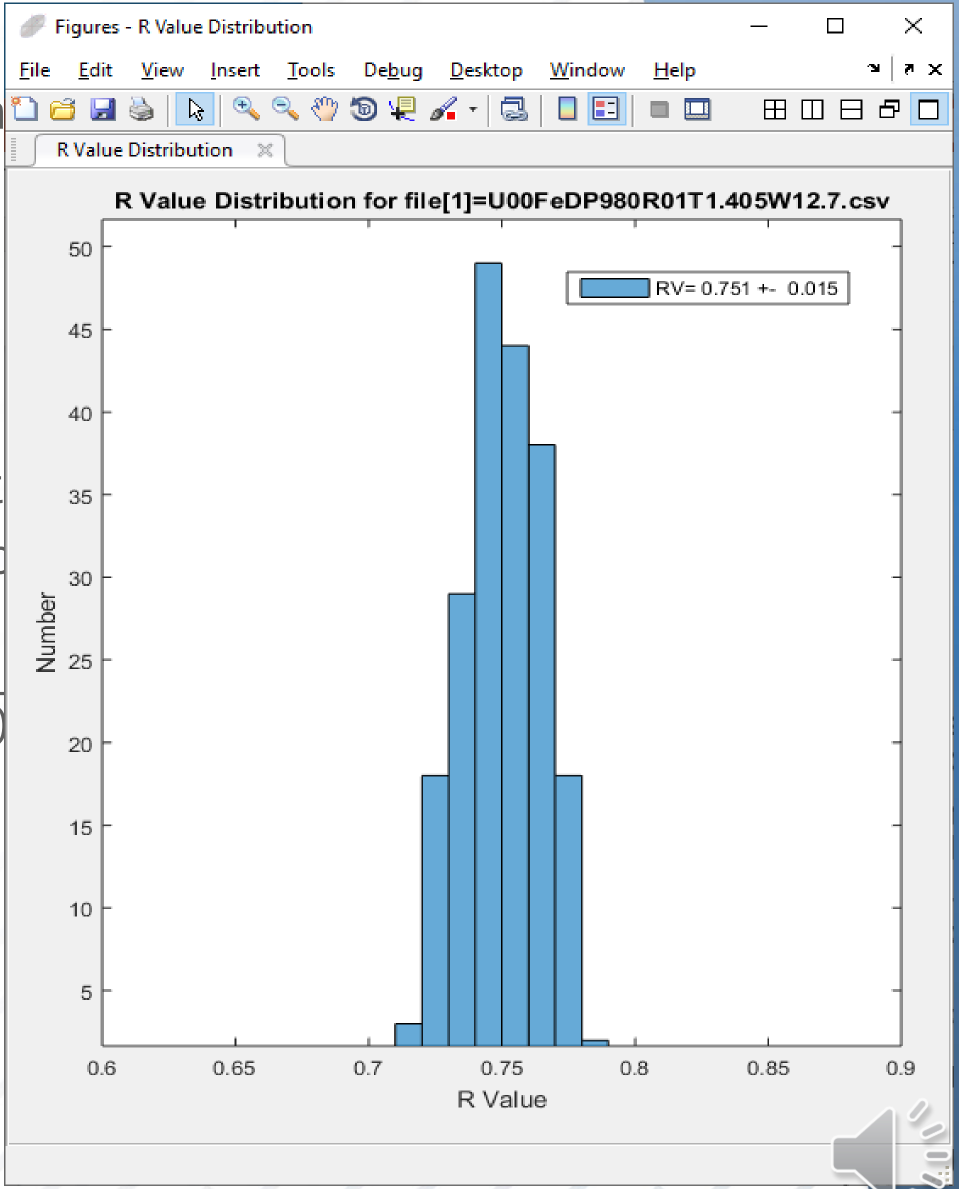
$$slope = -\frac{1+r}{r}$$

2) Change in slope is attributed to
   - Change in R Value (crystal text
   - Rise of Non-uniaxial tension co
   - Both

$$slope = -\frac{1+r+\alpha r}{r+\alpha(1+r)}$$

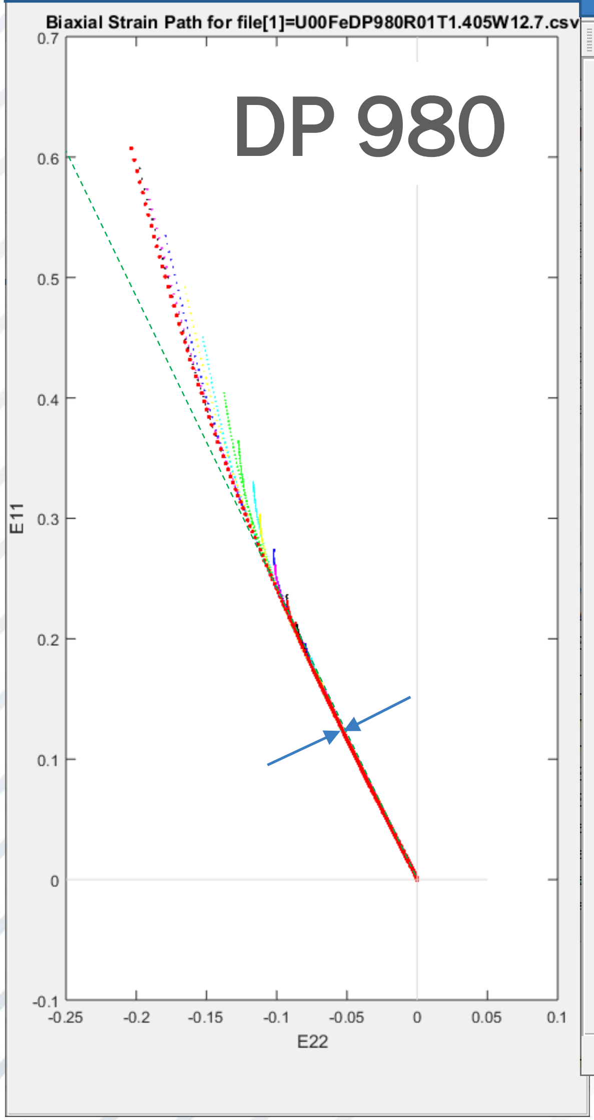
3) No noise in 201 Strain Paths → Insignificant error using the 0.5 m

4) R Value at 201 points provides material variation information

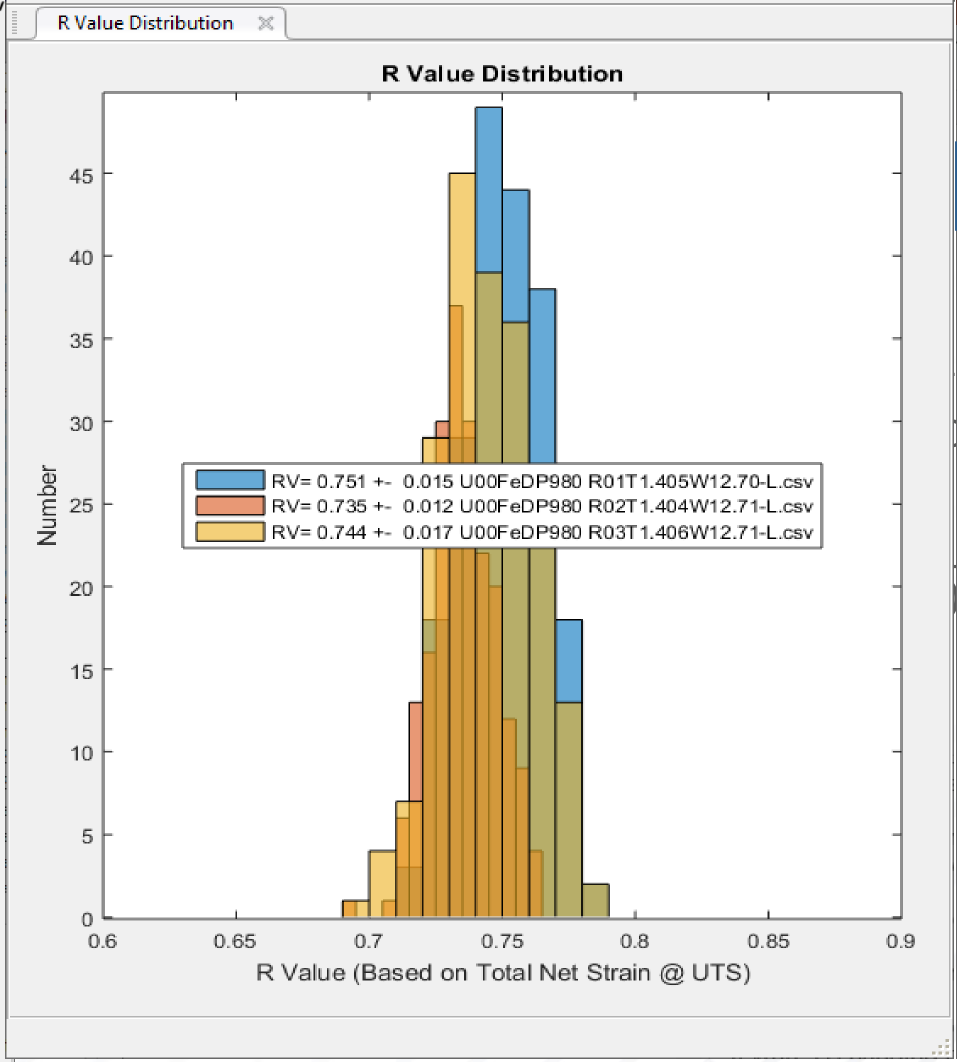


R VALUE MEASUREMENT

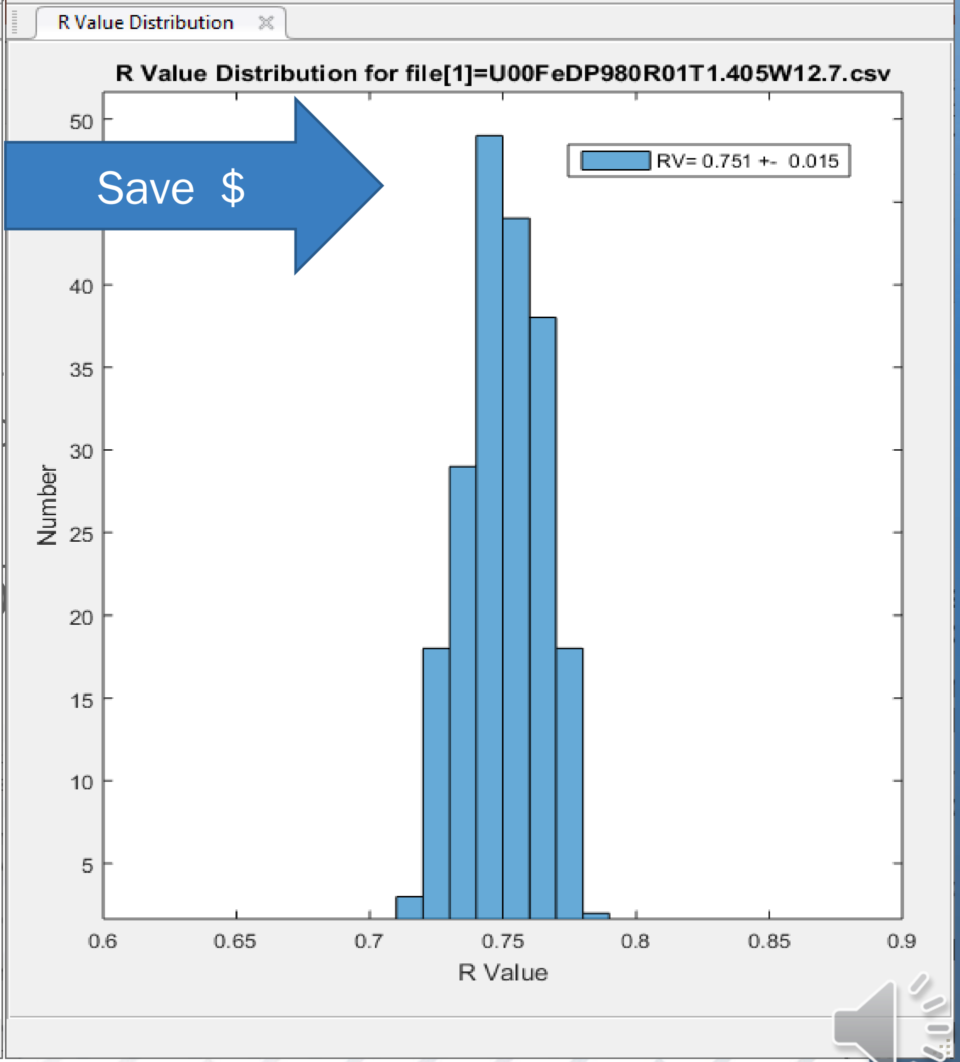
201 Strain Paths



3 Tests with 603 R Values



1 Test with 201 R Values



HOW TO BEST USE DIC

Standard Results

Multiple Points

1) Young's Modulus
2) Ultimate Tensile Strength
3) Uniform Elongation
4) **Hardening Behavior**
5) Total Elongation

Includes Width Strain Gauge

6) R Value
7) Poisson Ratio

Implicitly Includes Multiple Loading Conditions

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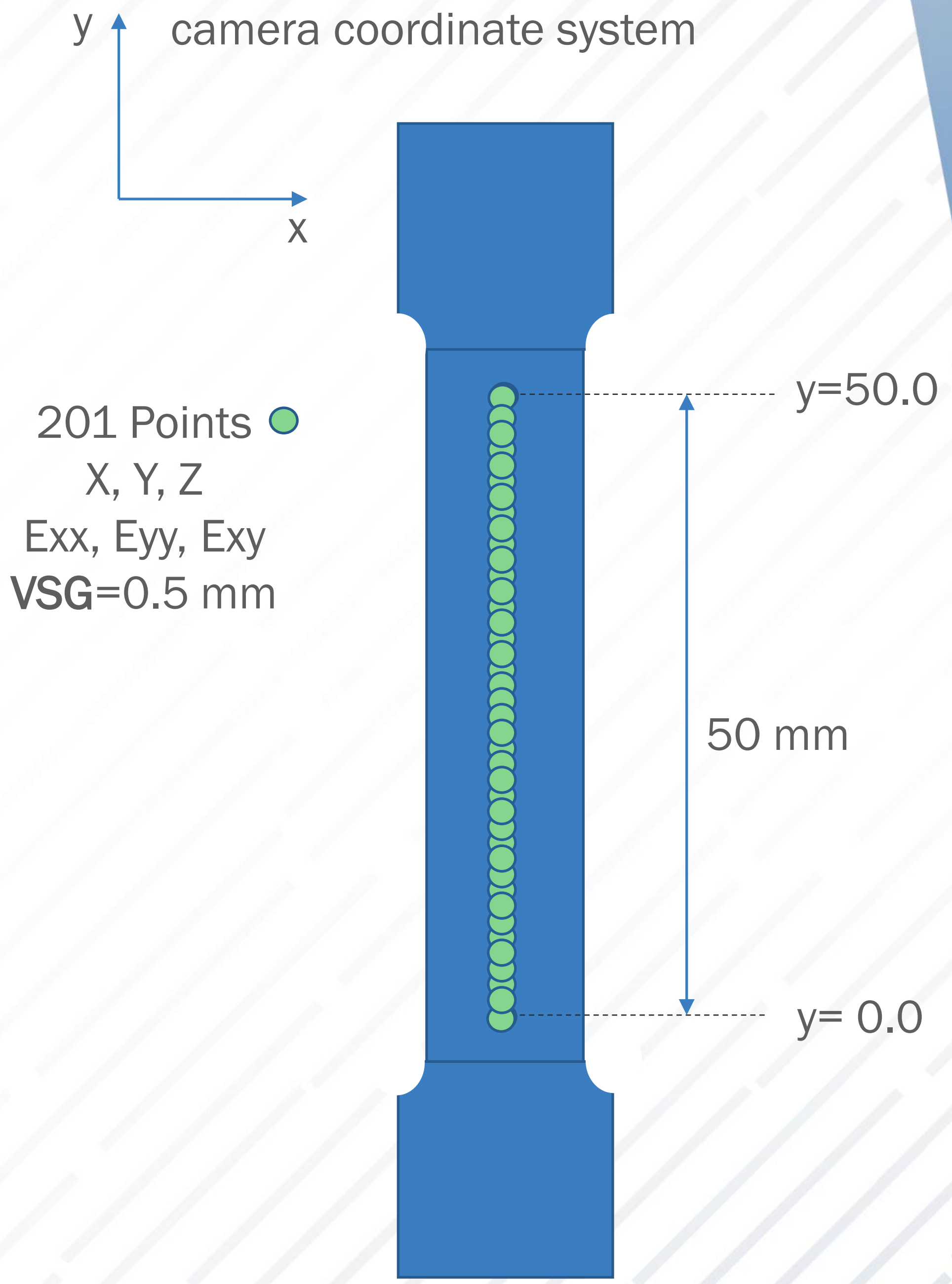
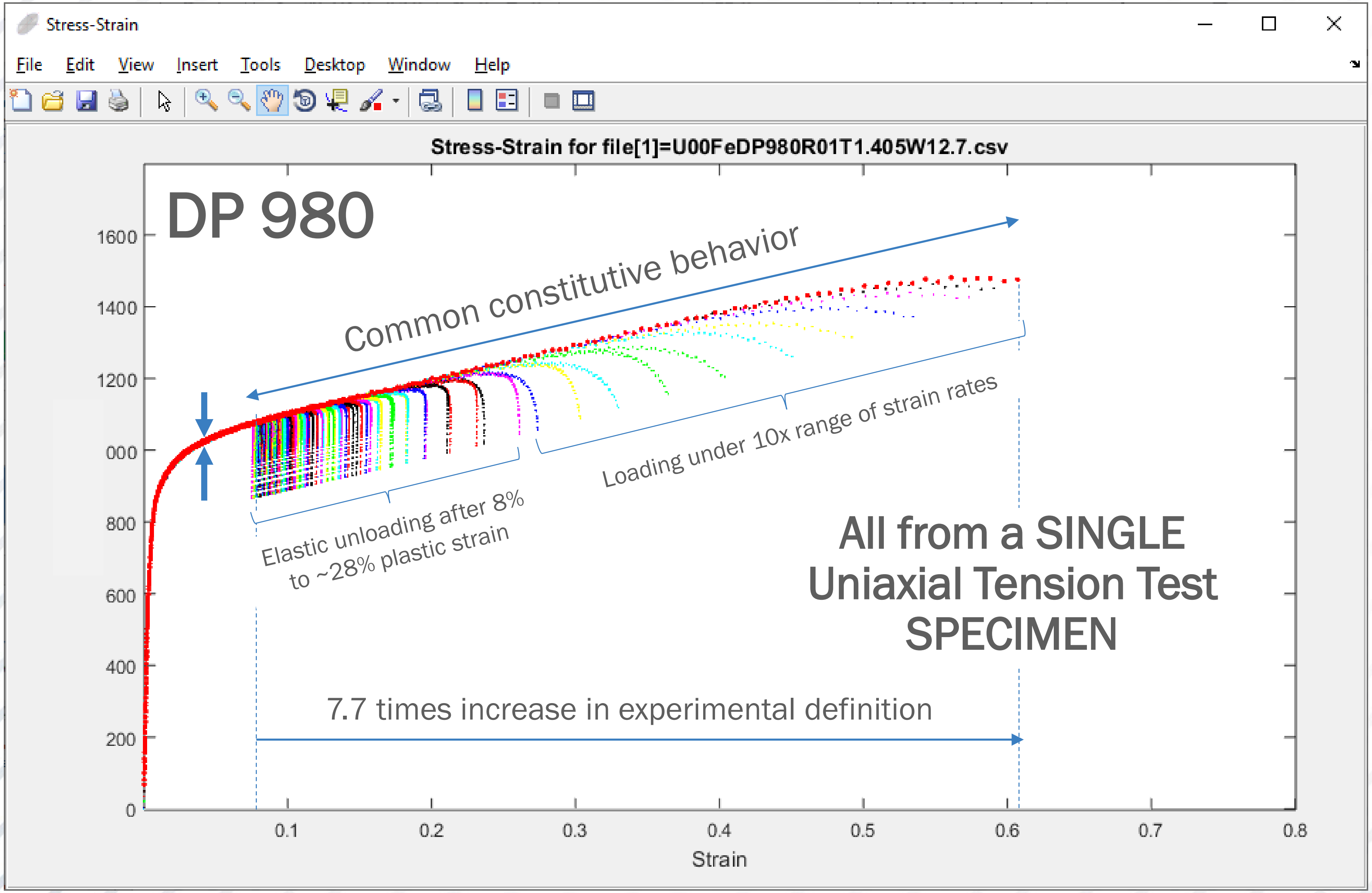
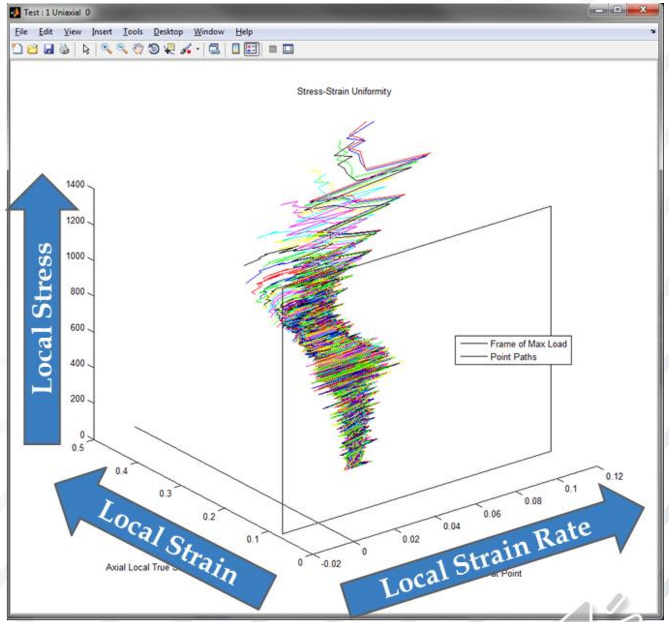


USEFUL INFORMATION BEYOND "UE"

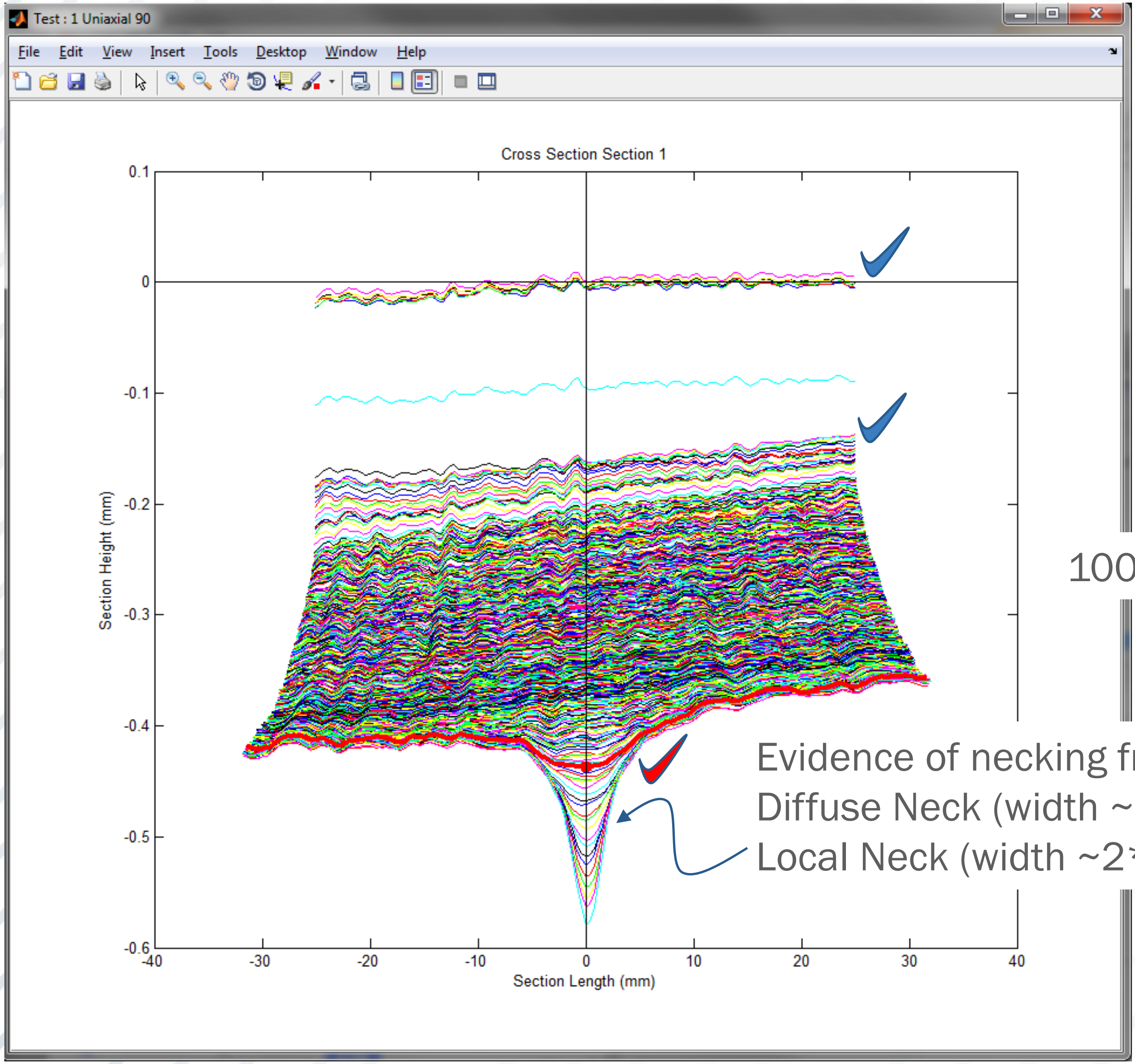


Benefits

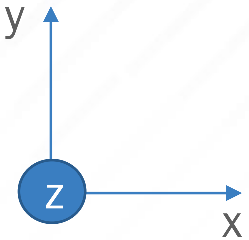
1) All 201 Points trace the 'same' hardening curve
2) Extends experimental curve from 8.2% engineering strain to ~61% true strain
3) Quantifies the degradation of the Elastic Modulus
4) Enables measurement of the m Value for strain rate sensitivity modeling
5) 'Same' hardening curve shows variation on hardening law parameters



DETECTION OF ONSET OF LOCALIZED NECKING



2 camera coordinate system



201 Points

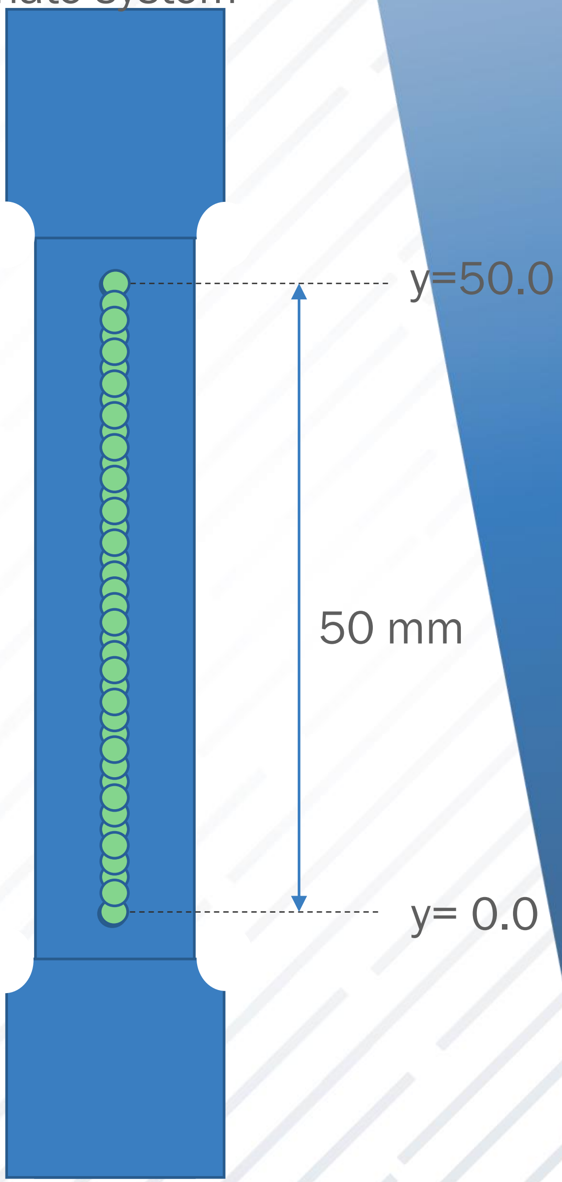
X, Y, Z

Exx, Eyy, Exy

VSG=0.5 mm

100x Magnified

Evidence of necking from a convolution of Diffuse Neck (width ~ 12 mm) with a Local Neck (width ~2*sheet thickness)



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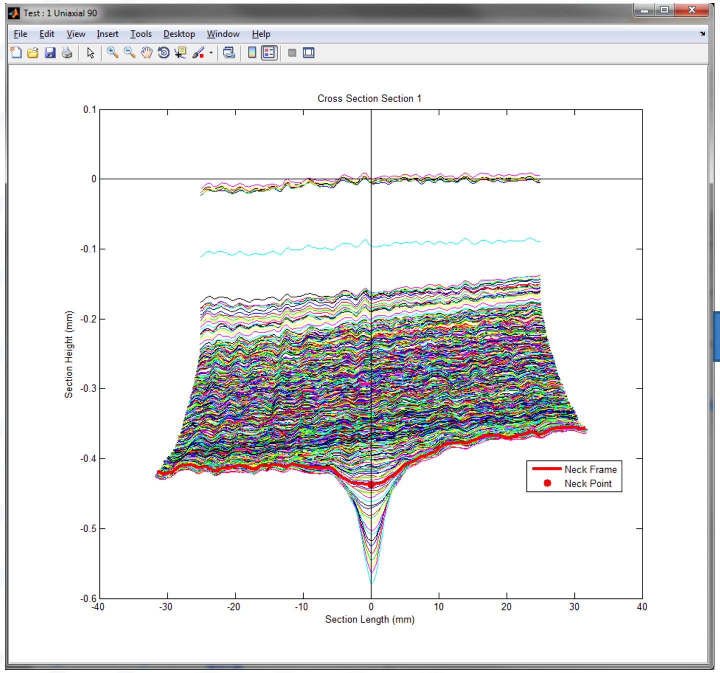

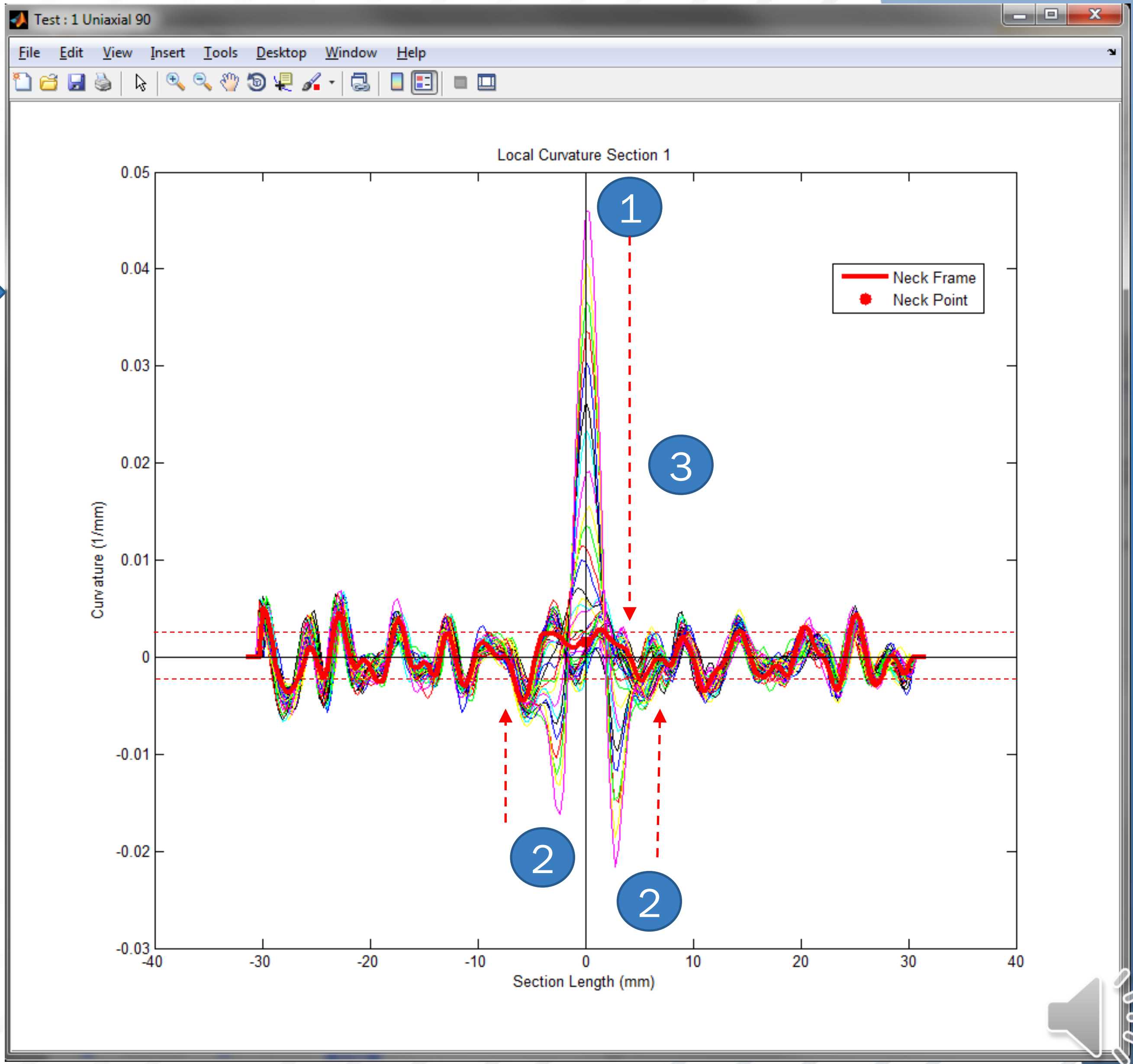

Signature of Localized Neck

1) One very high positive curvature at the valley of the candidate groove in the last DIC frame.

2) Two high NEGATIVE peak curvatures at a location within 2*sheet thickness of the location of the positive peak, corresponding to the two shoulders on the drop into the neck groove.

3) Rapid drop in the peak curvatures from frame to earlier frame to levels of curvature consistent with calculated curvatures at points outside the candidate groove (noise level).

CURRENT APPLICATIONS OF DIC TESTING

DIC technology has been aggressively and successfully applied to

- Uniaxial Tension Tests
  - ☑ Measure R Value to High Strain
    - ☑ Average
    - ☑ Std Deviation
    - ☑ Evolution
  - ☑ Measure Hardening Law to High Strain
    - ☑ Average
    - ☑ Std Deviation
    - ☑ Strain-Rate Sensitivity
    - ☑ Young's Modulus Degradation
  - ☑ Detect Onset of Localized Necking
    - ☑ Enables accounting of Nonlinear Strain Path Effect
- Bulge Tests
- Nakajima Tests
- Marciniak Tests
- Applying to other tests…

FUTURE

GDIS

1) Proposal to adopt industry standard for 2 Camera DIC Data Acquisition for all ASP and Supplier/OEM material testing

   - Propose application to all ‘standard’ tests
   - Propose ‘adaption’ to all non-standard tests

2) Methods undergoing testing/evaluation at CAL/NIST

3) Propose support of a National Database based on DIC Data

IN CLOSING…

The objective of simulation is to ELIMINATE physical testing…

Can we achieve this if we compromise
on the definition and calibration of our Material Models?

Can we achieve this if we compromise
on Material Testing?

ACKNOWLEDGEMENTS

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MARK IADICOLA, CAL/NIST
SANTE DICECCO, UNIVERSITY OF WATERLOO

FOR MORE INFORMATION

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THANK YOU

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SUPPORTING INFORMATION

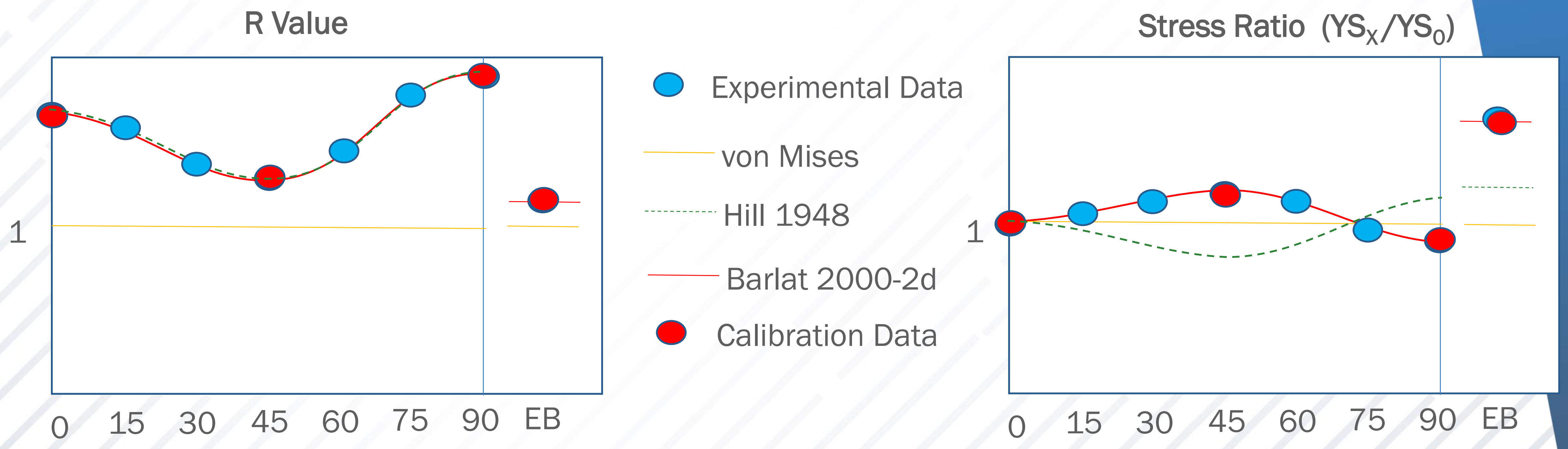
UNIAXIAL TENSION DATA FOR SIMULATION

1) Young's Modulus & Poisson Ratio ← Isotropic handbook values
   - Anisotropy of Elasticity ← Typical 10-20% variation affects spring-back proportionally
   - Degradation of YM with strain ← Requires load/unload/reload test
2) Proportional Limit (Elastic-to-Plastic Transition) ← 0.2% Offset Yield Stress
3) Hardening Law (True Stress vs Plastic Strain) ← YS, UTS, UE → K, n, e0
   - Extension beyond max load ← Needed if expecting to predict conditions up to fracture
   - Kinematic Hardening ← Requires tension-compression test
   - Anisotropic Hardening ← Requires tests in at least 3 loading orientations
   - Strain rate effects ← Requires jump test or multiple tests
4) R Value (Ratio of Plastic Strain Rates) ← based on Total NET Strain
5) Onset of Localized Necking ← Not detectable
6) Local Fracture Strain ← Not measured

HISTORY OF CONSTITUTIVE MODELS

The ultimate objective of simulation is to ELIMINATE physical testing…

Can we achieve this if we compromise
on the definition and calibration of our Material Models?



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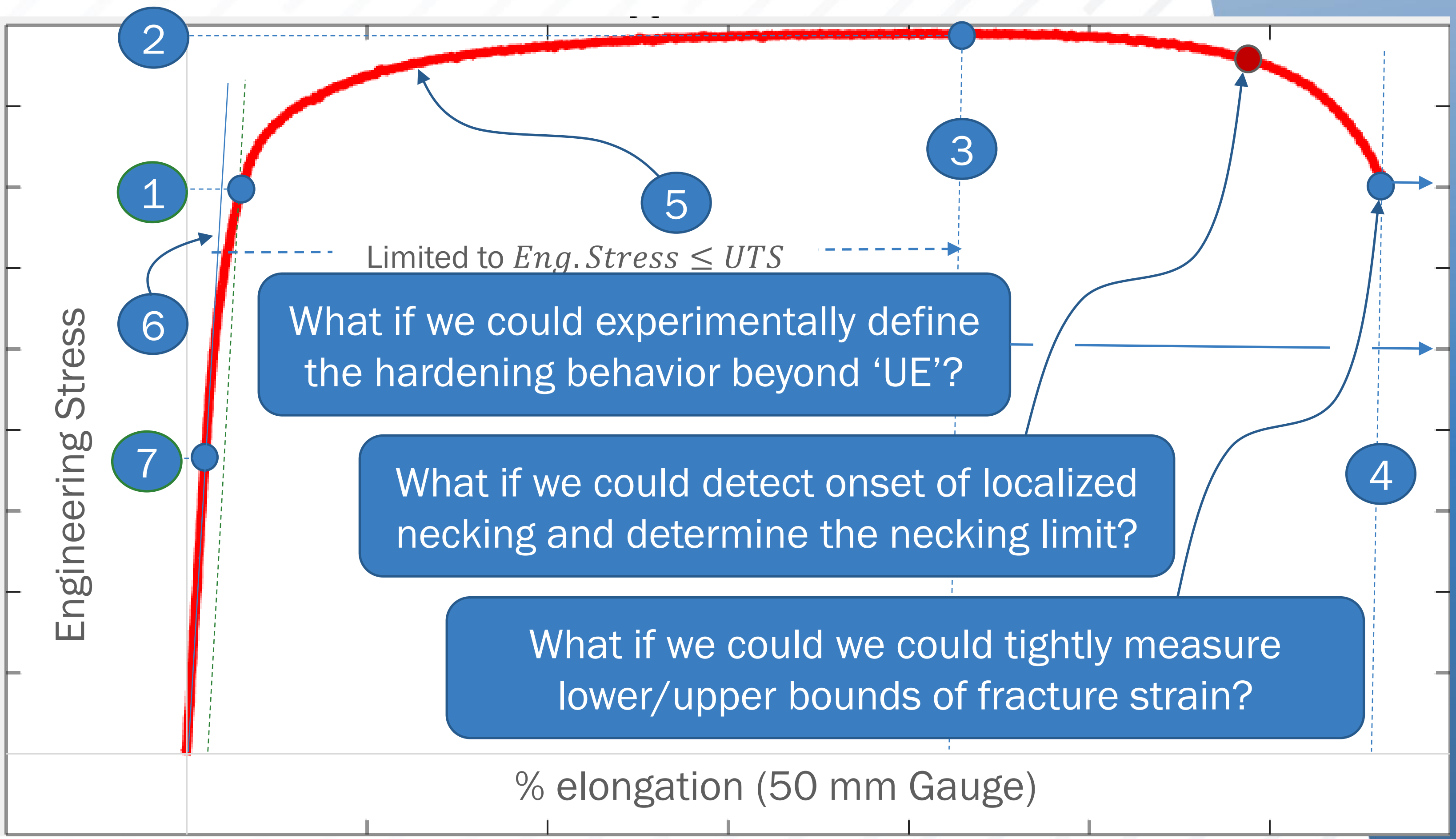
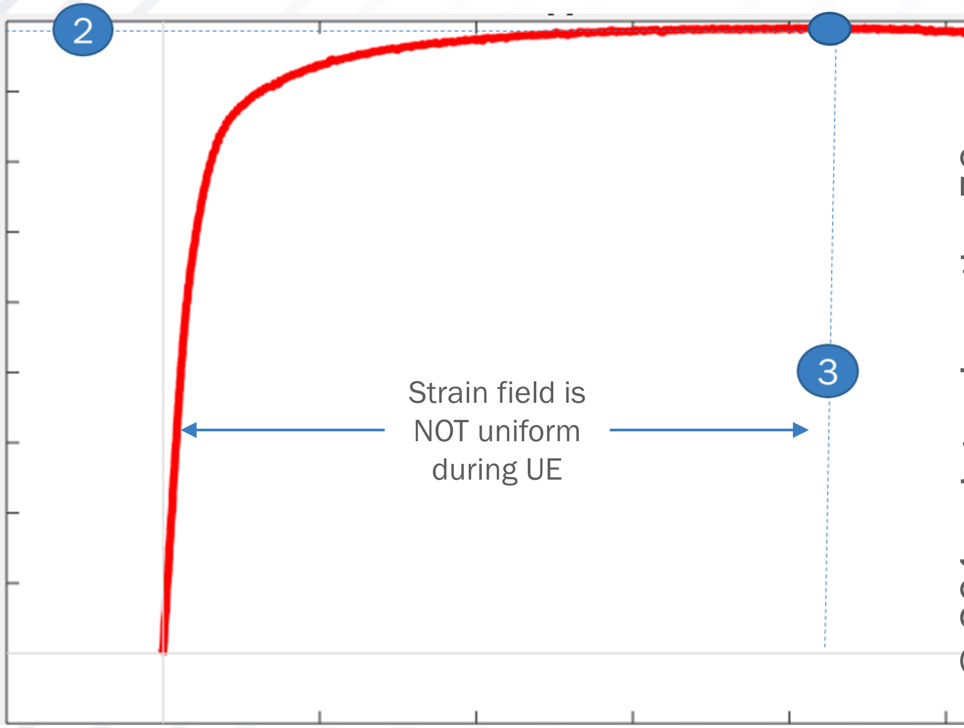


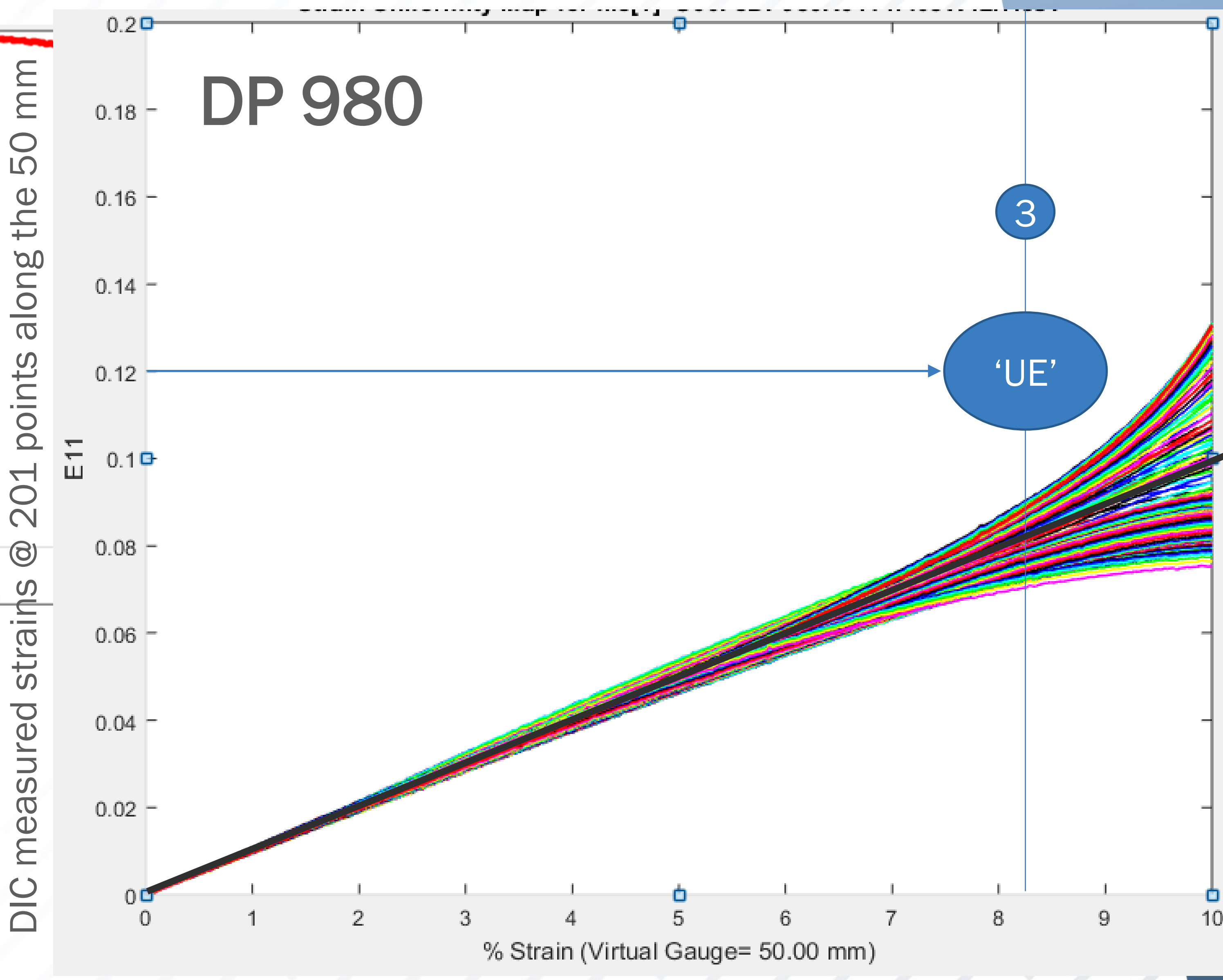
Additional Tension Tests

What if we could get a handle on this from a SINGLE Uniaxial Tension Test?

IS UNIFORM ELONGATION UNIFORM?



DIC Analysis Clearly Shows the Answer is NO



% Stretch of end points of a 50 mm Gauge

EXAMPLE OF CSV FILE CONTENT

	A	B	C	D	E	F
1	X [mm]	Y [mm]	Z [mm]	exx [1] - Hencky	eyy [1] - Hencky	exy [1] - Hencky
2	0.000	-25.000	0.019	0.00000	0.00000	0.00000
3	0.000	-25.001	0.018	-0.00009	-0.00002	-0.00009
4	-0.001	-25.000	0.020	-0.00002	0.00011	-0.00012
5	0.001	-24.998	0.019	0.00004	-0.00012	-0.00007
6	0.000	-24.999	0.017	-0.00026	-0.00020	-0.00011
7	0.000	-25.001	0.016	-0.00002	0.00000	-0.00004
8	0.000	-24.998	0.018	-0.00011	-0.00023	-0.00001
9	0.000	-25.000	0.019	0.00002	0.00002	-0.00006
10	0.000	-25.008	0.016	-0.00007	0.00003	-0.00004
11	0.001	-25.014	0.013	-0.00009	0.00015	-0.00017
12	0.000	-25.018	0.012	-0.00014	0.00021	-0.00010

1st of 201 Points...

	A	B	C	D	E	F
580	-0.06749	-31.9836	-0.04415	-0.0332459	0.0786817	-0.000278133
581	-0.06814	-31.9976	-0.04339	-0.0331969	0.0786263	-0.000335343
582	-0.07185	-32.0133	-0.04352	-0.0330825	0.0786386	-0.000235271
583	-0.07418	-32.0291	-0.03997	-0.0333873	0.0785958	-0.00036776
584	-0.07513	-32.0416	-0.04367	-0.033368	0.0784631	-0.000312553
585	-0.07954	-32.0598	-0.0395	-0.0332215	0.0783598	-0.000227205
586	-0.08045	-32.0748	-0.04288	-0.0331713	0.0782322	-0.000263781
587	-0.08527	-32.0915	-0.0449	-0.0333184	0.0784897	-0.000232748
588	-0.0849	-32.1053	-0.04264	-0.0331525	0.0783864	-0.000361529
589	-0.0867	-32.1204	-0.0467	-0.0330774	0.0782752	-0.000255177
590	-0.0921	-32.1386	-0.04722	-0.0331462	0.0782398	-0.000279237
591						

U00FeDP980_R01T1.405W12.70-L

...

ATJ	ATK	ATL	ATM	ATN	ATO	ATP	ATQ	ATR	ATS
- Henc	Count	Time_1	Time_0	Dev2/ai0	Dev2/ai1	Dev2/ai2	Dev2/ai3	acement_	Force_(kN)
75E-18	10	132.85	132.85	-2.536	0.0033	-0.0003	0.0004	-25.3598	0.033
00013	41	148.35	148.35	-2.535	0.0013	0.0004	-0.0006	-25.35	0.013
00012	42	148.85	148.85	-2.5353	-0.0009	-0.0006	-0.0013	-25.3533	-0.009
76E-05	43	149.35	149.35	-2.536	0.0017	-0.0003	-0.0013	-25.3598	0.017
00025	44	149.85	149.85	-2.5344	0.0072	0.0004	-0.0009	-25.3435	0.072
0E-05	45	150.35	150.35	-2.5334	0.0072	0	-0.0006	-25.3338	0.072
9E-05	46	150.85	150.85	-2.5347	-0.0019	-0.0003	-0.0003	-25.3468	-0.019
00013	47	151.35	151.35	-2.5344	0.0056	0	-0.0006	-25.3435	0.056
00018	48	151.85	151.85	-2.5334	0.0377	0	0	-25.3338	0.377
00014	49	152.60	152.60	-2.5334	0.0611	-0.0013	0.0004	-25.3338	0.611
00014	50	153.10	153.10	-2.5321	0.0883	-0.0006	0	-25.3208	0.883

Time, Load, Misc. Data

...

ATJ	ATK	ATL	ATM	ATN	ATO	ATP	ATQ	ATR	ATS
00024	618	673.20	673.20	-1.7913	1.5589	-0.0019	0.0007	-17.9127	15.589
00022	619	674.20	674.20	-1.7887	1.545	-0.0013	-0.0006	-17.8868	15.450
00028	620	675.20	675.20	-1.7877	1.5326	0.0004	-0.0003	-17.877	15.326
00028	621	676.20	676.20	-1.7861	1.5307	-0.0013	-0.0009	-17.8608	15.307
.0003	622	677.20	677.20	-1.7854	1.5096	-0.0003	-0.0003	-17.8543	15.096
00022	623	678.20	678.20	-1.7841	1.5083	-0.0006	0.0007	-17.8413	15.083
00026	624	679.20	679.20	-1.7822	1.4869	-0.0003	-0.0016	-17.8218	14.869
.0002	625	680.20	680.20	-1.7812	1.4781	-0.0009	0	-17.8121	14.781
7E-05	626	681.20	681.20	-1.7789	1.4645	-0.0009	-0.0013	-17.7894	14.645
00026	627	682.20	682.20	-1.7783	1.444	0.0004	-0.0003	-17.7829	14.440
00034	628	683.20	683.20	-1.7763	1.4349	-0.0003	-0.0009	-17.7634	14.349

PROPOSED DIC FILE NAMING CONVENTION

4 Part Multi-Character Suffix Code

U45Fe_DP1180_... _RnnnTt.tttWww.ww-L.csv

'-L' : File defines a section running down the longitudinal axis of the specimen; other recognized codes are '-S', '-R', '-T', and '-W'

Required ww.ww defines the gauge width of the uniaxial specimen

Required t.ttt defines the thickness of specimen to appropriate # of digits

nnn digits define the repeat test number ID (required when t.ttt is the same for 2 tests)

User defined material name (may include other details of the test in a complex DOE)

5 Character Prefix Code

1st Character : BUMNVCS Code : Bulge, Uniaxial, Marciniak, Nakajima, V-Bend, Cruciform, Shear
Character 2&3 : Two-digit angle of Major Loading Axis to the RD of the sheet
Character 4&5 : Chemical code of Primary Element (Fe, AL, or Mg)
(used to initialize elastic properties to improve automation of the elastic fitting)