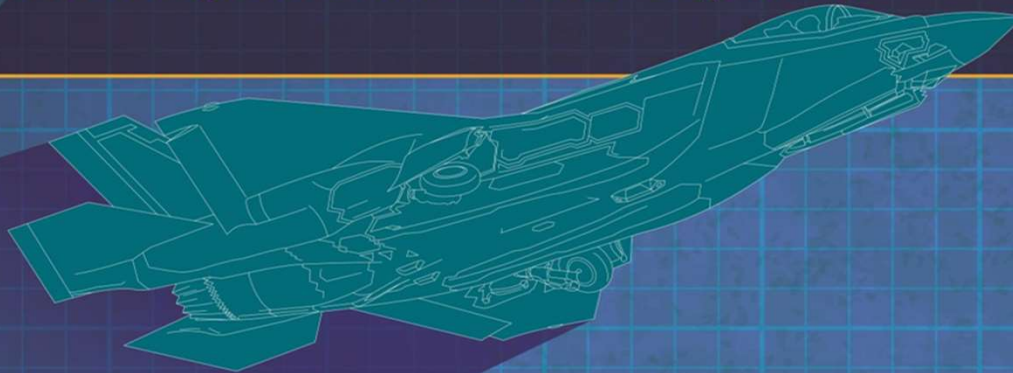


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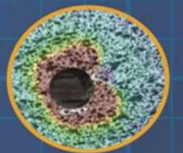


A Method for Validating the Simulation of Cold Expansion

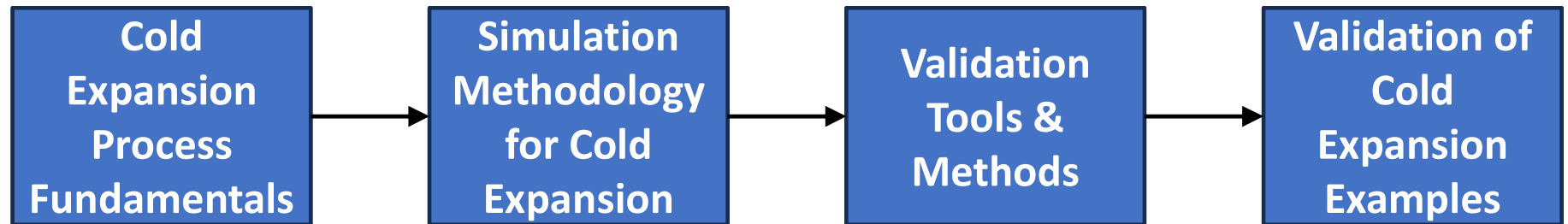
AA&S 2024

Presented by Matthew Kokaly, Ph.D.

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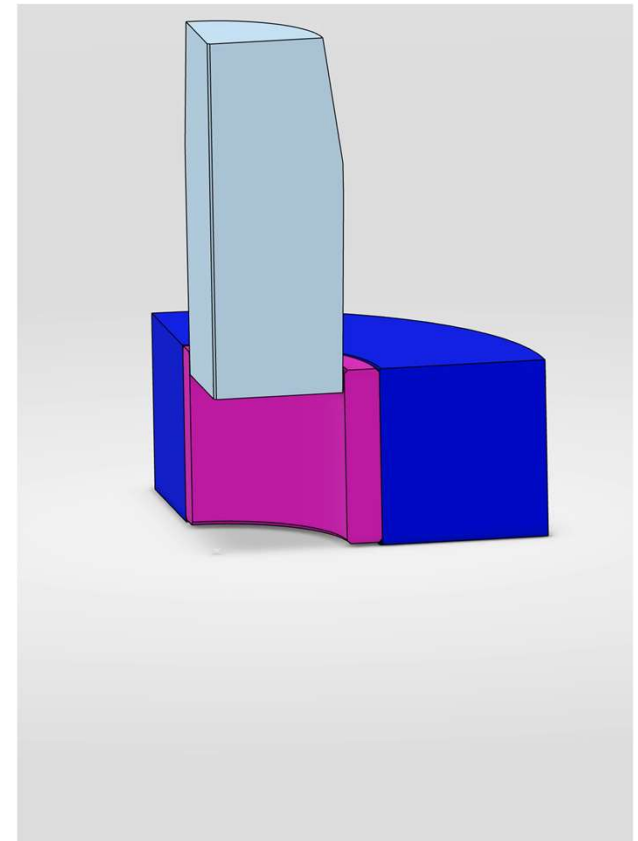
Flow of this Presentation



Cold Expansion Process Fundamentals

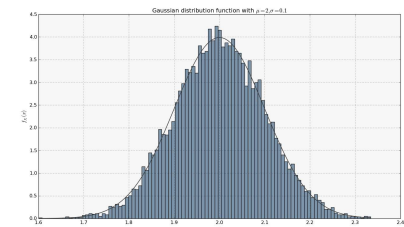
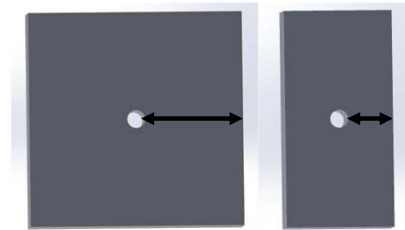
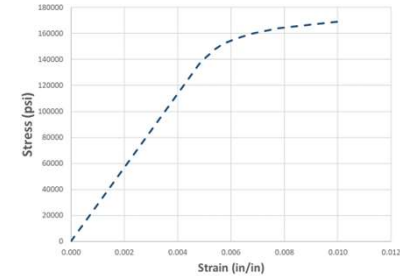
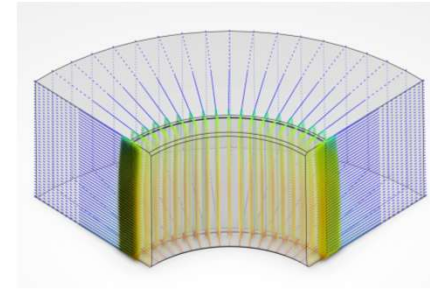
Cold Expansion Process Walkthrough

- Cold expansion of a hole is driven by a radial expansion at room temperatures.
- The radial expansion is usually induced by pulling an oversized tapered mandrel thru either a removable lubricated sleeve or part to be installed (such as a bushing or nut plate) inside the hole.
- The radial expansion is large enough to permanently deform the hole and if present, any insert (e.g bushing).
- The plasticity from the process results in compressive hoop stresses around the hole once the expansion is relaxed resulting in a fatigue life improvement.
- In the case of a bushing or nutplate, the residual interference is much higher than could be achieved by press or shrink-fit processes.



Key Aspects of the Cold Expansion Process

- Cold expansion is a displacement driven process. The level of radial expansion, usually expressed in terms of the % expansion, is the most critical parameter of the process and directly influences:
 - Extent and magnitude of the residual stress.
 - Amount of interference if a bushing or nutplate is involved.
 - Extent and magnitude of deformation in the post-processed condition
 - Pull force during the processing.
- Material response is critical
 - Plasticity is essential to the process with yield stress and strain hardening as key parameters
 - Materials must support sufficient elongation to prevent cracking during the process.
- Geometry of the structure to be cold expanded is an important factor
 - The shape of the part (e.g. edge margins and symmetry or lack of symmetry)
 - Thickness in the mandrel pull direction
 - Hole size
 - Tolerances must be controlled for a reliable process
- Some influential physical parameters are hard to define exactly for a specific case
 - Coefficients of Friction
 - Minimums vs actuals for material properties



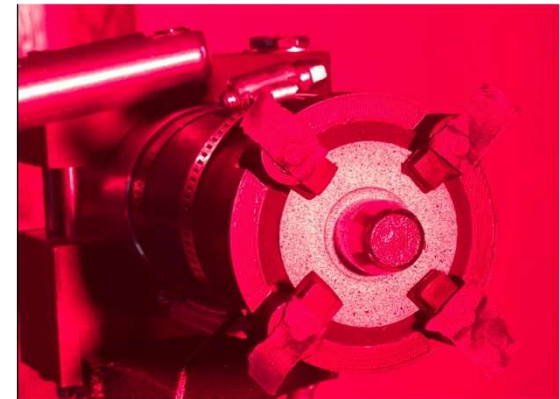
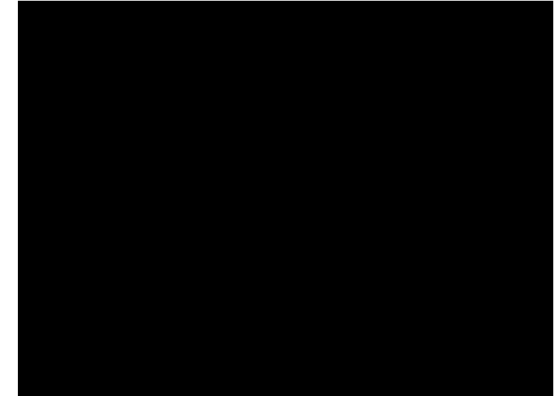
By Shishir Dasika - Own work, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=30730632>

Simulation Methodology for Cold Expansion

Simulation Model Characterization

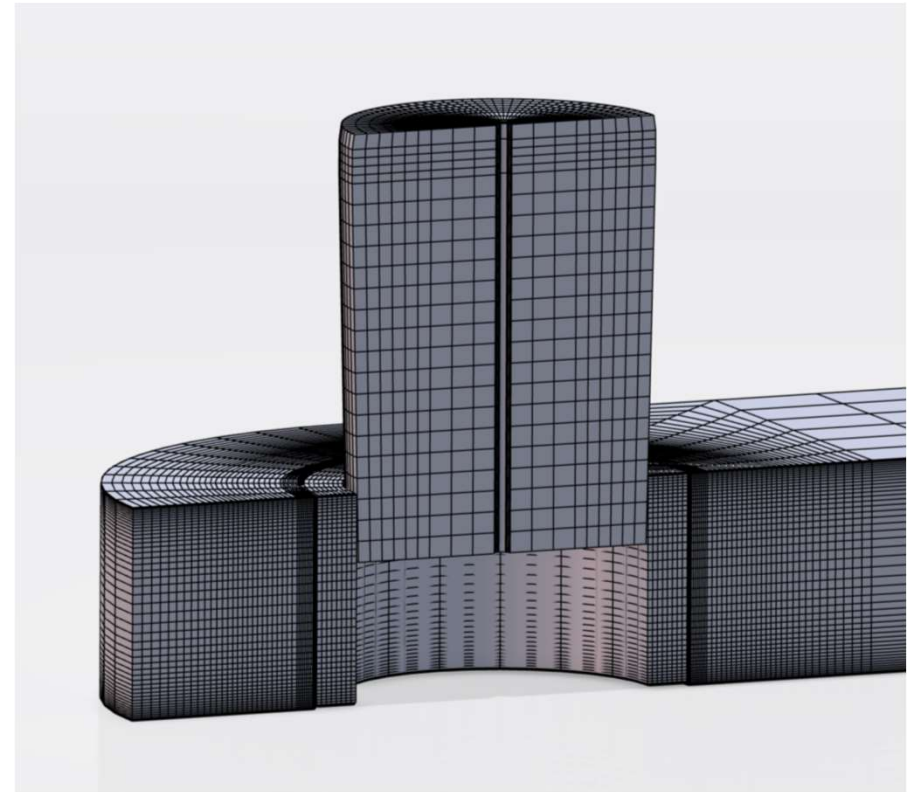
- Finite Element Analysis (FEA) is currently the best-in-class tool for simulating the cold expansion process
- 3-D Modeling of the mandrel pull thru is necessary
 - Significant thru thickness variation of strain and stress
- Type of FEA simulation
 - Dynamic Explicit
 - Positive: Solution is well suited to handle the exit of the mandrel and moments of large contact openings and closures
 - Negative: Noisy results, requires high levels of damping (kinetic) that could influence results, one small element results in very long run times
 - Static Implicit
 - Positive: 99% of the cold expansion process is in static equilibrium
 - Negative: Contact requires a lot of experience to mitigate numerical issues, exit of the mandrel is a severely discontinuous event with some kinetics
 - Static implicit simulation was chosen since the majority of the process takes place under static equilibrium and a variety of techniques can be used to mitigate the mandrel exit

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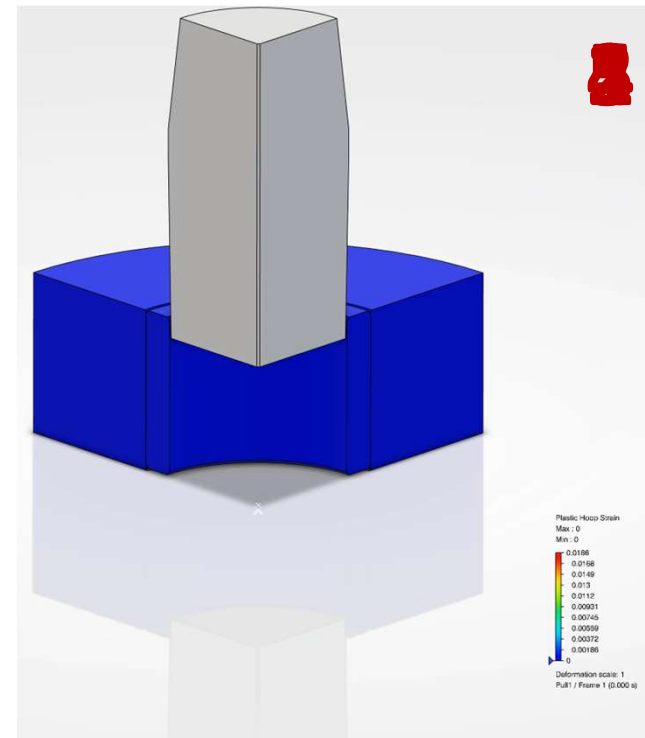
Meshing

- Perennial discussion on meshing
 - Practical Concerns
 - Stress and strain in the bulk of the material is generally a smooth distribution
 - Exterior of the surface is important for fatigue initiation but when looking at damage tolerance, the bulk of the material is most important
 - Material is subject to compression, large strains, localized bending around the major diameter of the mandrel and bending of the specimen about the hole during processing.
 - Majority of highly localized gradients in the stress and strain variation occur near the surface.
 - As a result, radial, hoop and axial mesh densities must all be considered and may or may not scale with size
 - Therefore the mesh is concentrated at the exteriors to capture the localized behavior and variations of displacement, strain and stress.
 - Mesh must be refined enough in the middle to capture the bulk response.
 - There is no universal mesh size due to changes in the level of radial interference with hole size.



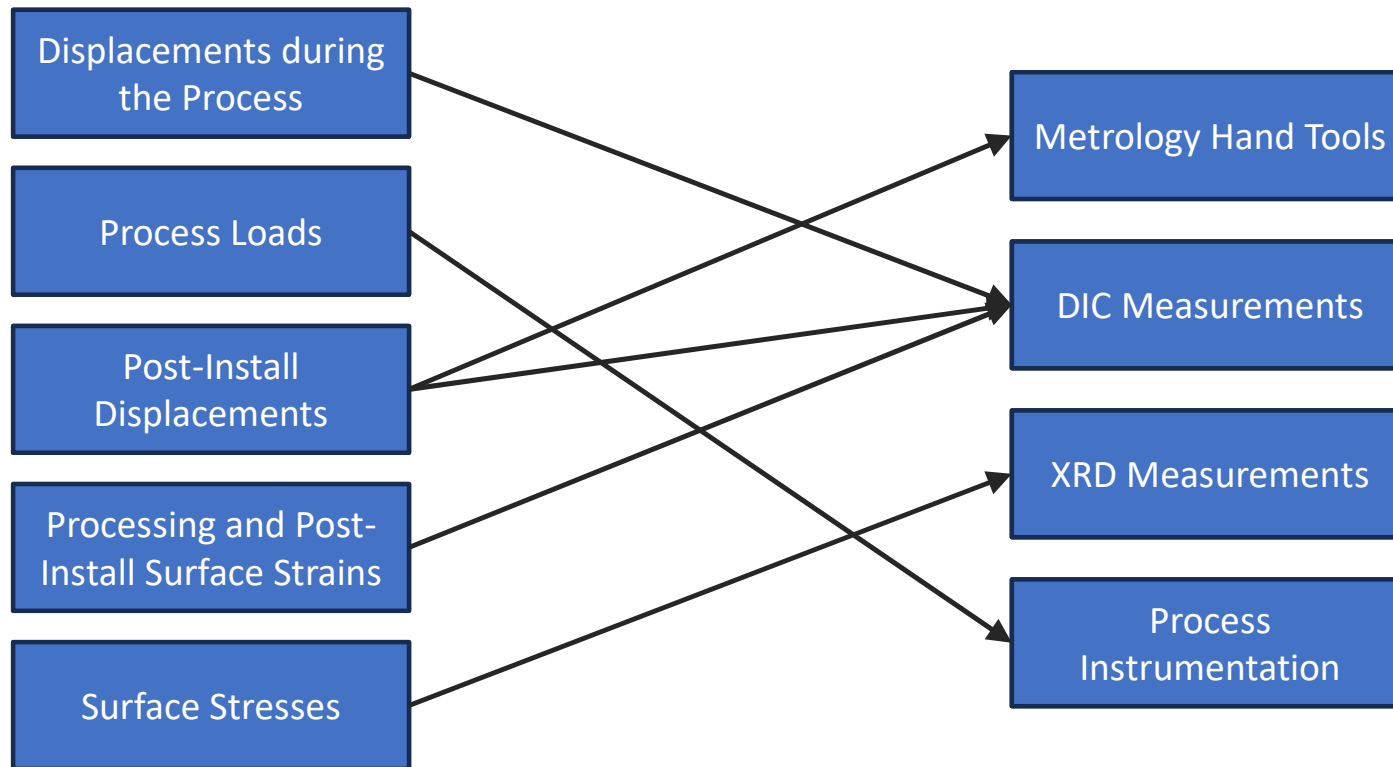
Key Moments During Simulation

1. Mandrel first contact
2. Mandrel major diameter is in contact
3. Specimen reverses cupping/bending about the hole when the mandrel flat is near the middle of the specimen
4. Contact switches from the entry to the exit corner of the mandrel major diameter flat as it approaches the exit
5. Mandrel major diameter exits the specimen



Validation Tools and Methods

Physical Effects and Measurement Tools



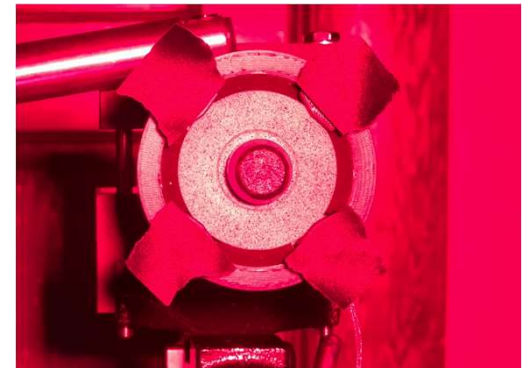
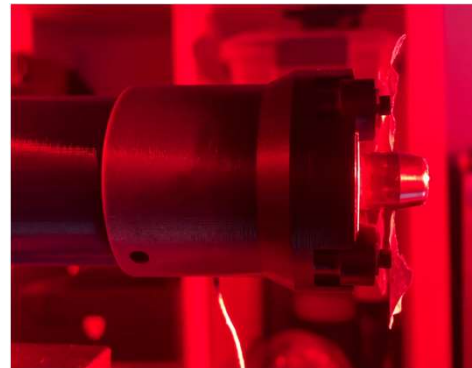
Hand Measurements for Displacements

- Post Install ID of the Bushing
- Post Install Outside Diameter/Surface of the Part
- Post Bushing Removal OD of the Bushing
- Post Bushing Removal of the SHD
- Post Bushing Outside Diameter /Surface of the Part
- Bushing Extrusion



DIC Measurements

- Bushing ID and specimen outer diameter/surface on pattern side (compare to hand metrology)
- Post-install diameter at the bushing/part interface on pattern side (not easily measured with hand metrology)
- Surface upset
- In-Situ and post-install strain measurements
 - Hoop
 - Radial



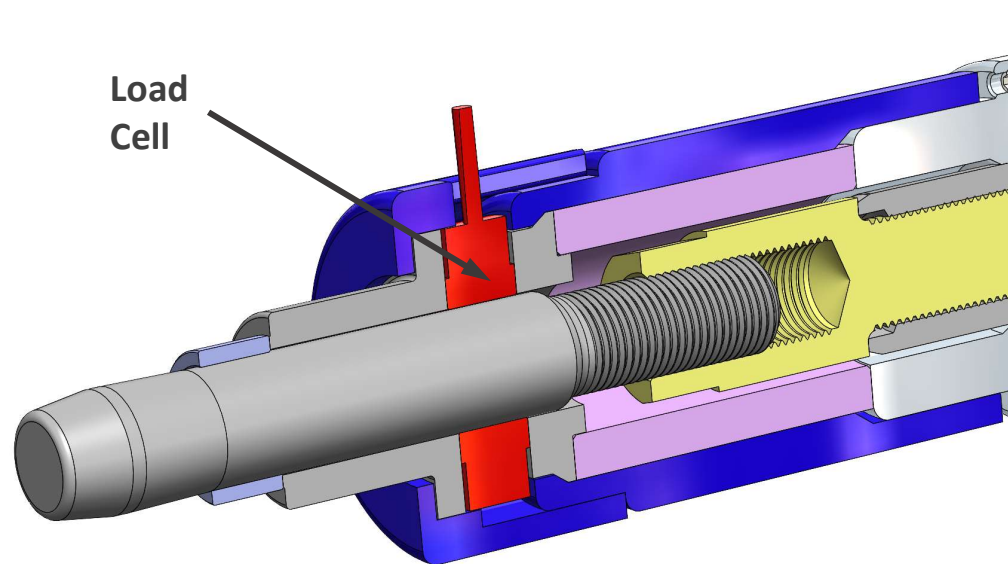
X-Ray Diffraction Measurements

- Residual stress state on surface of the specimen



Process Instrumentation

- Load Cell
 - Integrated in-line with the reactive load path



Correlations Of Interest

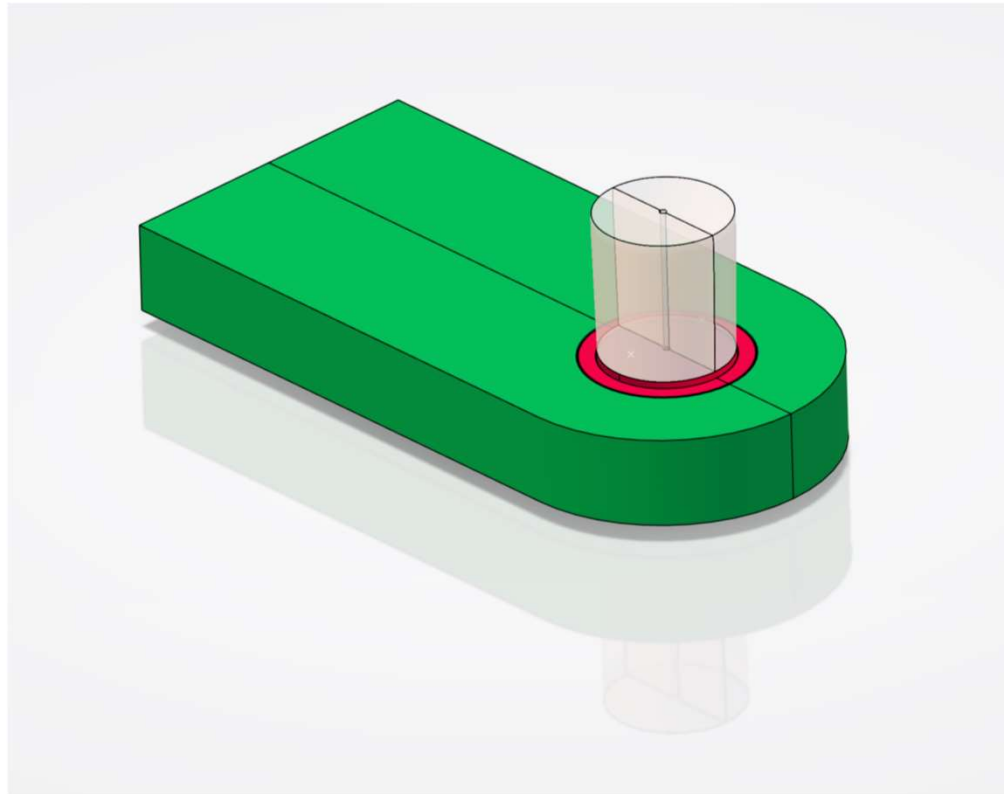
- **Displacement Correlations**

- Bushing ID Entry Change (Hand Tool, DIC, FEA)
- Bushing ID Exit Change (Hand Tool, FEA)
- Bushing OD Change (DIC, FEA)
- Specimen SHD Change (DIC, FEA)
- Specimen OD Entry Change (Hand Tool, DIC, FEA)
- Specimen OD Exit Change (Hand Tool, FEA)
- Specimen Radial Displacement along a Radial Line (DIC, FEA)
- Removed Bushing ID Entry (Hand Tool, FEA)
- Removed Bushing ID Exit (Hand Tool, FEA)
- Removed Bushing OD Entry (Hand Tool, FEA)
- Removed Bushing OD Exit (Hand Tool, FEA)
- Removed Specimen SHD Entry (Hand Tool, FEA)
- Removed Specimen SHD Exit (Hand Tool, FEA)

- Removed Specimen OD Entry (Hand Tool, FEA)
- Removed Specimen OD Exit (Hand Tool, FEA)
- **Strain Correlations**
 - Specimen Hoop Strain Along a Radial Line (DIC, FEA)
 - Bushing Hoop Strain Near the OD (DIC, FEA)
 - Specimen Radial Strain Along a Radial Line (DIC, FEA)
 - Bushing Radial Strain Near the OD (DIC, FEA)
- **Stress Correlation**
 - XRD Hoop and Radial Stress
- **Force Correlation**
 - Pull Force

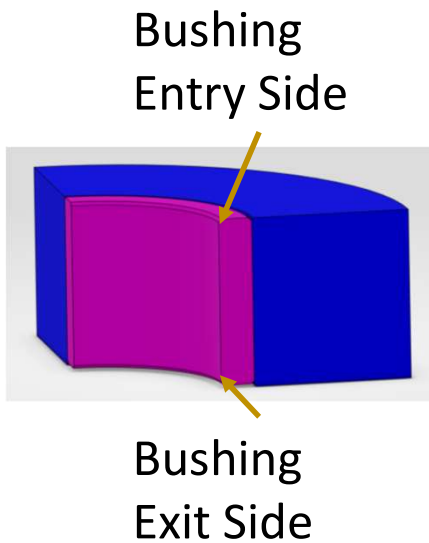
Simulation Validation Examples

Expanded Journal Bushing Example



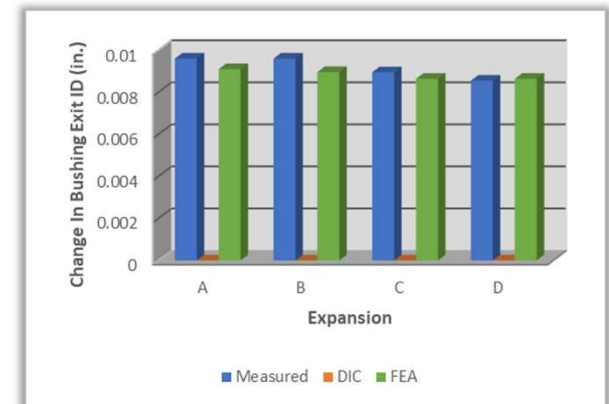
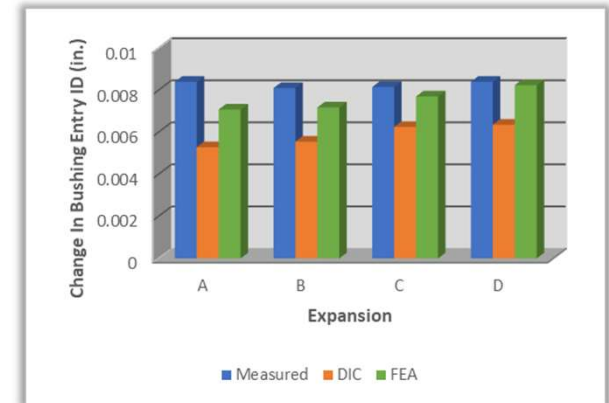
Displacement – Installed Change in Bushing ID

The Bushing ID validation indicates whether the simulation of combined bushing + specimen behavior response is correct post-installation. (B + S is correct)



Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	0.00725	0.00529	0.00708	0.00017
B	0.00810	0.00555	0.00718	0.00092
C	0.00815	0.00625	0.00770	0.00045
D	0.00840	0.00636	0.00824	0.00016

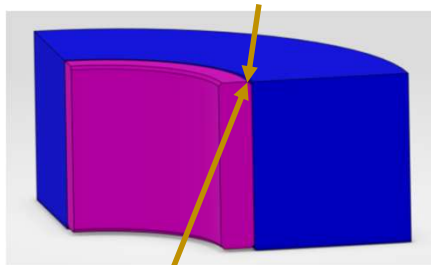
Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	0.00855	N/A	0.00864	0.00009
B	0.00895	N/A	0.00864	0.00031
C	0.00960	N/A	0.00896	0.00064
D	0.00960	N/A	0.00910	0.00050



Displacement – Installed Bushing & Specimen Interface Entry

The bushing and specimen interface diameter validation indicates whether the simulated bushing and specimen behaviors are providing the correct proportional responses post-installation (B and S proportions are correct in B + S)

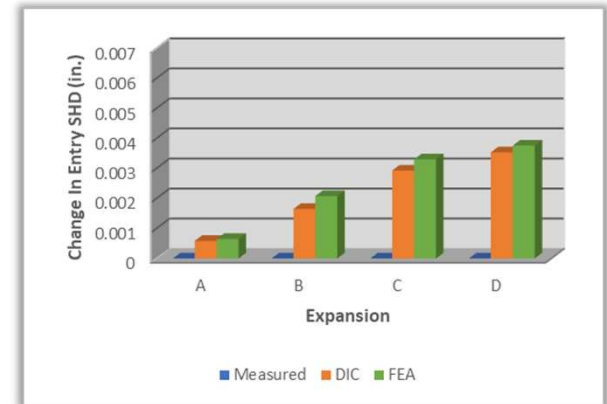
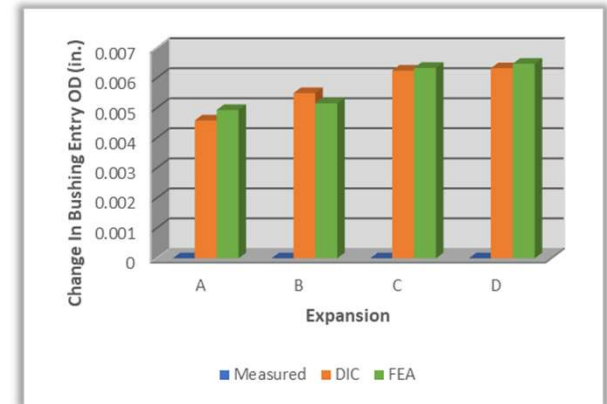
Bushing
Entry OD



Specimen
Entry SHD

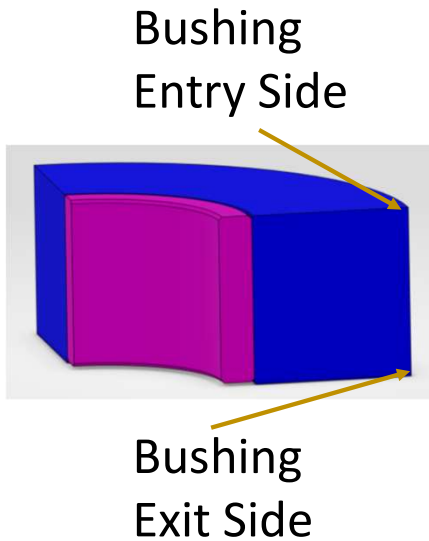
Expansion	Measured	DIC	FEA	Diff in DIC vs FEA
A	N/A	0.00459	0.00494	0.00035
B	N/A	0.00550	0.00516	0.00034
C	N/A	0.00625	0.00624	0.00001
D	N/A	0.00655	0.00648	0.00007

Expansion	Measured	DIC	FEA	Diff in DIC vs FEA
A	N/A	0.00059	0.00065	0.00006
B	N/A	0.00165	0.00208	0.00043
C	N/A	0.00293	0.00330	0.00037
D	N/A	0.00353	0.00376	0.00023



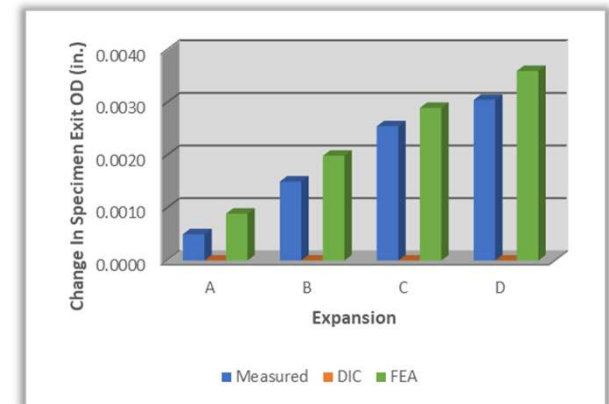
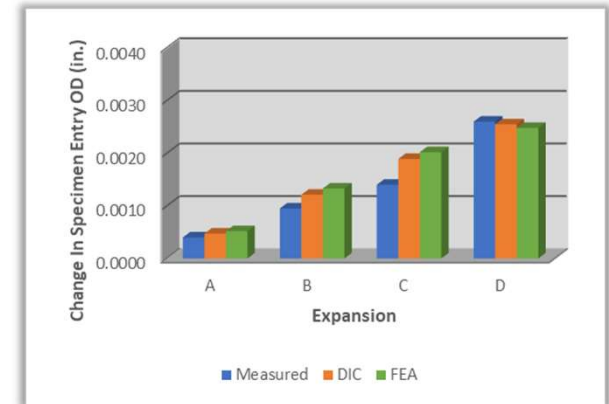
Displacement – Installed Specimen OD Changes

The specimen OD validation indicates that the simulation correctly captured the permanent deformation of the specimen with the bushing installed.



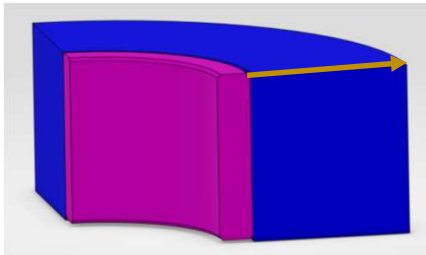
Expansion	Measured	DIC	FEA	Diff in DIC vs FEA
A	0.00040	0.00047	0.00052	0.00005
B	0.00095	0.00121	0.00133	0.00012
C	0.00140	0.00189	0.00202	0.00013
D	0.00260	0.00255	0.00248	0.00007

Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	0.00050	N/A	0.00089	0.00039
B	0.00150	N/A	0.00199	0.00049
C	0.00255	N/A	0.00290	0.00035
D	0.00305	N/A	0.00360	0.00055

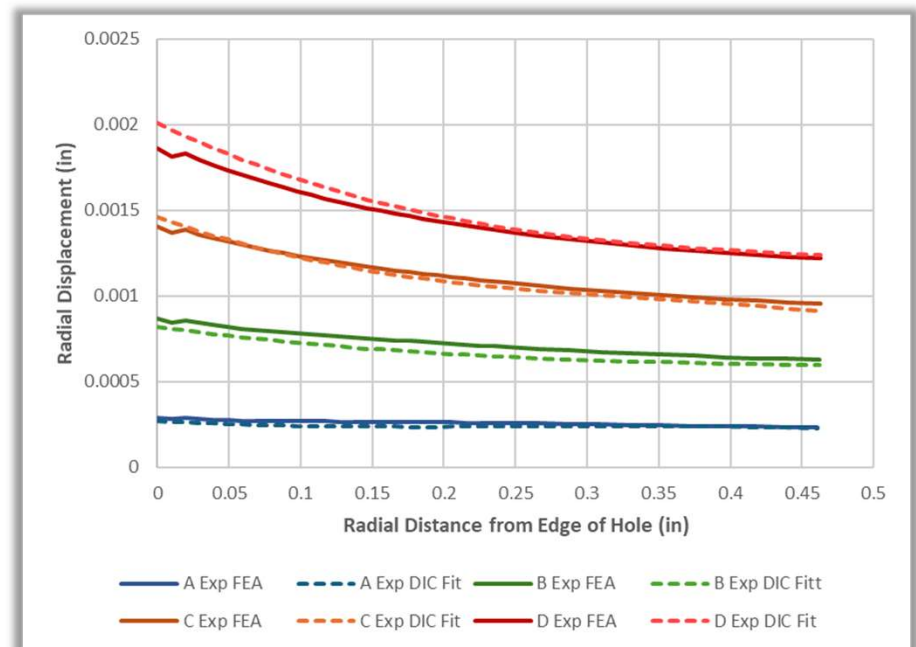


Displacement - Installed Specimen Radial Displacement along a Radial Line on Entry Side

The specimen radial displacement validation indicates that the simulation was reflective of what is present in the bulk of the material. As part of the validation method, the DIC data along four directions were fitted to a single curve and that fitted curve was used to compare to the FEA results. The R2 of the FEA results to the fitted curve was calculated as was the average and max difference at radial positions along the curve to show validation.

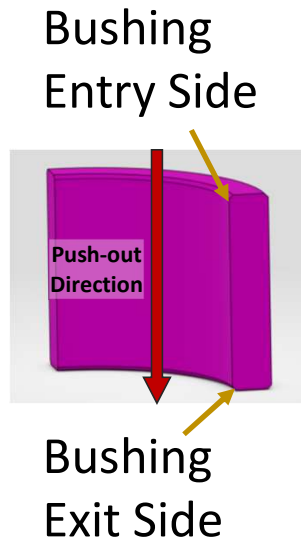


Expansion	R ² of DIC Fit of Raw Data	R ² FEA vs fitted DIC	Average Difference	Max Difference
A	0.1347	0.1996	0.00002	0.00003
B	0.9099	0.6192	0.00005	0.00006
C	0.9773	0.9572	0.00002	0.00006
D	0.9409	0.8910	0.00005	0.00016



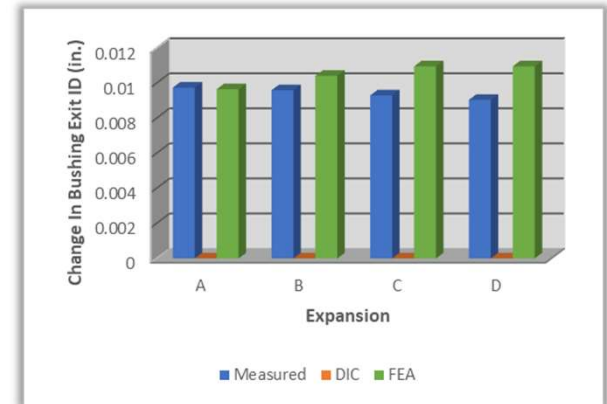
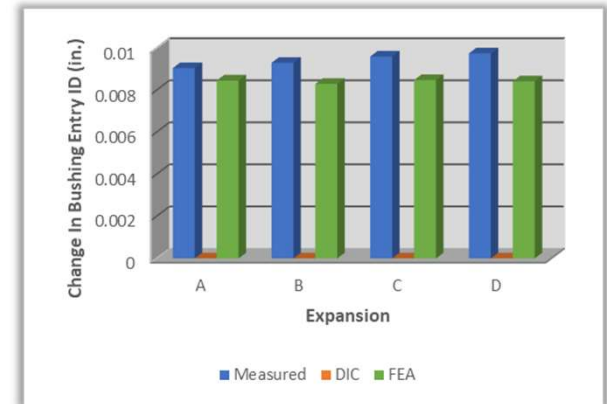
Displacement – Removed Bushing ID

The Bushing ID validation measured after it is pushed out is a second indicator that the simulation captured the behavior of the bushing correctly. Unfortunately, distortion of the bushing may occur during the pushout process, especially on the entry side where the high push-out load is applied but may occur throughout the bushing also.



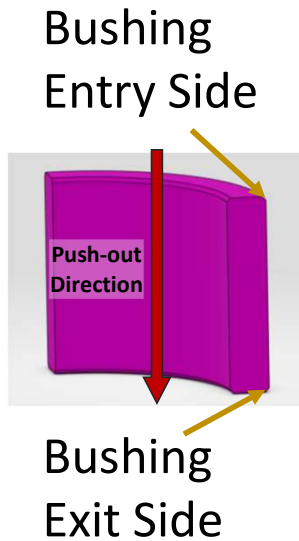
Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	0.00905	N/A	0.00846	0.00059
B	0.00930	N/A	0.00830	0.00100
C	0.00960	N/A	0.00848	0.00112
D	0.00975	N/A	0.00842	0.00133

Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	0.00975	N/A	0.00966	0.00009
B	0.0096	N/A	0.01042	0.00082
C	0.0093	N/A	0.01096	0.00166
D	0.00905	N/A	0.01096	0.00191



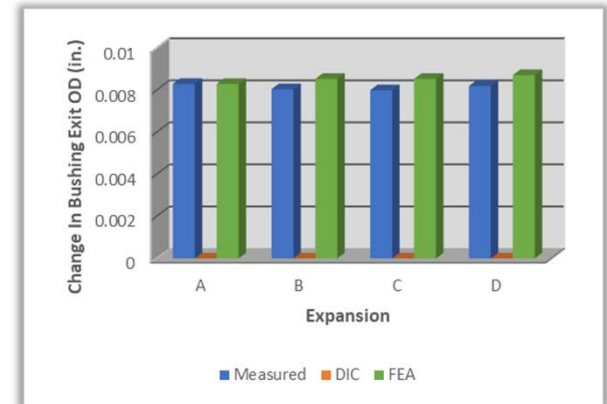
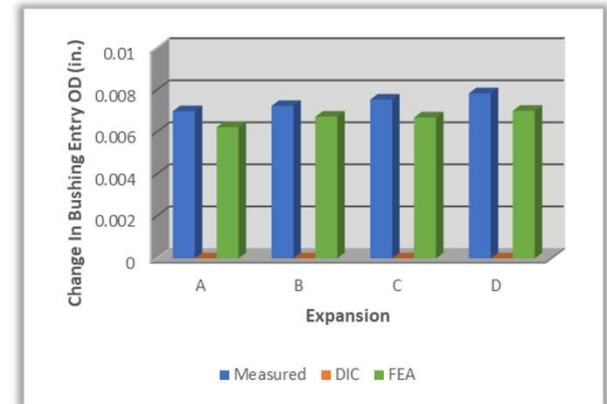
Displacement – Removed Bushing OD

The Bushing OD is used as one part of the calculation of the interference present between the bushing and the specimen. Unfortunately, the Bushing OD is subject to wear during the push-out process. The exit side experiences the least amount of sliding and is the better validation measurement in this case.



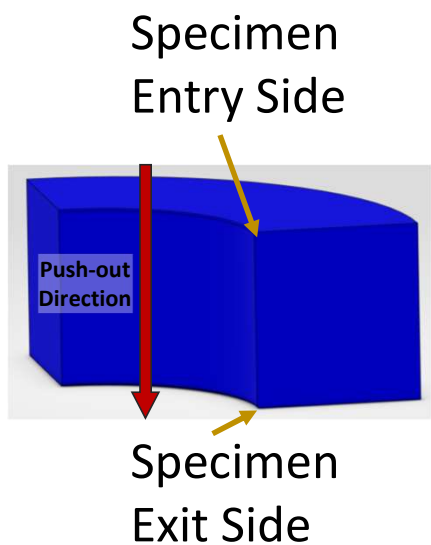
Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	0.00700	N/A	0.00624	0.00076
B	0.00725	N/A	0.00674	0.00051
C	0.00755	N/A	0.00670	0.00085
D	0.00785	N/A	0.00702	0.00083

Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	0.0083	N/A	0.0083	0.00000
B	0.00805	N/A	0.00854	0.00049
C	0.008	N/A	0.00854	0.00054
D	0.0082	N/A	0.00872	0.00052

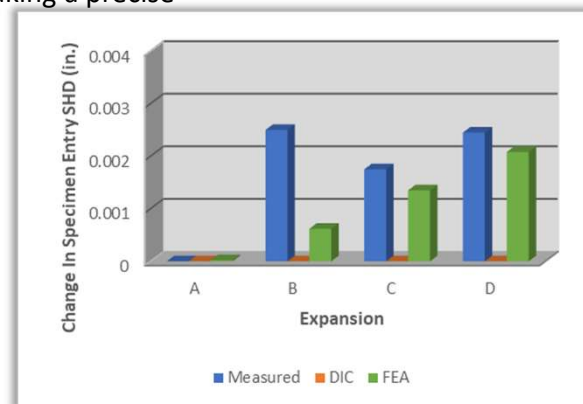


Displacement – Removed Specimen SHD

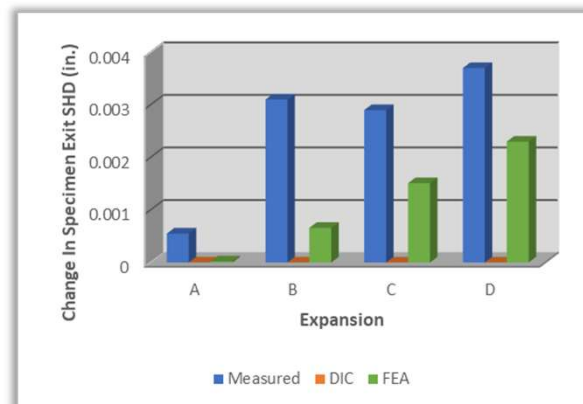
The Specimen SHD is the second part of the measurement of the interference that was present between the installed bushing and the specimen. Unfortunately, this surface is subjected to wear/distortion during push-out like the Bushing OD, with the entry side subjected to less wear in this case. Unfortunately, the two locations are on opposite ends making a precise measurement of interference difficult to obtain using metrology.



Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	0	N/A	0.00002	0.00002
B	0.0025	N/A	0.00062	0.00188
C	0.00175	N/A	0.00135	0.00040
D	0.00245	N/A	0.00208	0.00037

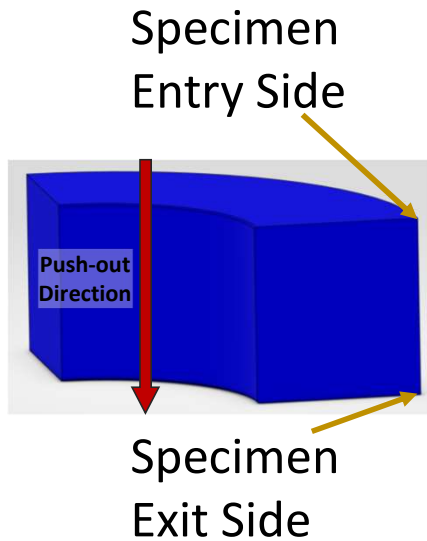


Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	0.00055	N/A	0.00002	0.00053
B	0.0031	N/A	0.00066	0.00244
C	0.0029	N/A	0.00151	0.00149
D	0.0037	N/A	0.0023	0.00140



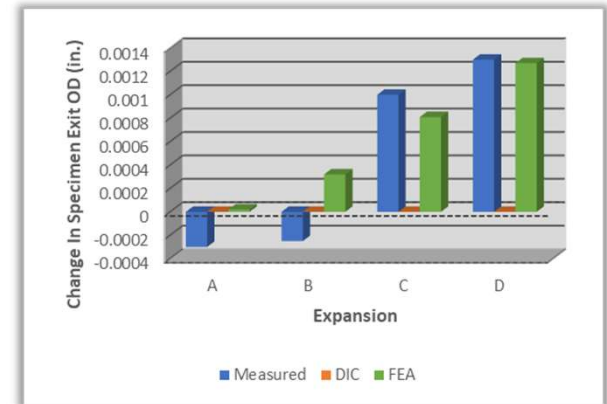
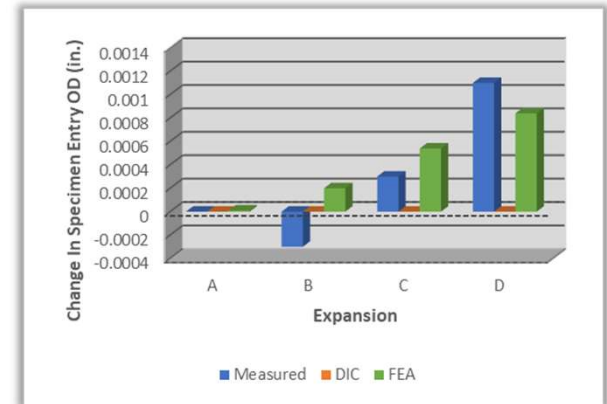
Displacement – Removed Specimen OD

The Specimen OD validation is a second indication that the strain and reversal of the strain in the specimen was correct in the simulation. This surface is not subject to wear like the Bushing OD and Specimen SHD.



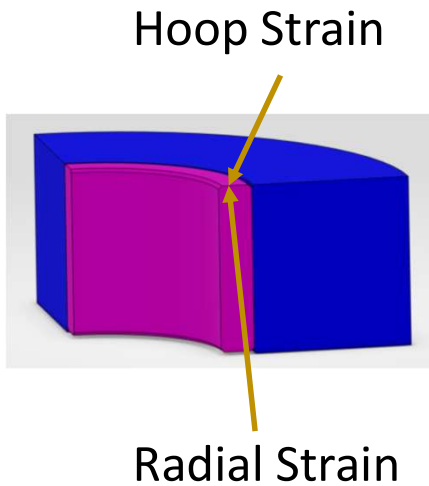
Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	0	N/A	0.00001	0.00001
B	-0.0003	N/A	0.0002	0.00050
C	0.0003	N/A	0.00054	0.00024
D	0.0011	N/A	0.00084	0.00026

Expansion	Measured	DIC	FEA	Diff in Measured vs FEA
A	-0.0003	N/A	0.00002	0.00032
B	-0.00025	N/A	0.00032	0.00057
C	0.001	N/A	0.00081	0.00019
D	0.0013	N/A	0.00127	0.00003



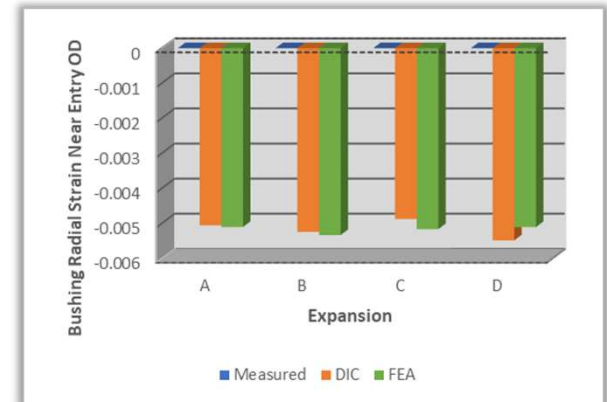
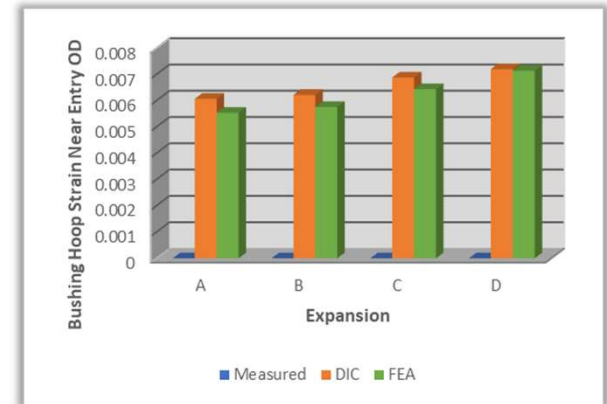
Strain – Bushing Strain Near Entry OD (DIC, FEA)

The bushing strain validation is an indicator that the strain and reversal of the strain in the bushing is correct in the simulation. More refinement of the DIC process is needed due to the relatively small thickness of the bushing when chamfers are considered and unexpected issues related to DIC setup.



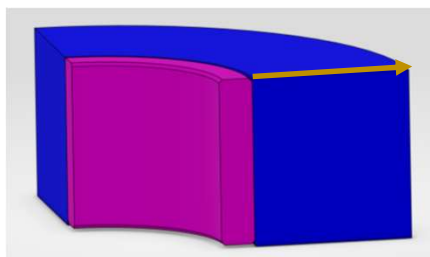
Expansion	Measured	DIC	FEA	% Diff in DIC vs FEA
A	N/A	0.00607	0.00554	8.7%
B	N/A	0.00622	0.00576	7.4%
C	N/A	0.00688	0.00644	6.4%
D	N/A	0.00720	0.00714	0.9%

Expansion	Measured	DIC	FEA	% Diff in DIC vs FEA
A	N/A	-0.00505	-0.0051	1%
B	N/A	-0.00524	-0.00533	1.7%
C	N/A	-0.00487	-0.00516	6.0%
D	N/A	-0.00548	-0.0051	6.9%

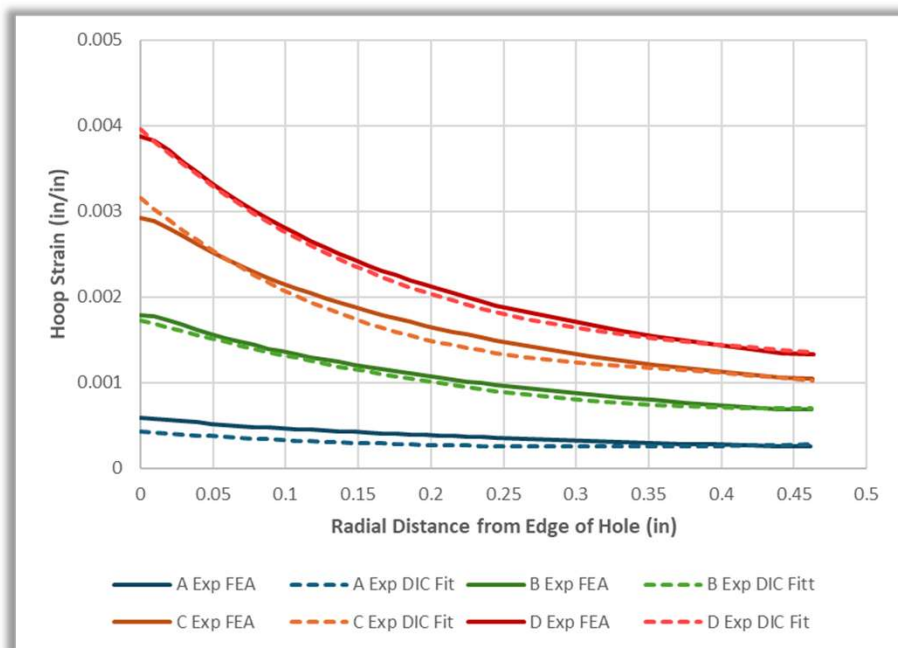


Strain – Specimen Hoop Strain Along a Radial Line on Entry Side

The specimen hoop strain validation along a radial line indicates that the simulation was reflective of that the bulk of the specimen behavior. As part of the validation method, the DIC data along four directions were fitted to a single curve and that fitted curve was used to compare to the FEA results. The R2 of the FEA results to the fitted curve was calculated as was the average and max difference at radial positions along the curve to check validation.

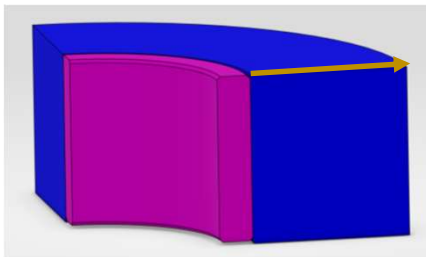


Expansion	R ² of DIC Fit to Raw Data	R ² (FEA vs DIC)	Average Difference	Max Difference
A	0.9405	0.3253	0.00011	0.00016
B	0.9242	0.9702	0.00005	0.00009
C	0.8876	0.9588	0.00010	0.00024
D	0.9842	0.9937	0.00005	0.00009

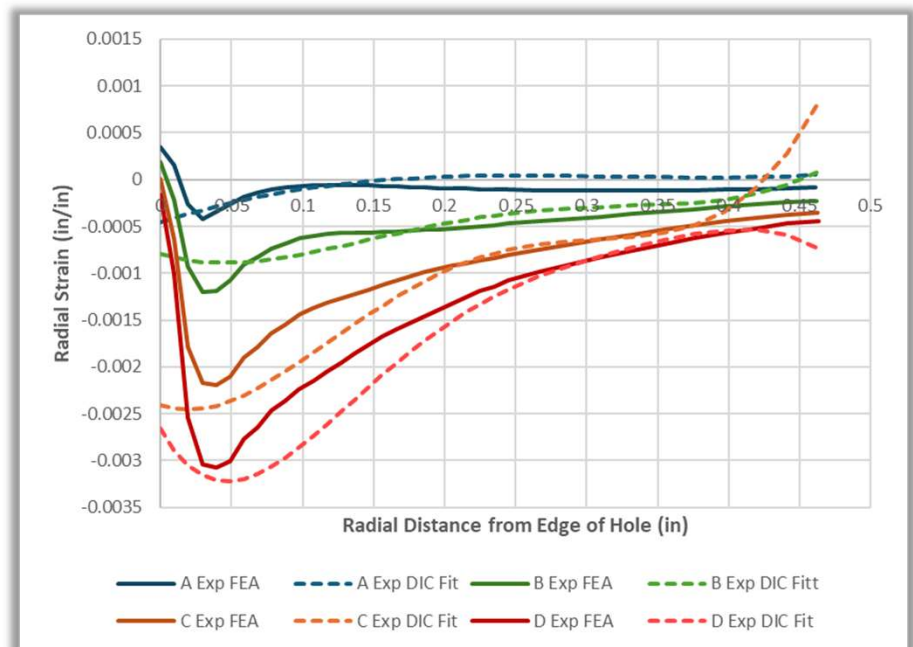


Strain – Specimen Radial Strain Along a Radial Line on Entry Side

The specimen hoop strain validation along a radial line indicates that the simulation was reflective of that the bulk of the specimen behavior. As part of the validation method, the DIC data along four directions were fitted to a single curve and that fitted curve was used to compare to the FEA results. The R2 of the FEA results to the fitted curve was calculated as was the average and max difference at radial positions along the curve. However, more work is needed as the DIC may have resulted in too much smoothing and was difficult to measure accurately near the edge of the hole with the current setup.



Expansion	R ² of DIC Fit to Raw Data	R ² (FEA vs DIC)	Average Difference	Maximum Difference
A	0.6299	0	0.00013	0.00081
B	0.7710	0.2687	0.00015	0.00098
C	0.9068	0.7410	0.00036	0.00242
D	0.9608	0.52373	0.00038	0.00250



Combined Correlation Matrix - Displacement

Overall, most displacement-based validations were excellent. The hardest to validate were related to cases exhibiting possible wear of the bushing and specimen during push-out for retention behavior.

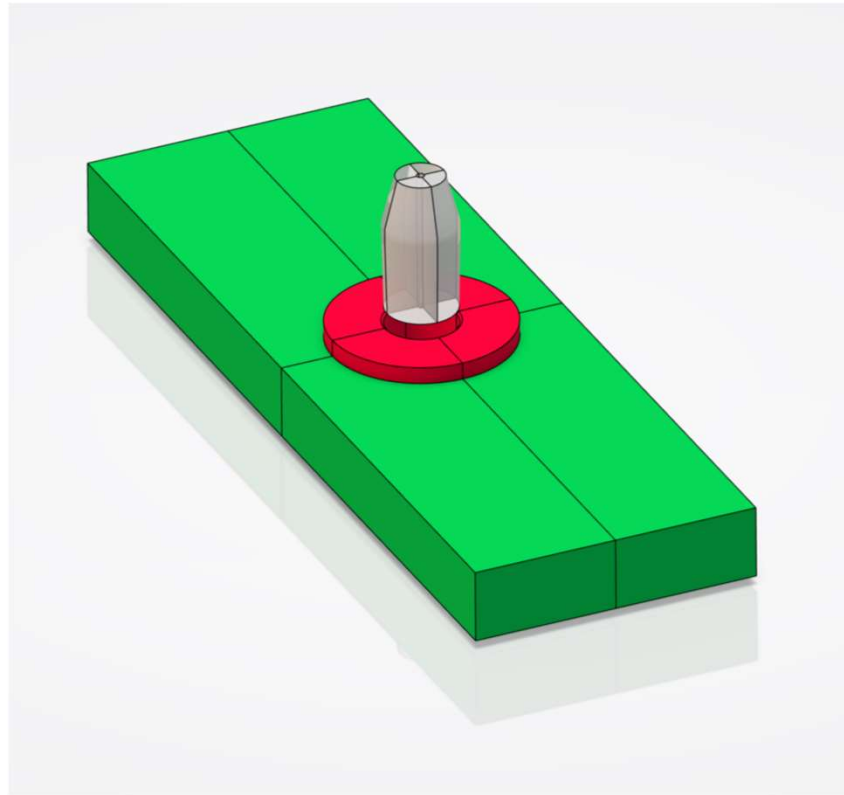
Expansion	Change in Installed Bushing Entry ID	Installed Bushing Exit ID Changes	Installed Bushing Entry OD Changes	Installed Specimen Entry SHD Change	Installed Specimen Entry OD Change	Installed Specimen Exit OD Change	Installed Specimen Radial Displacement Along a Radial Line on Entry Side	Removed Bushing Entry ID	Removed Bushing Exit ID	Removed Bushing Entry OD	Removed Bushing Exit OD	Removed Specimen Entry SHD	Removed Specimen Exit SHD	Removed Specimen Entry OD	Removed Specimen Exit OD
A	0.00017	0.00009	0.00035	0.00006	0.00005	0.00039	0.1996 0.00002 0.000043	0.00059	0.00009	0.00076	0.00000	0.00002	0.00053	0.00001	0.00032
B	0.00092	0.00031	0.00034	0.00043	0.00012	0.00049	0.6192 0.00005 0.00006	0.00100	0.00082	0.00051	0.00049	0.00188	0.00244	0.00050	0.00057
C	0.00045	0.00064	0.00001	0.00037	0.00013	0.00035	0.9572 0.00002 0.00006	0.00112	0.00166	0.00085	0.00054	0.00040	0.00149	0.00024	0.00019
D	0.00016	0.00050	0.00007	0.00023	0.00007	0.00055	0.8910 0.00005 0.00016	0.00133	0.00191	0.00083	0.00052	0.00037	0.00140	0.00026	0.00003
Potential Push-Out Wear Effects															

Combined Correlation Matrix – Strain and Force

Most of the hoop strain measurements were in good agreement. The radial strain was hardest to validate for reasons likely related to complexity of the expansion near the hole and limitations of the current DIC setup.

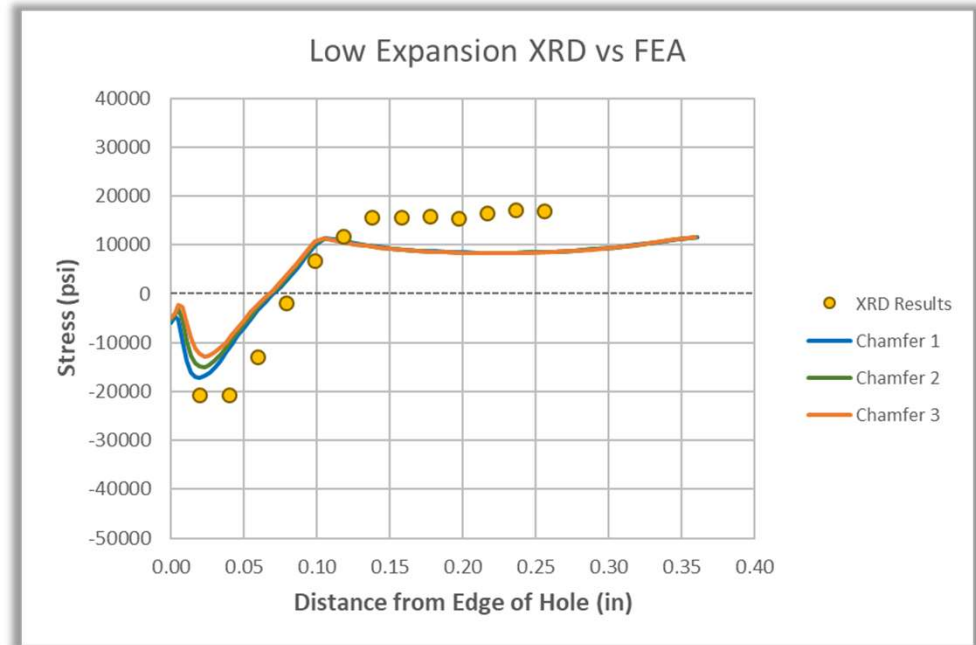
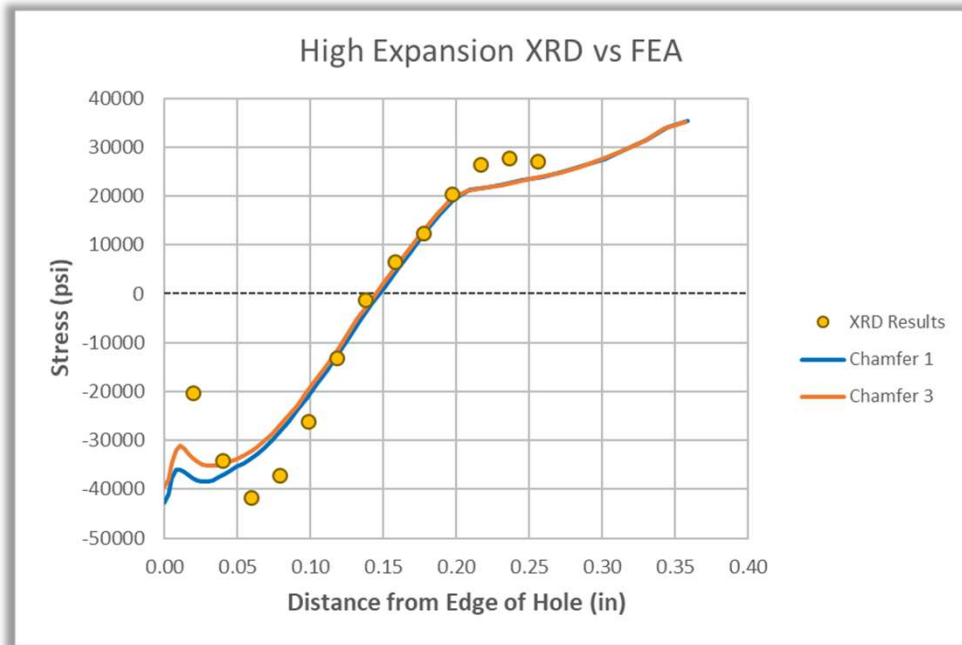
Expansion	Specimen Hoop Strain Entry Along a Radial Line				Bushing Hoop Strain Near Entry OD	Specimen Radial Strain Entry Along a Radial Line			
	R2 FEA vs DIC	Average Difference	Maximum Difference			R2 FEA vs DIC	Average Difference	Maximum Difference	Bushing Radial Strain Near Entry OD
A	0.3253	0.00011	0.00016	8.7%		0	0.00013	0.00081	1%
B	0.9702	0.00005	0.00009	7.4%		0.2687	0.00015	0.00098	1.7%
C	0.9588	0.00010	0.00024	6.4%		0.7410	0.00036	0.00242	6.0%
D	0.9937	0.00005	0.00009	0.9%		0.5237	0.00038	0.00250	6.9%

Thin-Walled Bushing Example



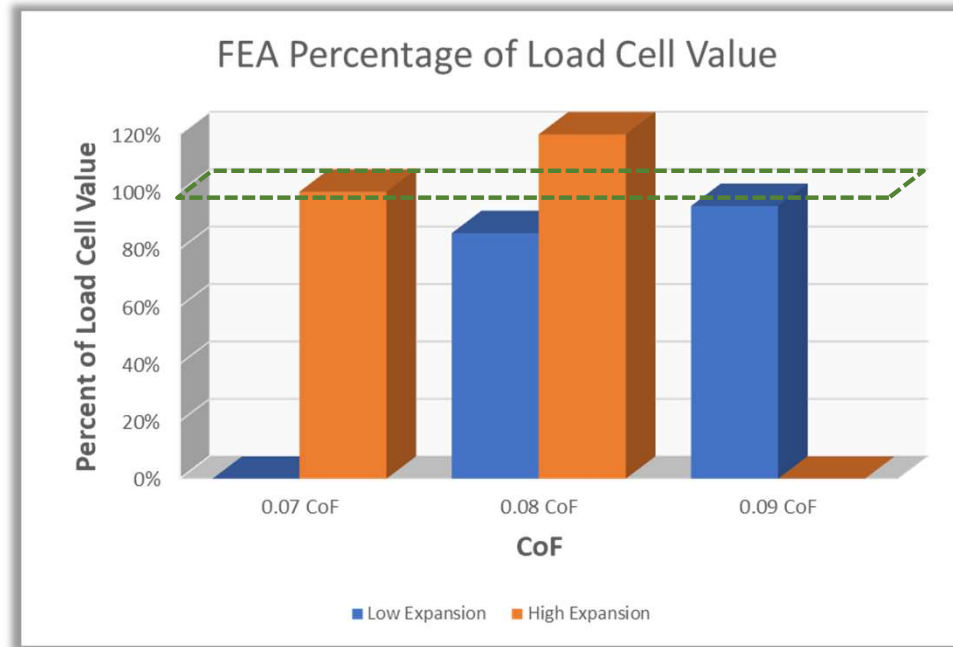
XRD Measurements vs FEA Simulation

XRD measurements were in good agreement except at the extremes. More investigation is needed. Currently we suspect that the chamfer has an effect as well as FEA extrapolation as the $\frac{1}{4}$ model was not adequate for capturing the true behavior with a membrane mesh overlay. Actuals of the plastic behavior were not available which may have also affected the simulation prediction.



Pull Force Load Cell vs FEA

Pull force simulation predictions and hence validations were highly dependent on the CoF. However, its not clear if there is more modeling work needed or if its due to a real variation in CoF. This may make it difficult to use a correlation of the pull force to the state of stress in the part.



Expansion	Load Cell (lbs)	FEA Load (0.07 CoF)	FEA Load (0.08 CoF)	FEA Load (0.09 CoF)
Low	1502	N/A	1285 (86%)	1427 (95%)
High	2134	2100 (98%)	2582 (121%)	N/A

Summary

- Features that capture important physics characteristic of the cold expansion process were chosen for validation.
- Redundancy in physical measurements by different tools is very beneficial, even if one of those tools is less accurate or not at the same exact location.
- % difference has its limitations as you approach the accuracy of the measurement tool. Absolute difference is more insightful in those cases.
- Comparisons between distributions of values is hard but worthwhile.
- Validation provides insight into both the simulation and experimental measurements. Unknown influences can be identified that should be quantified in future comparisons.
- Some comparisons are susceptible to large scatter based on simulation reliance on physical parameters that exhibit scatter.
- Cold expansion simulations were successfully validated using a wide range of measurements.