Sensitivity of Nitinol Fatigue Strain to Material Inputs in Finite Element Analysis

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Lessons

1. For surrogate specimen tests, strain limit diagram (SLD) points depend on FEA to relate displacement to strain

2. Small variations in FEA material calibration can result in large changes to strains

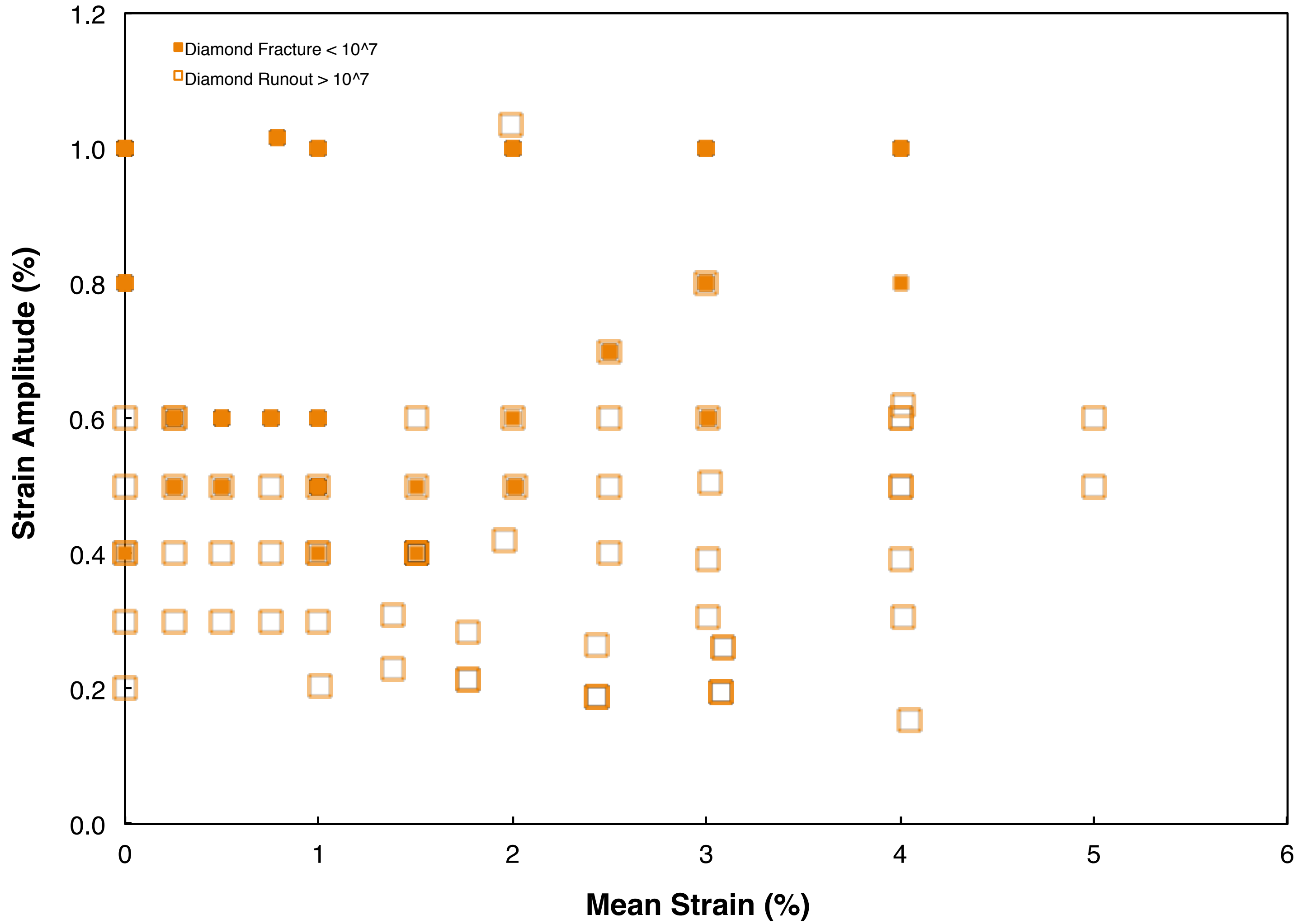
3. Results are especially sensitive to E_A and UP-LP

4. It is important to use multiple samples to calibrate material inputs

5. Surrogate specimen experience a wide range of stress and strain, and some target SLD conditions can not be achieved

6. Pre-strain may be an important additional dimension to consider when analyzing fatigue

Strain Limit Diagram (SLD)



Pelton, A. R. (2011). Nitinol Fatigue: A Review of Microstructures and Mechanisms. Journal of Materials Engineering and Performance, 20(4-5), 613–617. doi:10.1007/s11665-011-9864-9

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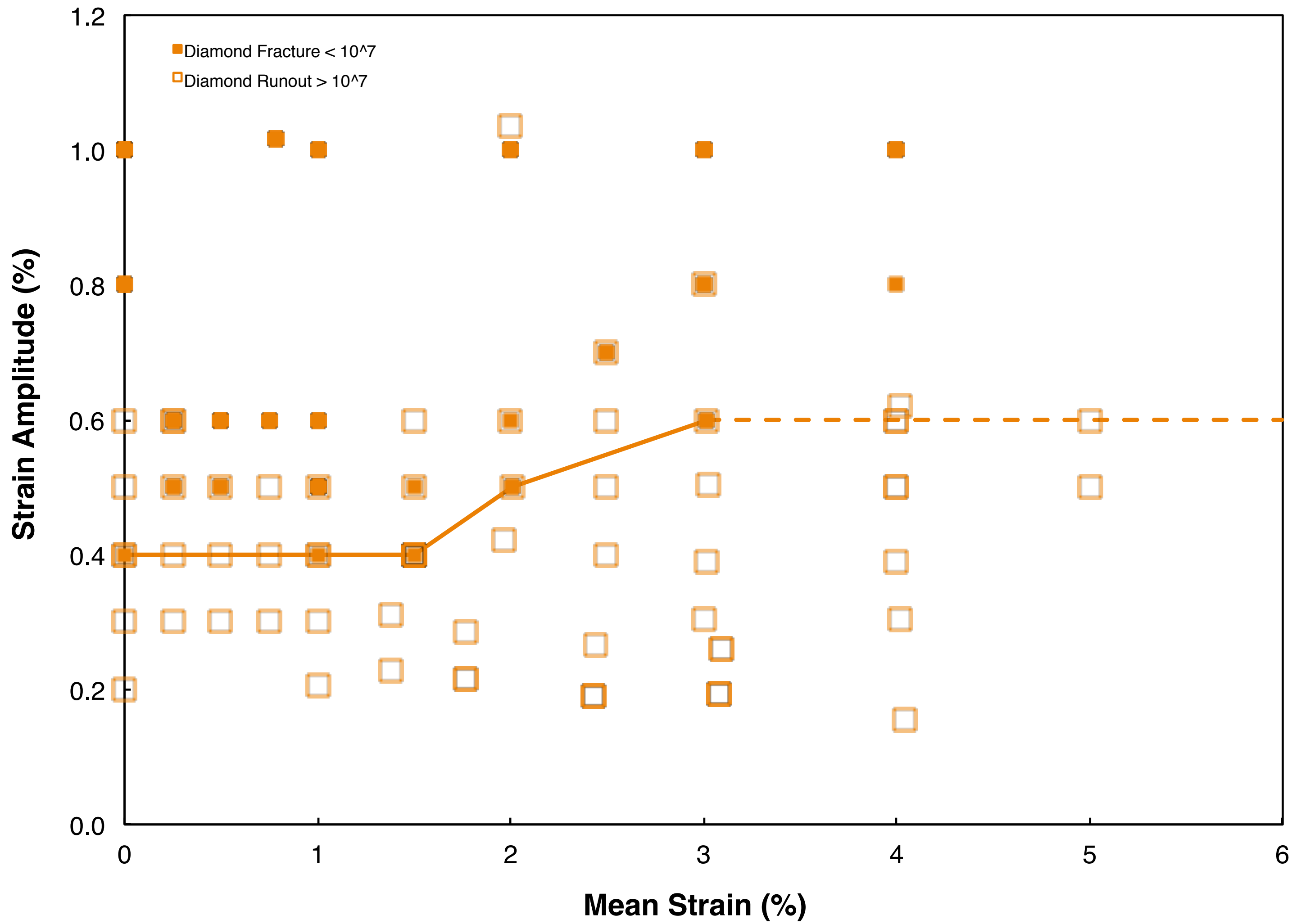

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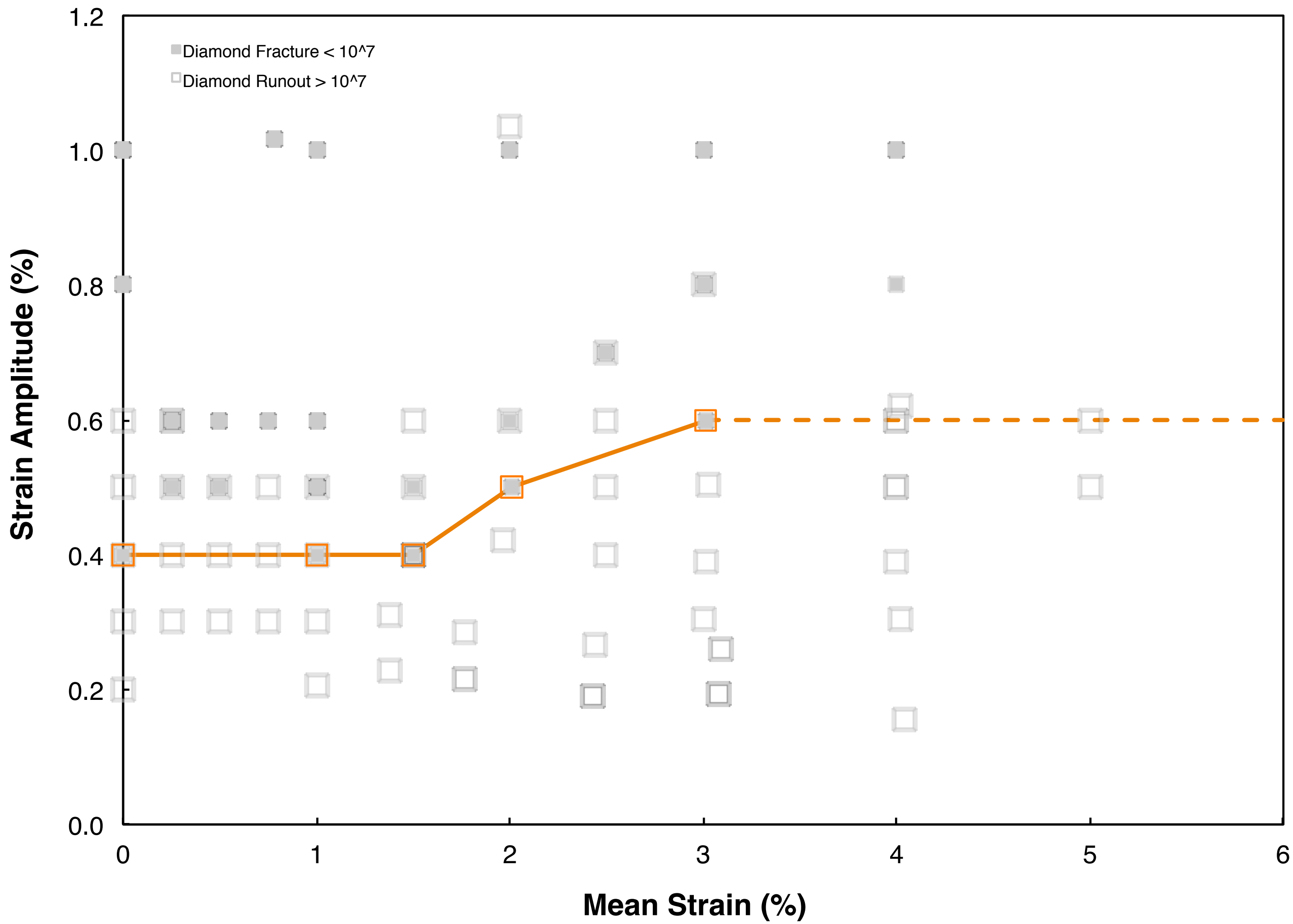
Strain Limit Threshold



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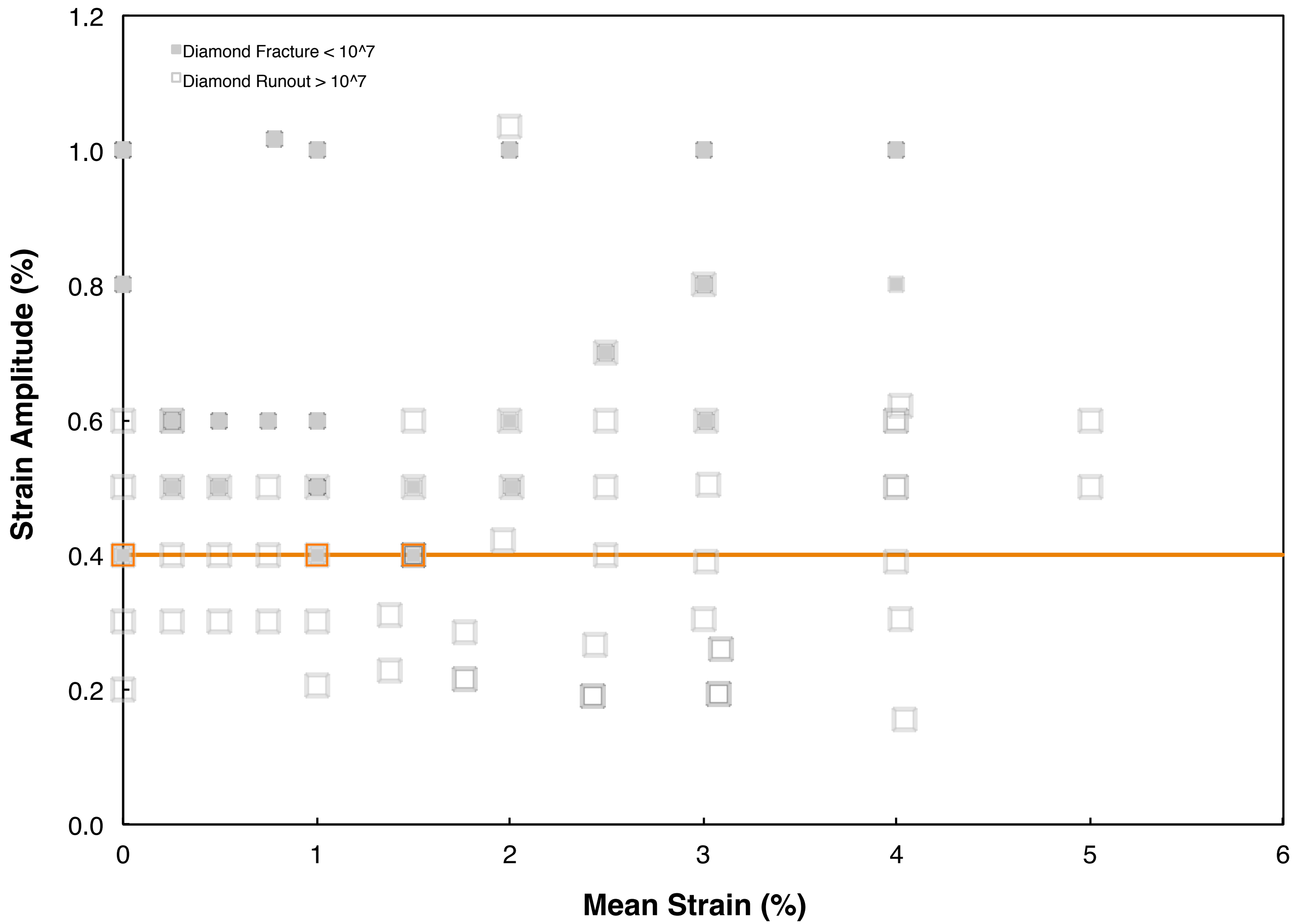

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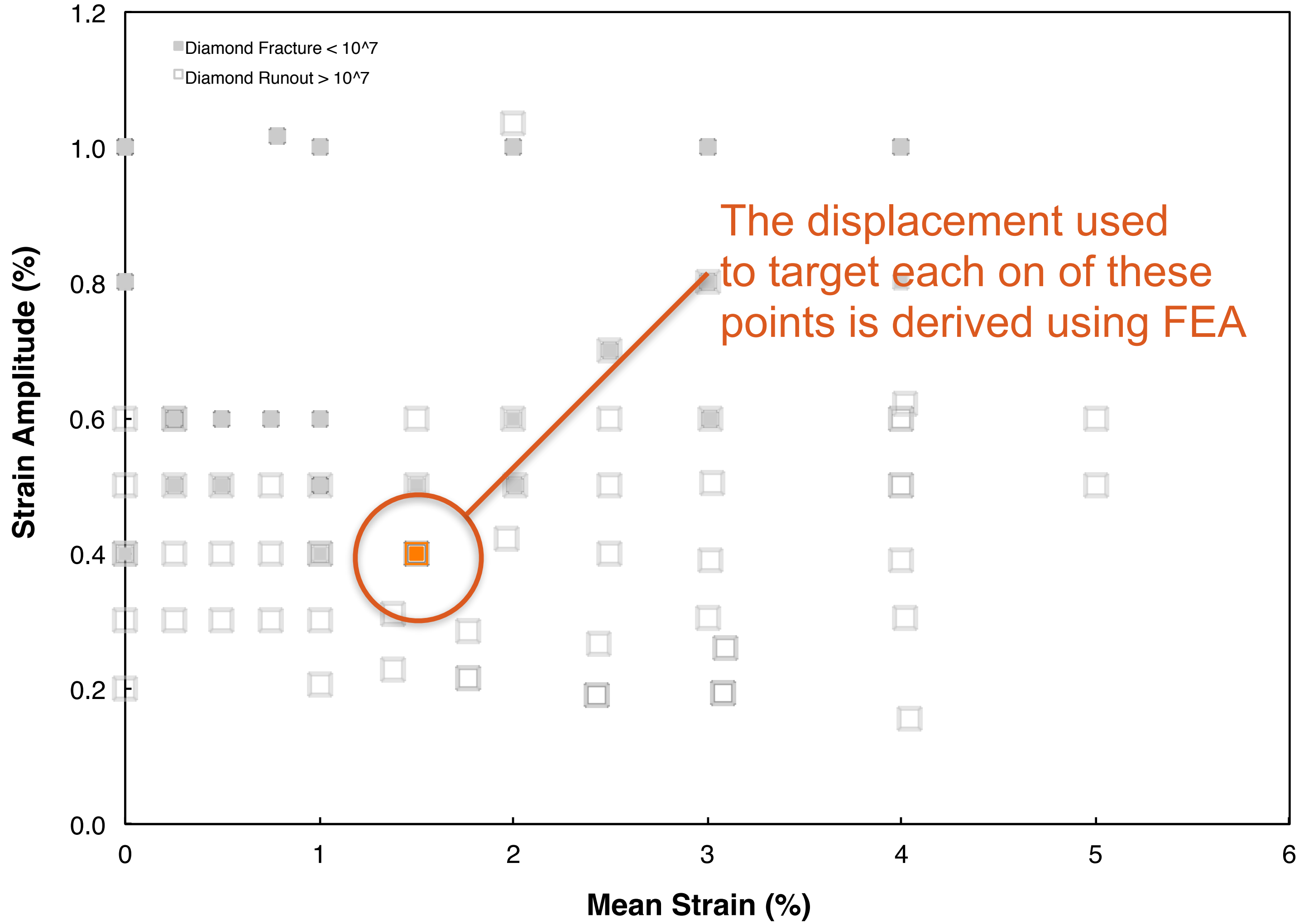
Strain Limit Point

*The SLD fatigue threshold is driven by **strain amplitude***



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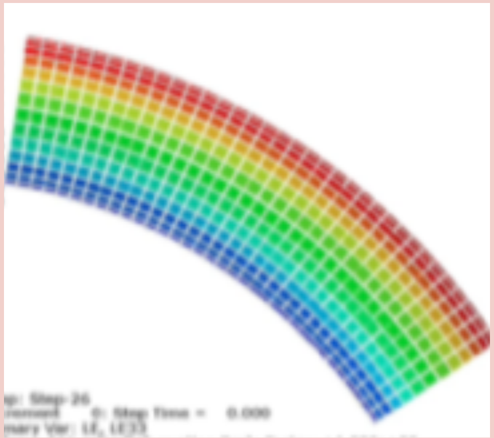
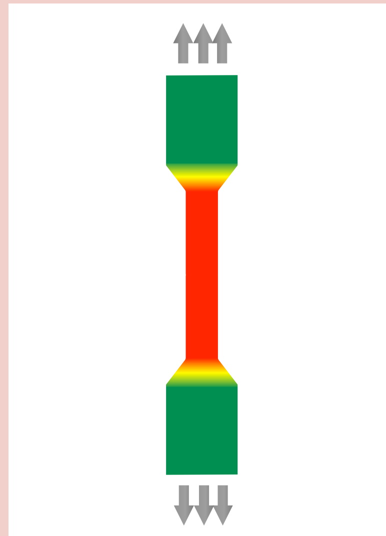
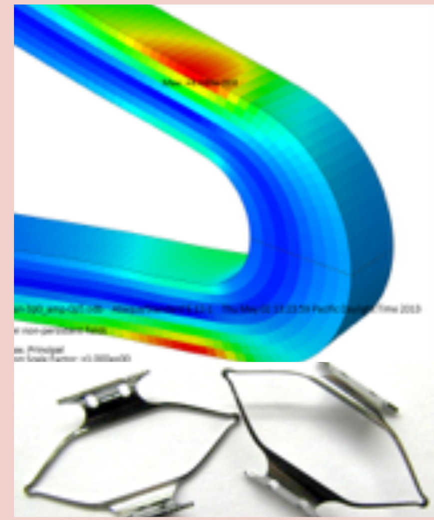
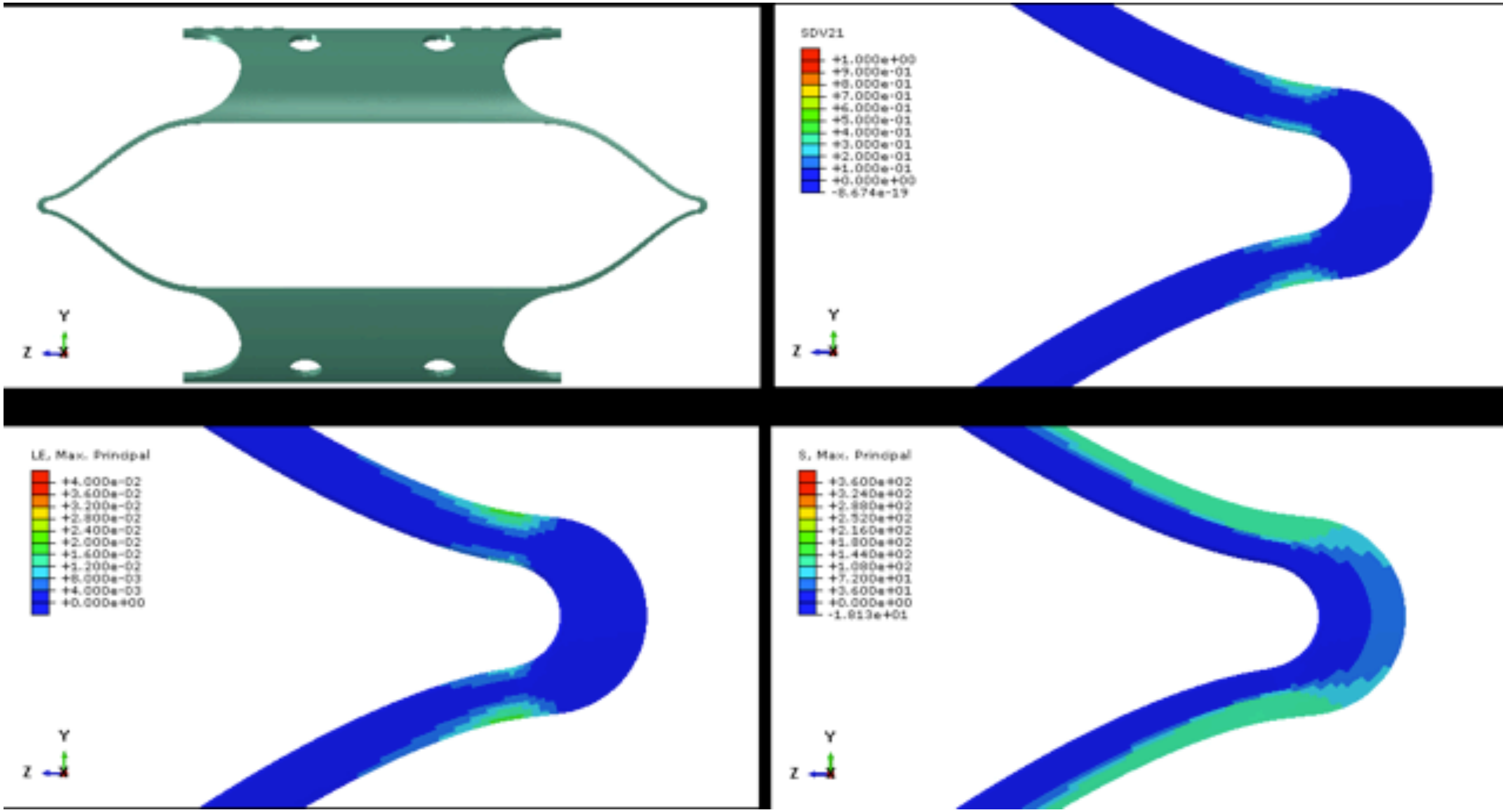
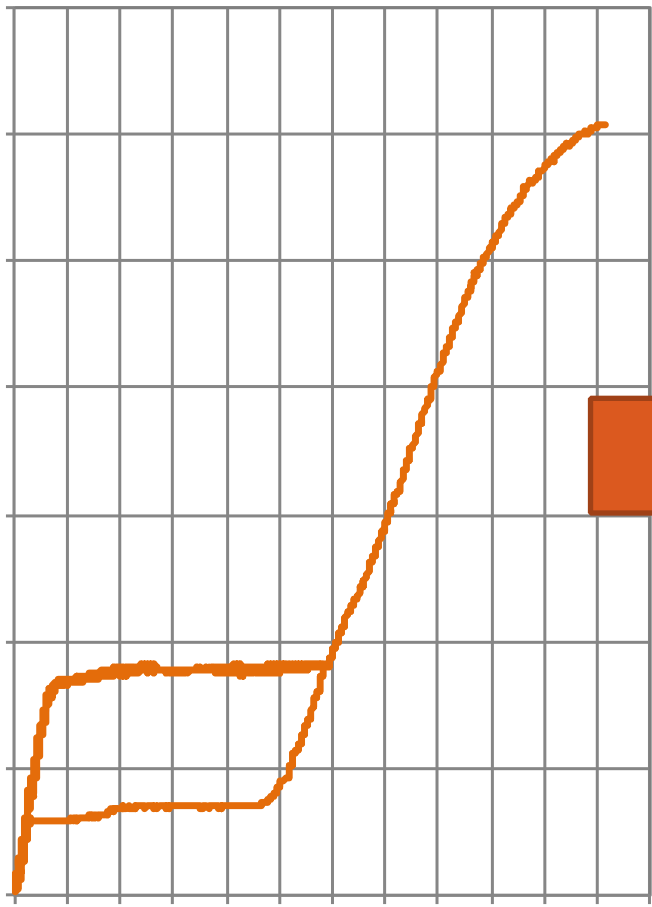
Surrogare specimen testing relies upon FEA

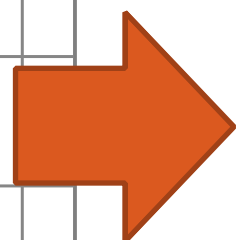
rotary bend	tensile specimen	surrogate specimen
		
tensile/compressive fully reversed	uniform tension-tension	complex: tension, compression, bending
not representative of typical devices	conservative; entire gage volume at same σ-ε	realistic; localized volume at critical σ-ε
σ-ε easily calculated	σ-ε easily calculated	**σ-ε requires FEA**

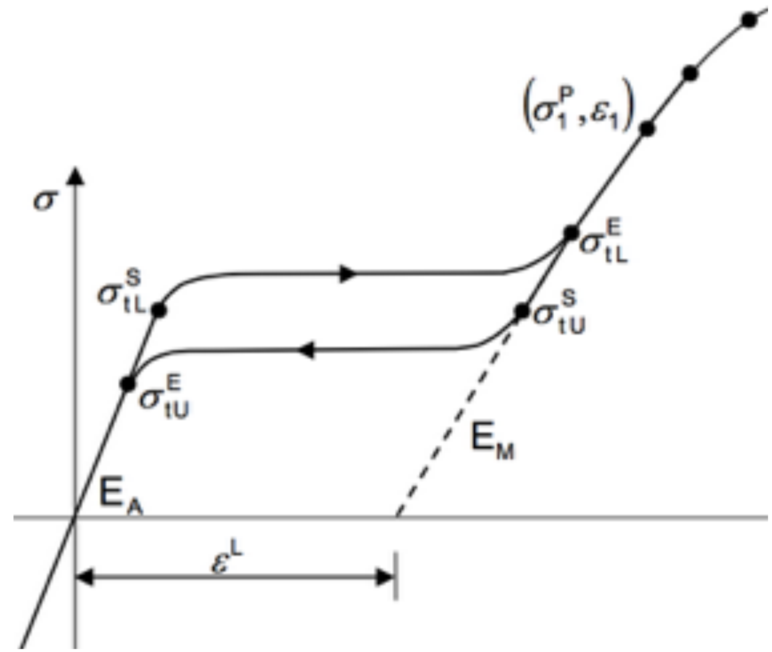
Surrogate specimen: *Crosshead displacements for each targeted σ-ε condition are derived using iterative FEA*



FEA material properties: *Uniaxial tension testing results are used to define UMAT input parameters*





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*User Material, constants=26, unsymm
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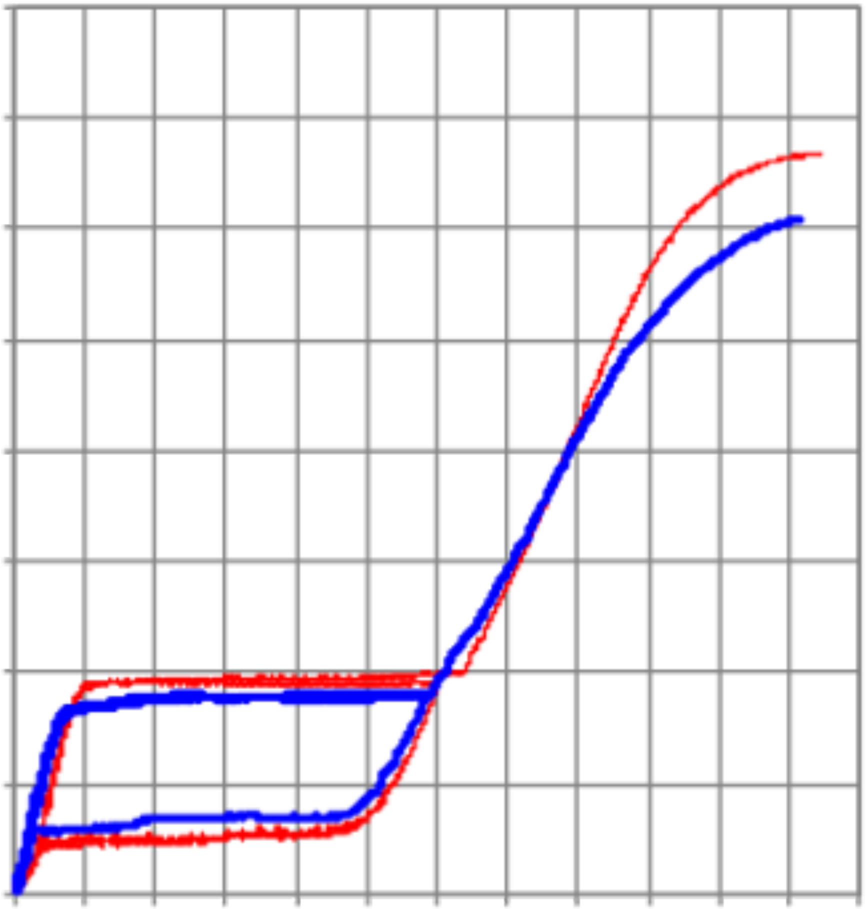
   37.,   7.8,  120.,   90.,  480., 0.041,    0.,    5.
 1002., 0.088, 1090., 0.094, 1174.,   0.1, 1229.,  0.11
 1260.,  0.12
```

Variation in the DATA or the MODEL will influence σ-ε points

Lessons

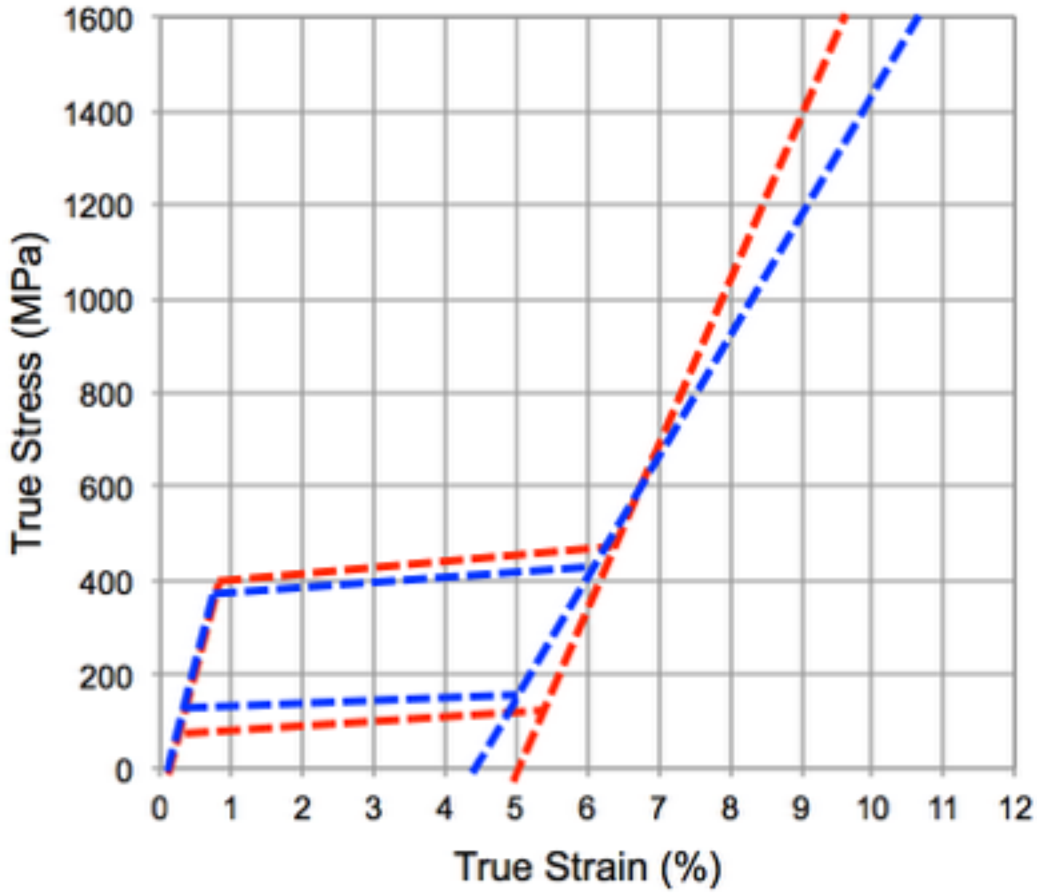
1. **For surrogate specimen tests, strain limit diagram (SLD) points depend on FEA to relate displacement to strain**
2. Small variations in FEA material calibration can result in large changes to strains
3. Results are especially sensitive to E_A and UP-LP
4. It is important to use multiple samples to calibrate material inputs
5. Surrogate specimen experience a wide range of stress and strain, and some target SLD conditions can not be achieved
6. Pre-strain may be an important additional dimension to consider when analyzing fatigue

Uniaxial test results from two material samples



- Same composition
- Same specification
- Different supplier
- Similar results

Extracting σ-ε points from material data

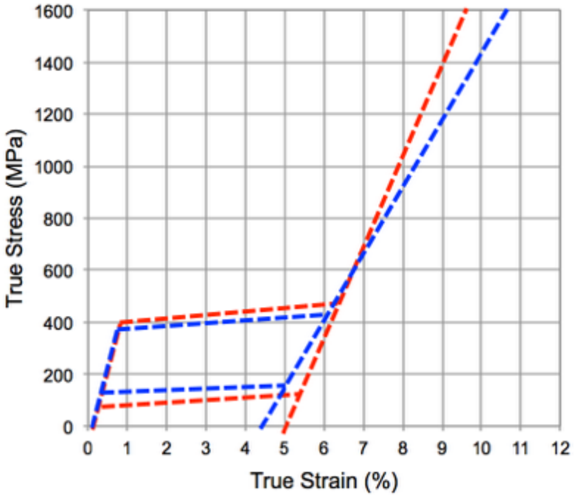


Comparing red to blue

- E_A equivalent
- E_M shifted down
- UP shifted up
- LP shifted down

Small shifts in extracted values

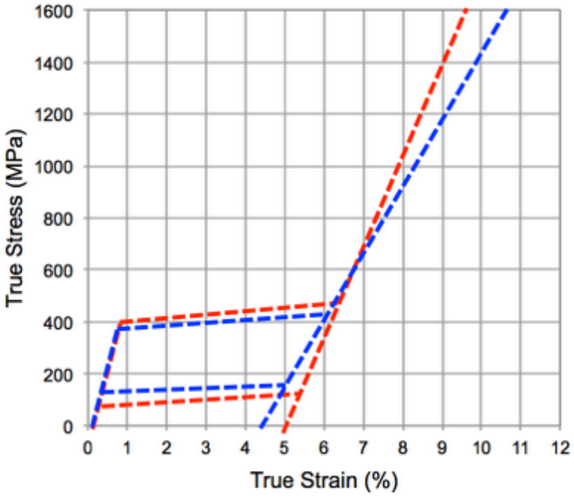
20-30% shifts in stress and martensite unloading modulus



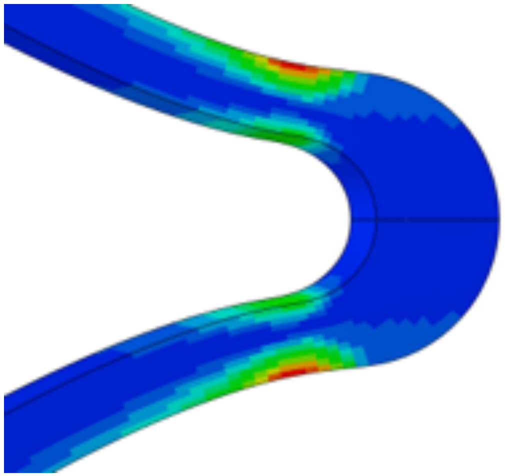
	Lot 1	Lot 2	|L2-L1|	$\frac{L2-L1}{½(L2+L1)}$
UP (MPa)	430	400	⬇30	⬇7%
LP (MPa)	105	150	⬆45	⬆35%
UP-LP (MPa)	325	250	⬇75	⬇26%
E_M (GPa)	35	26	⬇9	⬇30%

Strain amplitude prediction changes by 70%!

stress, modulus shifts of 20-30% are significantly amplified



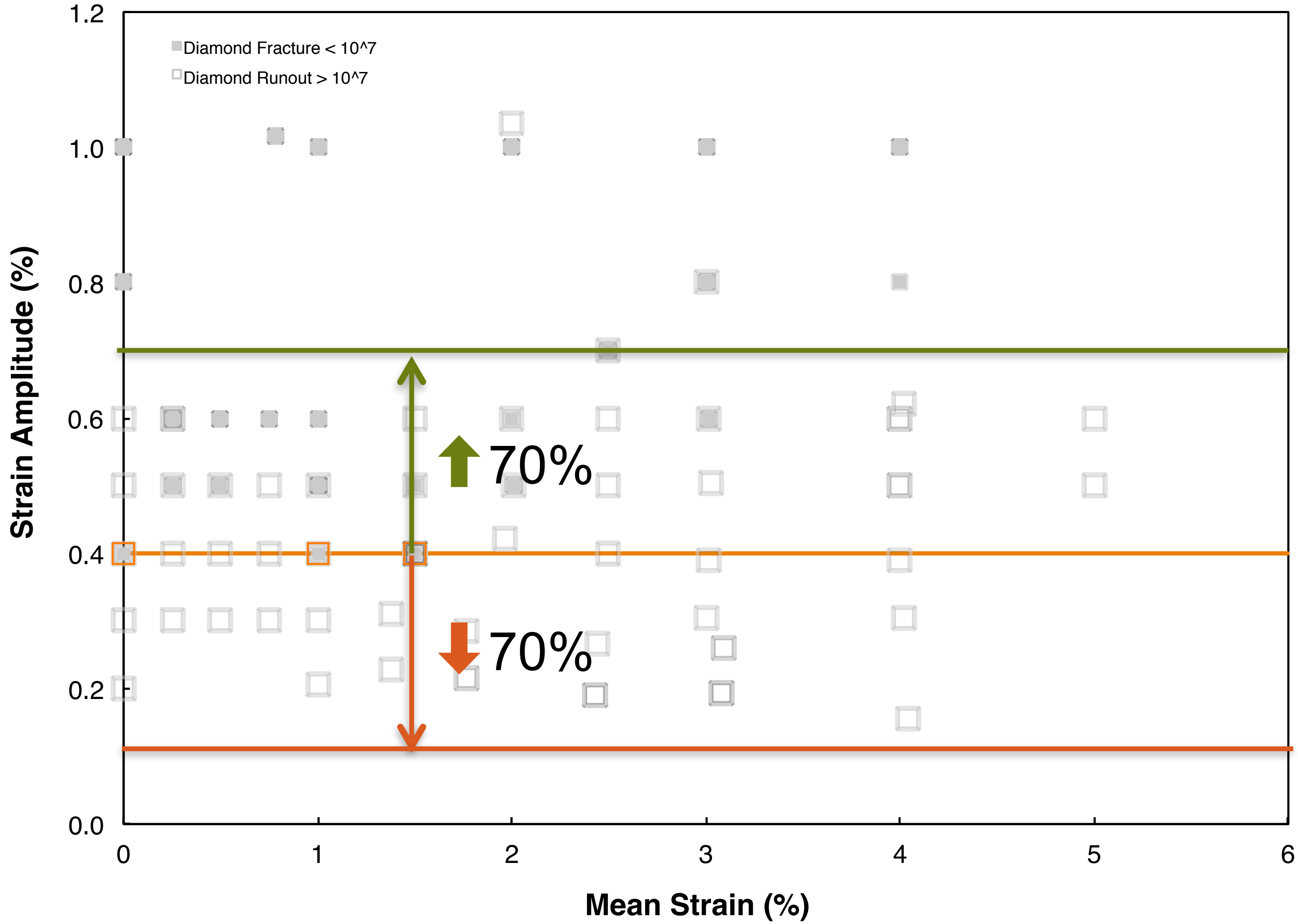
	Lot 1	Lot 2	|L2-L1|	L2-L1 / ½(L2+L1)
UP (MPa)	430	400	↓30	↓7%
LP (MPa)	105	150	↑45	↑35%
UP-LP (MPa)	325	250	↓75	↓26%
E_M (GPa)	35	26	↓9	↓30%



	Lot 1	Lot 2	|L2-L1|	L2-L1 / ½(L2+L1)
Strain Amplitude	0.0042	0.0087	↑0.0045	↑70%

Implications to SLD threshold

Could our fatigue limit threshold points by wrong by ±70%?



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Let's consider two potential sources of variability

Suspect #1

The Model

Sensitivity of σ-ε results to Abaqus UMAT parameters

Suspect #2

The Data

Sensitivity of σ-ε results to variation in tensile test results and interpretation of parameters

Suspect #1: The Model

- Completed 12+ FEA simulations of a diamond surrogate.
- Cyclic displacements fixed to target: **3.00% ± 1.00%** in baseline model.
- Varied model inputs:
  $\pm E_A$, $\pm E_M$, ±UP, ±LP, ±UPΔLD
- Measured sensitivity of:
  ε_{mean}, $\boldsymbol{\varepsilon_{amp}}$, σ_{mean}, σ_{amp}

Suspect #1: The model

12+ models varying material input parameters

	condition	E_A	E_M	ε_L	σ^L_s	σ^L_e	σ^U_s	σ^U_e	UP-LP
1	E_M = 25, baseline	49,230	25,000	0.041	320	380	150	120	215
2	E_M = 45, +80%	49,230	**45,000**	0.041	320	380	150	120	215
3	E_M = 35, +40%	49,230	**35,000**	0.041	320	380	150	120	215
4	E_M = 15, -40%	49,230	**15,000**	0.041	320	380	150	120	215
5	E_A = 39, -20%	**39,000**	25,000	0.041	320	380	150	120	215
6	E_A = 59, +20%	**59,000**	25,000	0.041	320	380	150	120	215
7	UP-LP = 155, -28%	49,230	25,000	0.041	**290**	**350**	**180**	**150**	**155**
8	UP-LP = 275, +28%	49,230	25,000	0.041	**350**	**410**	**120**	**90**	**275**
9	σ^L_s= 350, +9%	49,230	25,000	0.041	**350**	**410**	**180**	**150**	**215**
10	σ^L_s= 290, -9%	49,230	25,000	0.041	**290**	**350**	**120**	**90**	**215**
11	σ^U_s= 180, +20%	49,230	25,000	0.041	320	380	**180**	**150**	**185**
12	σ^U_s = 120, -20%	49,230	25,000	0.041	320	380	**120**	**90**	**245**

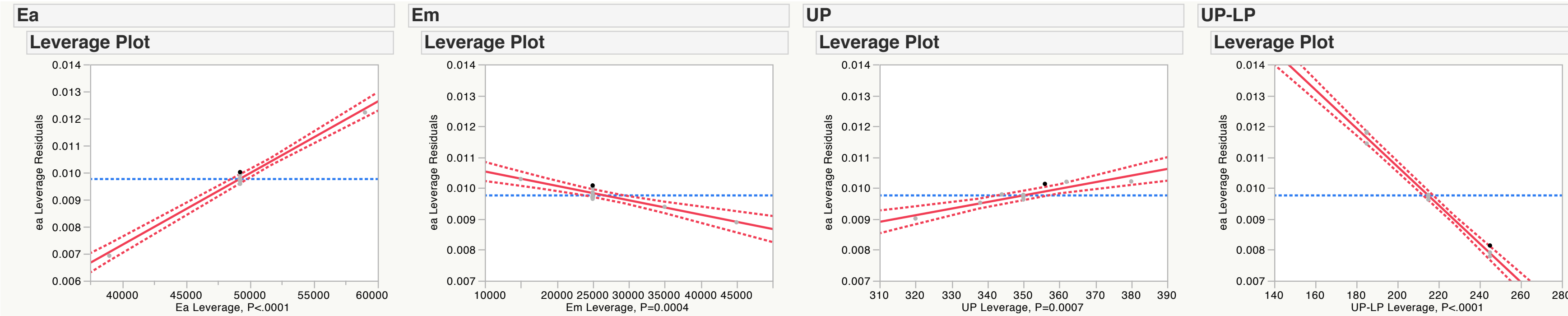
Suspect #1: The model

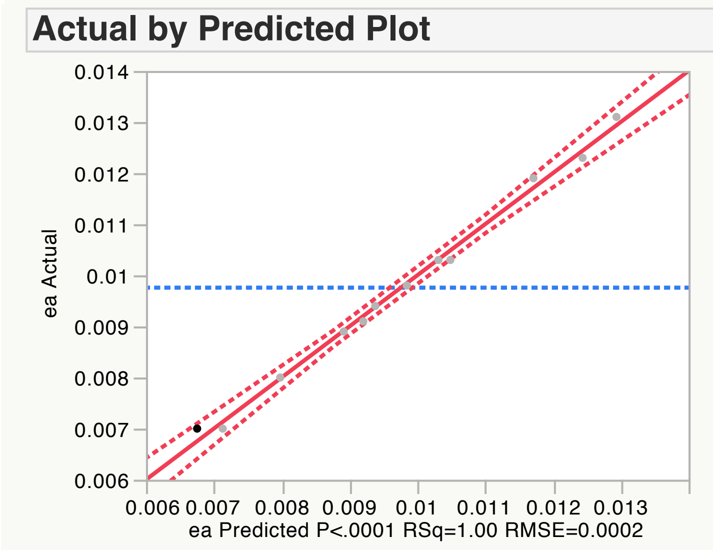
Selected results for each condition

	condition	ε_{mean}	$\varepsilon_{amplitude}$	σ_{mean}	$\sigma_{amplitude}$
1	E_M = 25, baseline	0.030	**0.010**	409	164
2	E_M = 45, +80%	0.030	**0.009**	413	171
3	E_M = 35, +40%	0.030	**0.009**	411	168
4	E_M = 15, -40%	0.030	**0.010**	408	161
5	E_A = 39, -20%	0.021	**0.007**	389	155
6	E_A = 59, +20%	0.037	**0.012**	422	169
7	UP-LP = 155, -28%	0.027	**0.013**	466	149
8	UP-LP = 275, +28%	0.032	**0.007**	357	181
9	σ^L_s= 350, +9%	0.026	**0.010**	403	148
10	σ^L_s= 290, -9%	0.034	**0.009**	417	182
11	σ^U_s= 180, +20%	0.027	**0.012**	432	147
12	σ^U_s = 120, -20%	0.033	**0.008**	383	182

Suspect #1: The model

Least squares regression for sensitivity of strain amplitude





Term	Estimate	Std Error	t Ratio	Prob>|t|
UP-LP	-6.222e-5	2.344e-6	-26.55	<.0001*
Ea	2.6531e-7	1.218e-8	21.79	<.0001*
Em	-4.654e-8	7.235e-9	-6.43	0.0004*
UP	2.1389e-5	3.706e-6	5.77	0.0007*

$$\varepsilon_a = 3.84\cdot 10^{-3} + \left(2.65\cdot 10^{-7}\cdot E_A\right) - \left(4.65\cdot 10^{-8}\cdot E_M\right) + \left(2.14\cdot 10^{-5}\cdot UP\right) + \left(6.22\cdot 10^{-5}\cdot UP\Delta LP\right)$$

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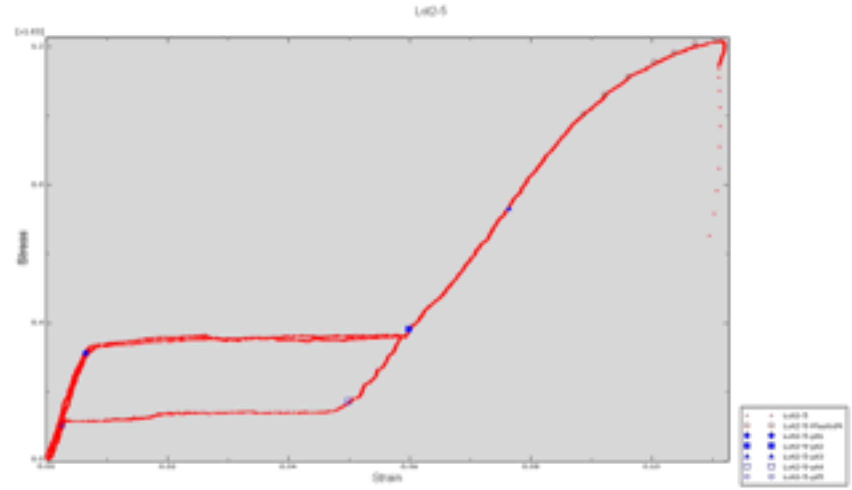
Suspect #2: The Data

- Variability in test results
  - Variation in material properties, test, or samples
  - n=5 tests for Lot 1
  - n=5 tests for Lot 2
- Variability in calibration
  - Variation in selection of points from tensile results
  - UMAT parameter extraction repeated 5 times for each test
- Total of 50 UMAT parameter sets



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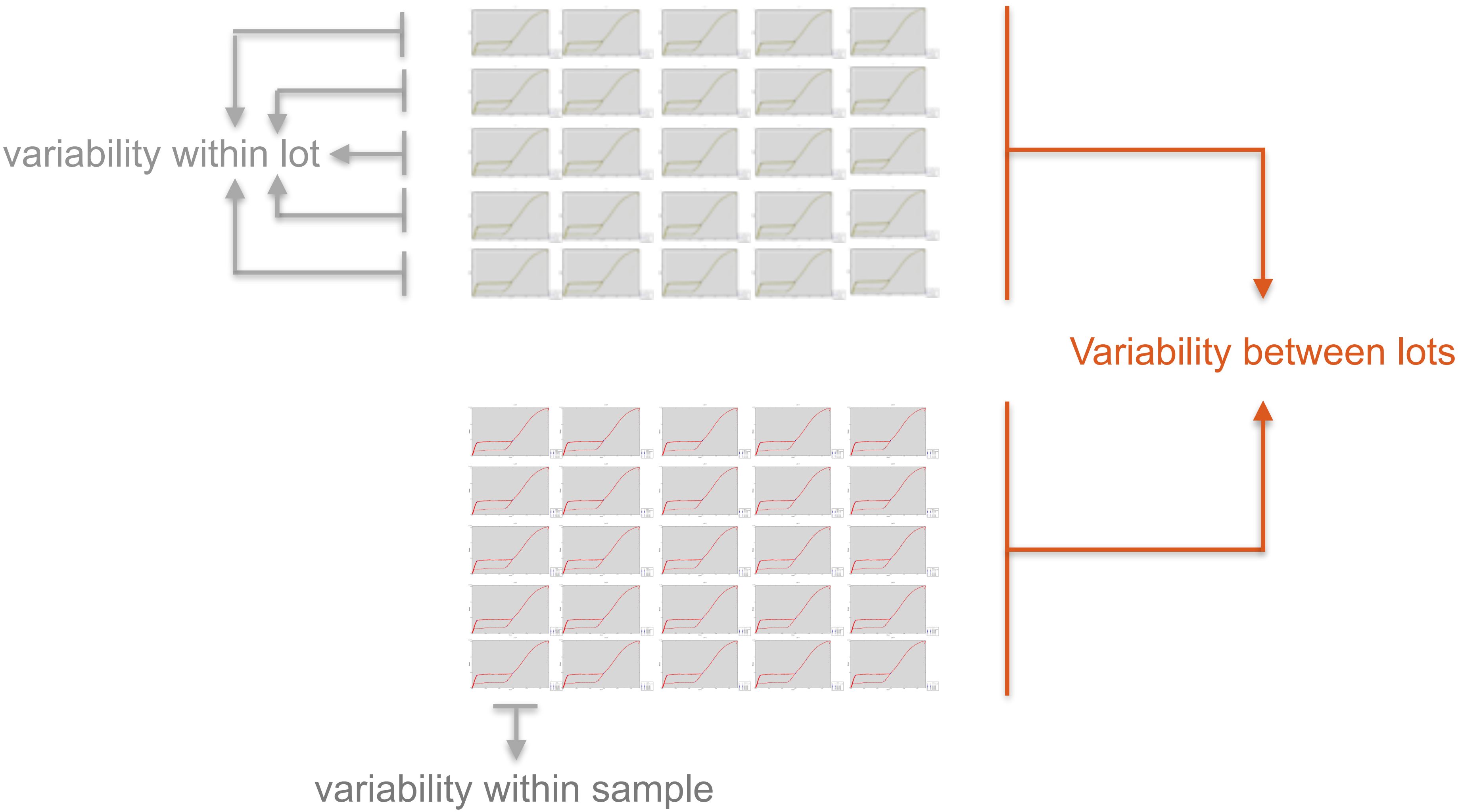


Suspect #2: The Data

A whole bunch of statistics to compare lots

		Lot1				Lot2				Difference	Percent	P-value
		mean	stdev	Lower 95%	Upper 95%	mean	stdev	Lower 95%	Upper 95%			
Ea	GPa	49	6	46.3	51.5	52	4	50.5	53.8	3	6%	0.98
Em	GPa	28	1	27.2	28.2	21	1	20.6	21.4	-7	-29%	<.0001*
eL	#	0.046	0.002	0.045	0.047	0.040	0.001	0.040	0.041	-0.0056	-13%	<.0001*
UP	MPa	395	7	392	397	352	6	348	354	-43	-12%	<.0001*
LP	MPa	165	6	162	167	126	8	123	130	-39	-27%	<.0001*
UL-LP	MPa	230	6	227	232	225	12	220	230	-5	-2%	0.03*

** also studied, not reported here: variation within lot, variation within sample*

Combining data variation + model variation

In this case, the most sensitive inputs don't change much

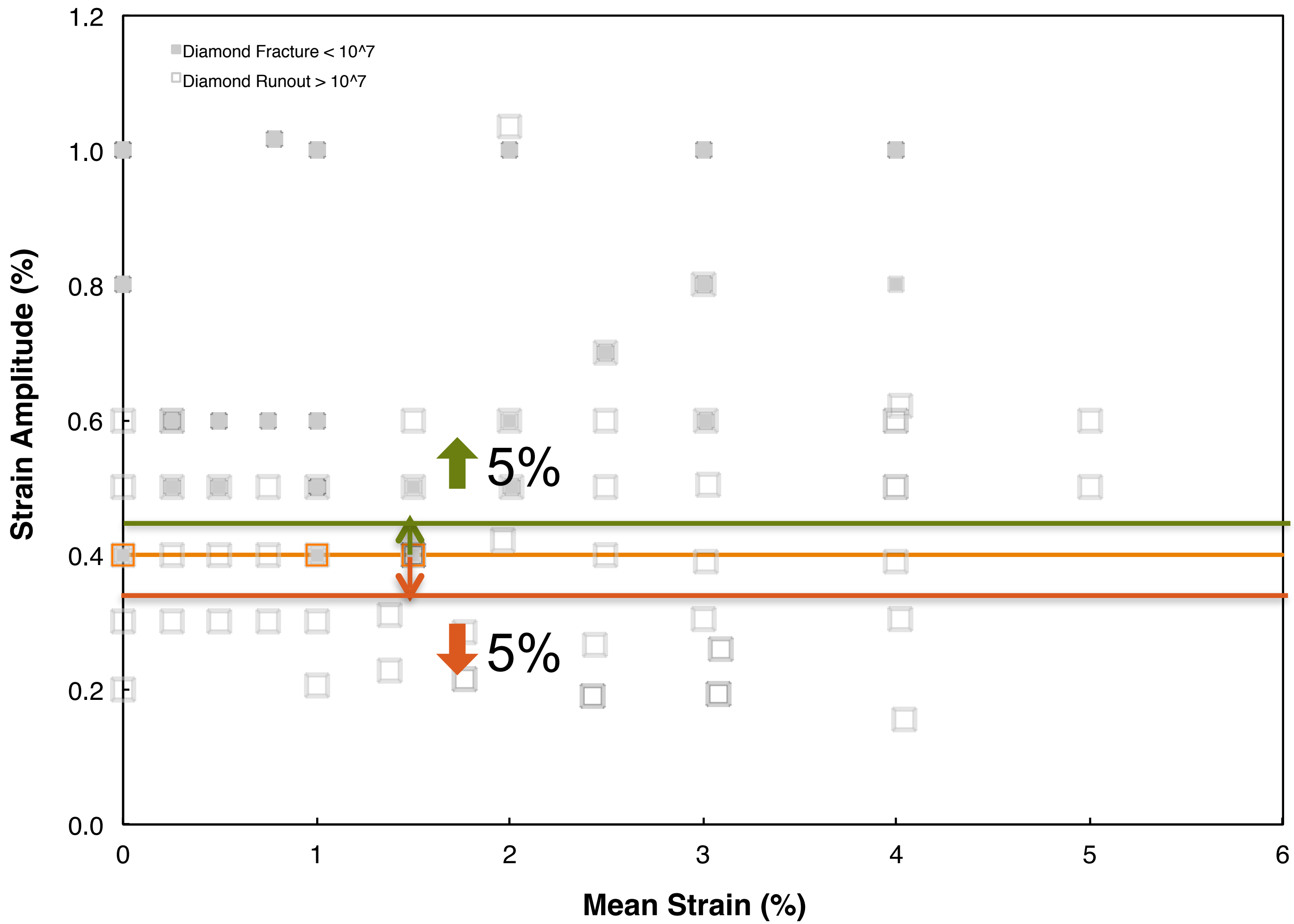
	Grand Mean Lot 1	Grand Mean Lot 2	|L2-L1|	$\frac{L2-L1}{½(L2+L1)}$
E_A (MPa)	49,000	52,000	↑3,000	↑6%
E_M (MPa)	28,000	21,000	↓9	↓29%
UP (MPa)	395	352	↓30	↓12%
LP (MPa)	165	127	↑45	↓26%
UP-LP (MPa)	230	225	↓75	↓2%

$$\varepsilon_a = 3.84 \cdot 10^{-3} + \left(2.65 \cdot 10^{-7} \cdot E_A\right) - \left(4.65 \cdot 10^{-8} \cdot E_M\right) + \left(2.14 \cdot 10^{-5} \cdot UP\right) + \left(6.22 \cdot 10^{-5} \cdot UP \Delta LP\right)$$

	Grand Mean Lot 1	Grand Mean Lot 2	|L2-L1|	$\frac{L2-L1}{½(L2+L1)}$
Strain Amplitude	0.0097	0.0102	↑0.0005	↑5%

Implications to SLD threshold

With careful testing and calibration, we're OK in this case



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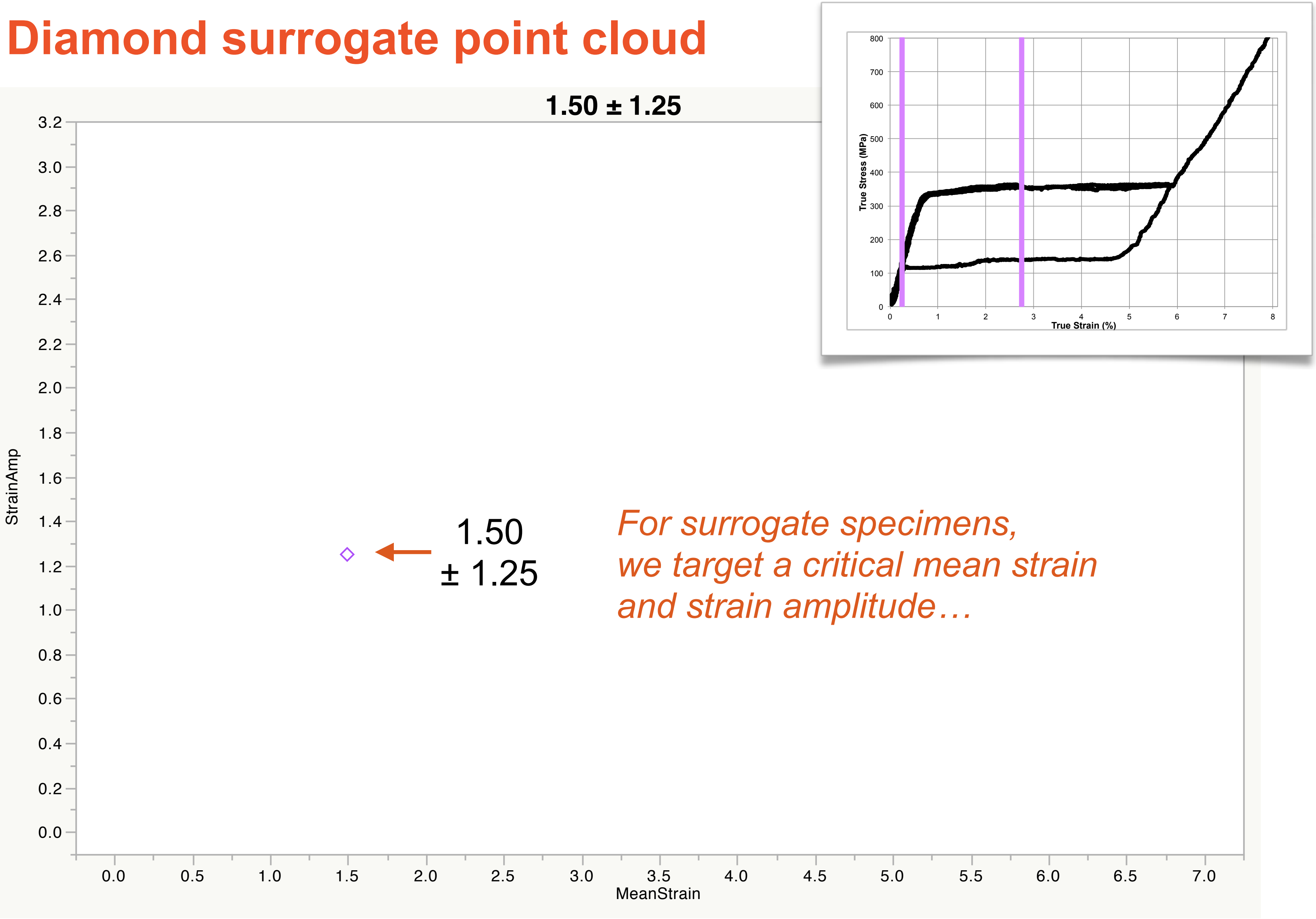
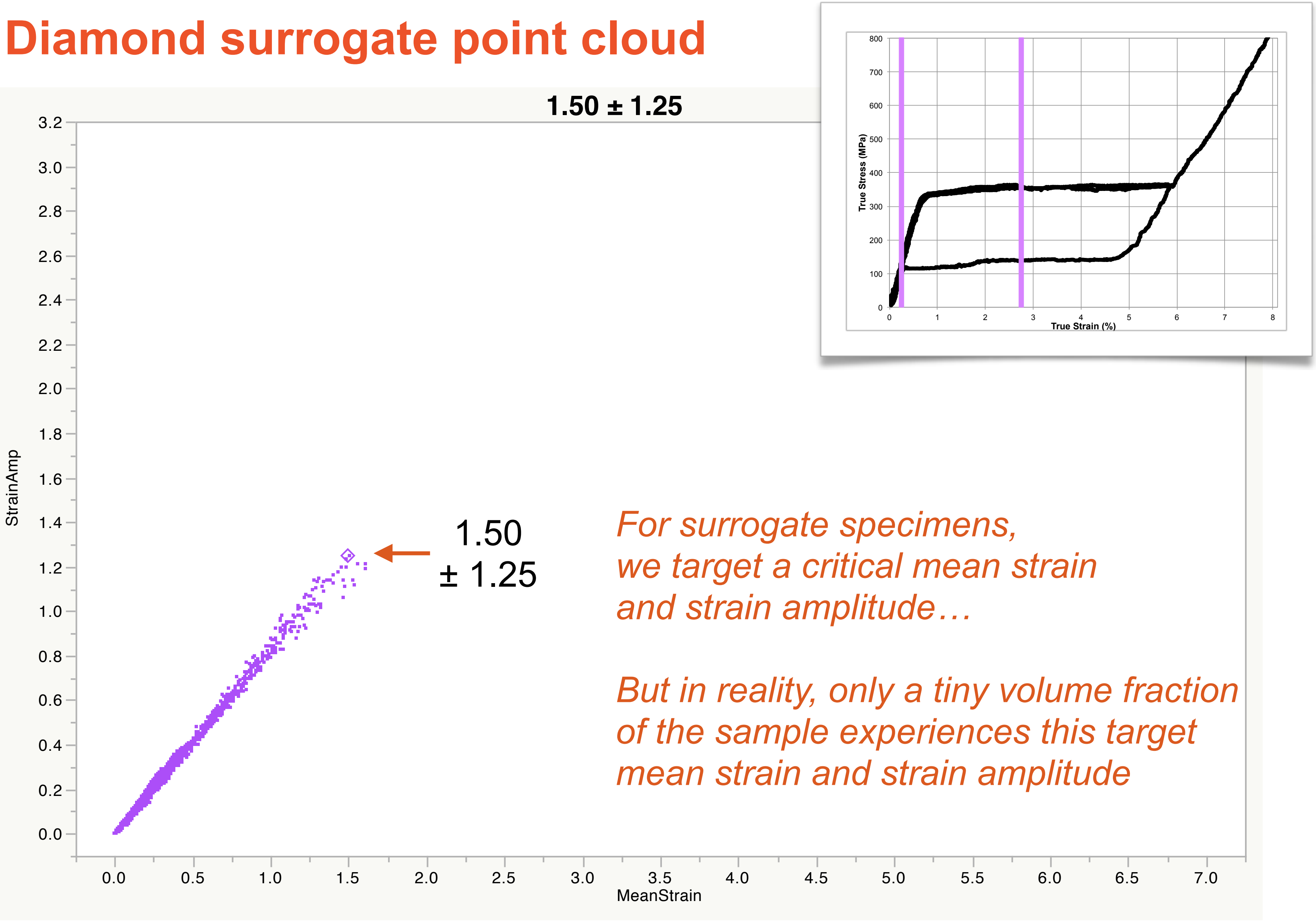
Diamond surrogate point cloud



For surrogate specimens, we target a critical mean strain and strain amplitude…

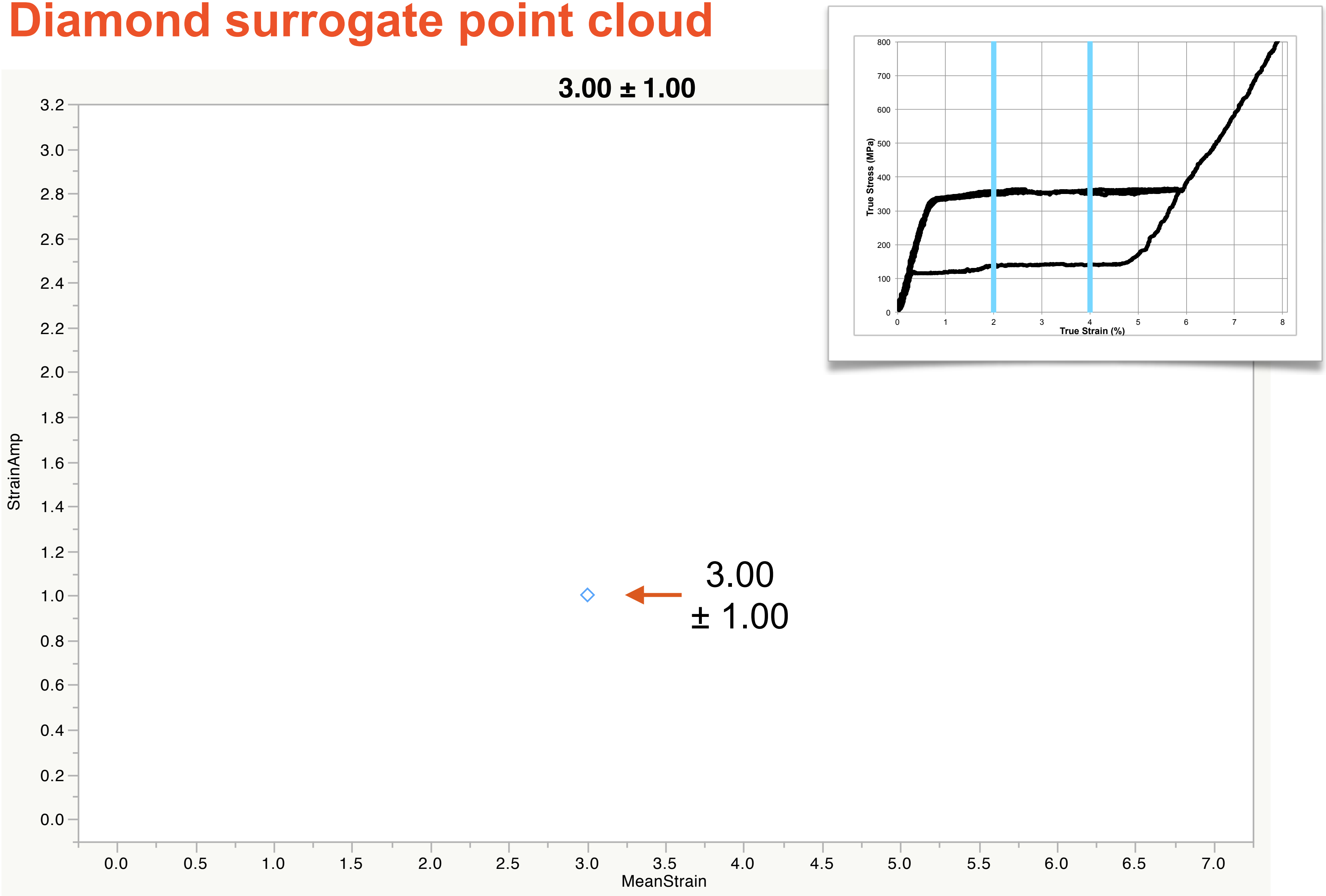
Diamond surrogate point cloud



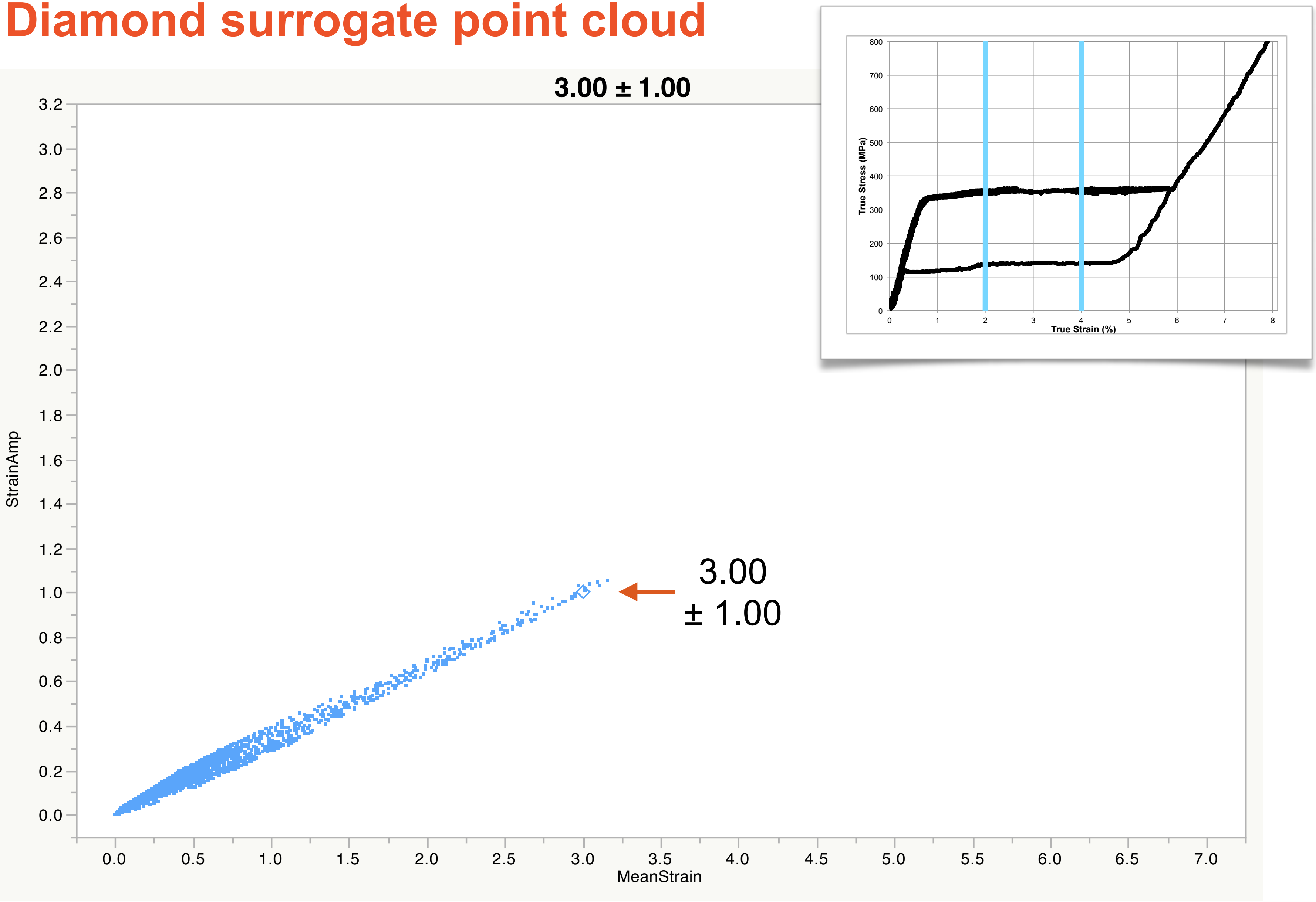
For surrogate specimens, we target a critical mean strain and strain amplitude…

But in reality, only a tiny volume fraction of the sample experiences this target mean strain and strain amplitude

Diamond surrogate point cloud



Diamond surrogate point cloud



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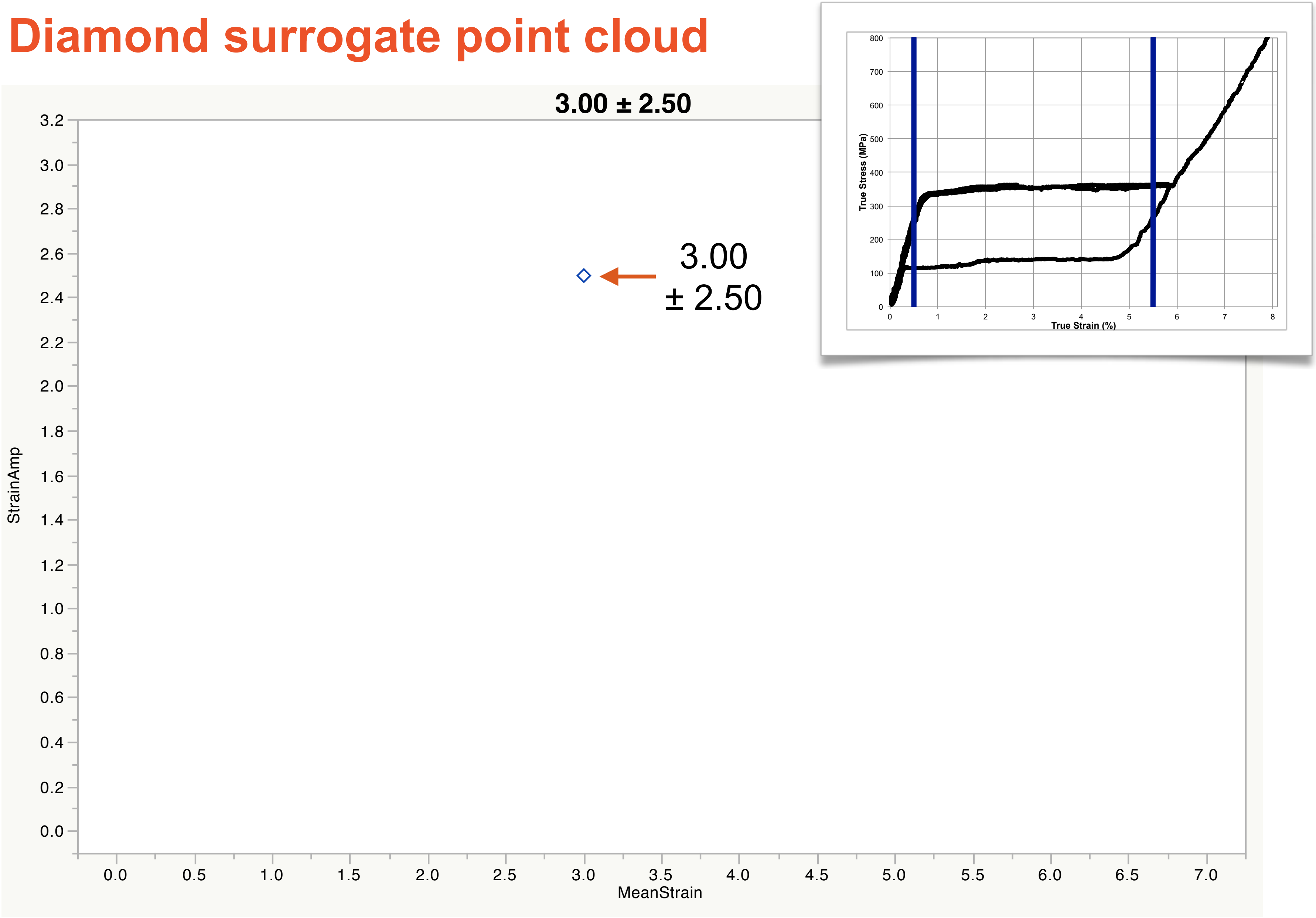

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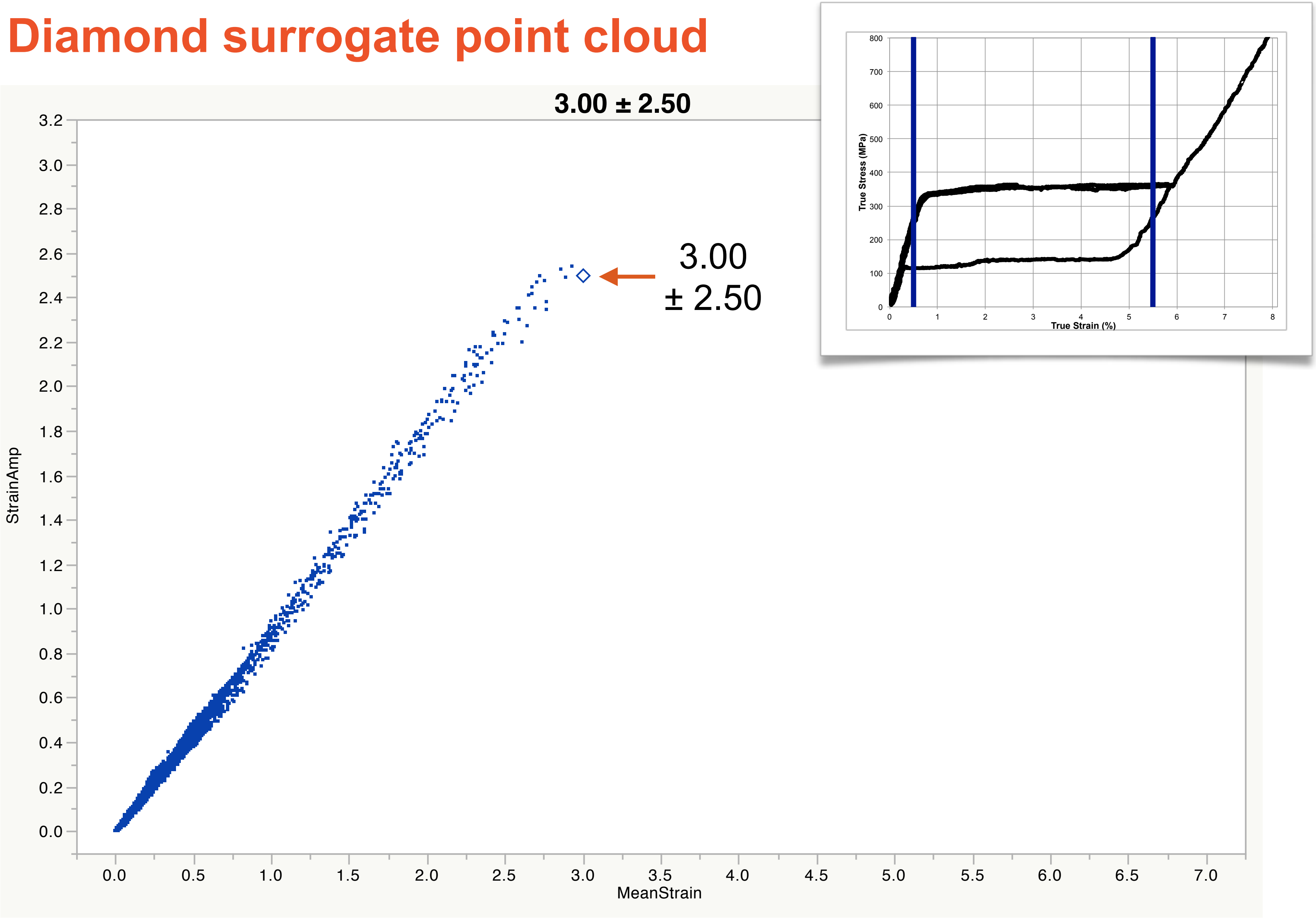

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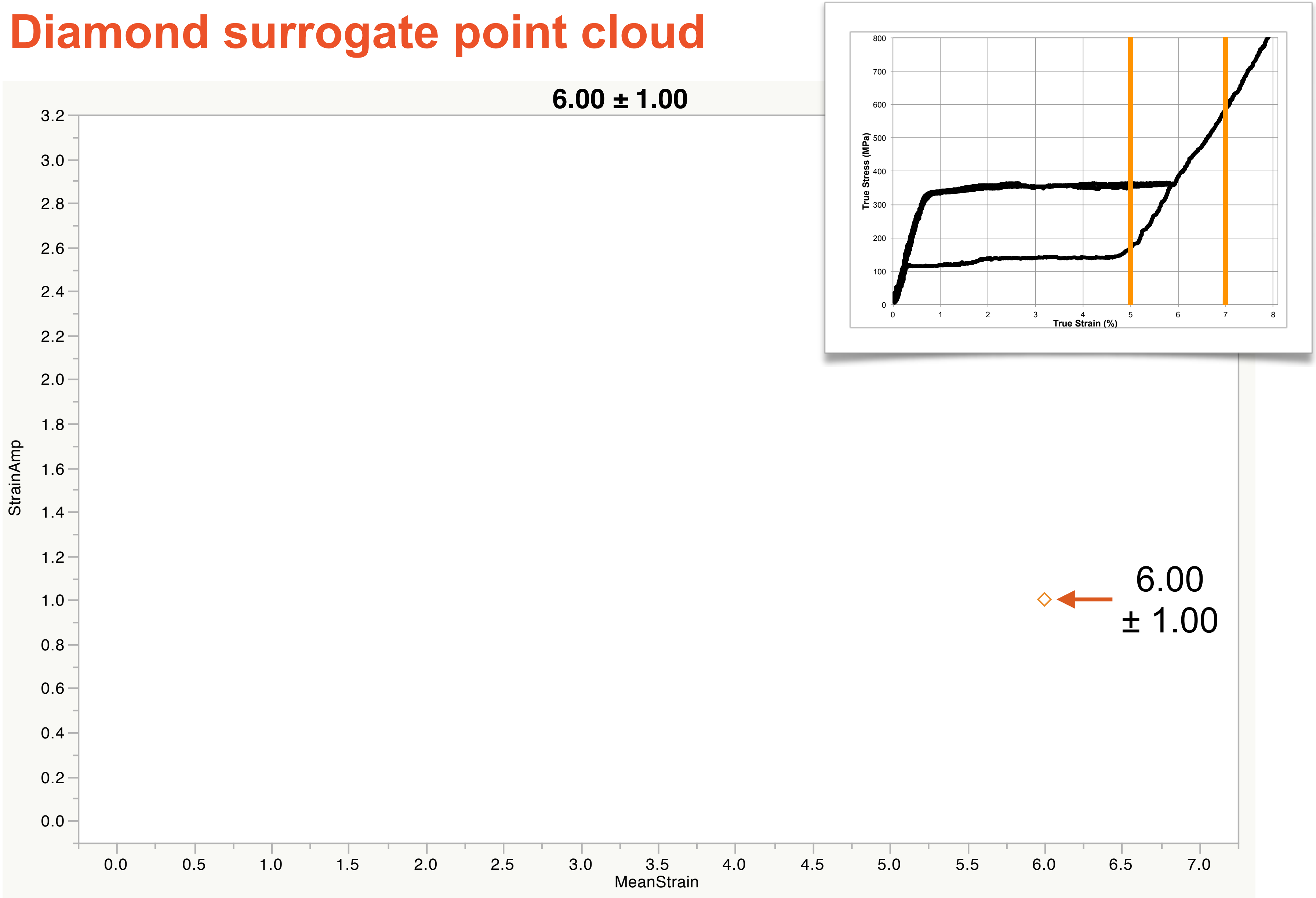

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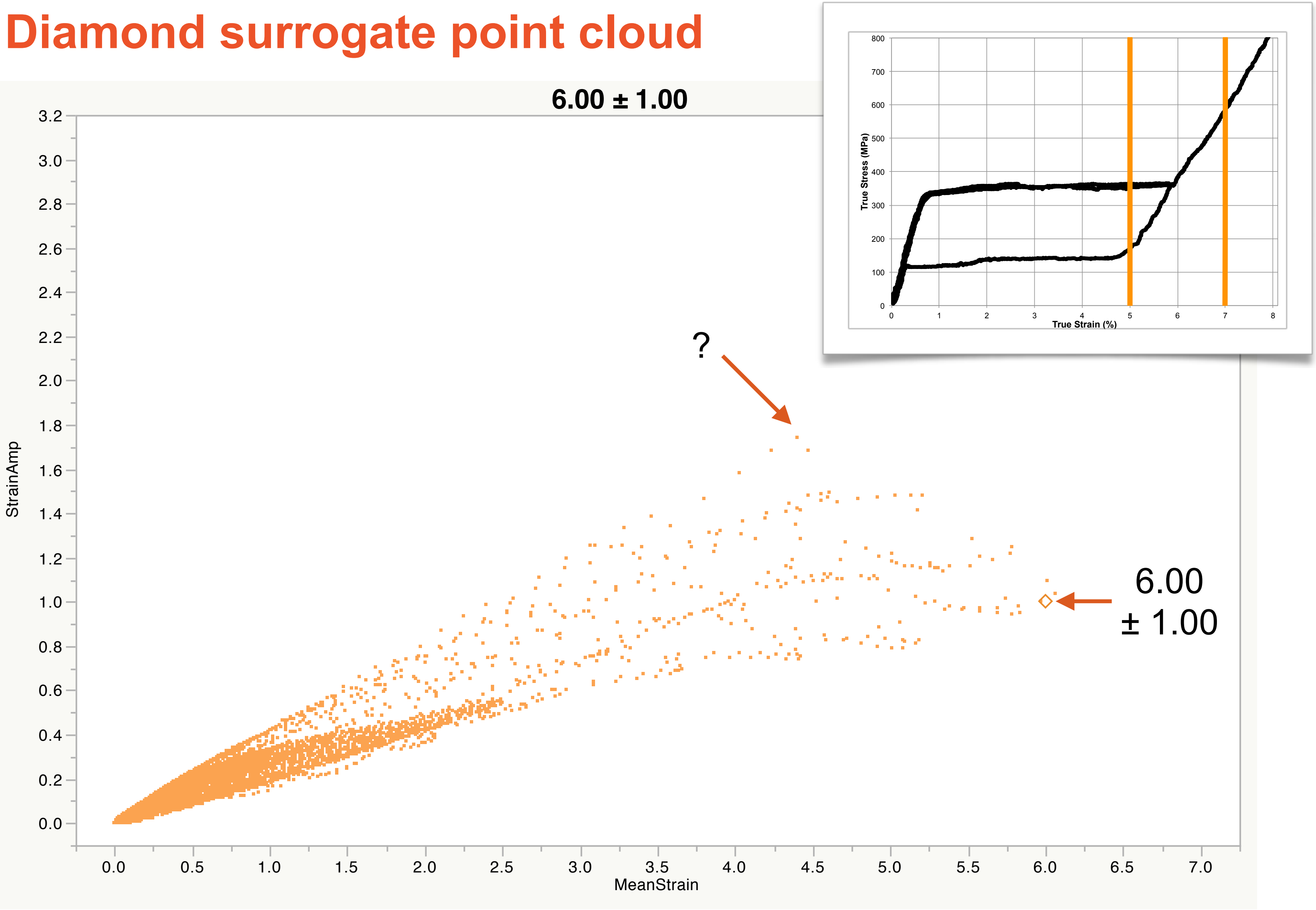

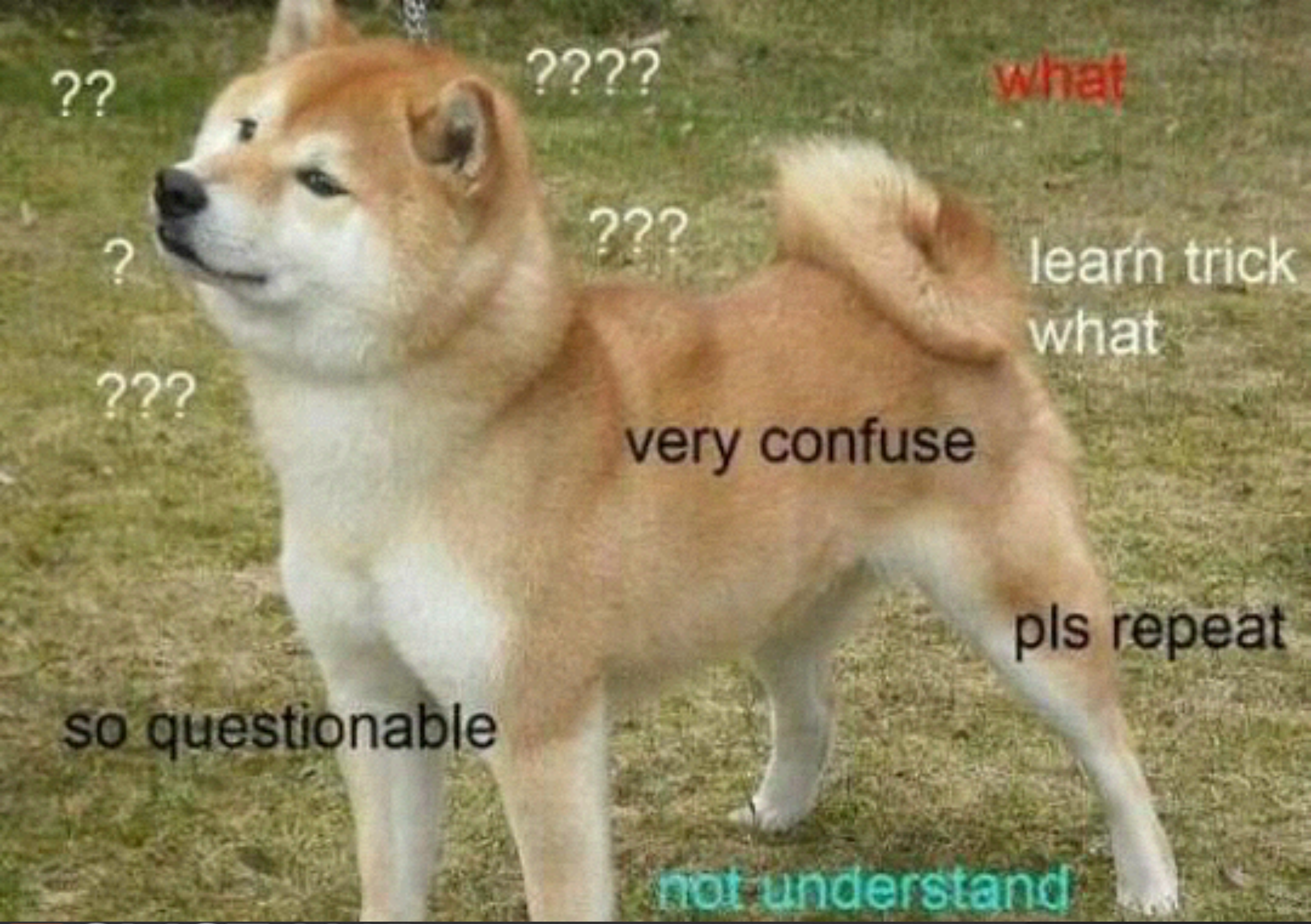
??
????
what
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learn trick
what
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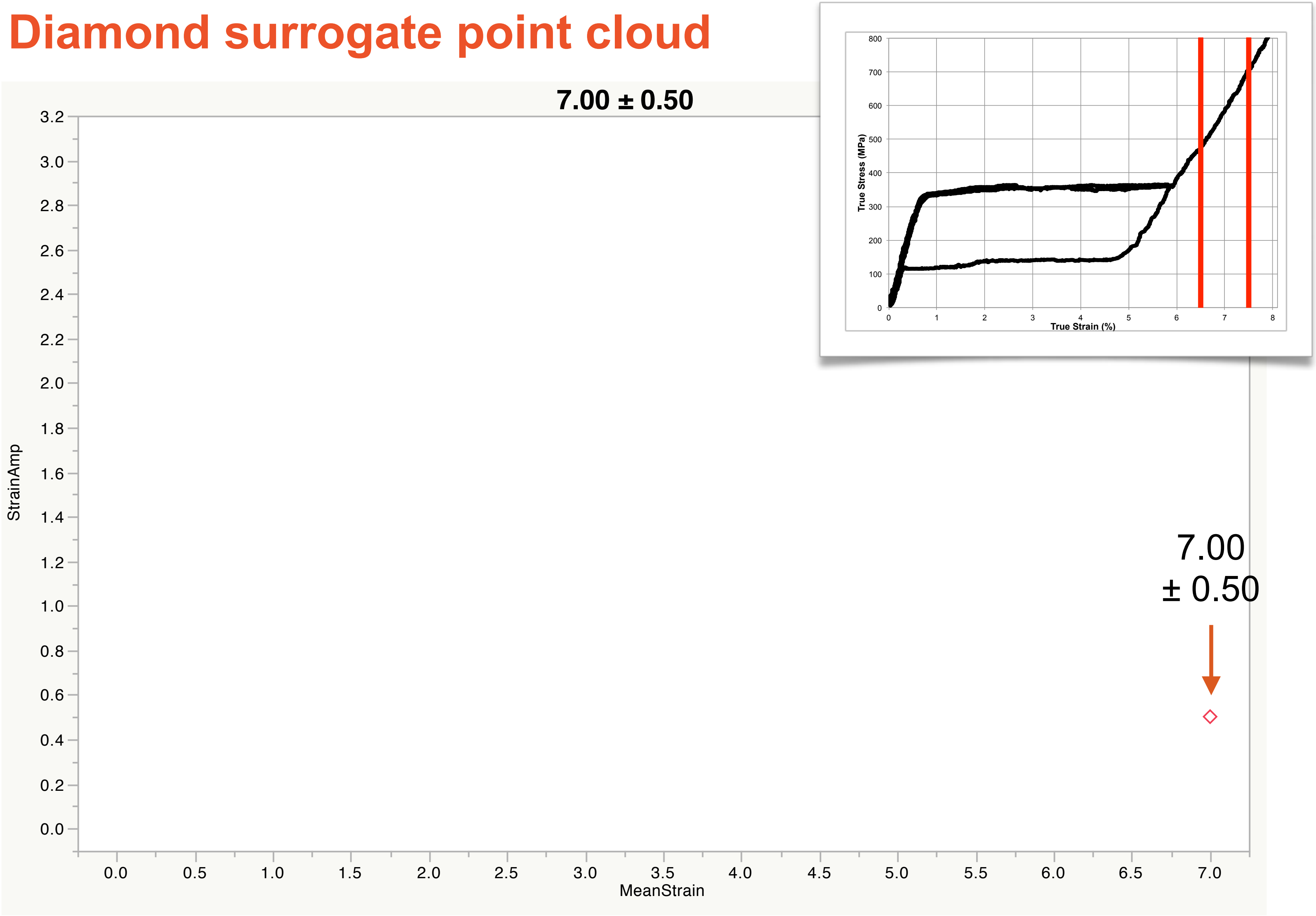
very confuse
pls repeat
so questionable
not understand

Diamond surrogate point cloud



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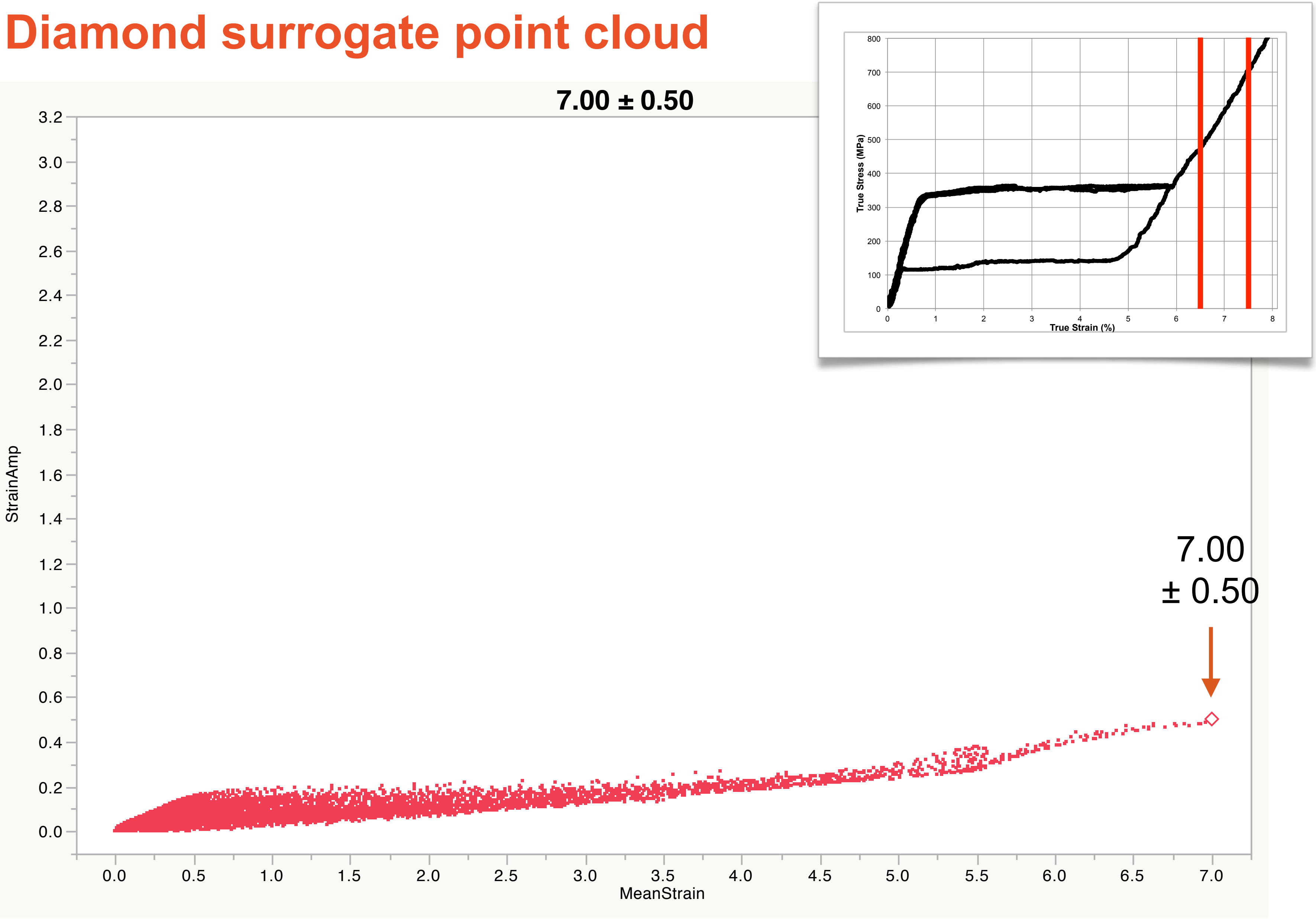

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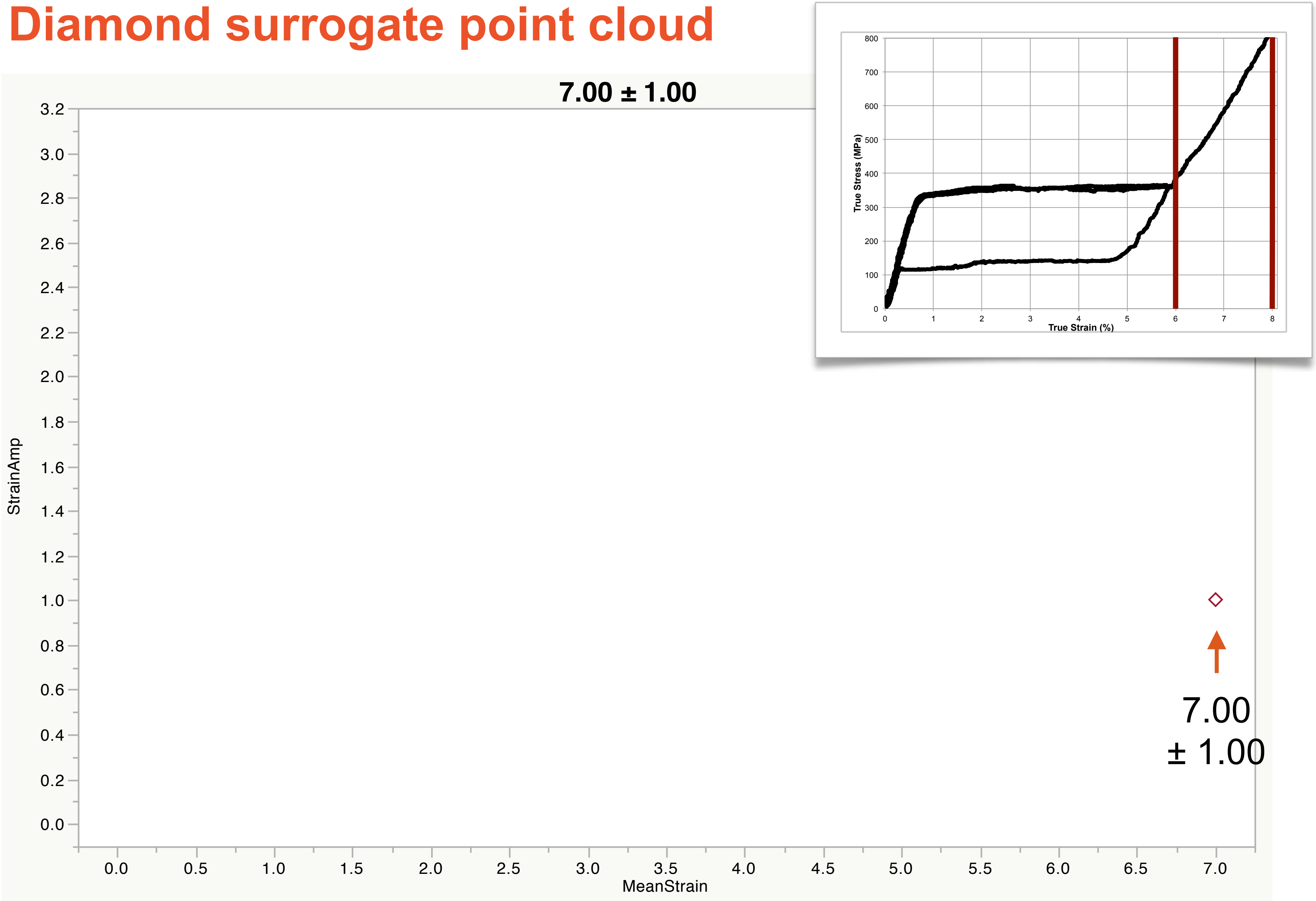

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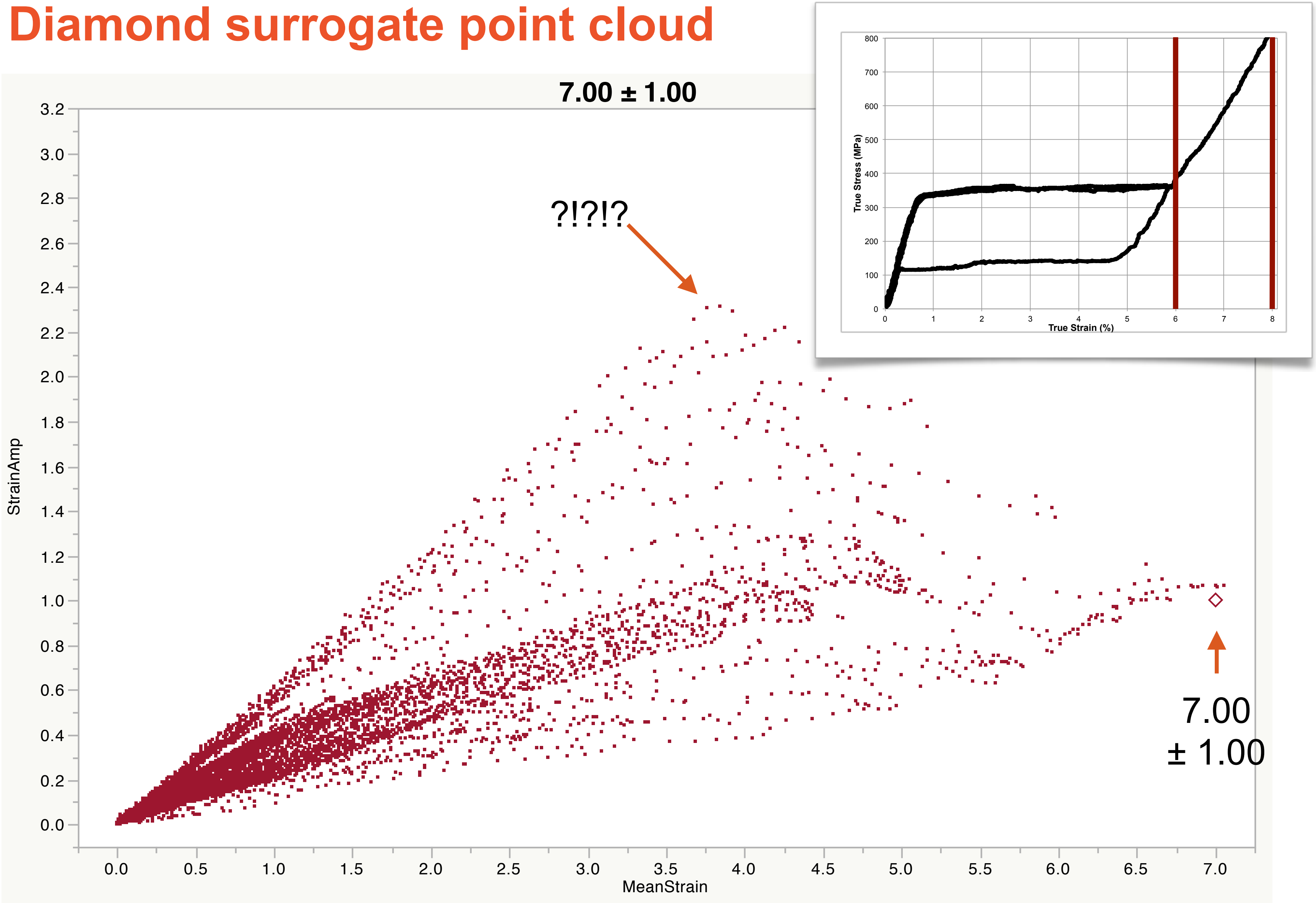
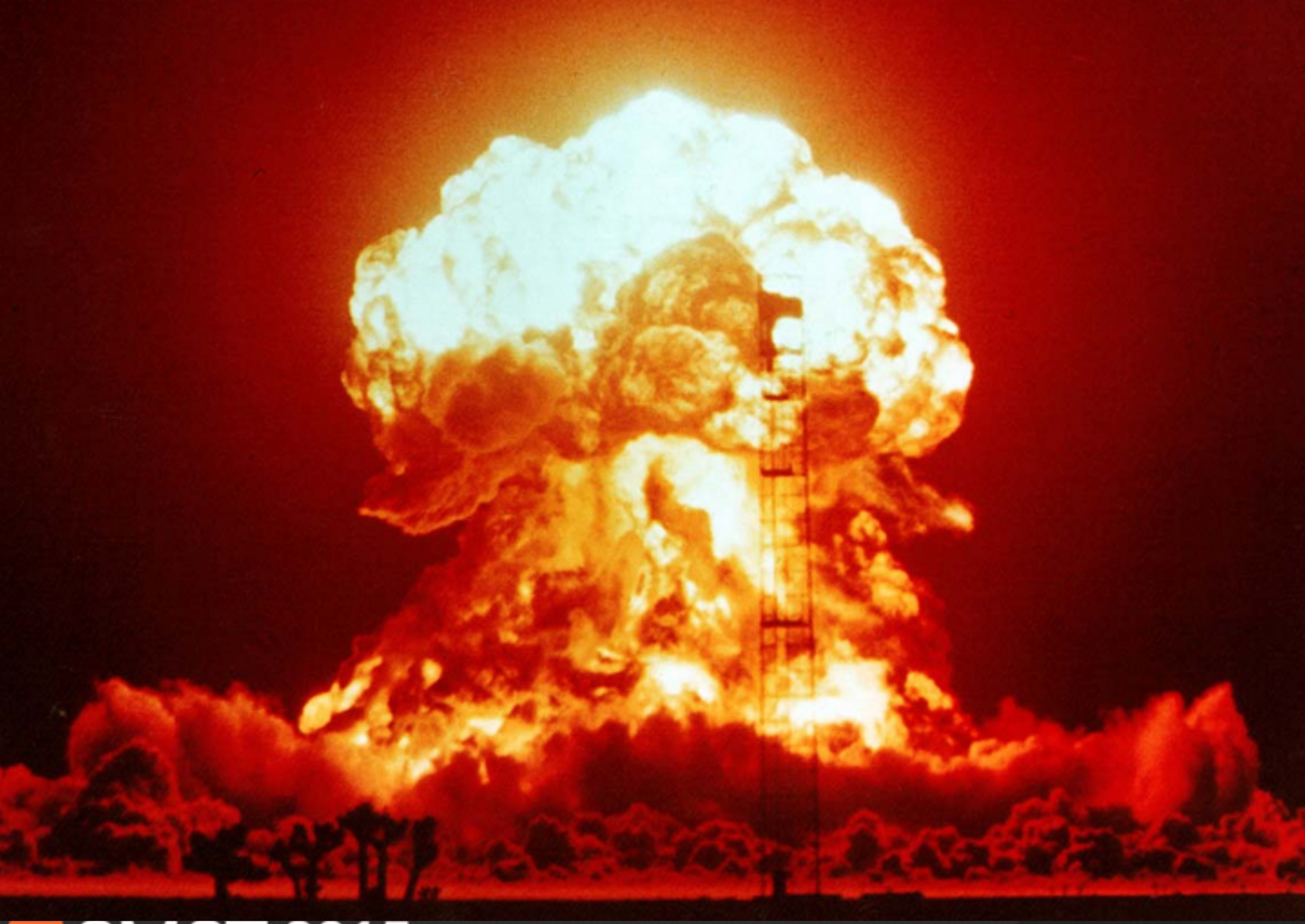
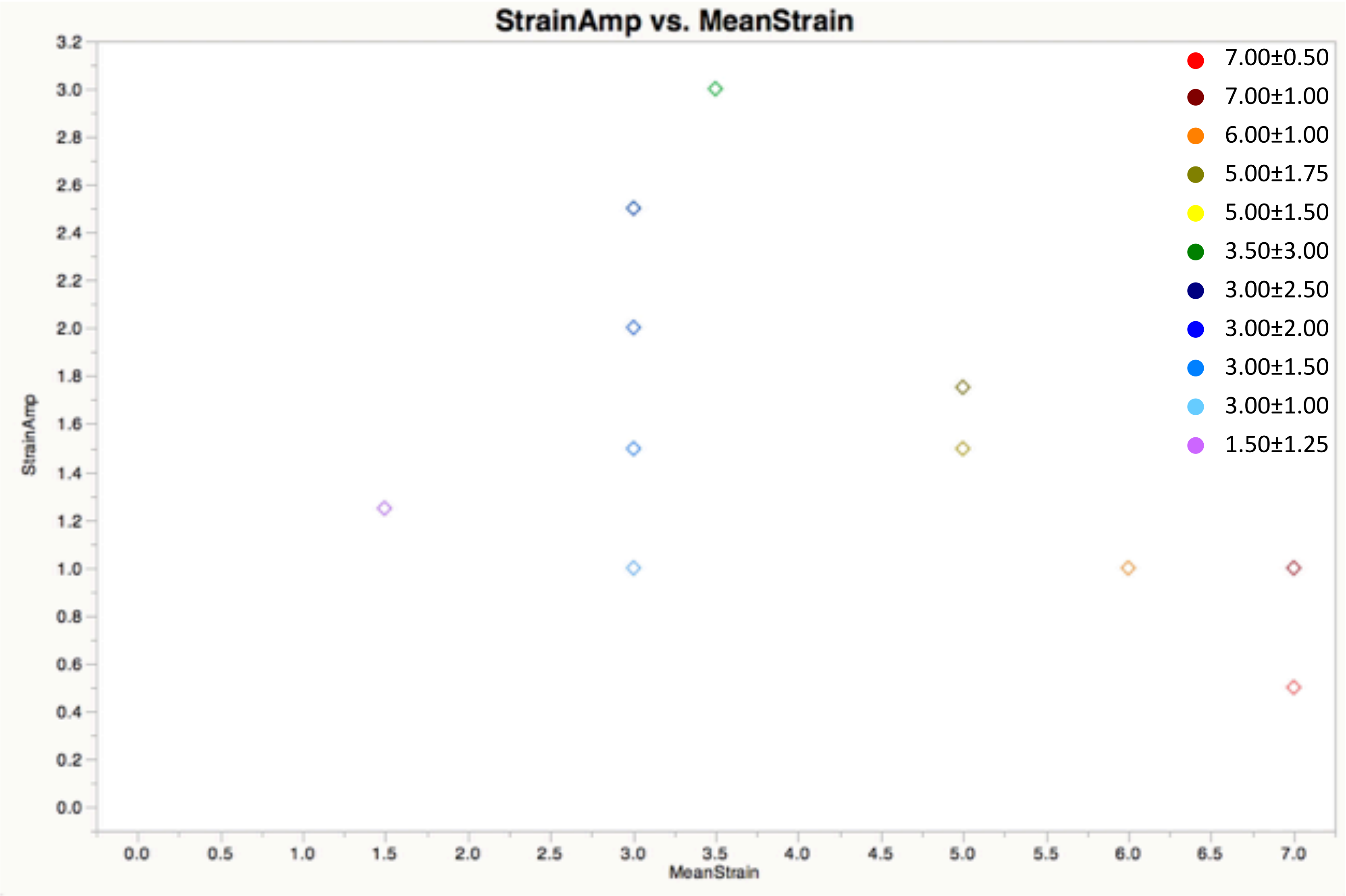




11 desired conditions to test

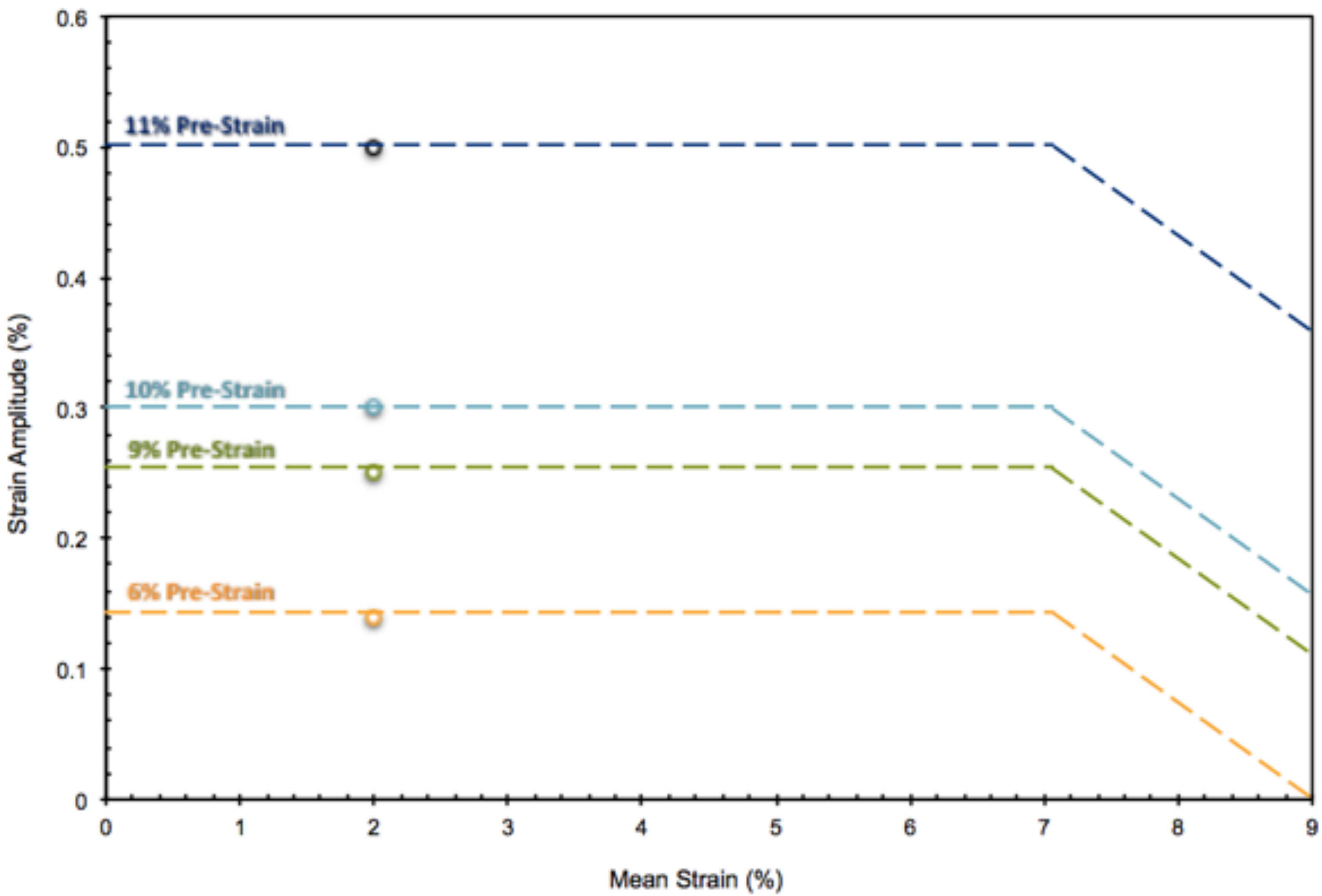
Each condition is actually 34,000 different conditions!



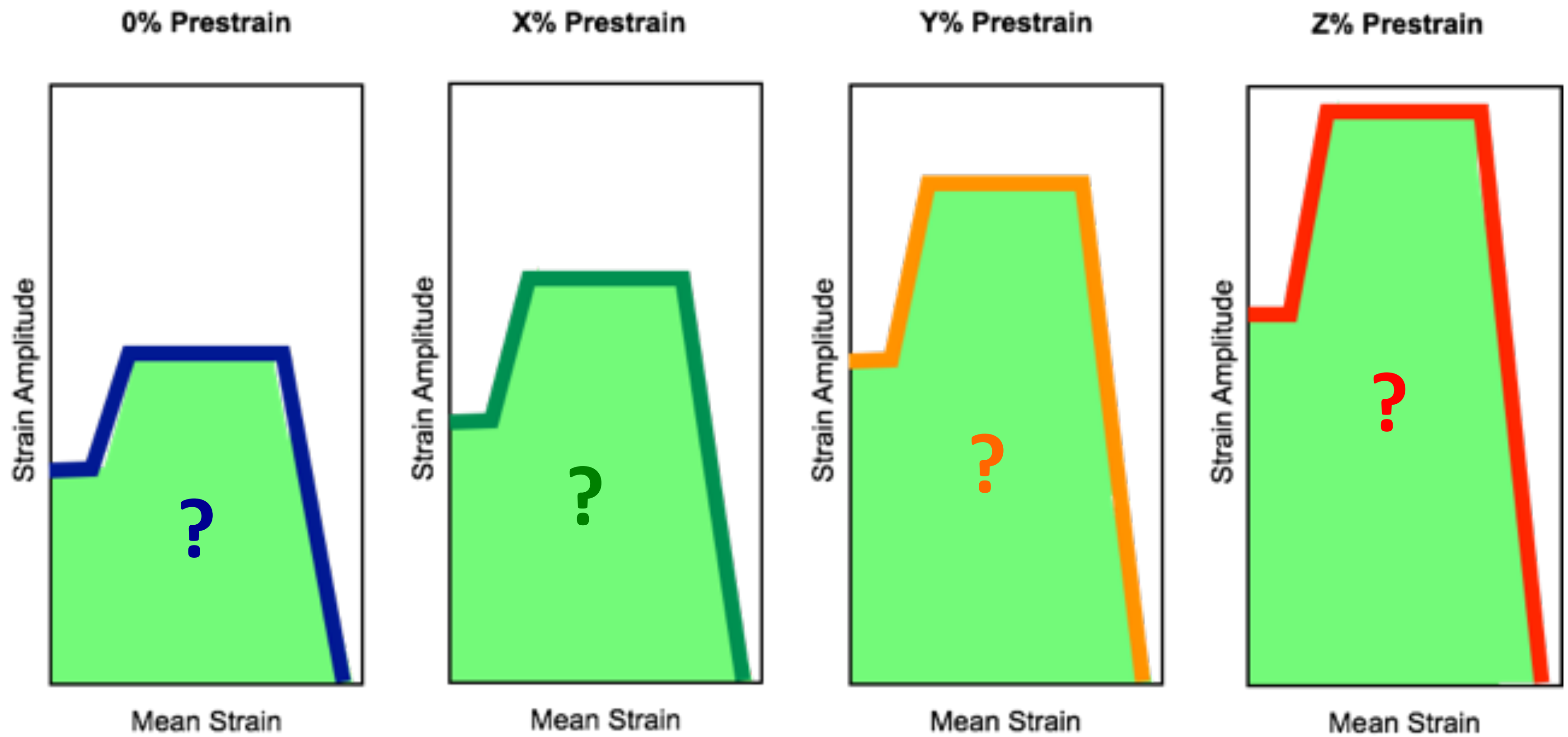
Lessons

1. For surrogate specimen tests, strain limit diagram (SLD) points depend on FEA to relate displacement to strain
2. Small variations in FEA material calibration can result in large changes to strains
3. Results are especially sensitive to E_A and UP-LP
4. It is important to use multiple samples to calibrate material inputs
5. **Surrogate specimen experience a wide range of stress and strain, and some target SLD conditions can not be achieved**
6. Pre-strain may be an important additional dimension to consider when analyzing fatigue

Strain Limit Diagram – Effect of Pre-Strain

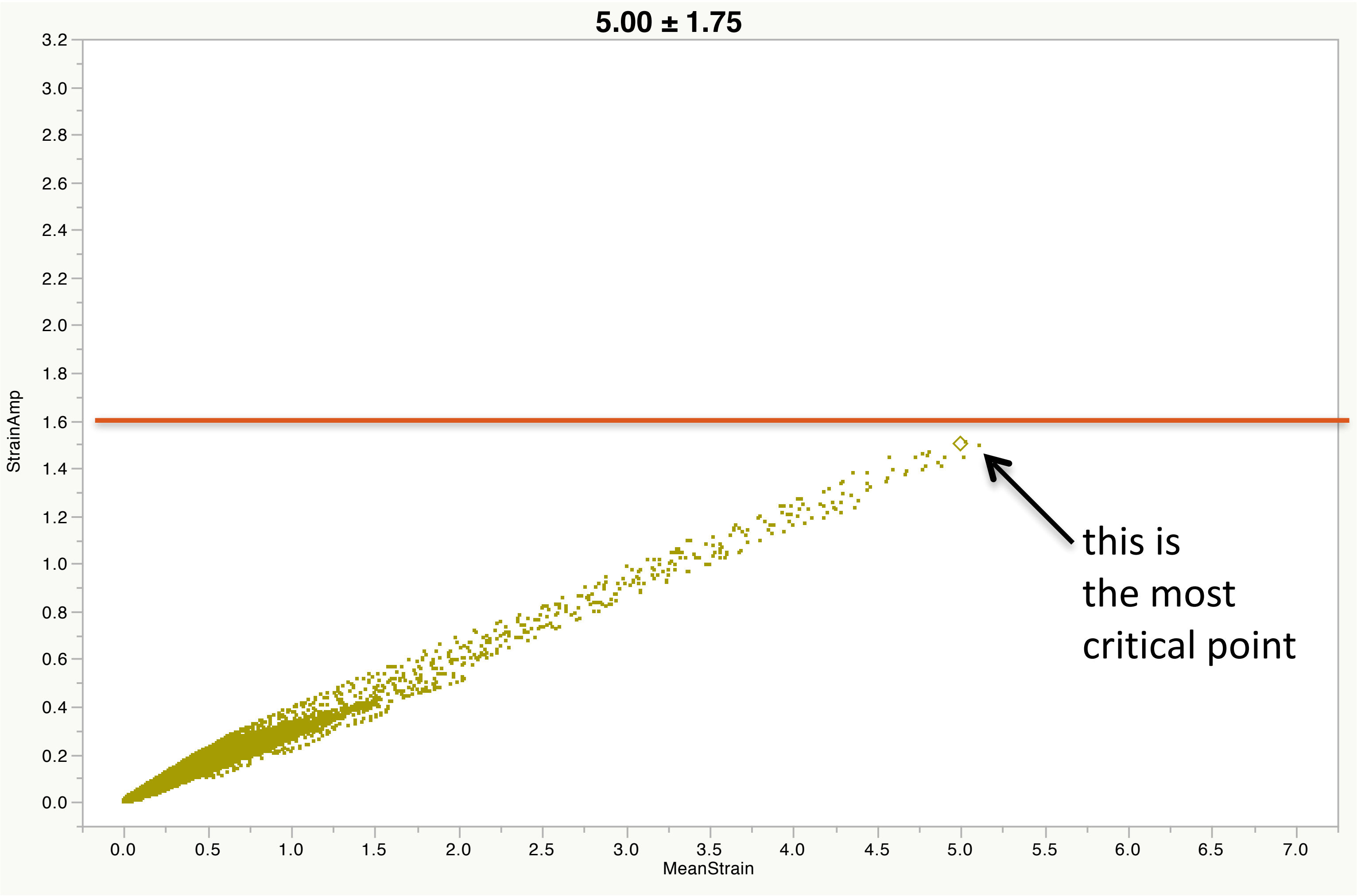


There are indications that increasing prestrain increases the fatigue safety threshold. Prestrain is potentially a third variable to consider when defining fatigue safety criteria, and when analyzing simulation results.
(0% < X% < Y% < Z%)



Typical point cloud + fatigue strain limit diagram

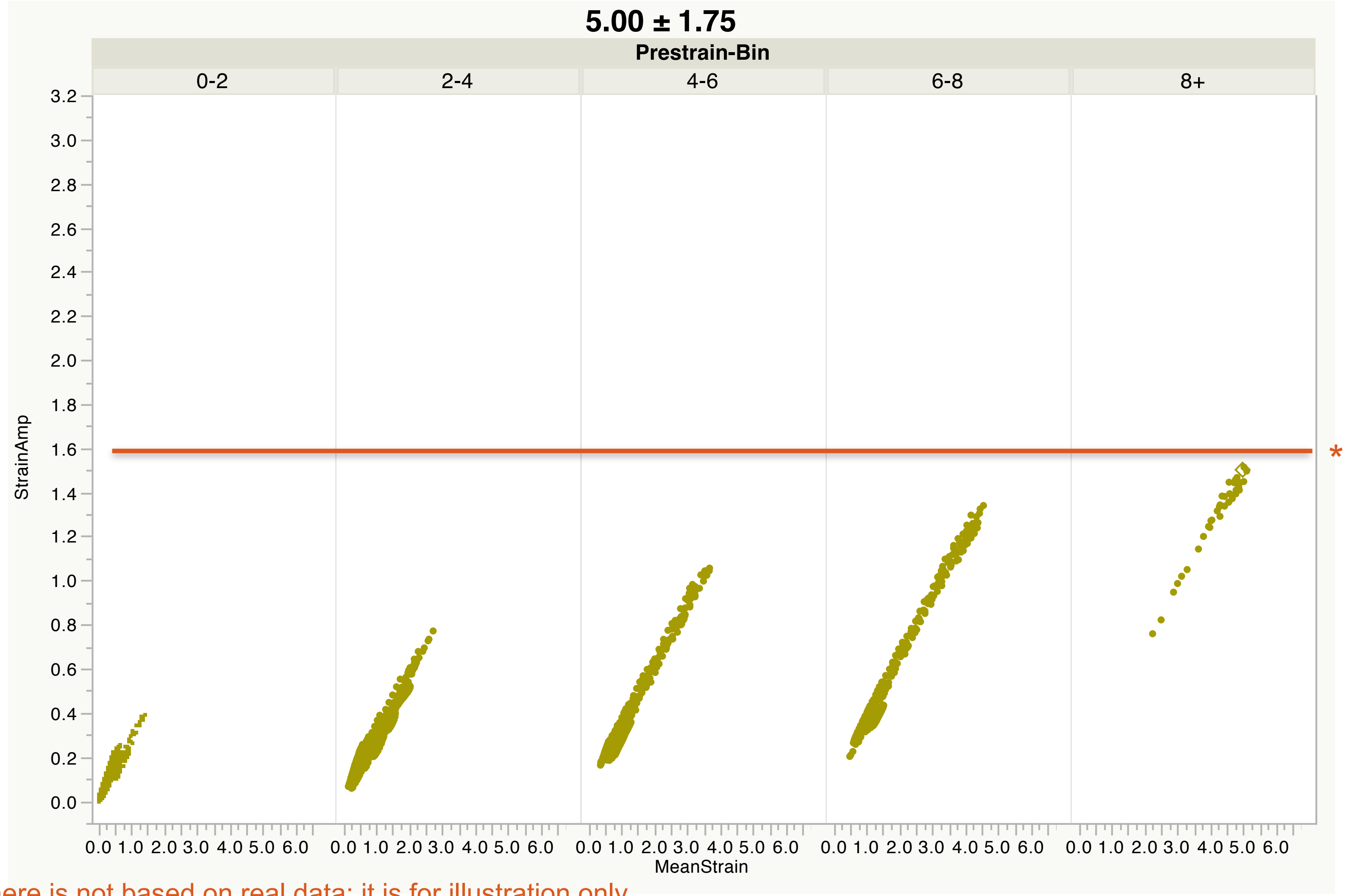
(let's assume this limit criteria represents the maximum prestrain condition)



* limit line here is not based on real data; it is for illustration only

Every point in the specimen has a different pre-strain

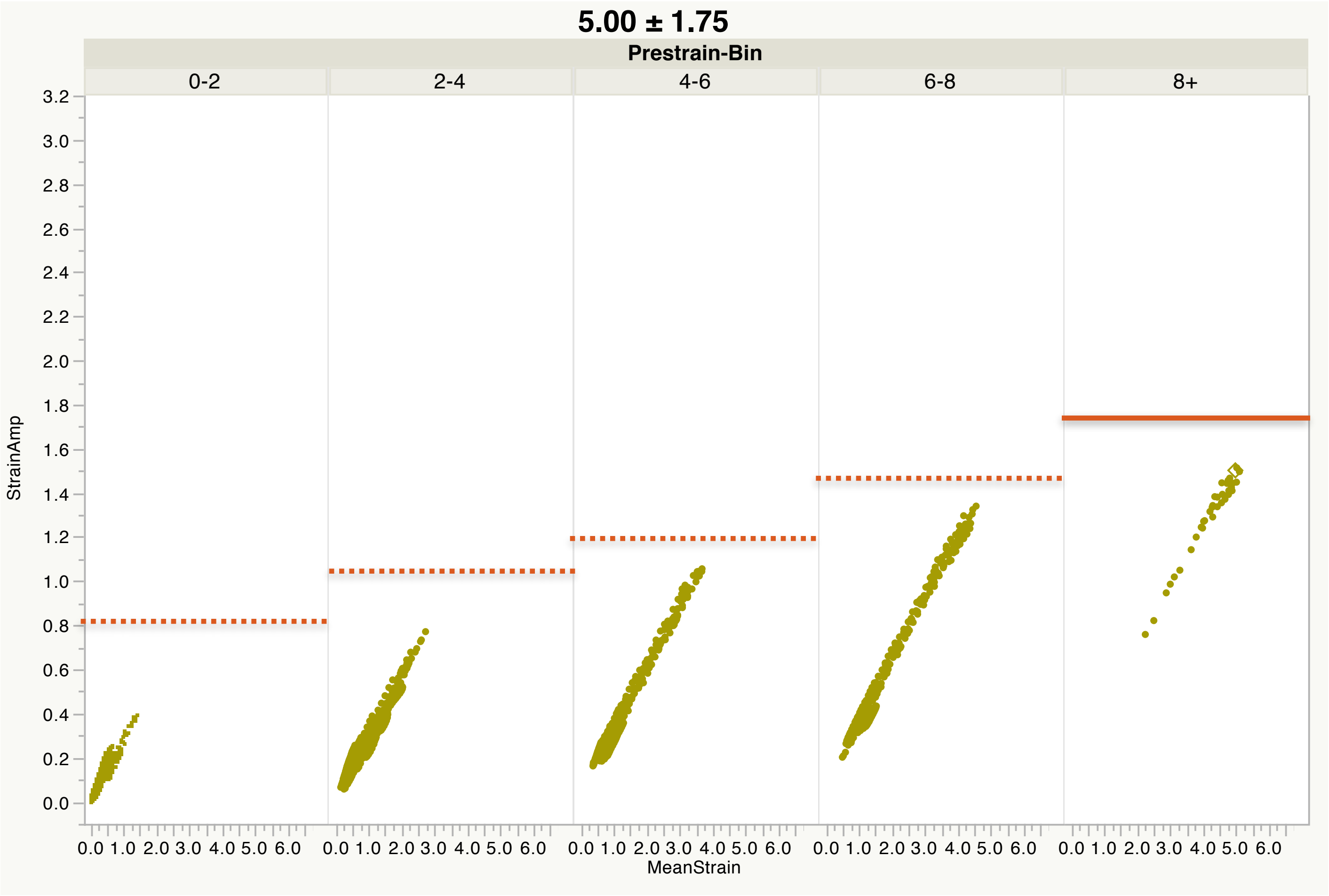
So let's split up the point cloud into some pre-strain "bins"



* limit line here is not based on real data; it is for illustration only

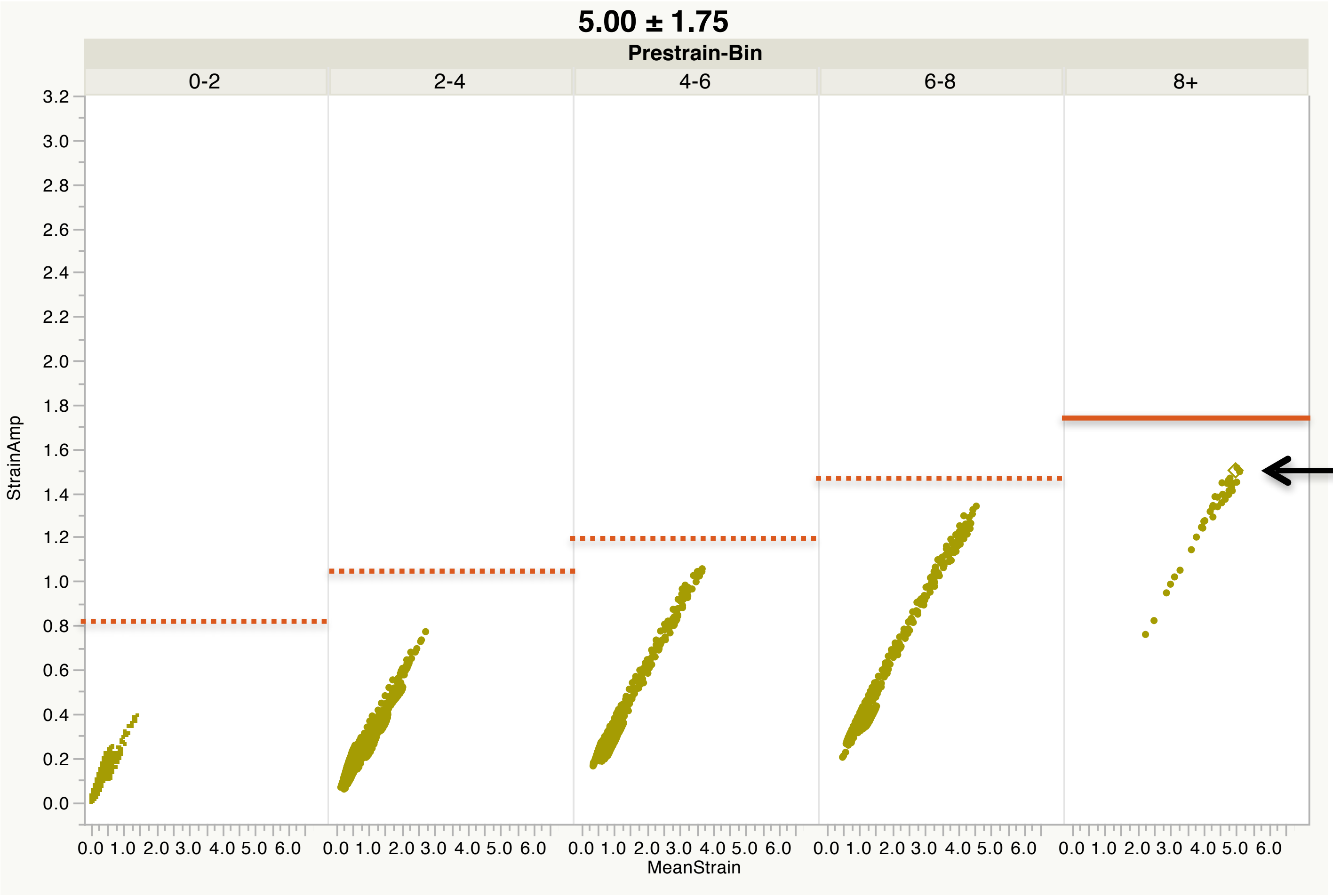
The strain amplitude threshold varies with pre-strain

So let's consider the pre-strain limit associated with each element



* limit lines here is not based on real data, but do follow a trend similar to observed test results

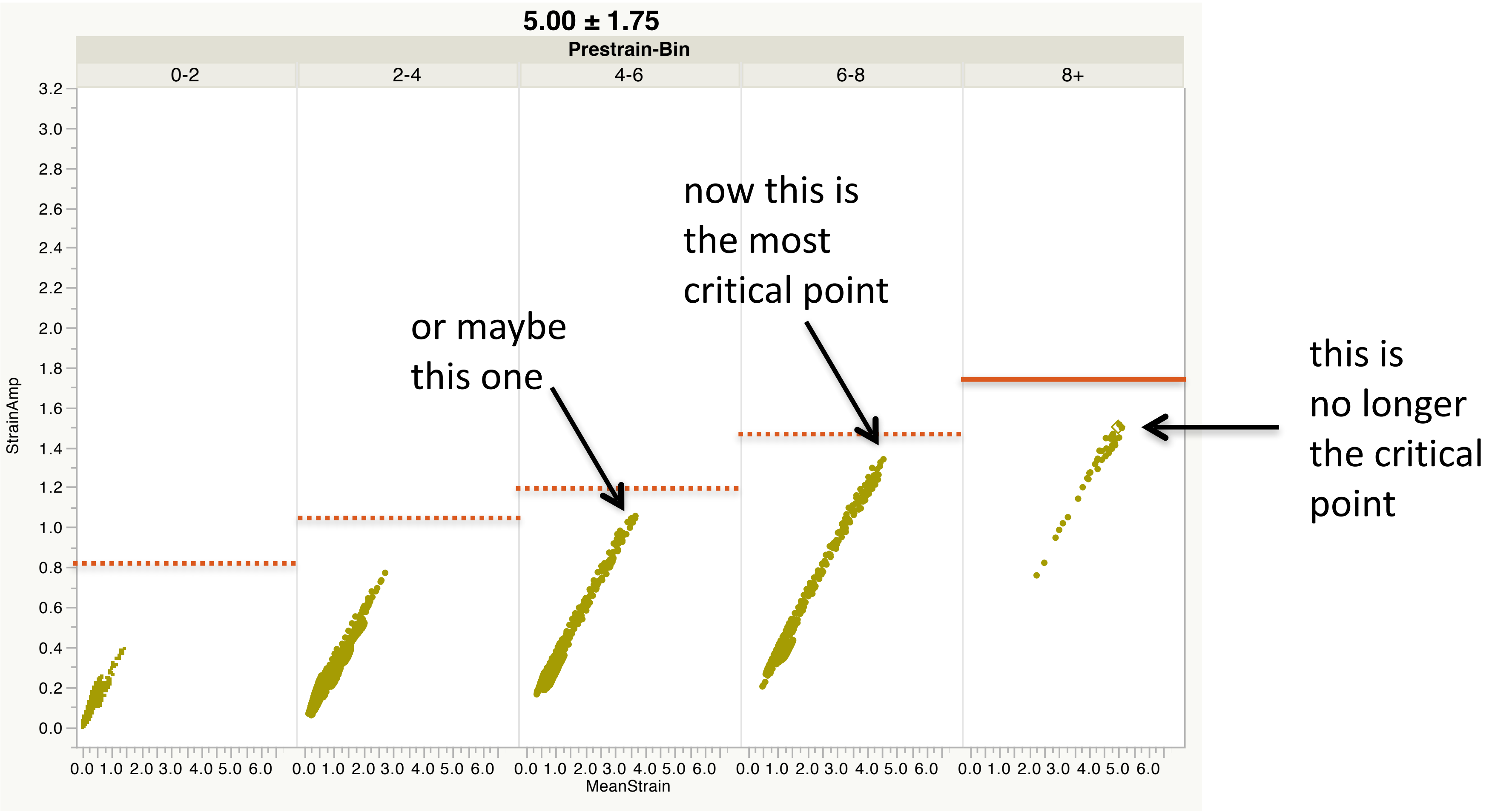
The most critical point may shift depending pre-strain



this is no longer the critical point

* limit lines here is not based on real data, but do follow a trend similar to observed test results

The most critical point may shift depending pre-strain



* limit lines here is not based on real data, but do follow a trend similar to observed test results

Lessons

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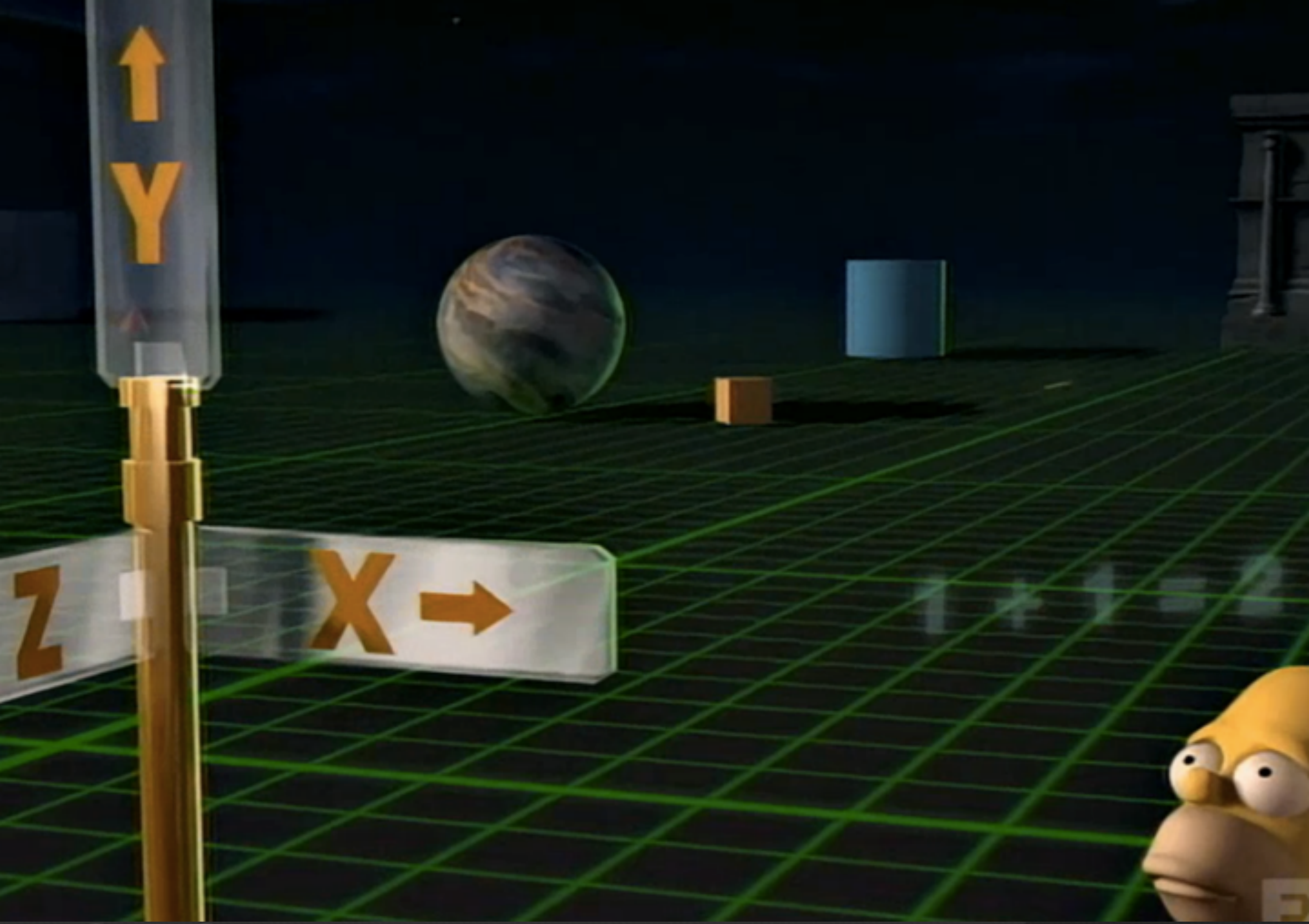
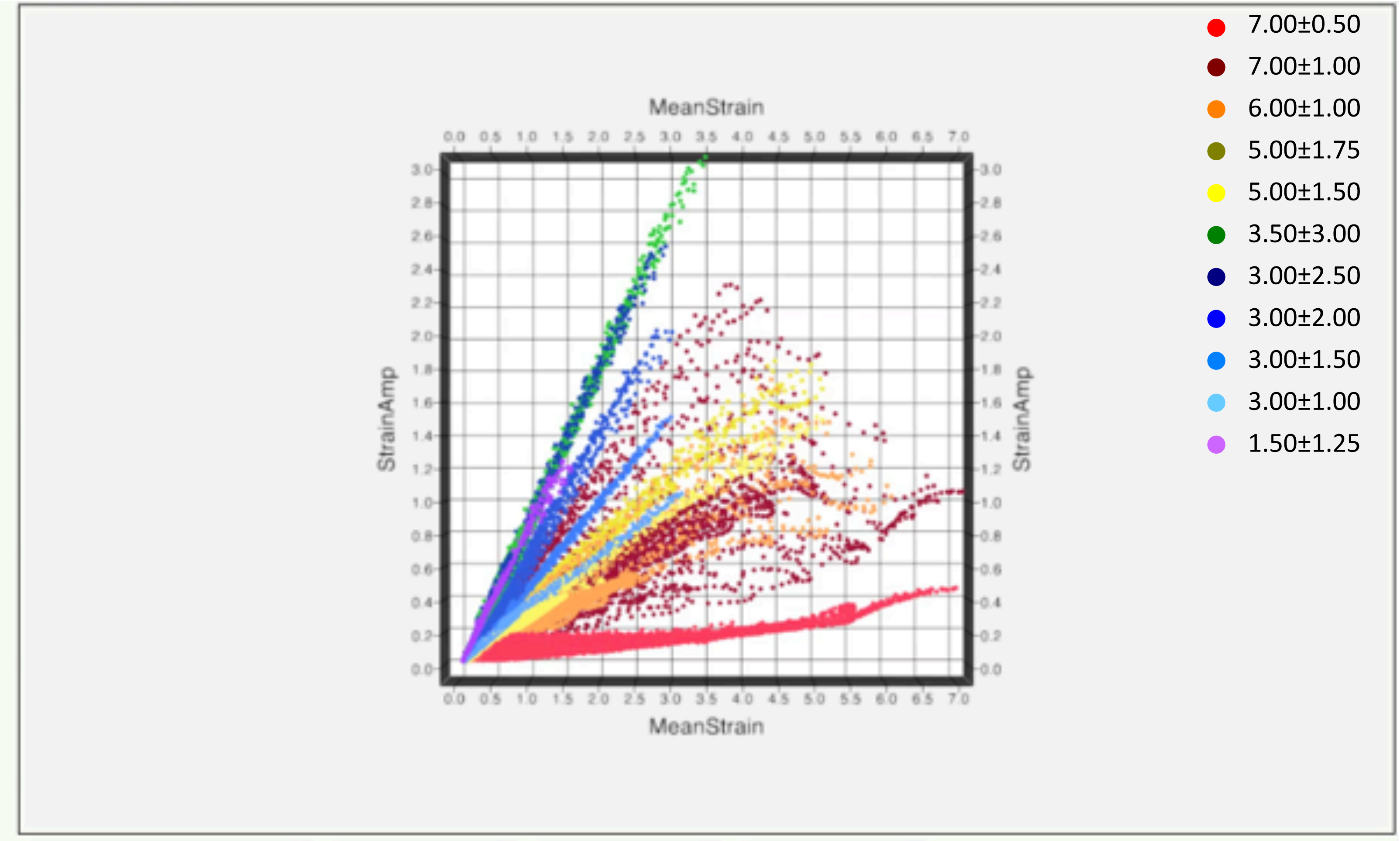
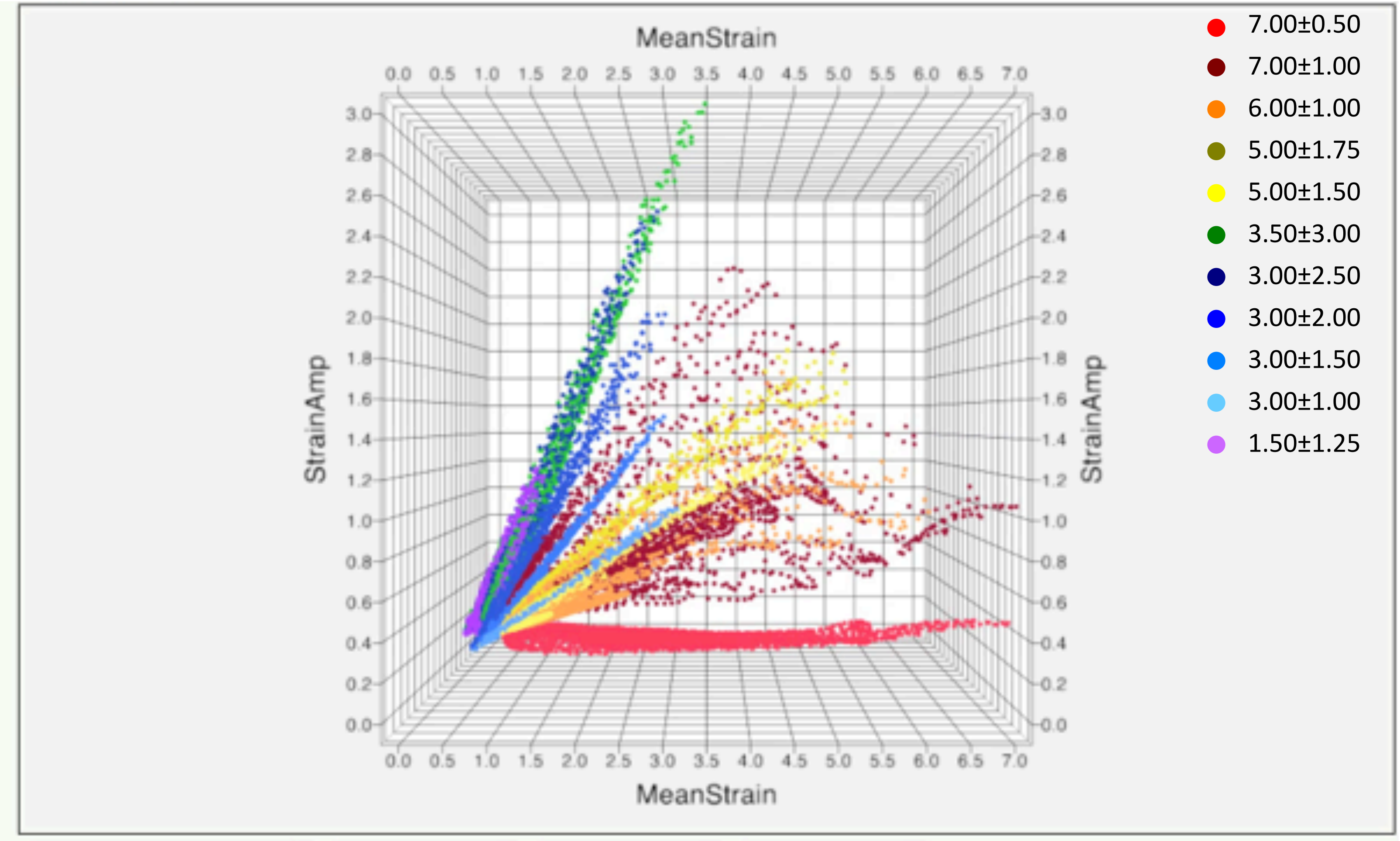

Y
Z
X
1 + 1 = 2

Conventional strain limit diagram
diamond surrogate design, 11 conditions

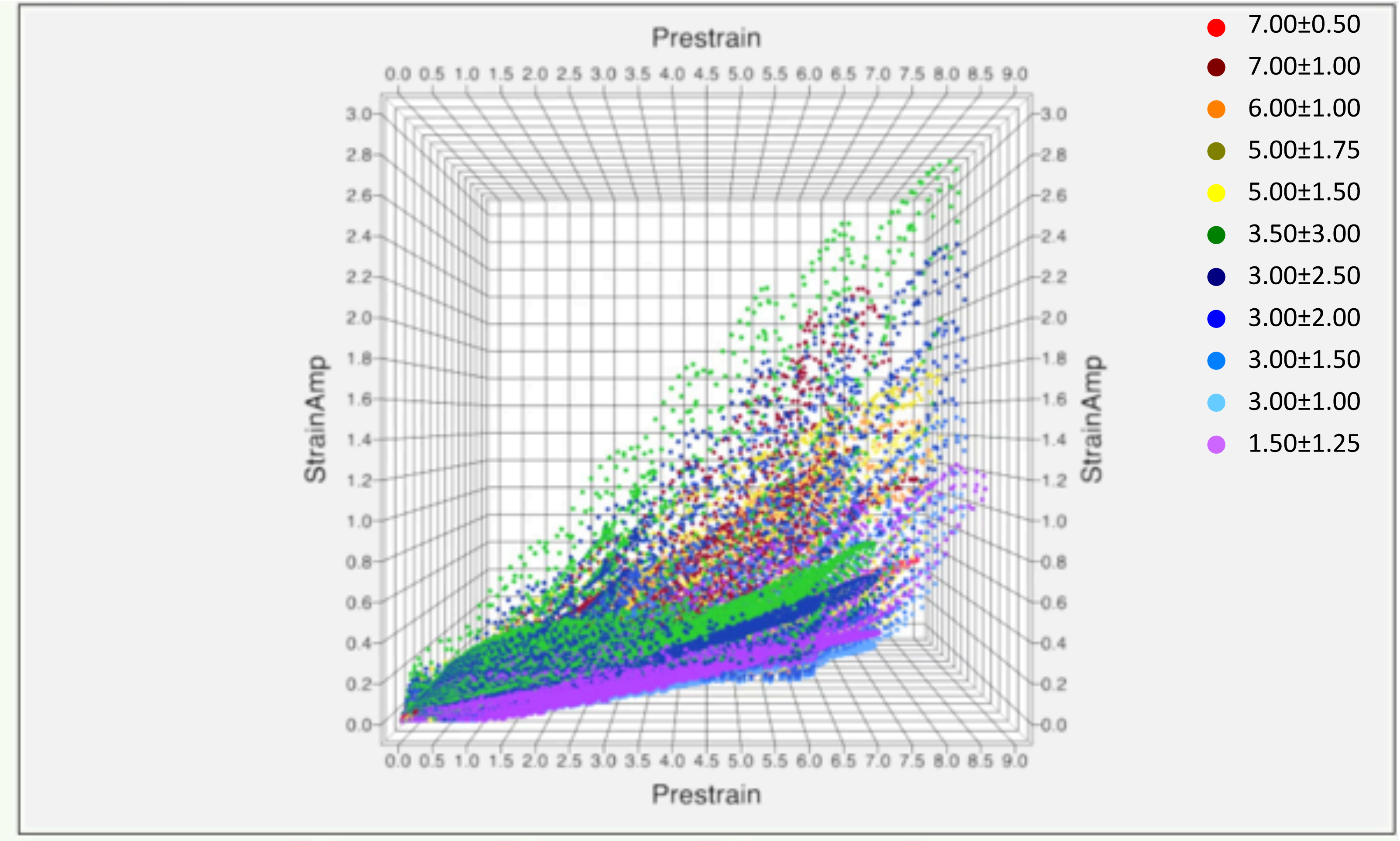


Extending the strain limit diagram to 3D

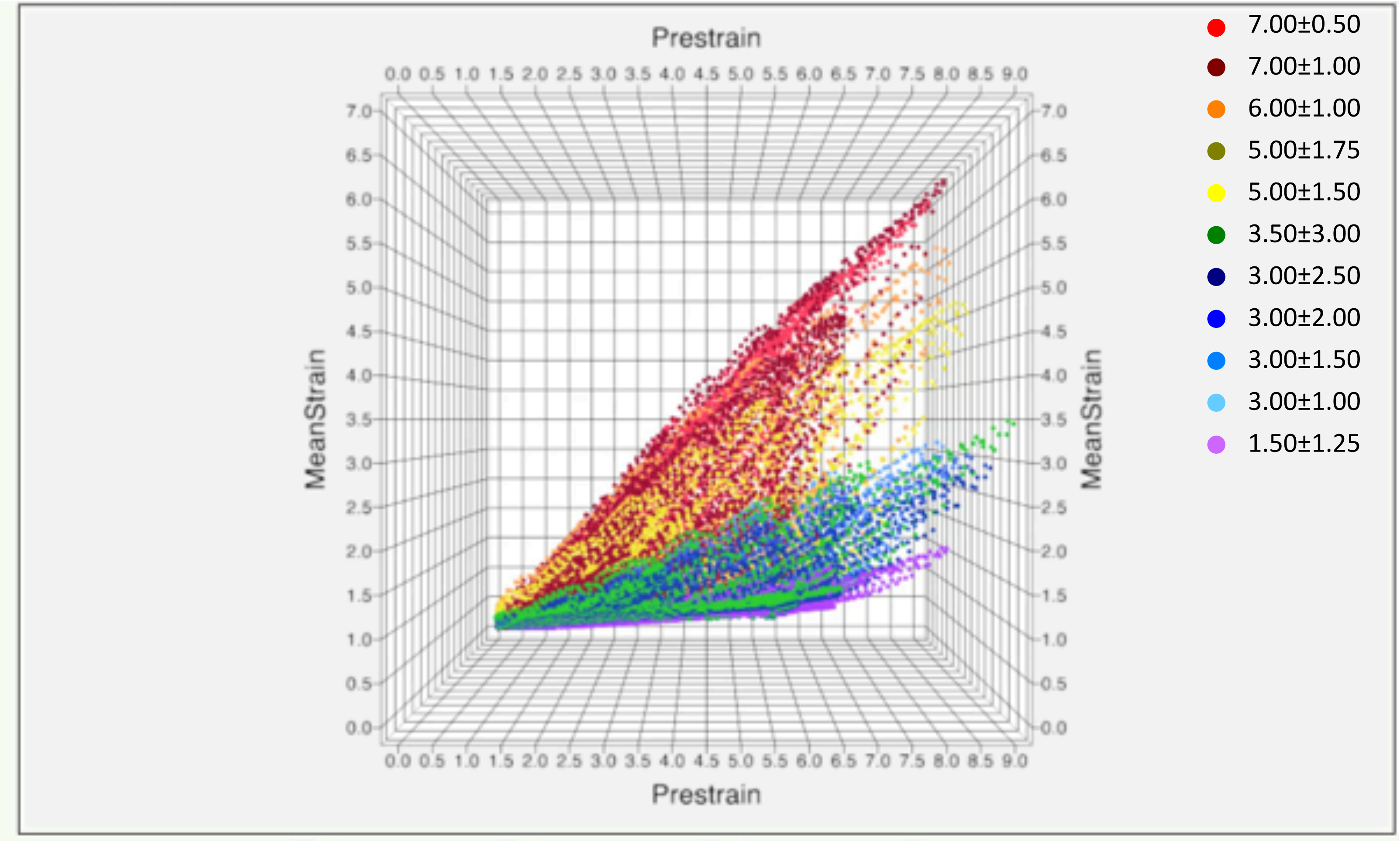
pre-strain vs. strain amplitude



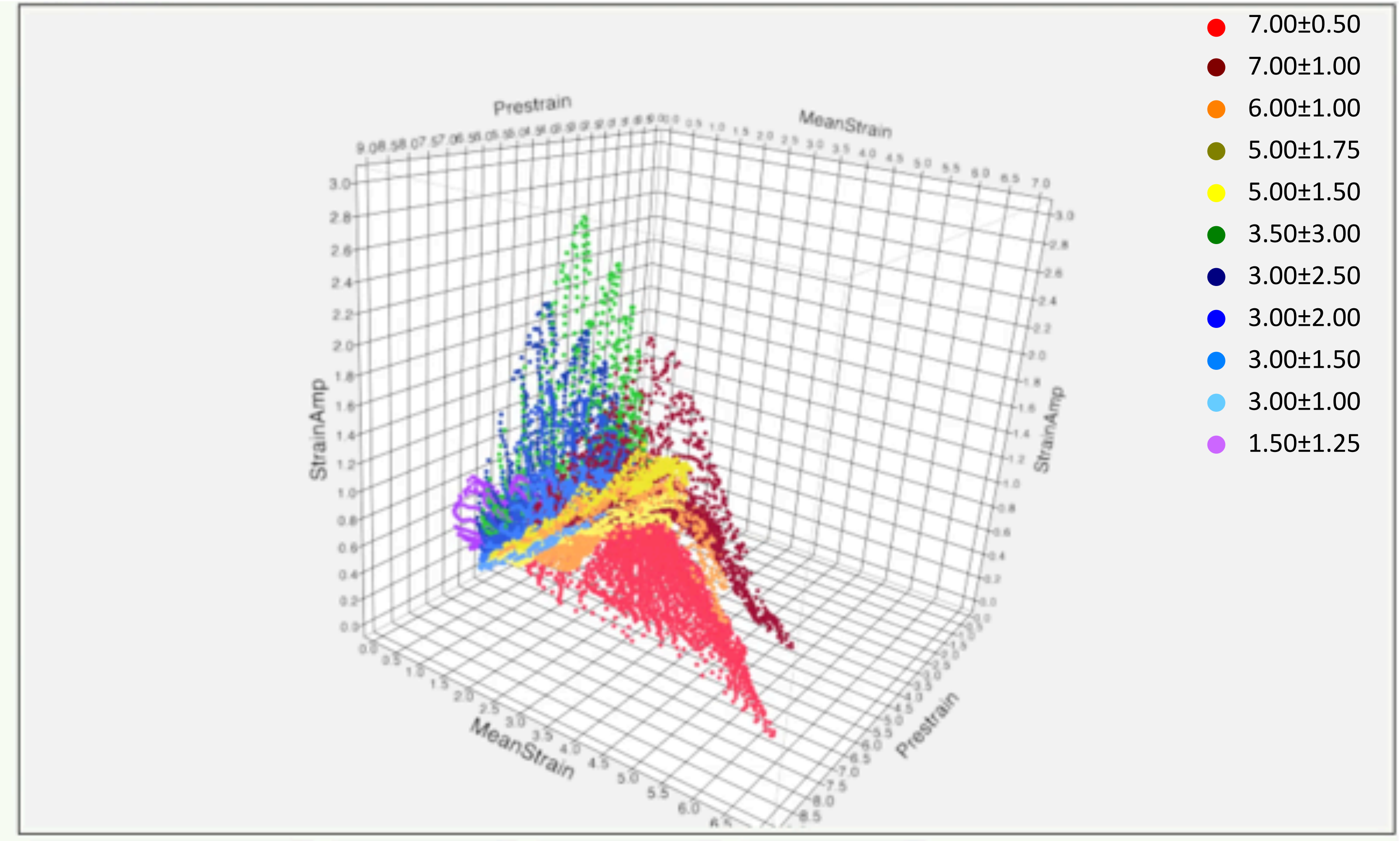
Extending the strain limit diagram to 3D
pre-strain vs. mean strain



Extending the strain limit diagram to 3D
back to the original view



This is not a test of 11 conditions in two dimensions
it is a test of 11 sets of 35,000+ conditions in three dimensions!



Conclusion

Fatigue criticality depends on

not just two, but at least three dimensions

(and maybe these aren't even the right ones;
mean stress is likely to be implicated as well)

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watch screencast recording

http://youtu.be/2JjMATP3ovY

give feedback

craig.bonsignore@nitinol.com