



Working Group on
Engineered Residual
Stress Implementation

Interference Fit Fastener – Working Group

DIC results and comparisons

February 2025

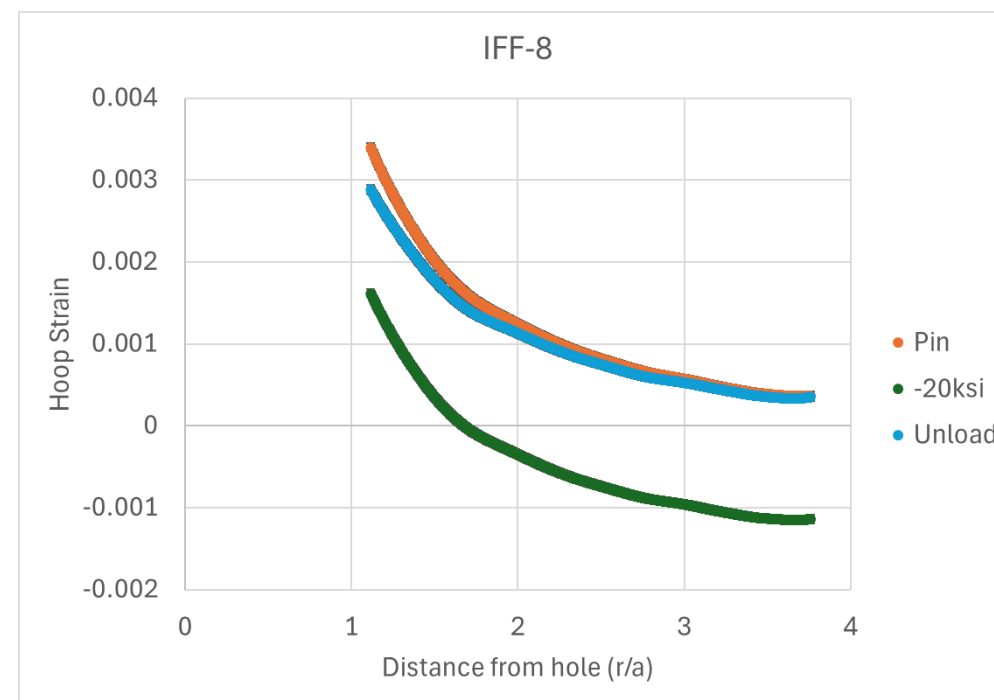
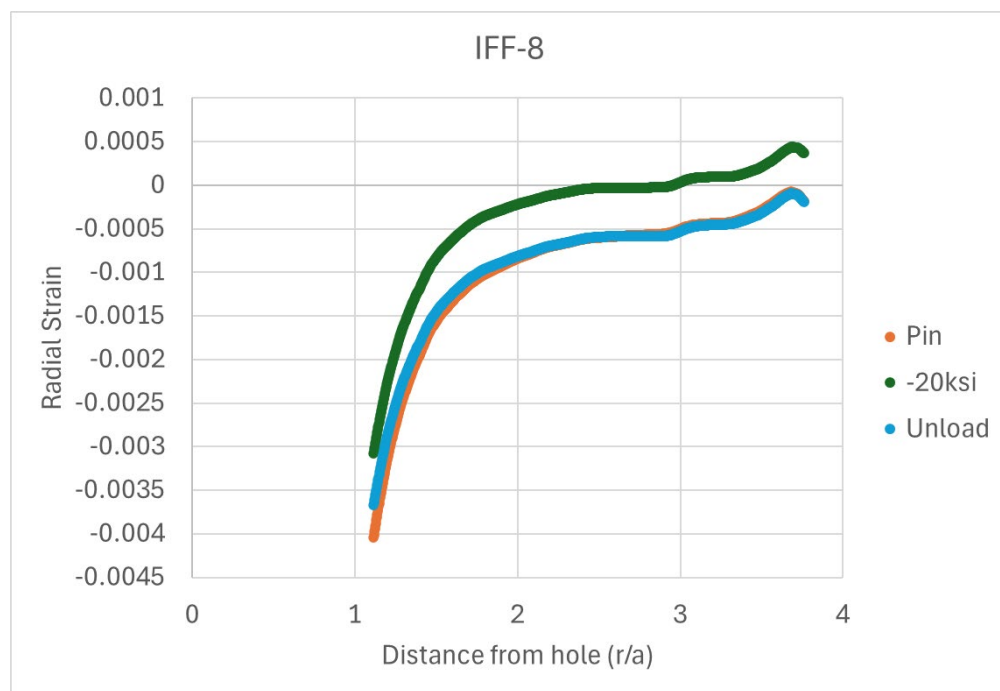
Initial DIC measurements

Example DIC results from initial measurements below

- 0.6% interference; -20 ksi applied stress
- Results start at 0.014" from the hole edge

DIC strain vs position data is averaged over a 0.02"x0.02" square

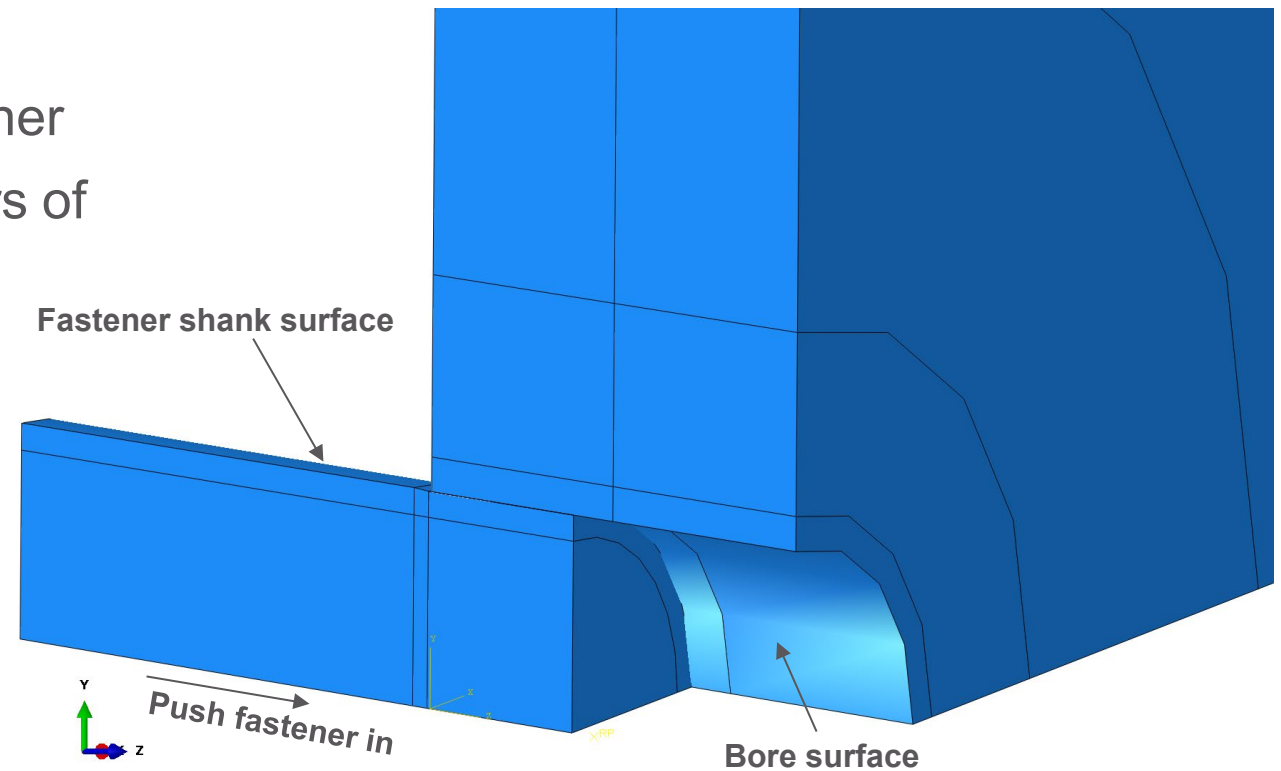
IFF round robin: no averaging was performed on the results submitted by all participants



Process model – example effect of the averaging

Use Renan's model results for comparisons to evaluate effect of the averaging

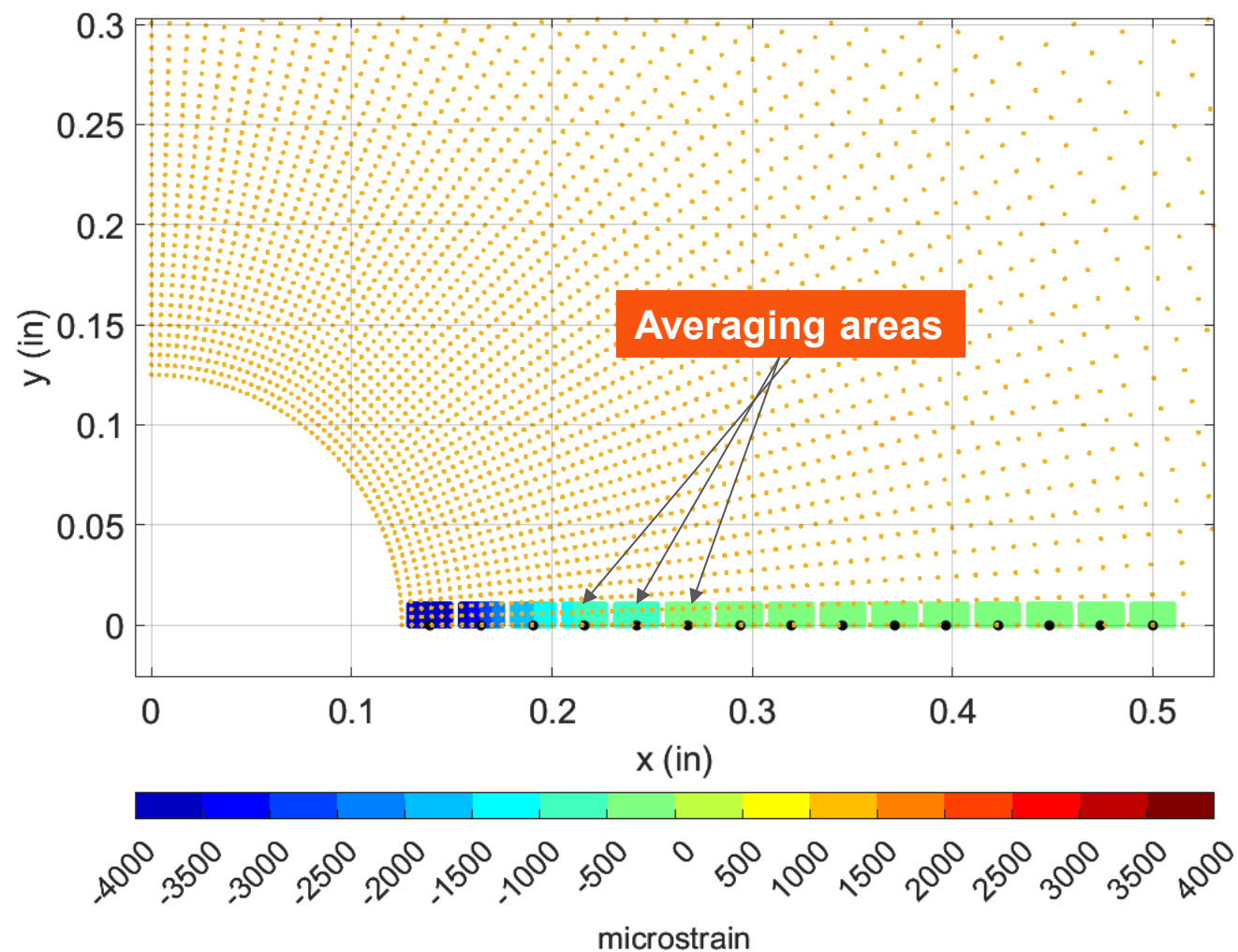
- Sample and fastener; fastener pushed into the hole
- $\frac{1}{4}$ symmetry
- Frictionless contact between bore and fastener
- Chamfer between minor and major diameters of fastener



Process model – averaging

Averaging of the model results was performed for comparison to DIC results

- Figure shows 15 points (black circles) along radial direction
- Strain was interpolated with uniform spacing within a $0.02'' \times 0.02''$ square centered at the black point
 - Since the model was a symmetry model, we only have results for the half of the square shown
- The averaged results were compared to a simple pointwise interpolation along the radial line
- All IFF round robin results are pointwise values (not averaged as DIC)



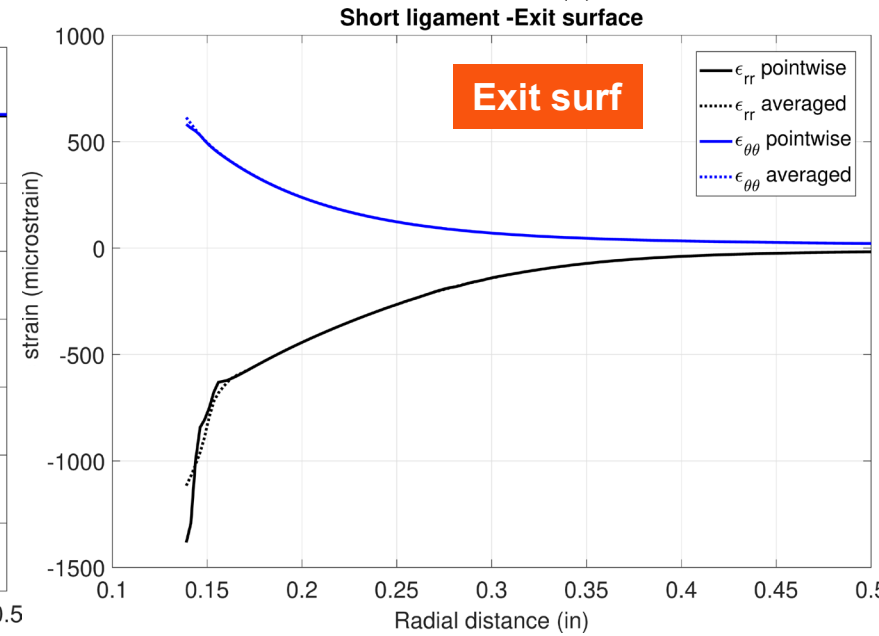
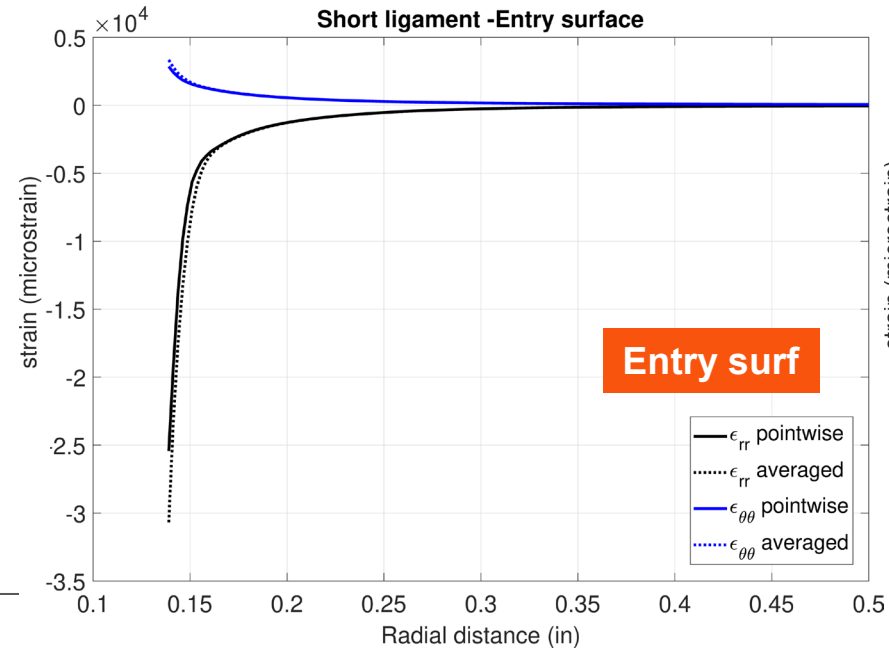
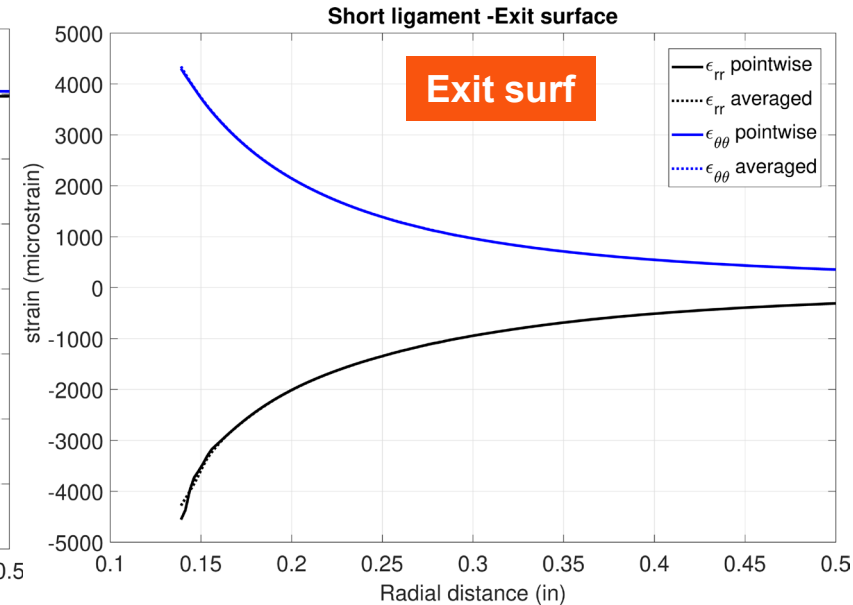
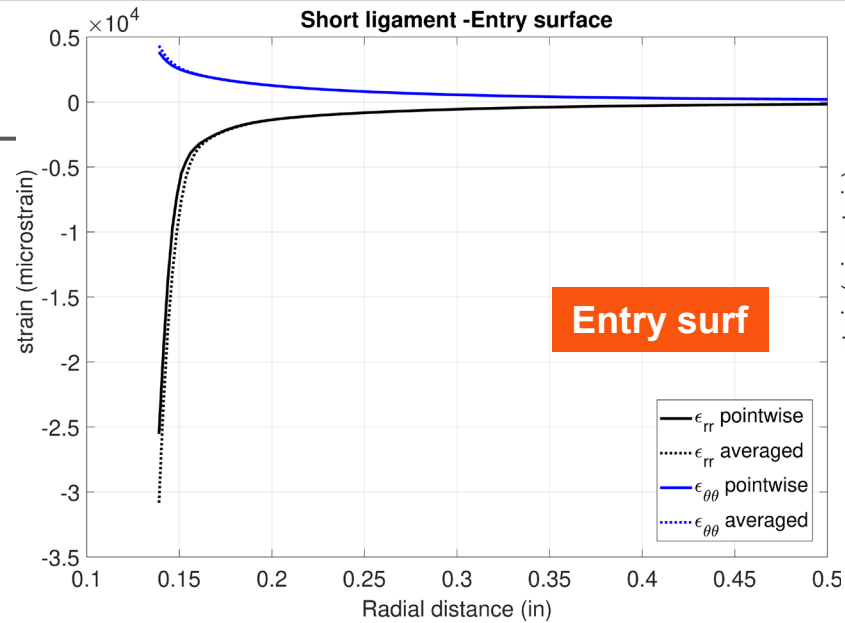
Process model – averaging

Results start at $x = 0.125 + 0.014 = 0.139$ " (0.014" from hole edge)

- This is where DIC results start

Fastener installed step, 0.6% IFF

Fastener removed step, 0.6% IFF

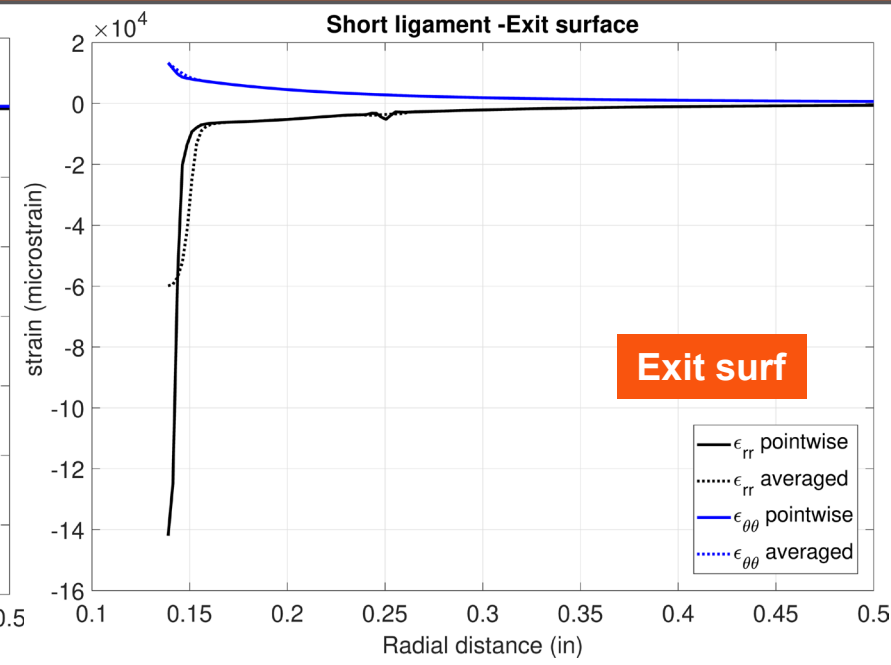
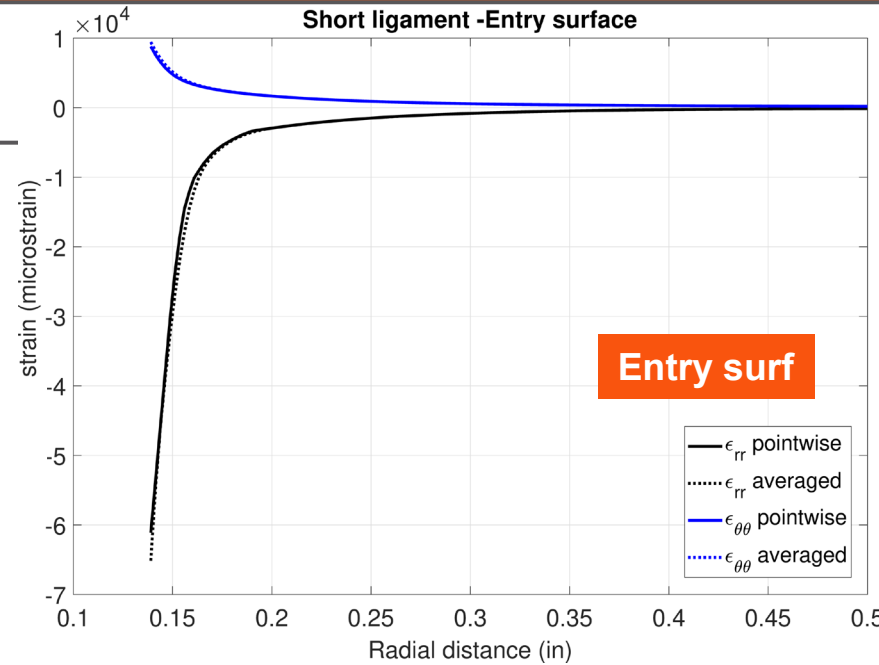


Process model – averaging

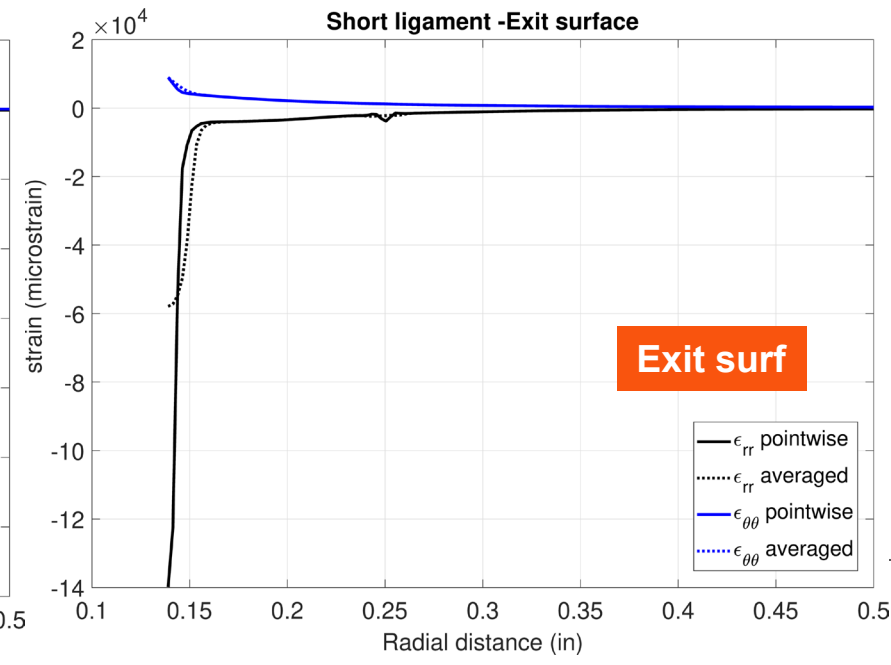
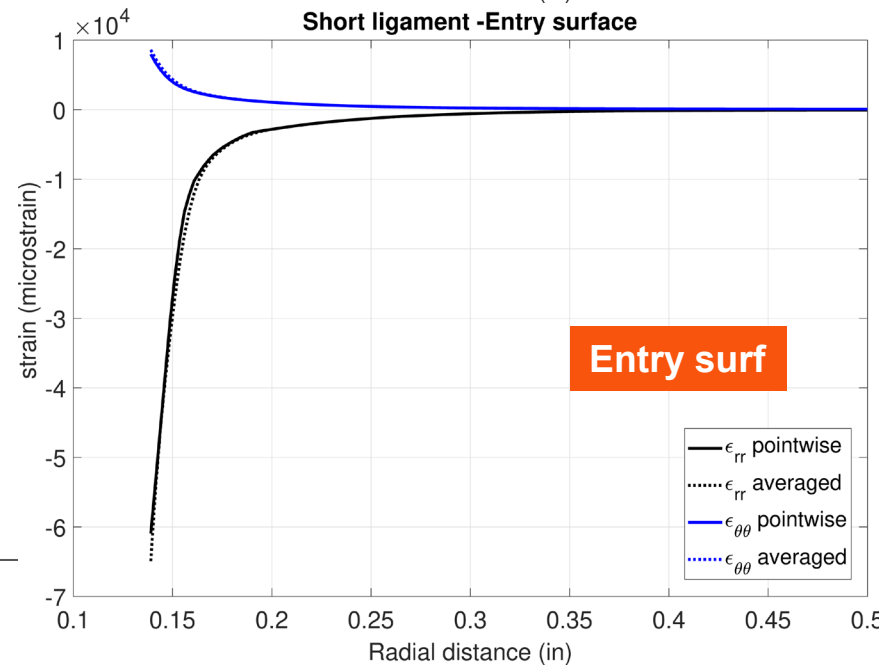
Results start at $x = 0.125 + 0.014 = 0.139$ " (0.014" from hole edge)

- This is where DIC results start

Fastener installed step, 1.2% IFF



Fastener removed step, 1.2% IFF



Summary

Except very close to the hole, averaging does not seem to have a large effect

- In areas where it did, the model strains are extremely high (and unrealistic, $> 25,000$ microstrain)

Following slides compare FE results from round robin (pointwise values) to DIC results (averaged values)

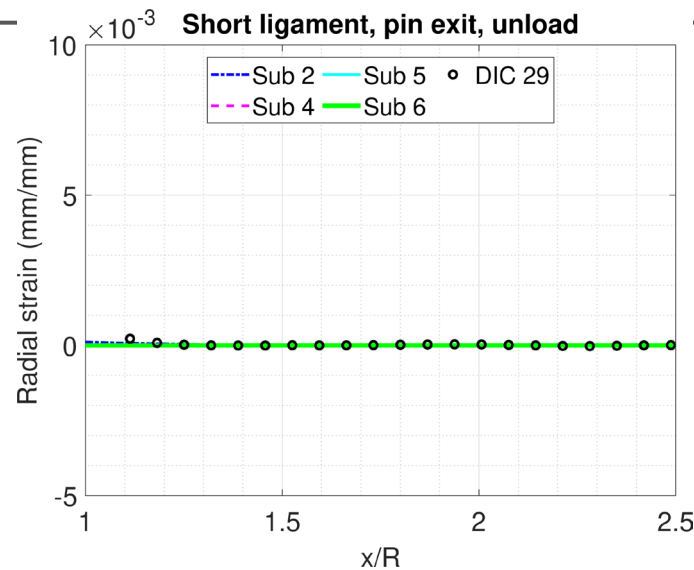
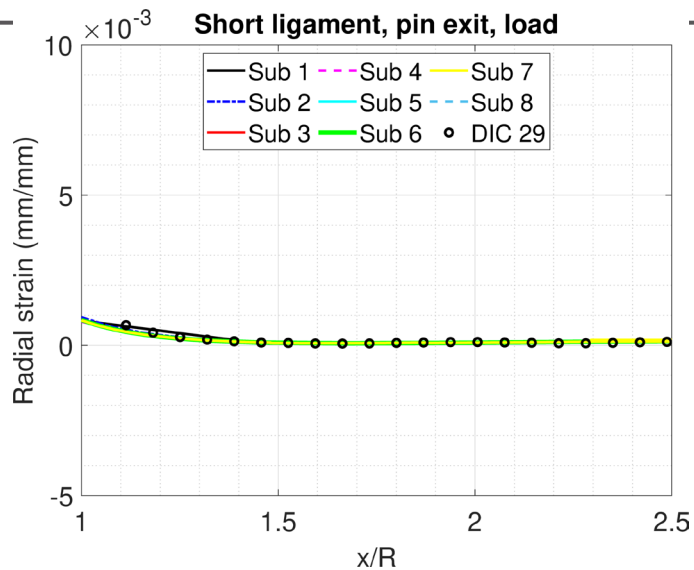
Open hole

FE round robin (pointwise)

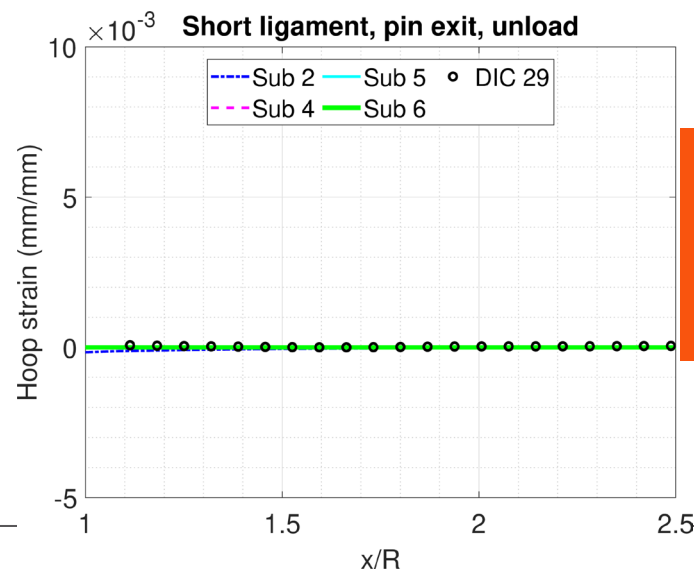
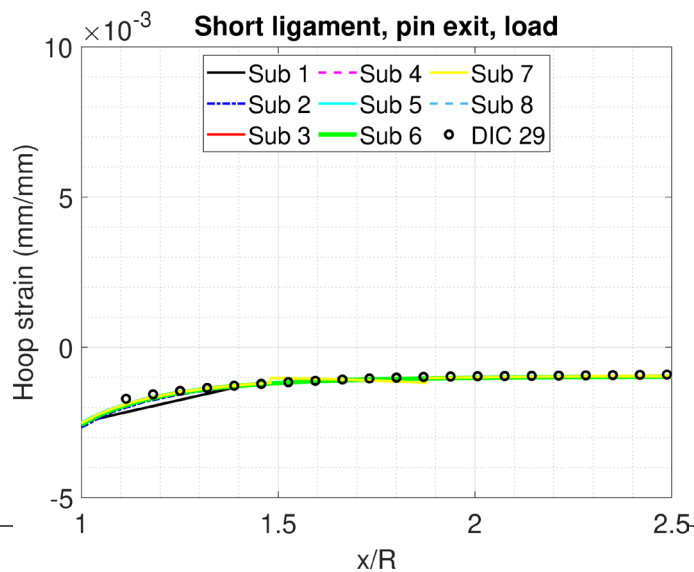
DIC strains (averaged)

Models vs DIC – Open hole, -10 ksi remote stress

Radial strain



Hoop strain

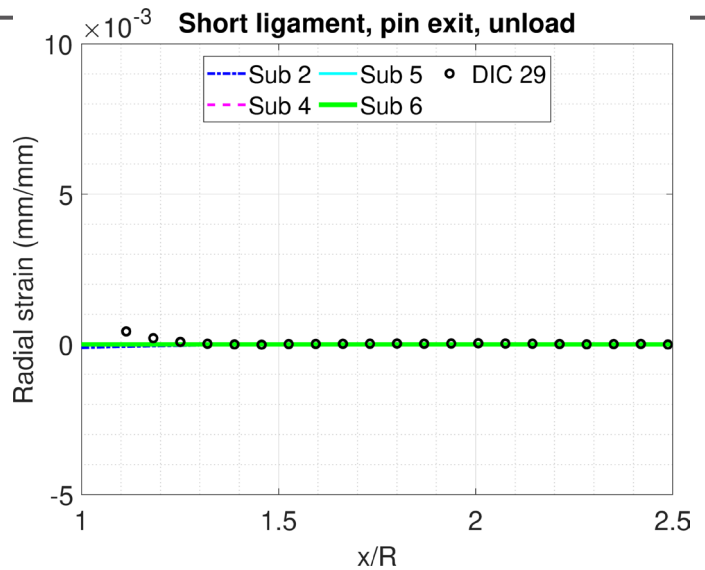
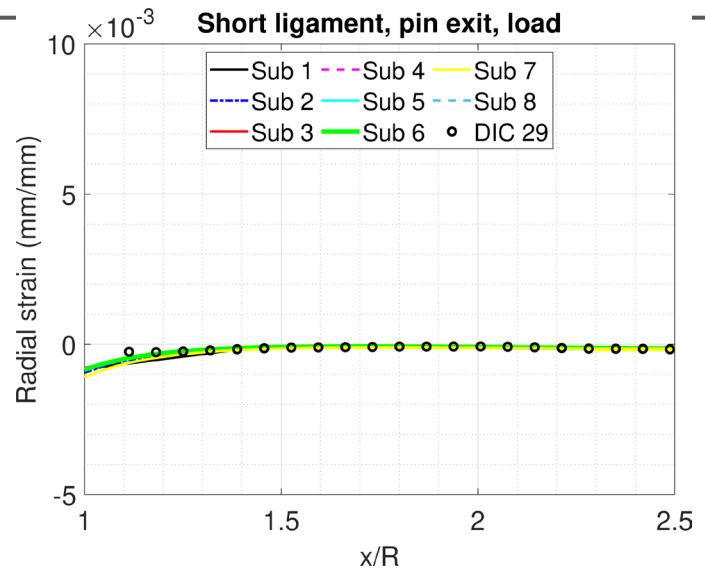


Notes (applies to all results from here on):

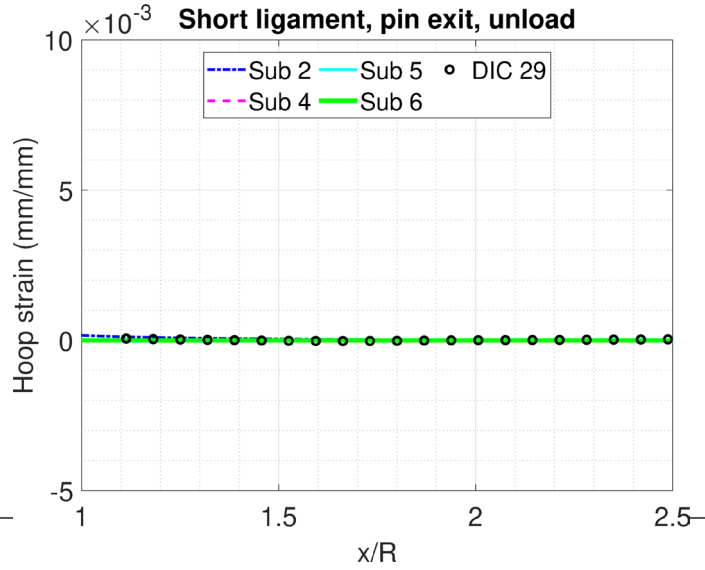
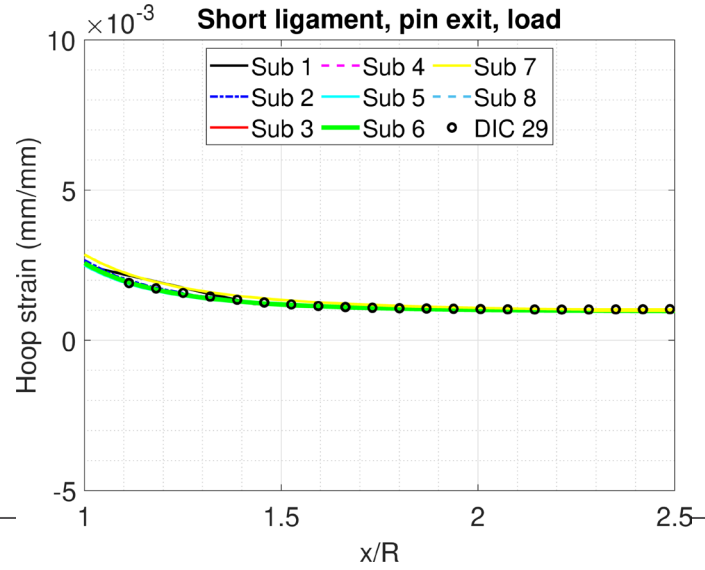
- Results beyond $x/R = 2.5$ not shown to focus plot near hole only
- DIC points were subsampled to plot for easier visualization

Models vs DIC – Open hole, 10 ksi remote stress

Radial strain

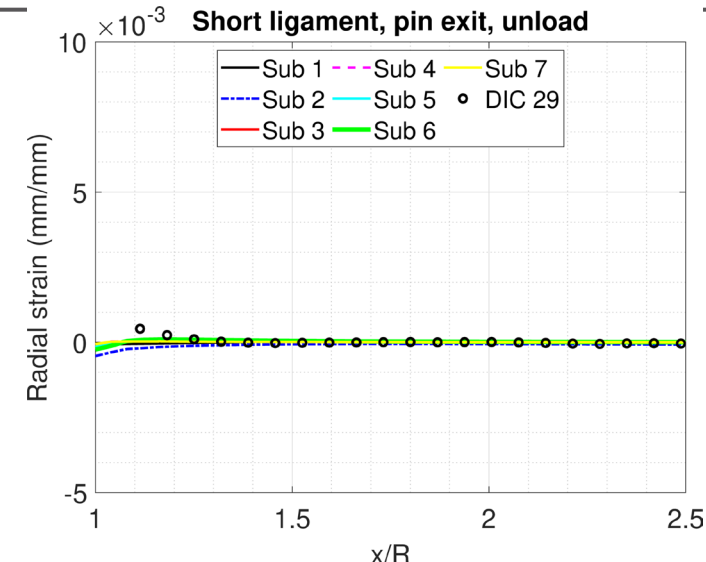
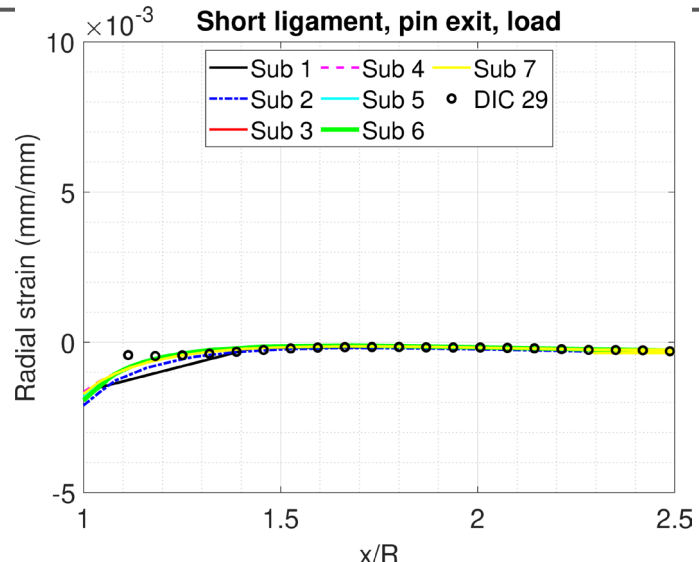


Hoop strain

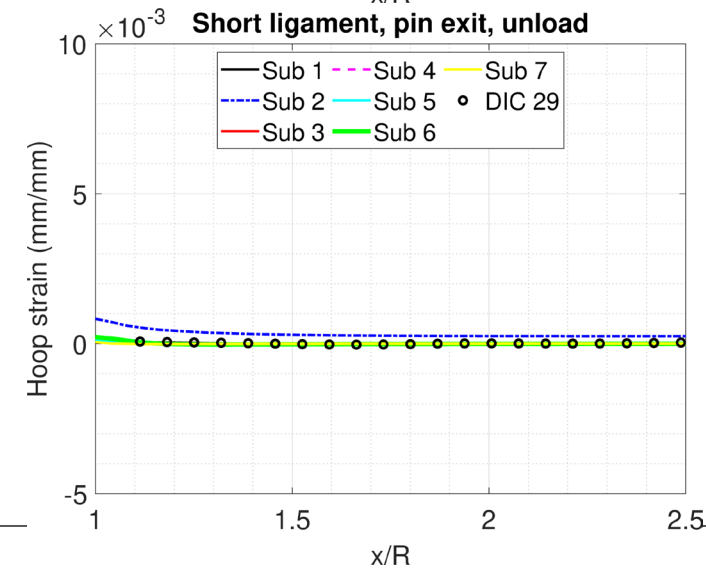
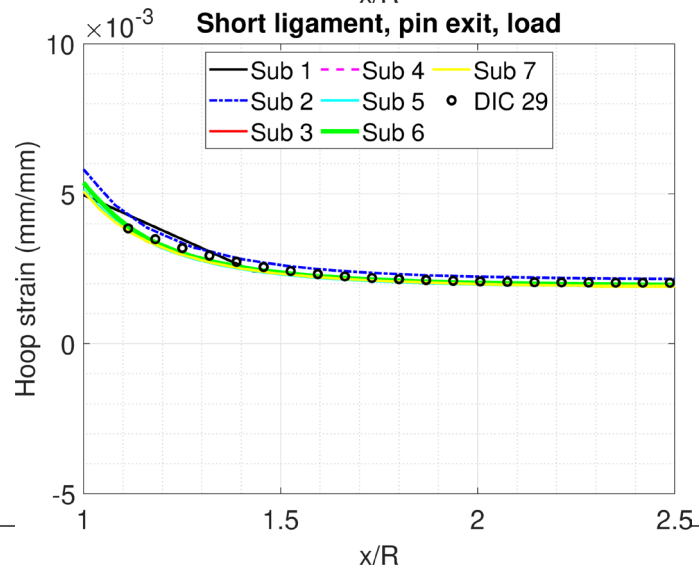


Models vs DIC – Open hole, 20 ksi remote stress

Radial strain

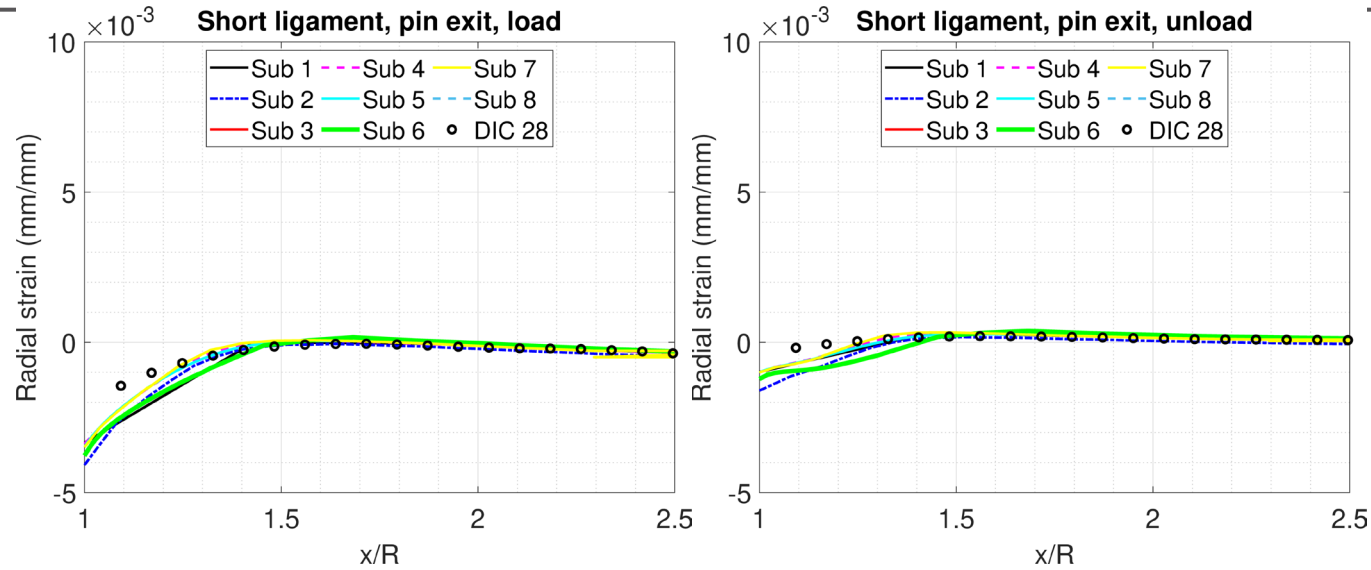


Hoop strain

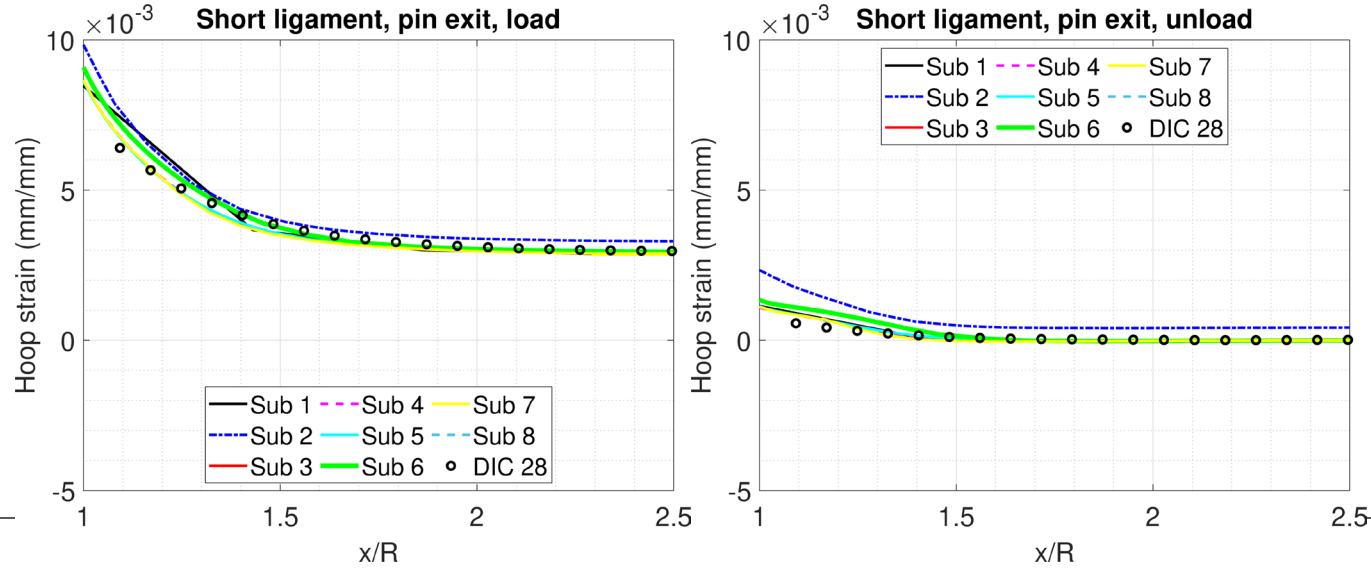


Models vs DIC – Open hole, 30 ksi remote stress

Radial strain



Hoop strain



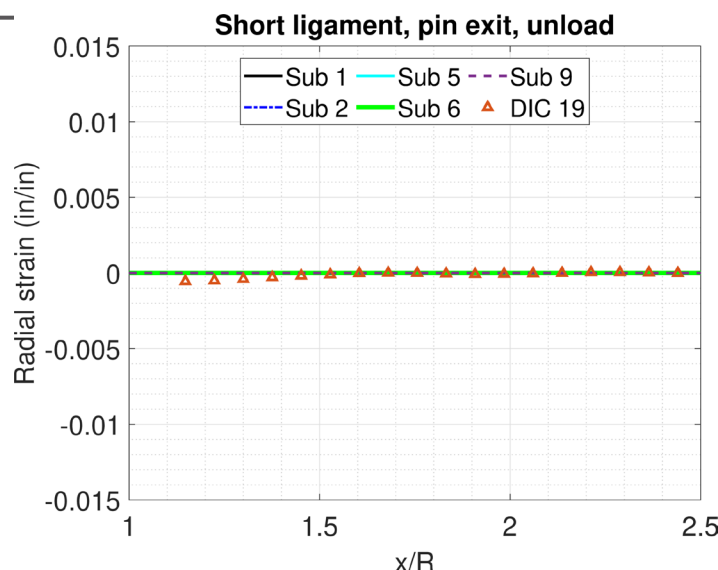
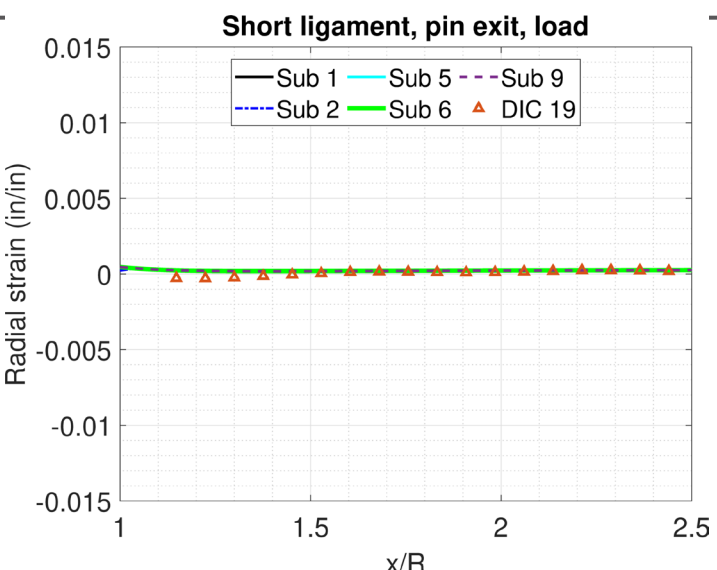
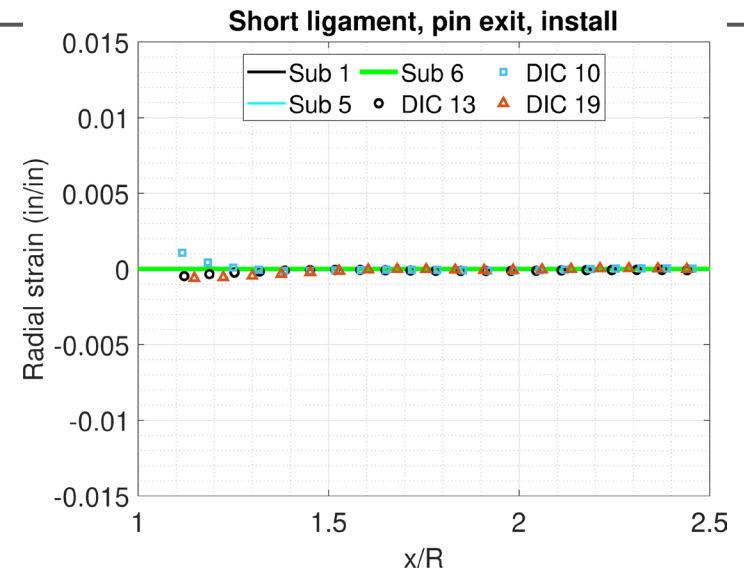
Neat fit + remote load

FE round robin (pointwise)

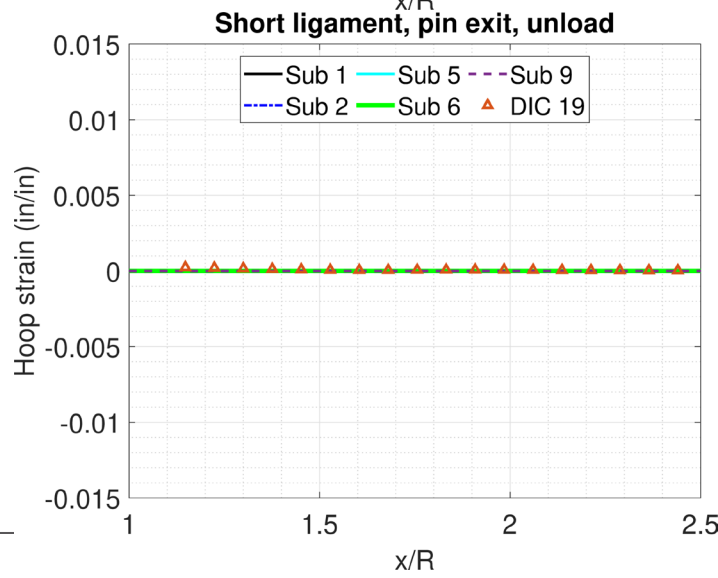
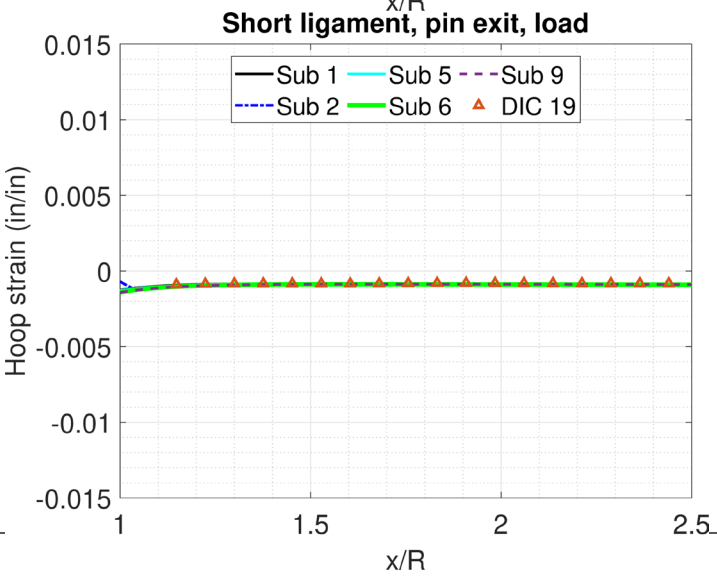
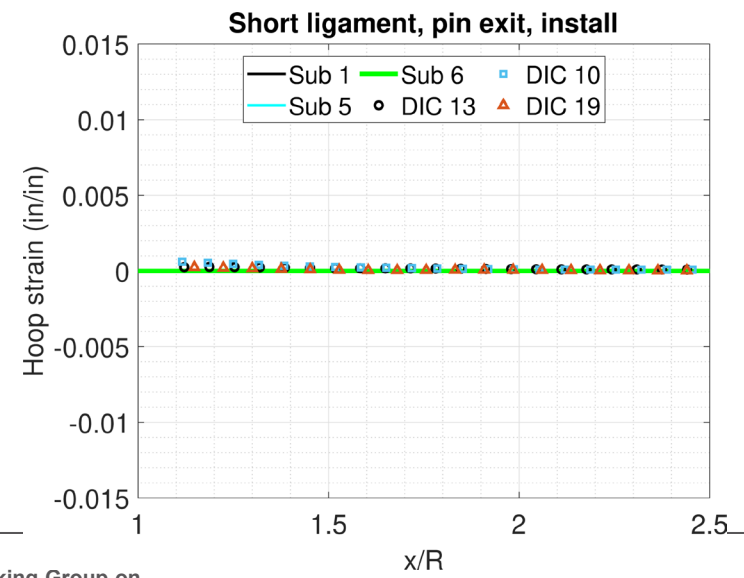
DIC strains (averaged)

Models vs DIC – neat fit, -10 ksi remote stress

Radial strain



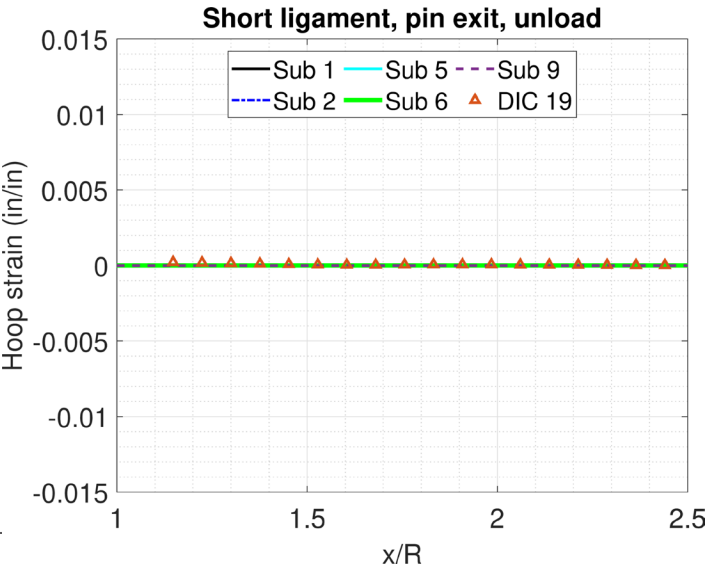
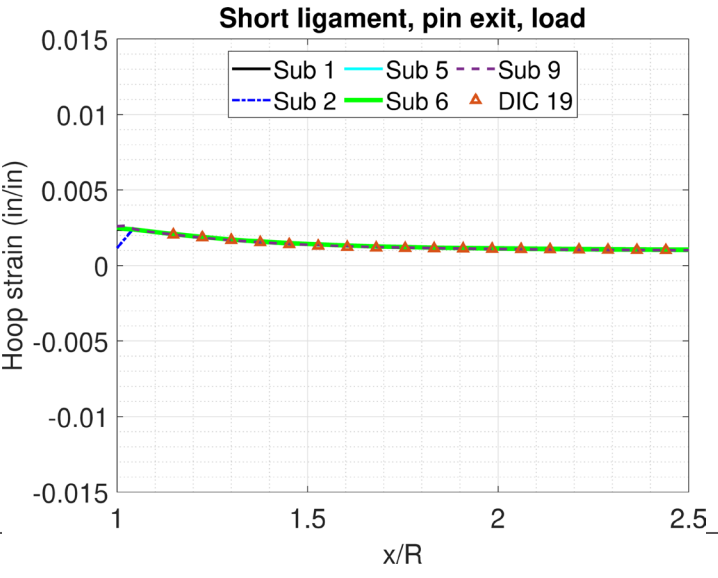
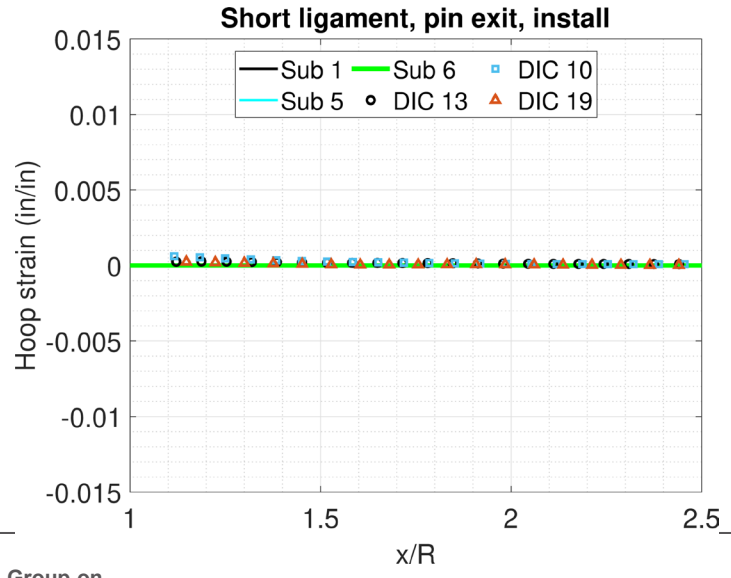
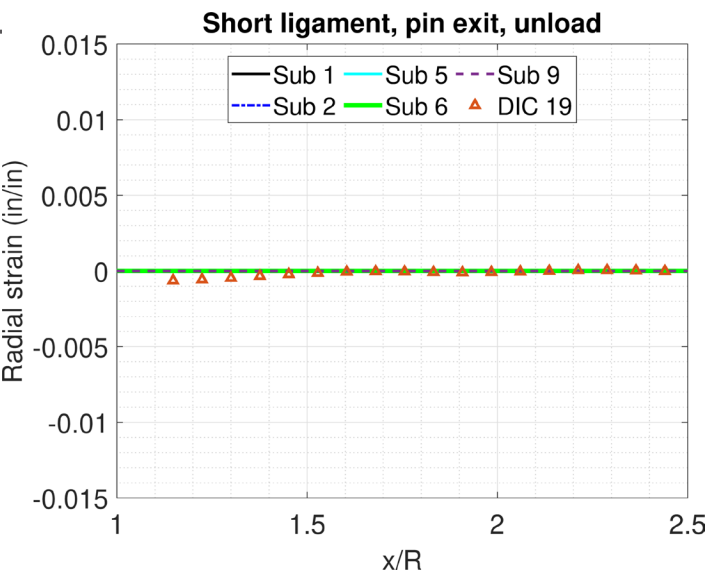
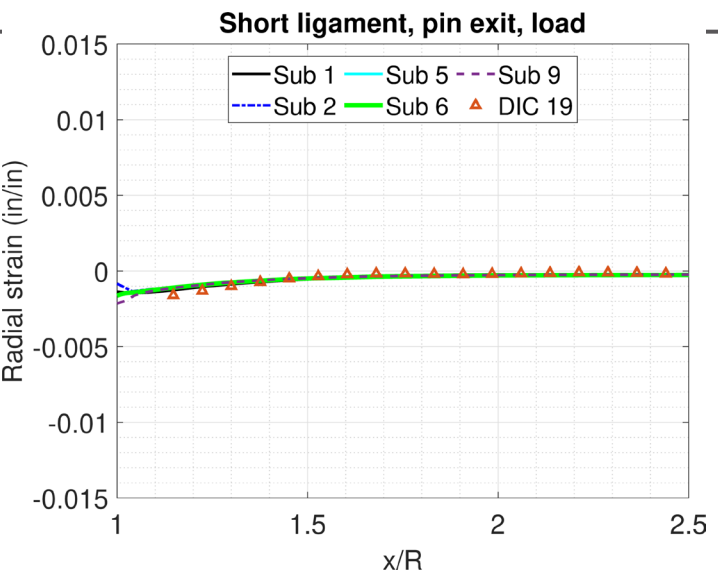
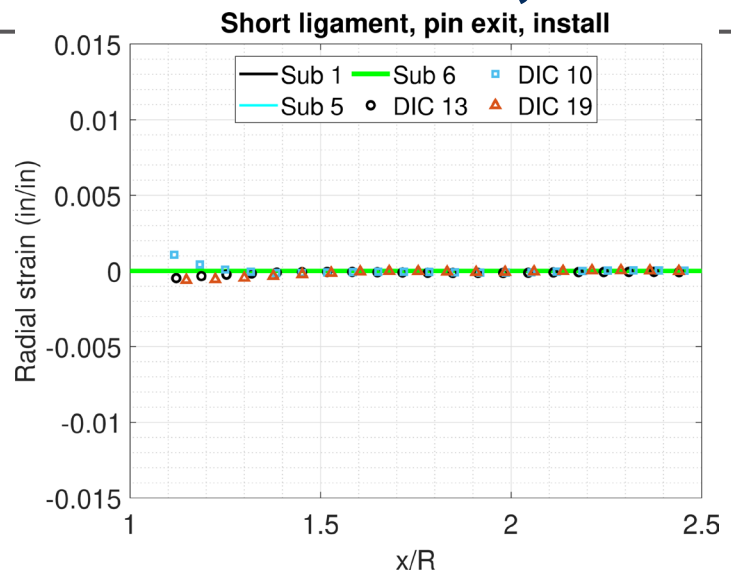
Hoop strain



Models vs DIC – neat fit, 10 ksi remote stress

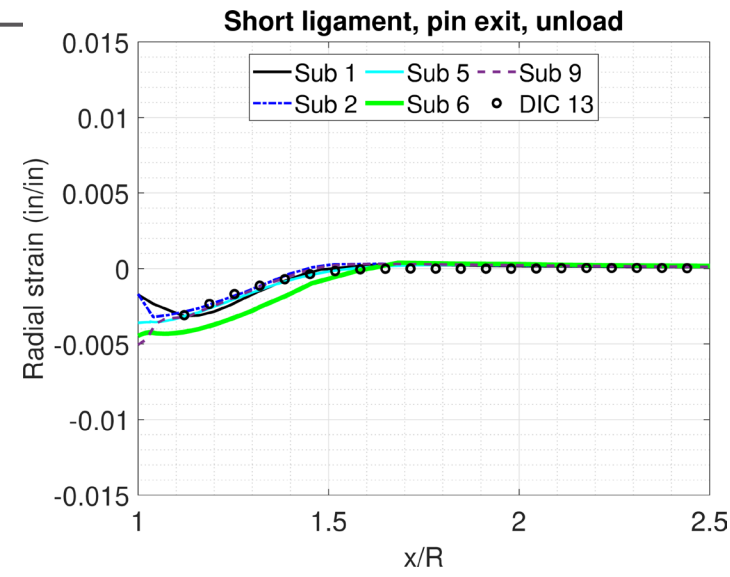
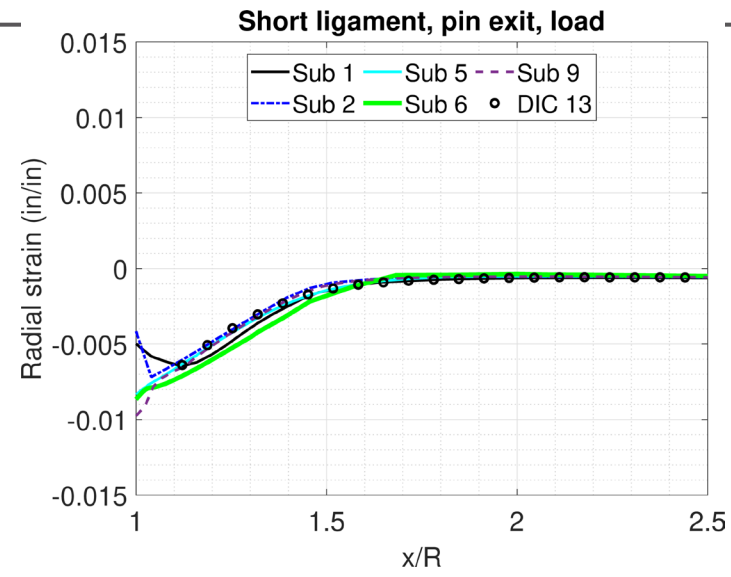
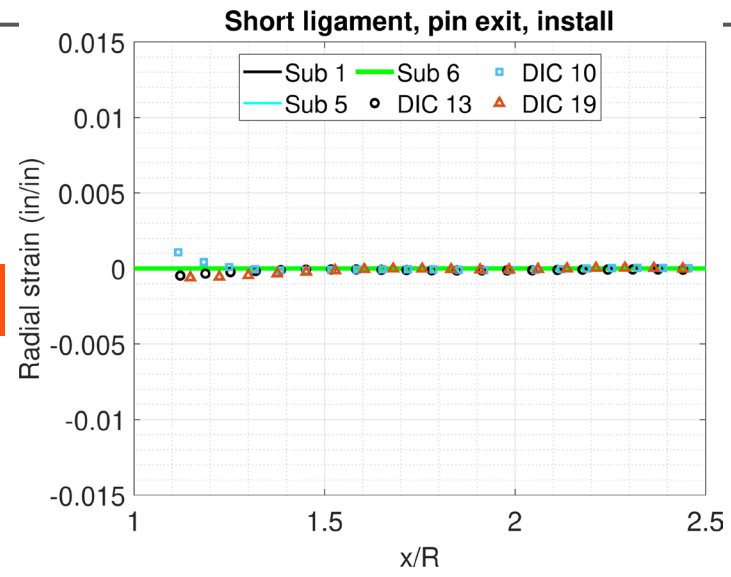
Radial strain

Hoop strain

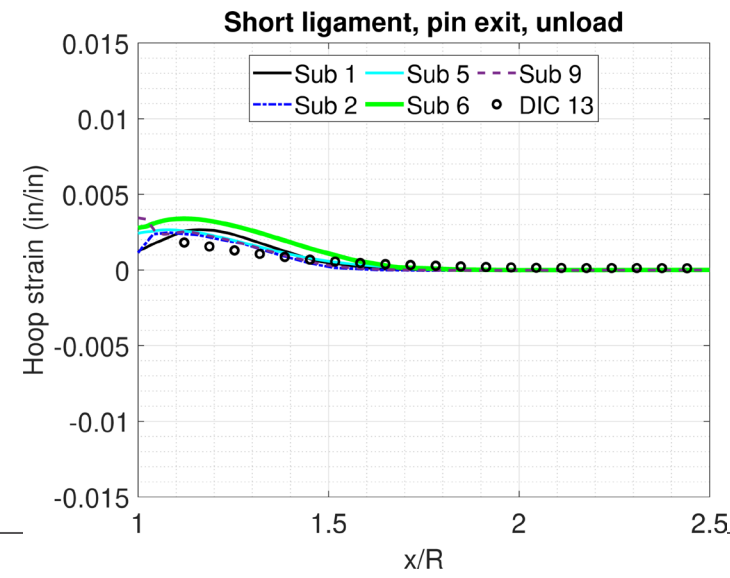
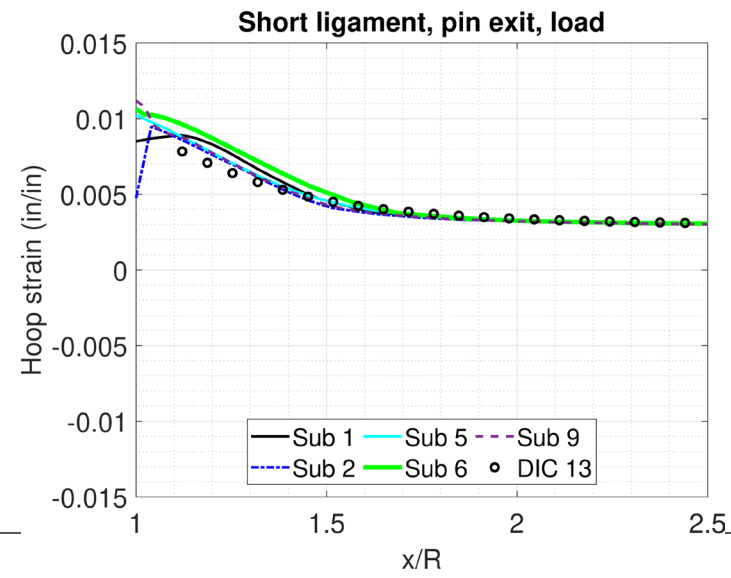
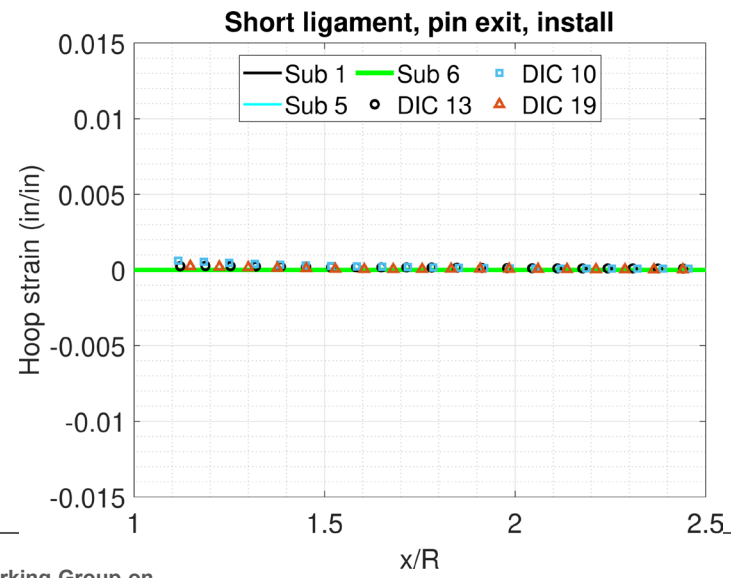


Models vs DIC – neat fit, 30 ksi remote stress

Radial strain



Hoop strain



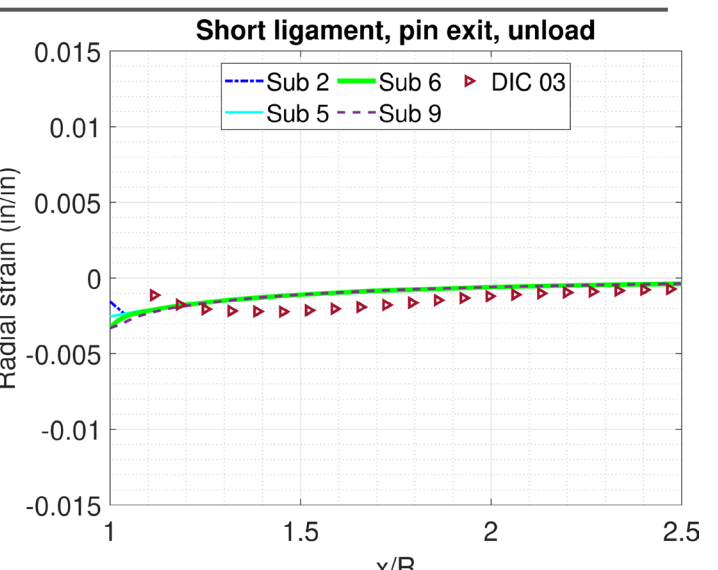
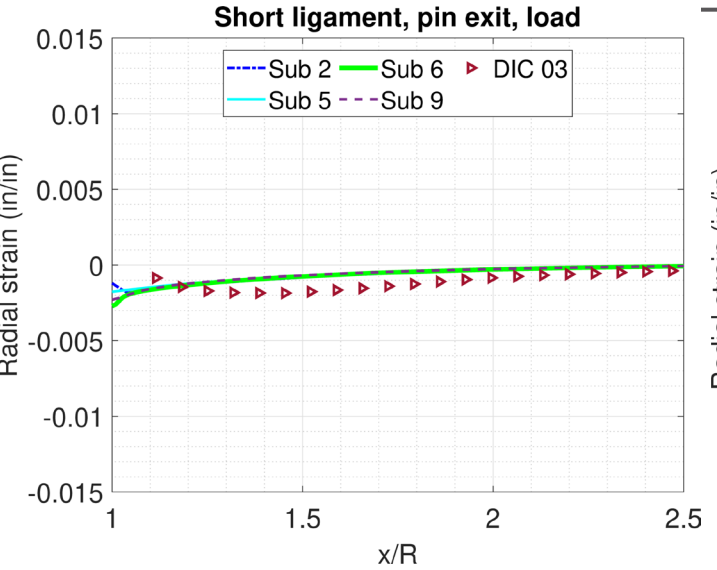
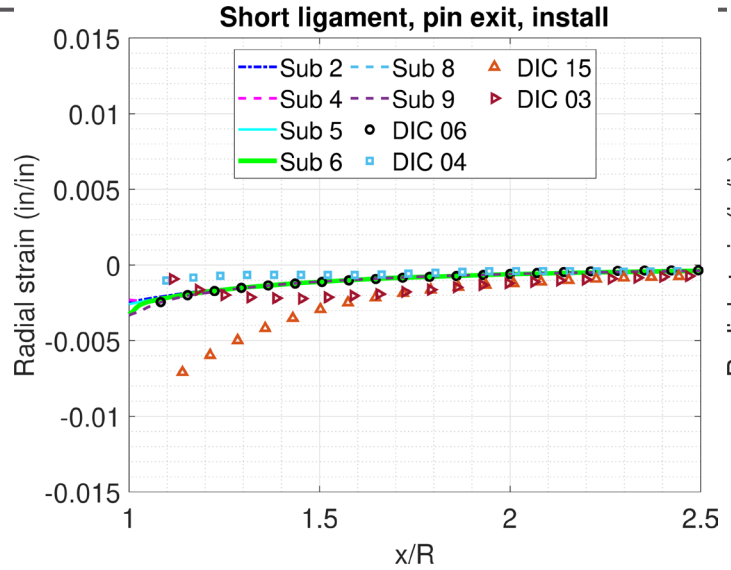
0.3% IFF + remote load

FE round robin (pointwise)

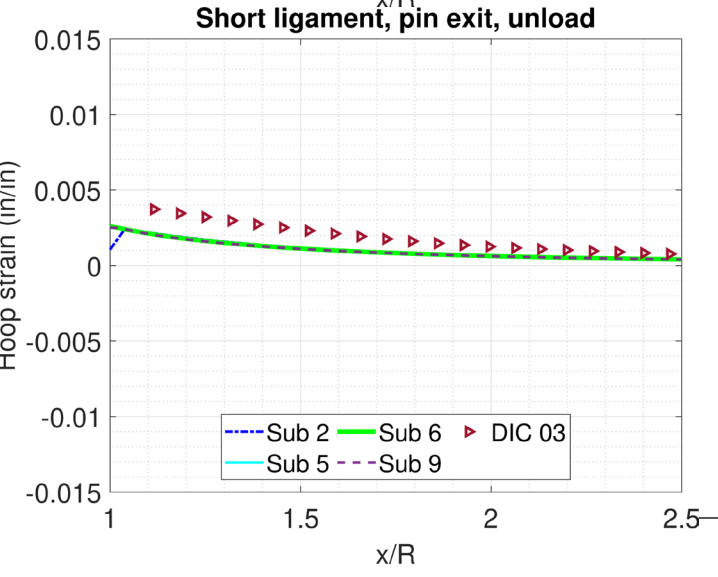
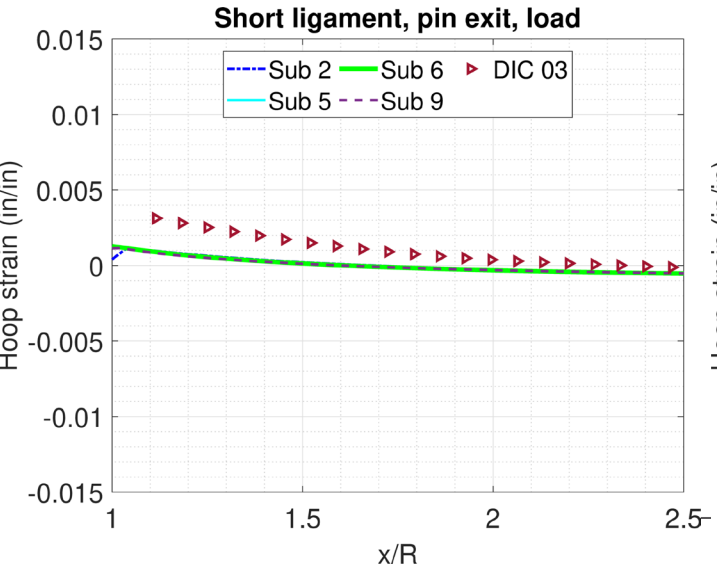
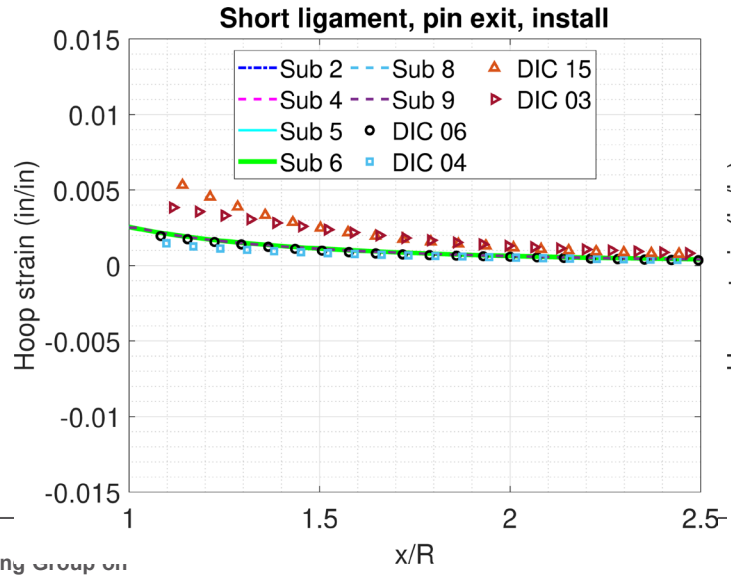
DIC strains (averaged)

Models vs DIC – 0.3% IFF, -10 ksi remote stress

Radial strain

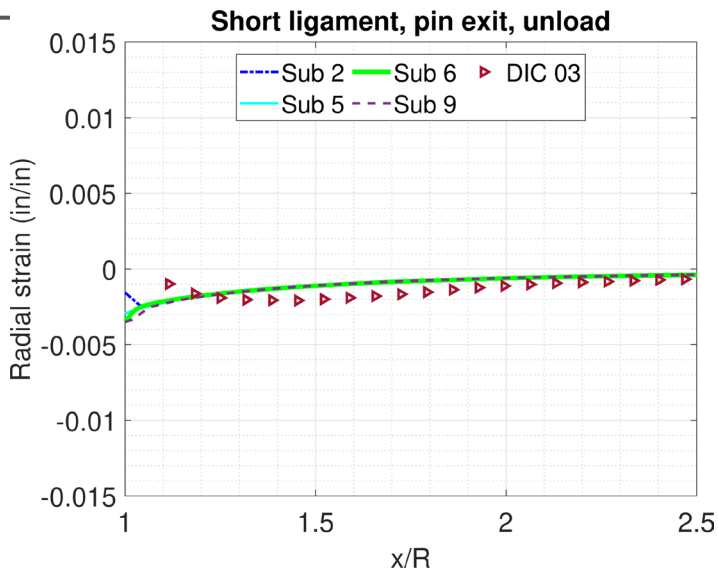
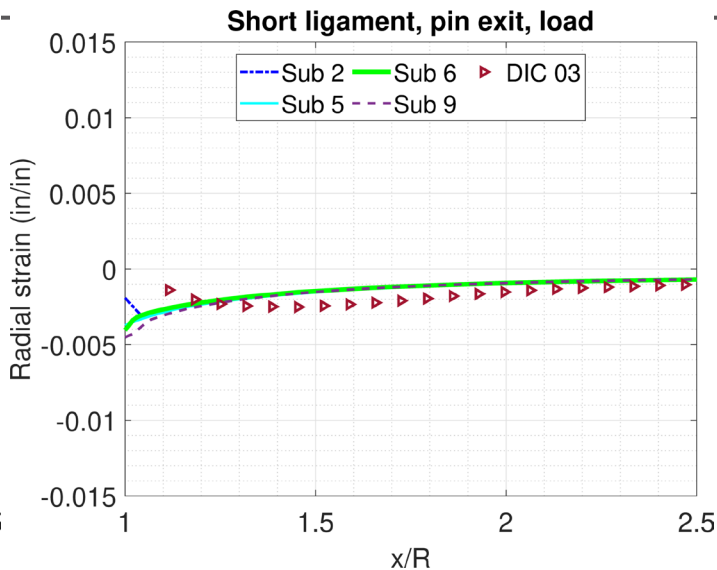
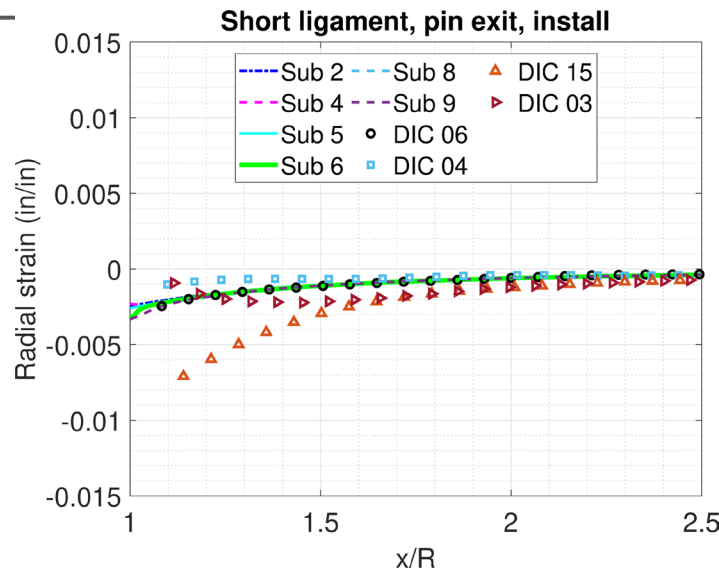


Hoop strain

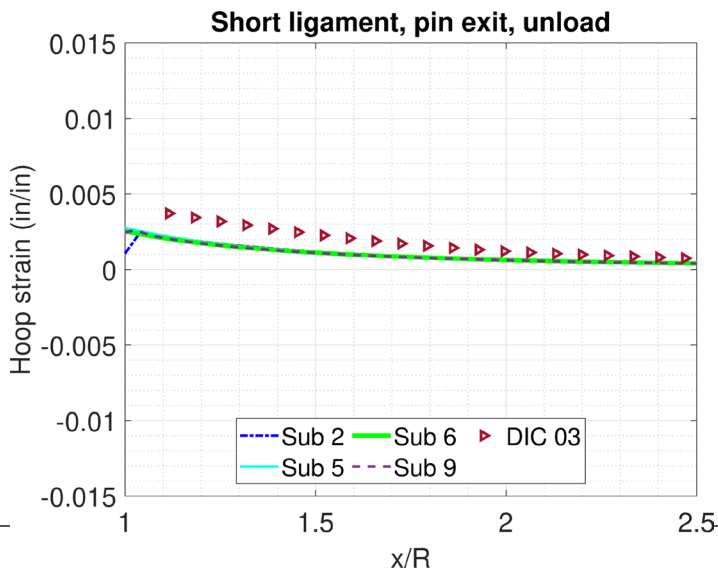
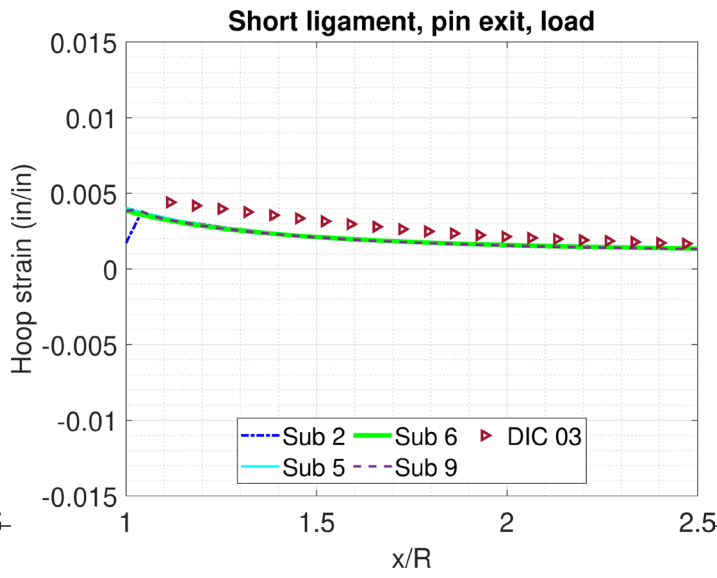
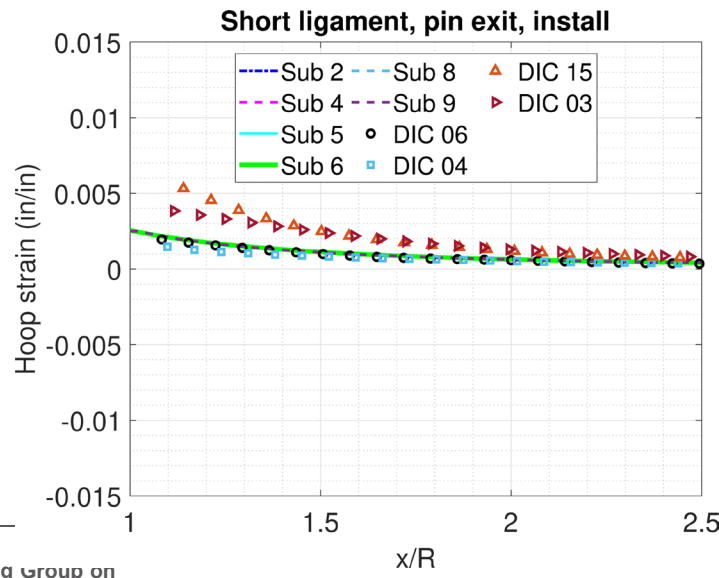


Models vs DIC – 0.3% IFF, 10 ksi remote stress

Radial strain

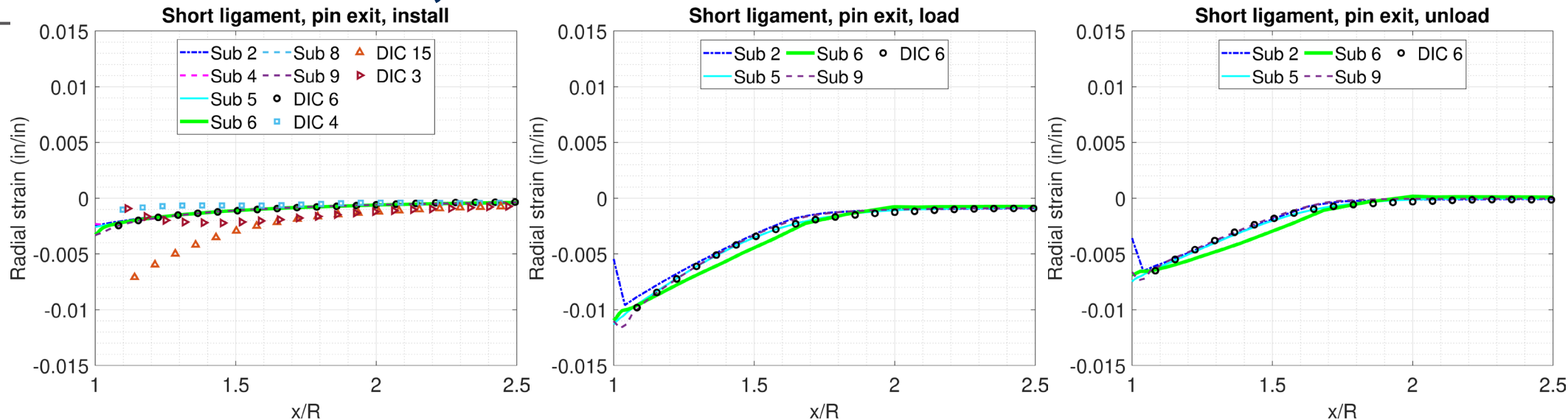


Hoop strain

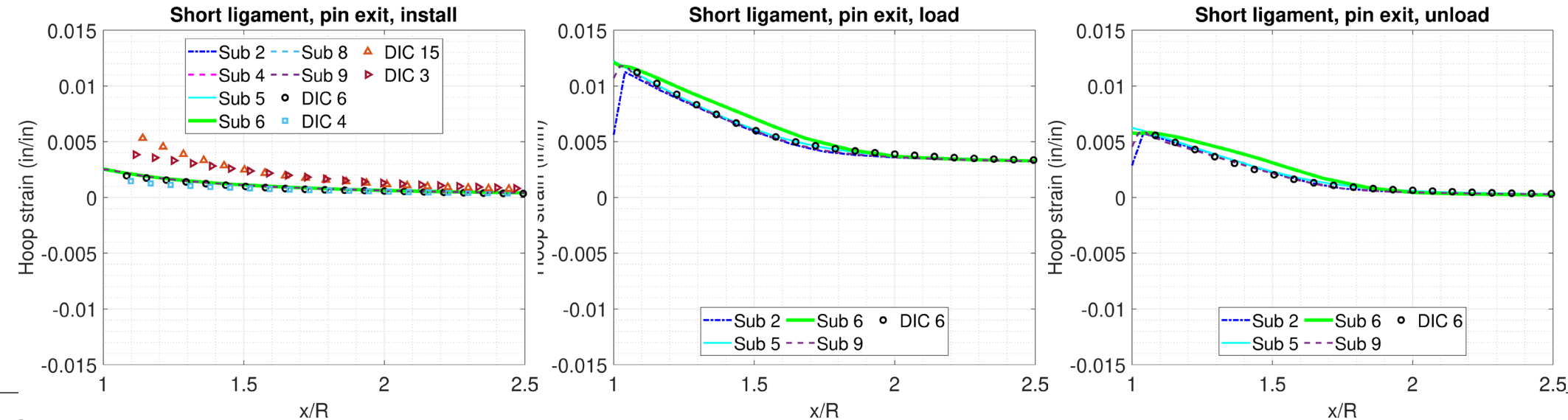


Models vs DIC – 0.3% IFF, 30 ksi remote stress

Radial strain



Hoop strain



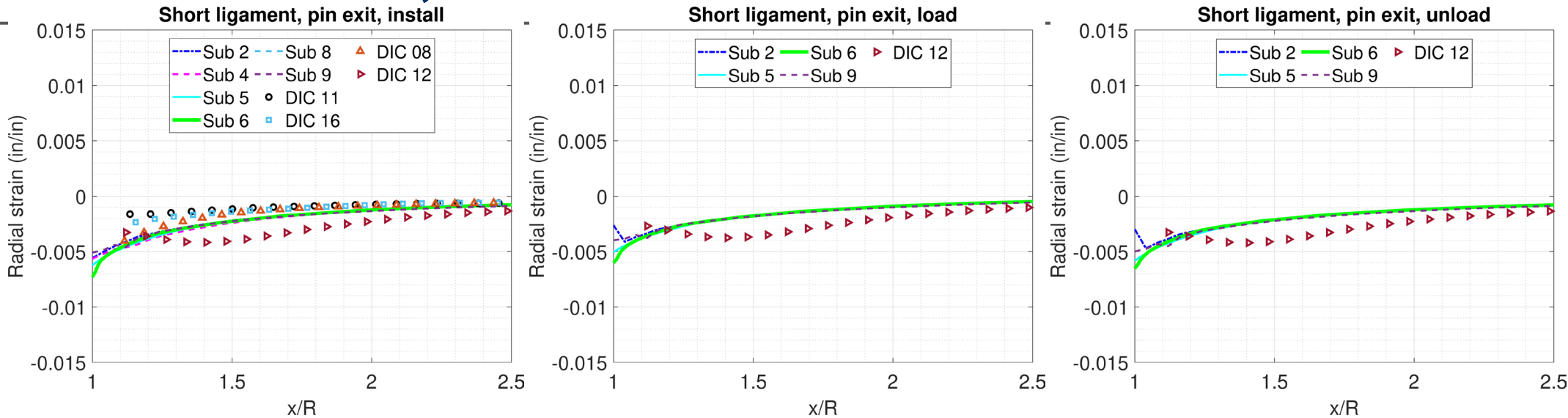
0.6% IFF + remote load

FE round robin (pointwise)

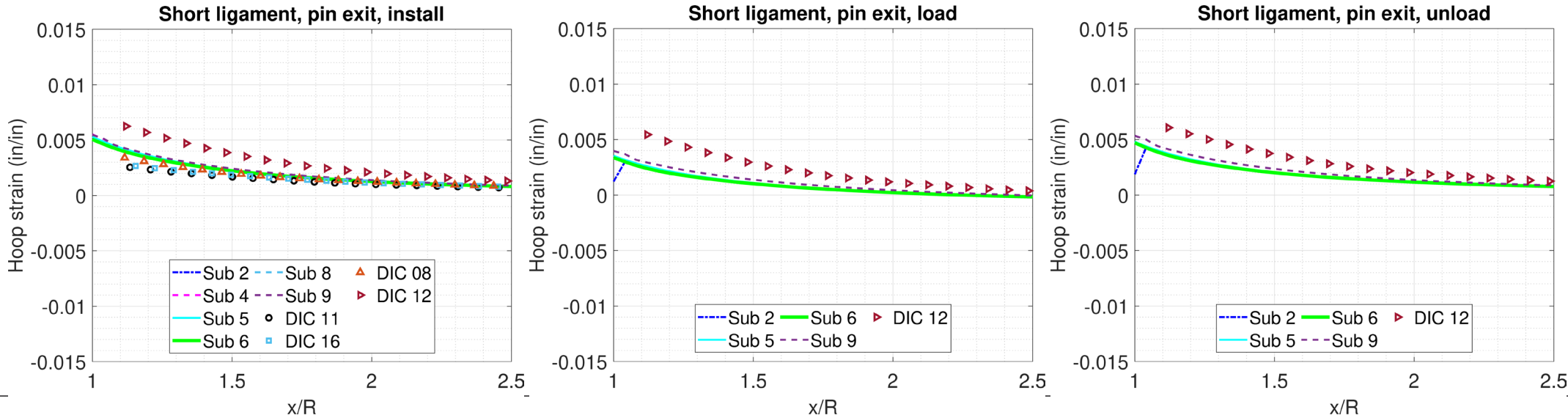
DIC strains (averaged)

Models vs DIC – 0.6% IFF, -10 ksi remote stress

Radial strain

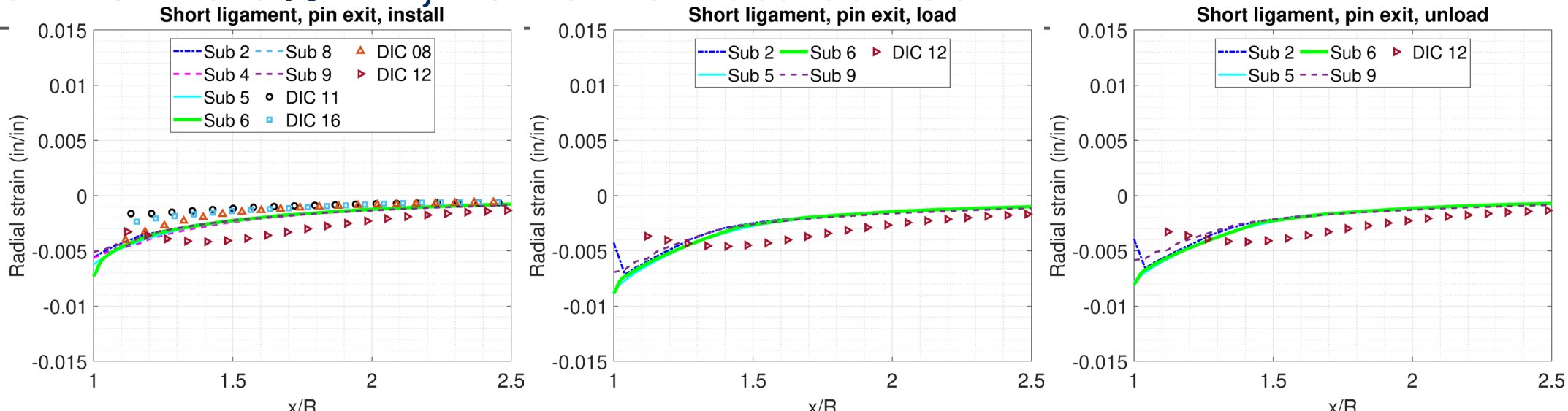


Hoop strain

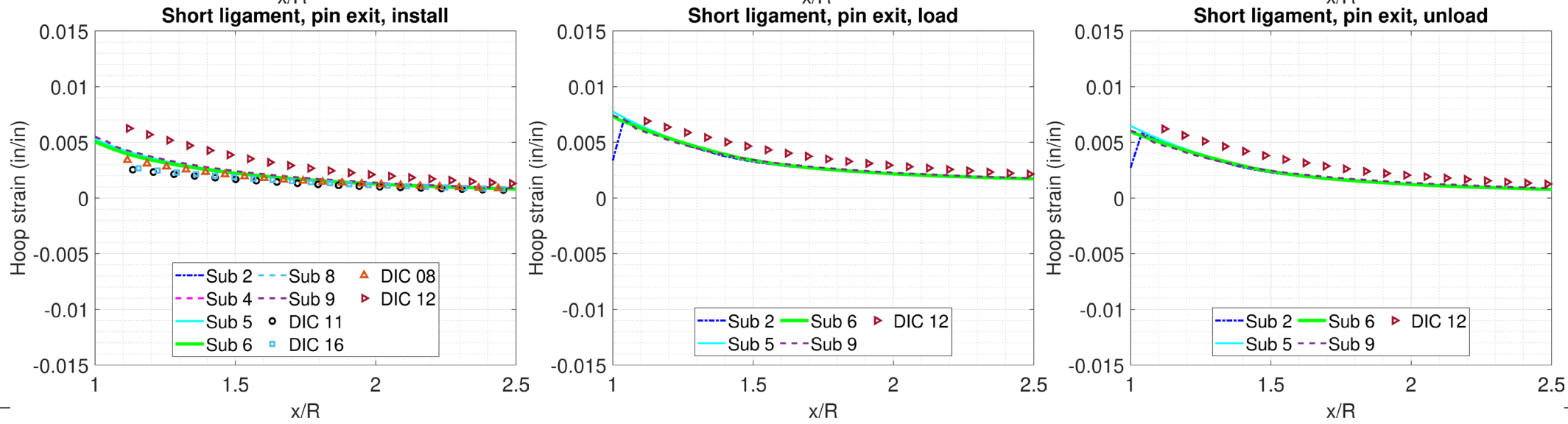


Models vs DIC – 0.6% IFF, 10 ksi remote stress

Radial strain

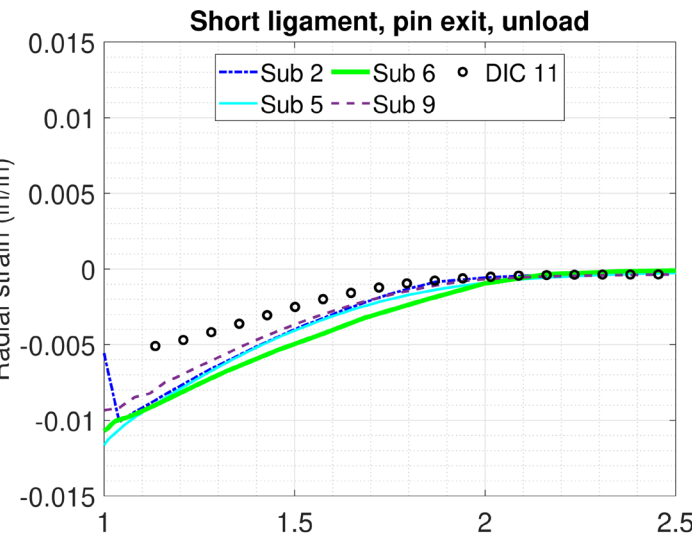
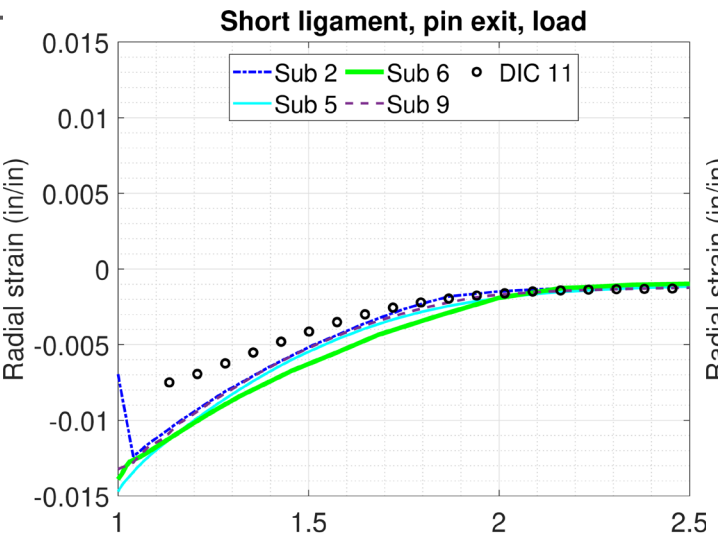
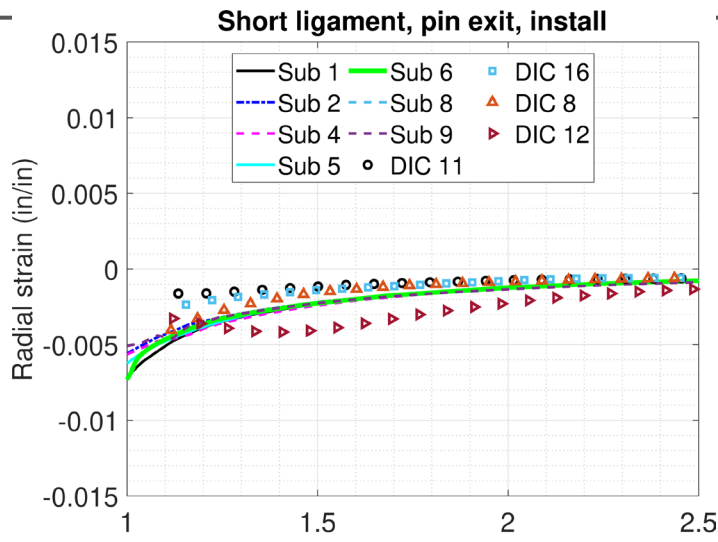


Hoop strain

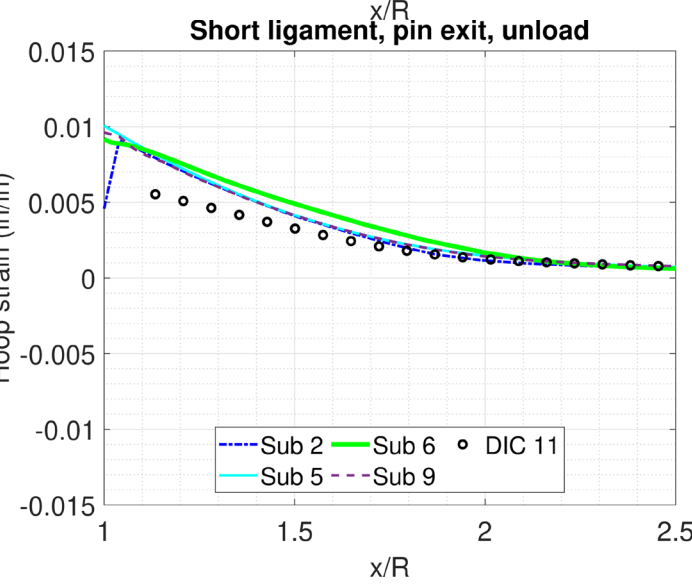
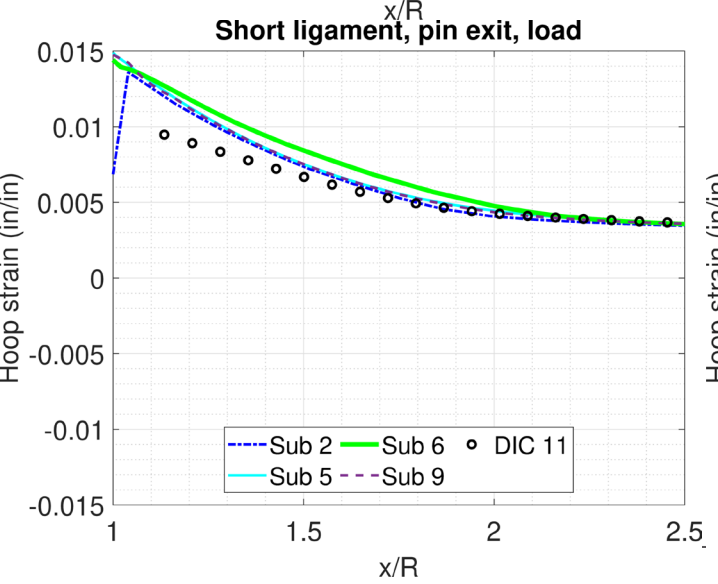
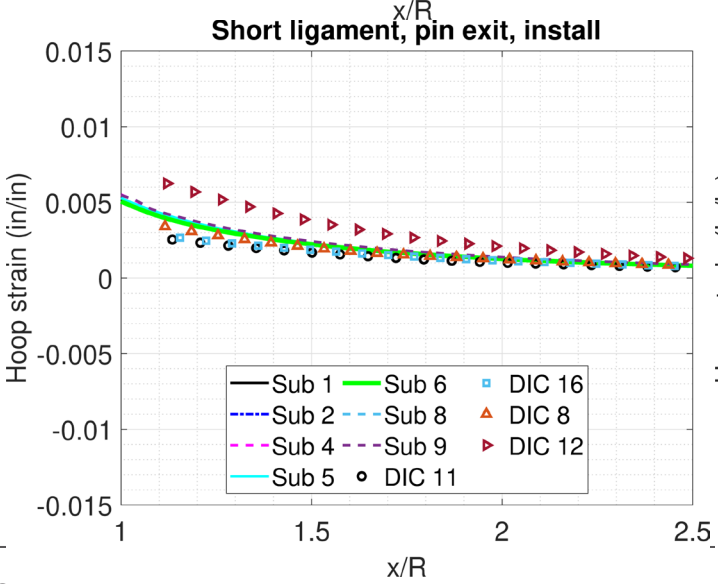


Models vs DIC – 0.6% IFF, 30 ksi remote stress

Radial strain



Hoop strain



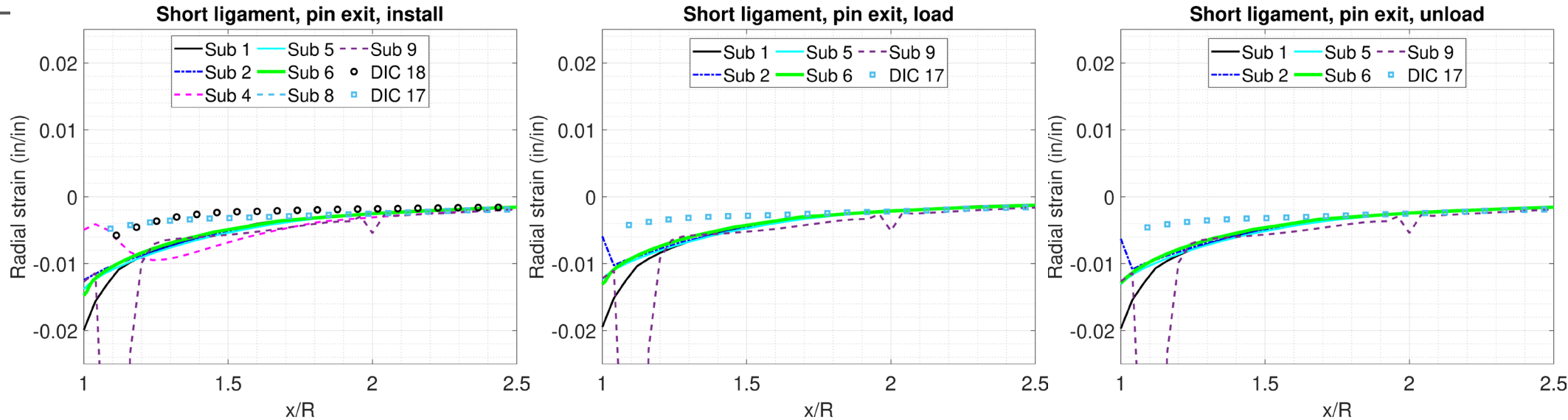
1.2% IFF + remote load

FE round robin (pointwise)

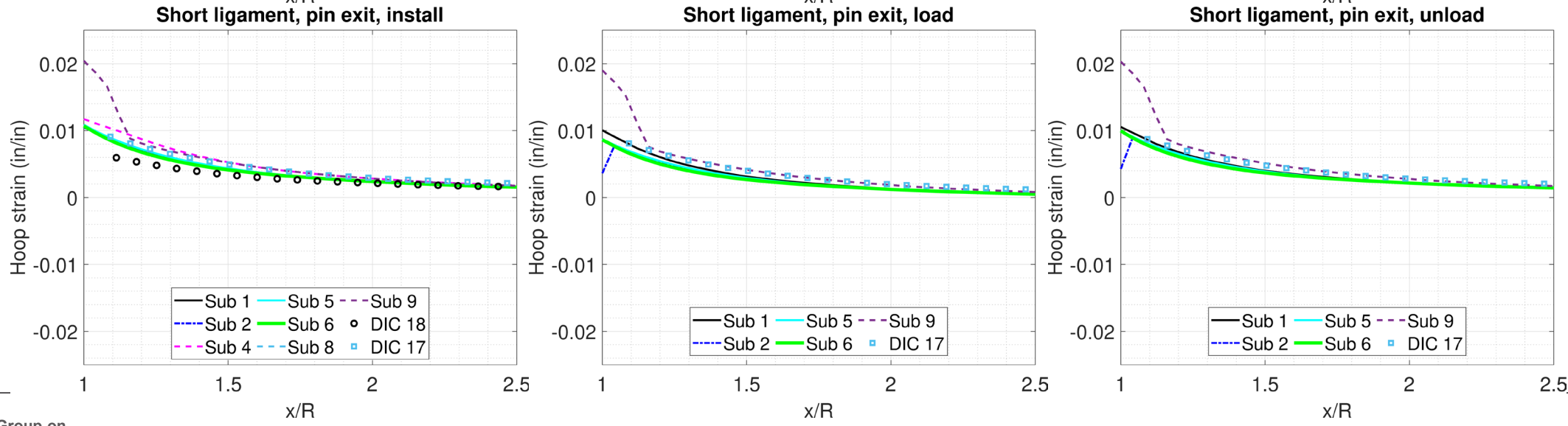
DIC strains (averaged)

Models vs DIC – 1.2% IFF, -10 ksi remote stress

Radial strain

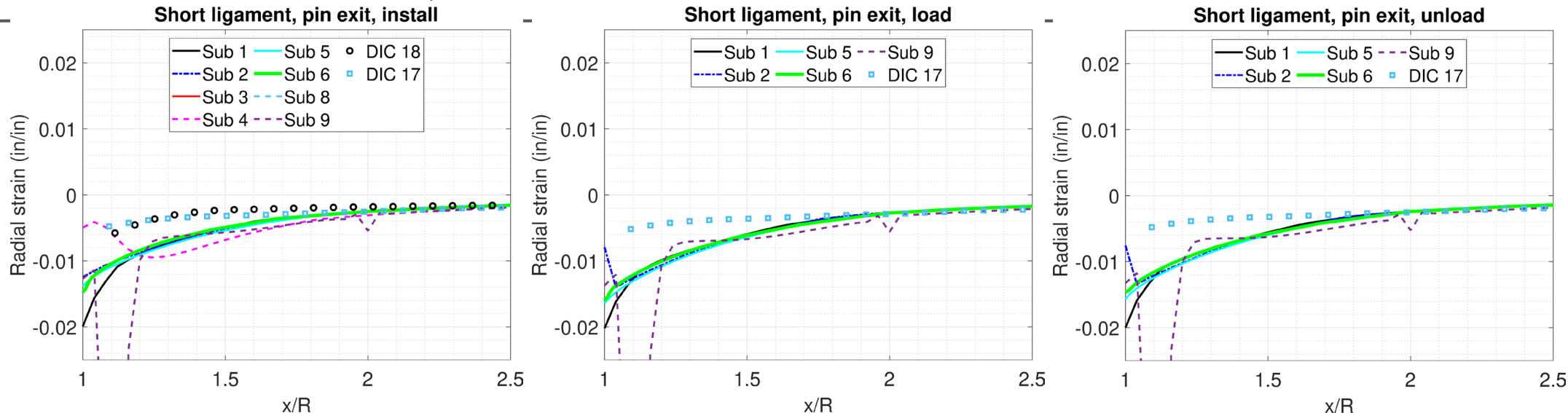


Hoop strain

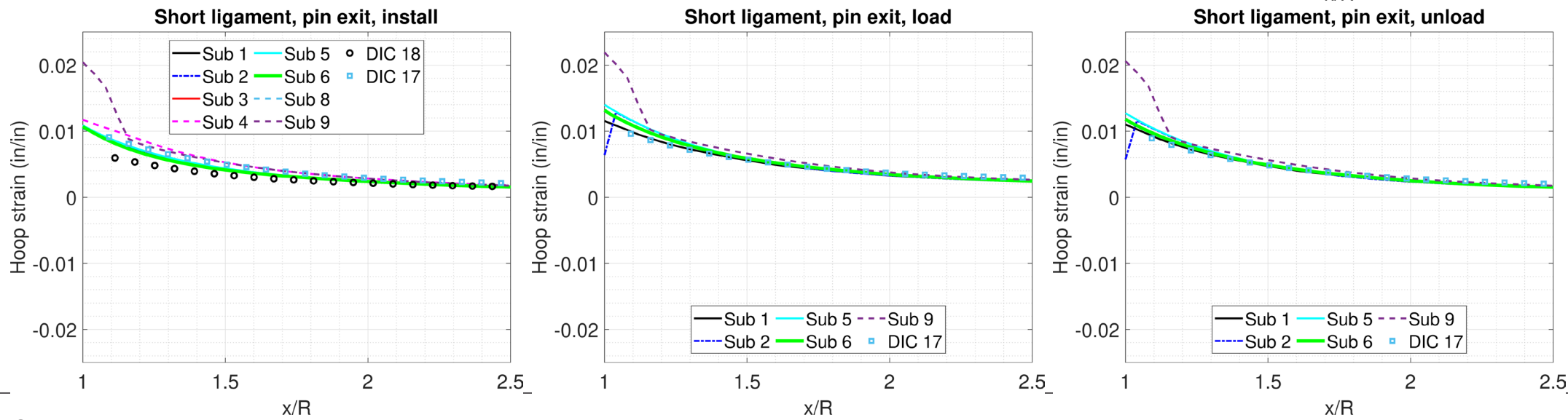


Models vs DIC – 1.2% IFF, 10 ksi remote stress

Radial strain



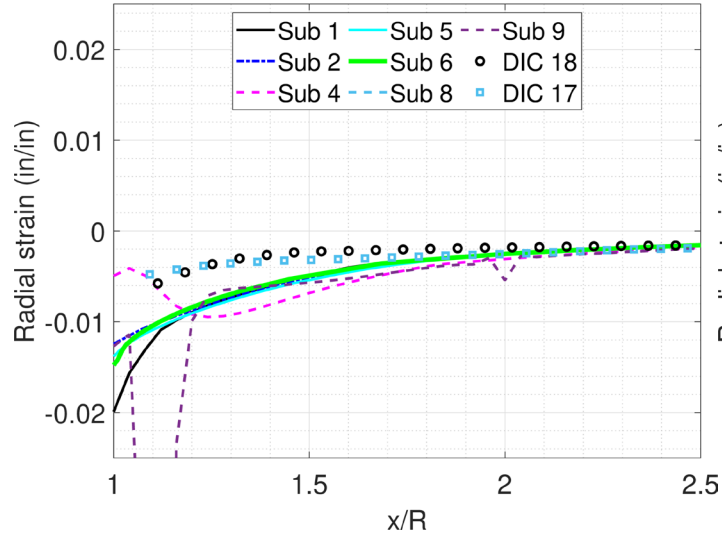
Hoop strain



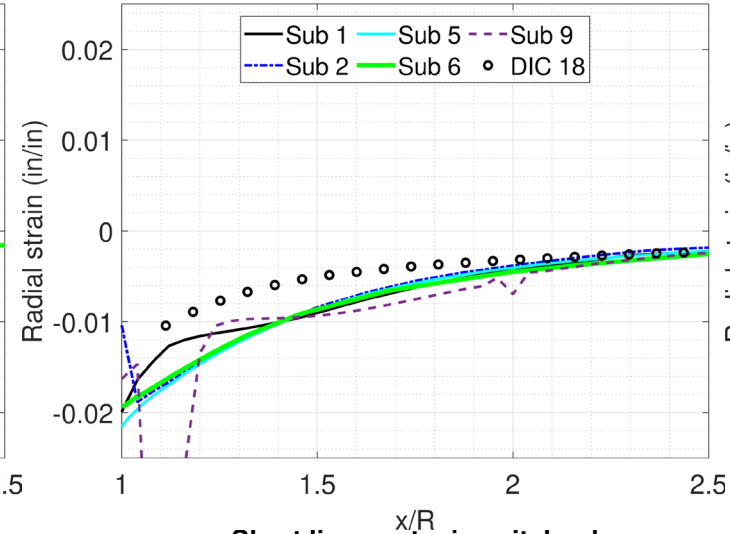
Models vs DIC – 1.2% IFF, 30 ksi remote stress

Radial strain

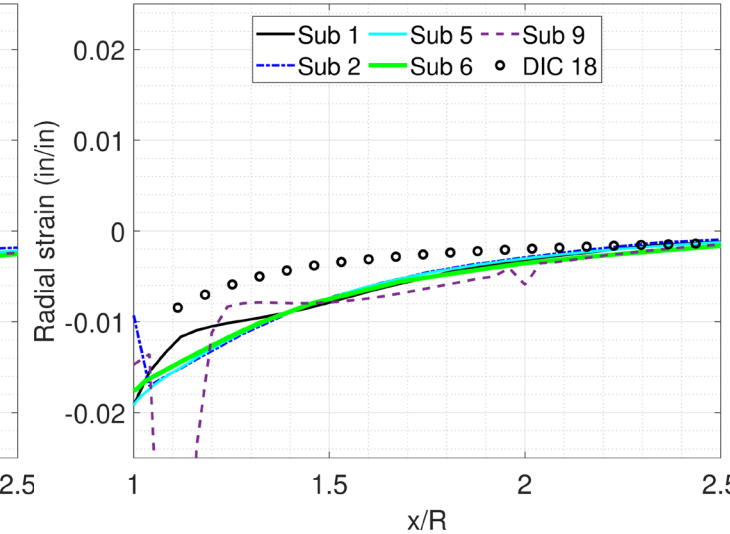
Short ligament, pin exit, install



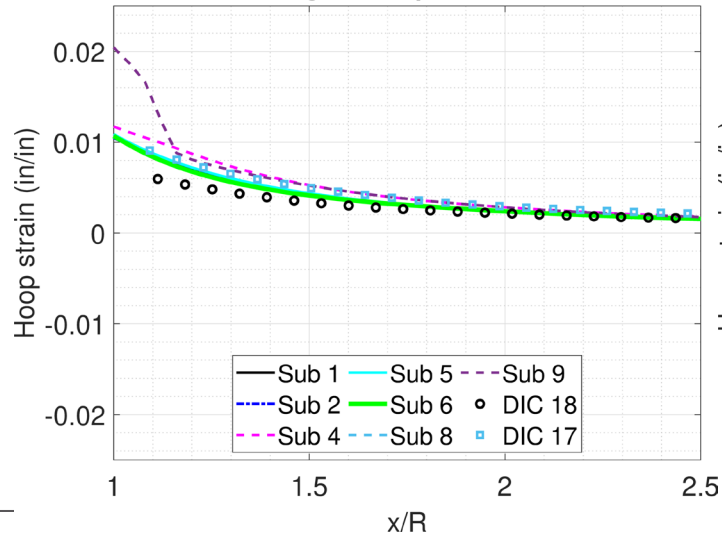
Short ligament, pin exit, load



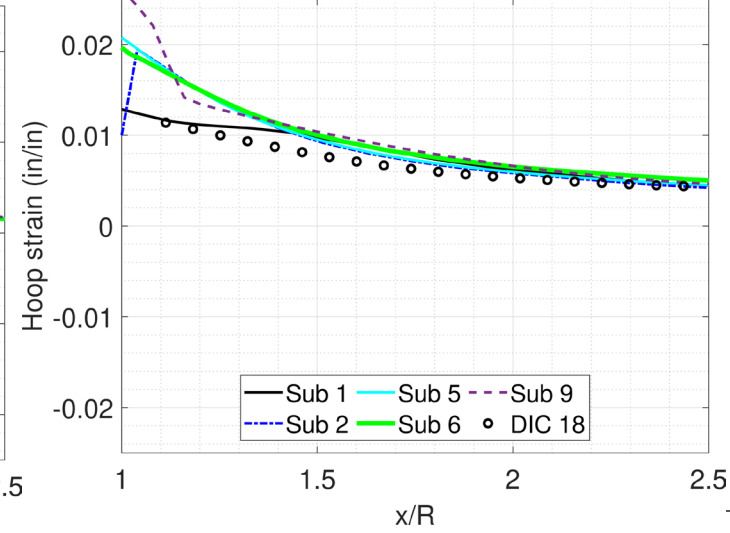
Short ligament, pin exit, unload



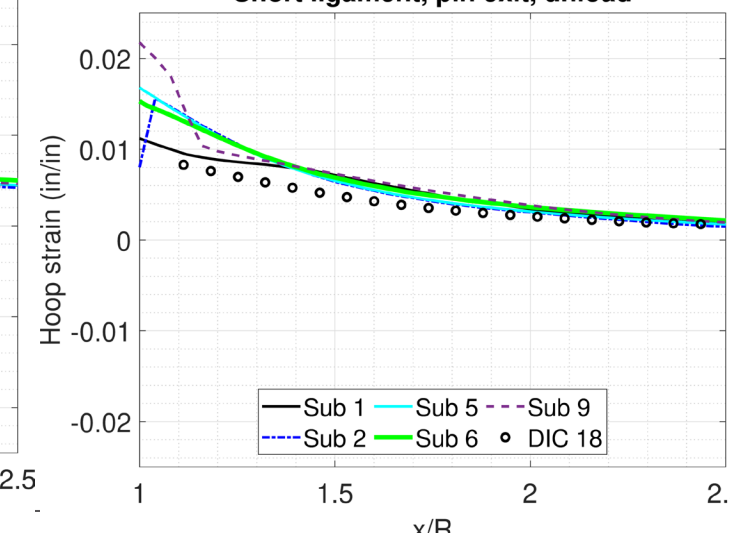
Short ligament, pin exit, install



Short ligament, pin exit, load



Short ligament, pin exit, unload



Hoop strain

Backup Slides

A-10 IFF Testing & Analysis Program

Phased approach with increasing complexity

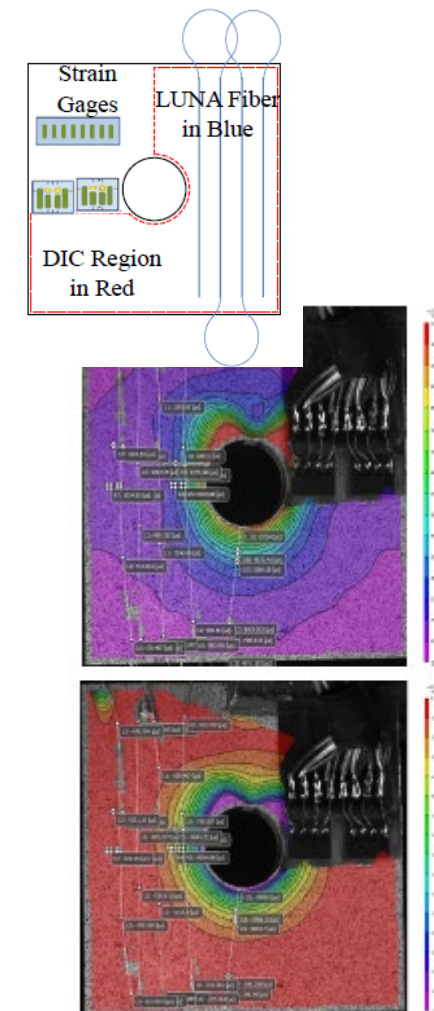
- Phase 1: assessment of as-installed state
 - Simulate and empirically quantify the strain and stress state near a hole in the presence of an interference fit fastener
 - 3 levels of interference
 - 3D nonlinear FE process modeling; DIC and strain gages for surface strain measurements
- Phase 2: fastener installed + remote loading
 - Repeat Phase 1 but with the addition of remote loading and unloading (multiple load levels and interference levels)
- Phase 3: analytical methodology to account for interference fit fasteners during crack growth
 - Perform multi-point fatigue crack growth analyses including interference fit fastener conditions
 - Blind predictions prior to fatigue testing to be performed in Phase 4
- Phase 4: fatigue crack growth testing with interference fit fasteners
 - Perform fatigue crack growth testing of neat fit and interference fit conditions
 - Use fatigue test data for validation and refinement of analytical methodology

Parameter	Levels
Coupon material	2024-T351 plate
Pin material	52100 steel pin
Coupon thickness	0.25 inch
Nominal hole size	0.25 inch
Interference conditions	Open hole
	Neat fit
	0.3% interference
	0.6% interference
Strain monitoring	1.2% interference
	DIC (all specimens)
	Strain gage (initial specimen)
Static stress levels (Phase 2)	-30 ksi
	-10 ksi
	0
	10 ksi
	20 ksi
Fatigue crack growth testing (Phase 4)	30 ksi
	Constant amplitude loading S _{max} = xxx ksi, R = xxx
	Spectrum?

A-10 IFF Testing & Analysis Program

Verification Tests

- Design conditions
 - Fasteners – gauge pins with ground transition geometry
- Data capture
 - 3D geometric measurements of fastener and hole
 - Calculate applied interference along bore
 - Surface strains (primarily DIC)
 - Leverage lessons learned from ERSI Cx 2x2 Residual Stress Validation Effort
 - Conditions
 - After fastener install
 - At each applied load
 - After each unload
 - After fastener removal
 - Transition point for fastener gapping
 - 3D geometric measurements after loading and fastener removal
 - Calculate retained interference along bore and characterize any plasticity



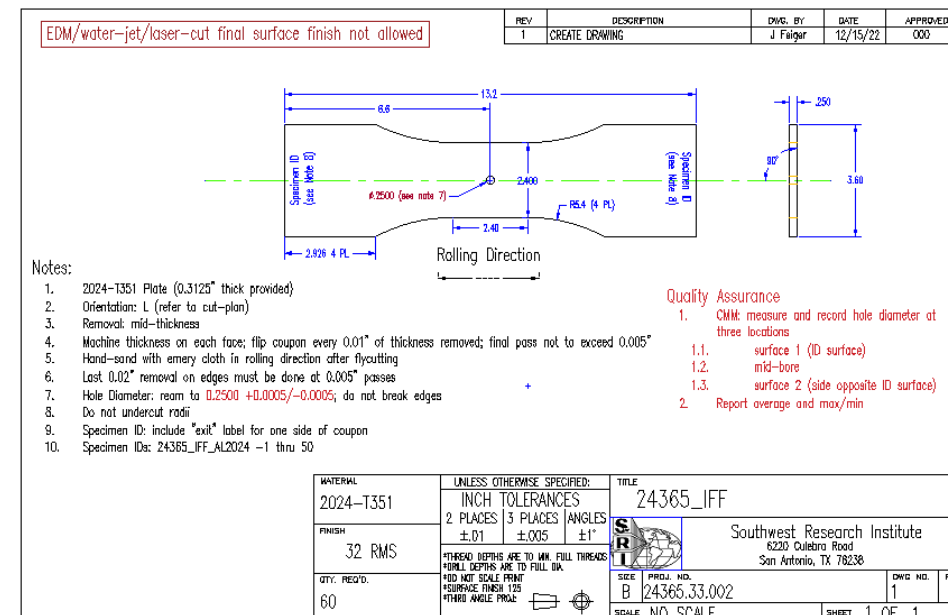
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Coupon design

- “Dog-bone” with geometric center located 0.25” diameter hole
- Same geometry used in prior ERS studies
- Extracted in the L direction at mid-thickness

Material

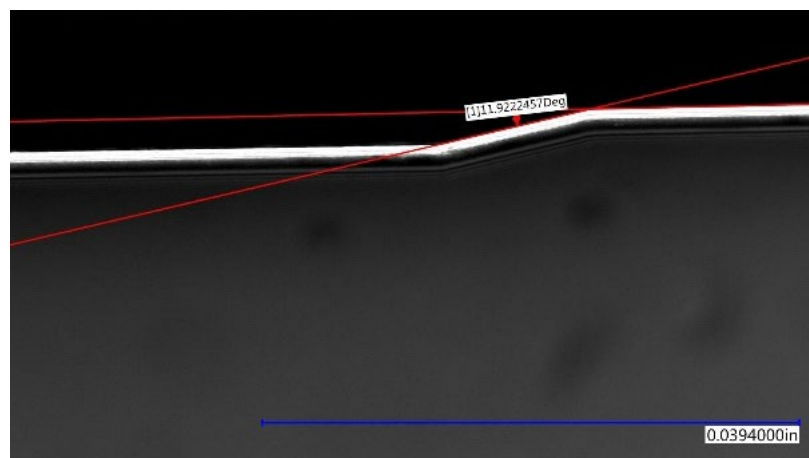
- 2024-T351 plate (0.3125” thick)
- Material Testing
 - Tensile (5 coupons)
 - ASTM E8
 - FCGR (multiple R values)
 - ASTM E647
 - M(T) geometry



A-10 IFF Testing & Analysis Program

Coupon manufacturing

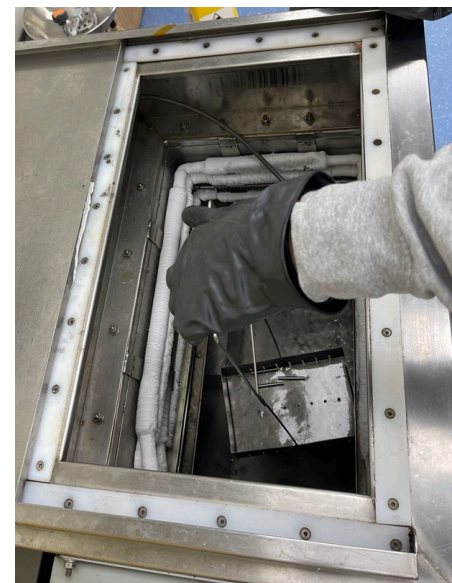
- 50 coupons have been fabricated
- Holes measured via CMM
- Gage pins were custom ordered to match the interference fit required per specimen
 - 0.3%, 0.6%, and 1.2% interference
- Gage pins were machined to match the chamfer of a Hi-Lok
 - One pin from each interference level was measured using an optical comparator to ensure the appropriate chamfer angle was achieved during machining. A sample measurement is provided below.



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Fastener Preparation

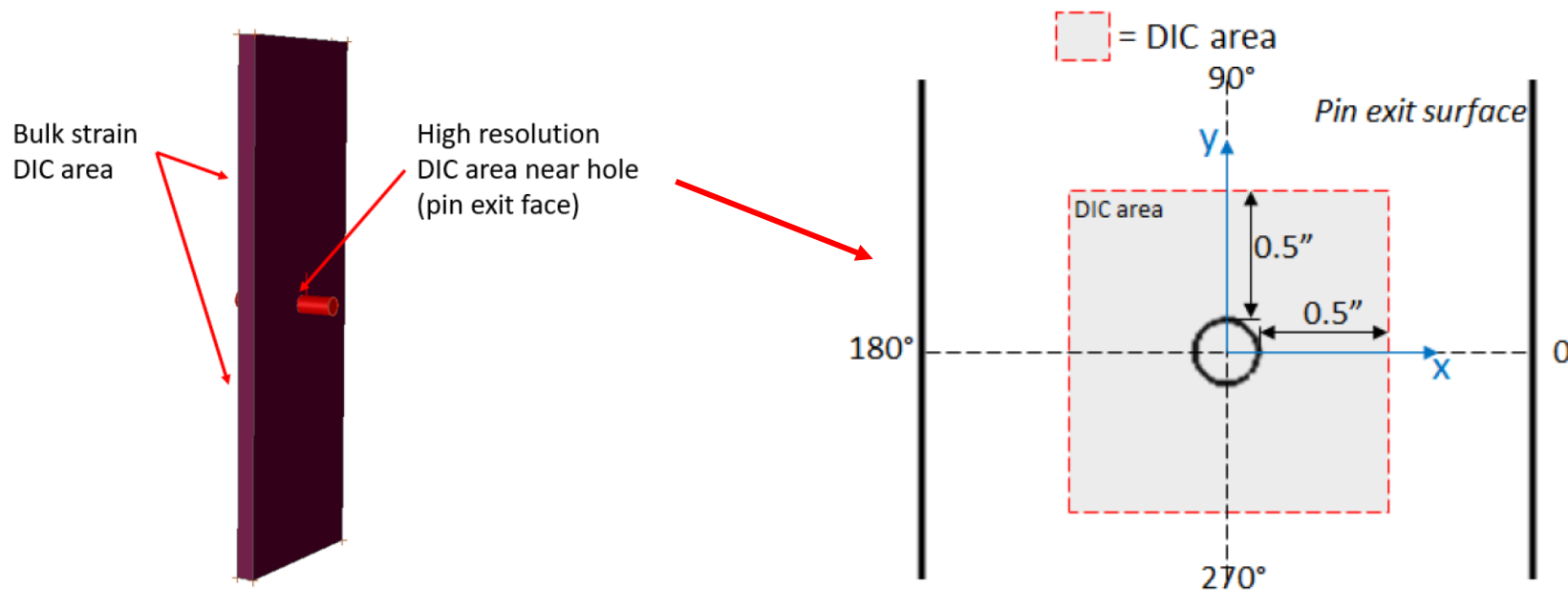
- To mimic the Hi-Lok installation, cetyl alcohol lubricant, Perma-Slik 1460W, will be used to coat the pins prior to installation.
- Per the lubricant's instructions, the pins will be degreased with trichlorethylene. Then, the pins will be dipped in the lubricant and dried in a slow moving, heated air oven.
- A coated pin is shown on the left and the degreasing process on the right.



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DIC setup

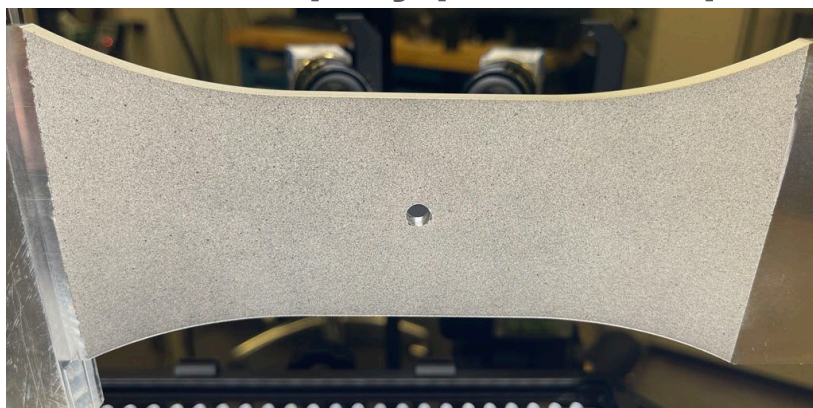
- Collect digital image correlation (DIC) data globally on the pin entrance side and locally on the pin exit side
 - Global Side: 6" x 2.5" FOV
 - Local Side: 1" X 1" FOV



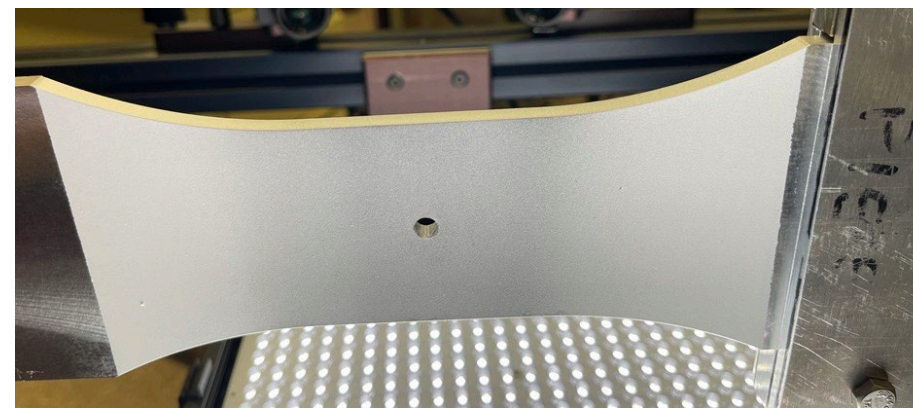
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Coupon prep for DIC

Global Side: speckled with black spray paint/stamp



Local Side: airbrushed with a fine, black ink mist



A-10 IFF Testing & Analysis Program

DIC Setup

- Correlated Solutions software and hardware
- 3D setup
- Global side: 5 MP cameras with 25mm lens
- Local side: 8 MP cameras with 17 mm lens



A-10 IFF Testing & Analysis Program

Pin installation setup

- Servo-mechanic test frame at constant rate of displacement
- Gage section supported
- Relief hole at 3x diameter the fastener hole
- Record load and displacement during installation
- Preserve speckle pattern with Teflon and silicone layer



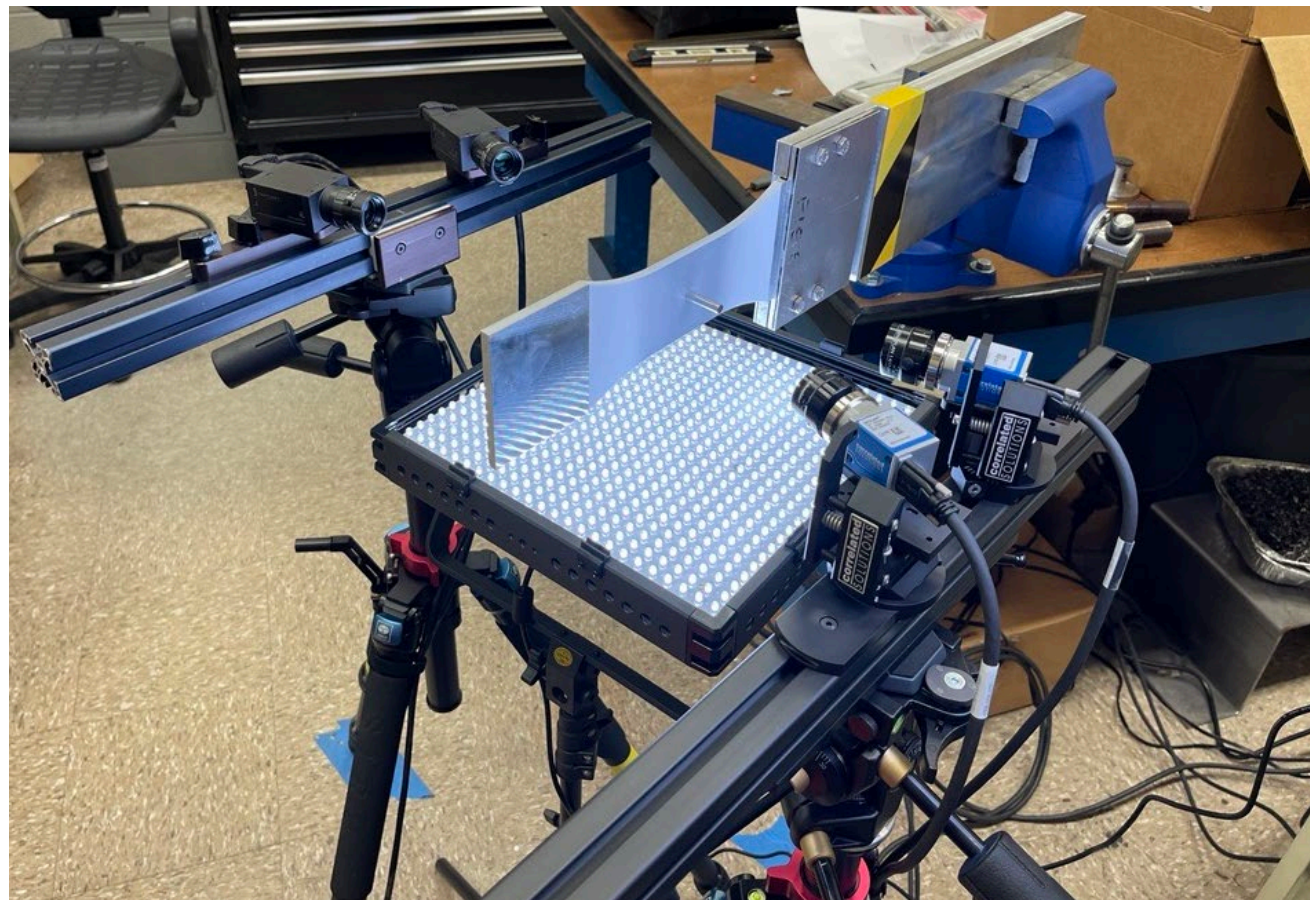
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DIC prior to pin installation



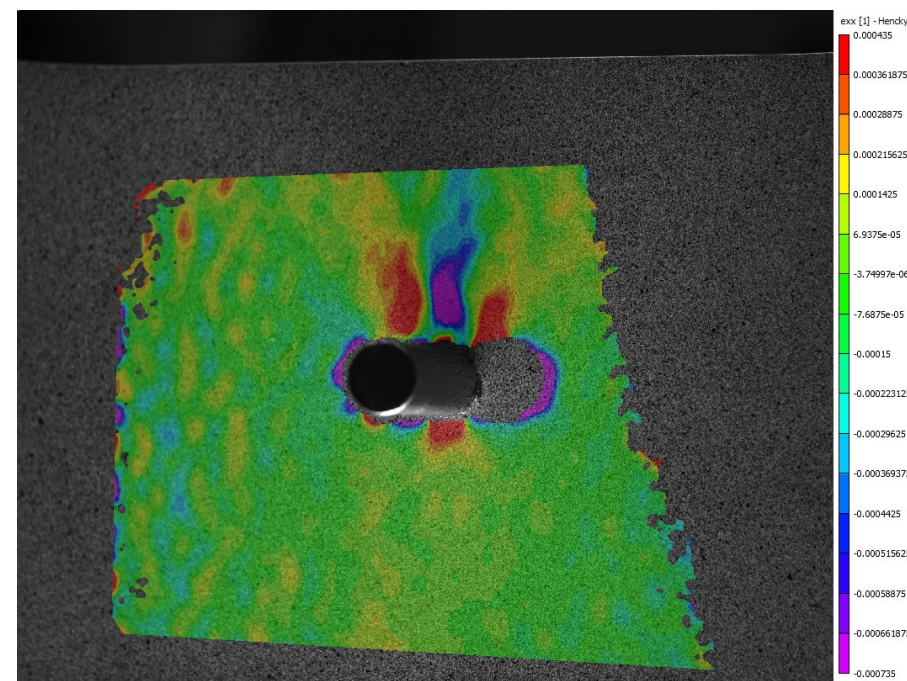
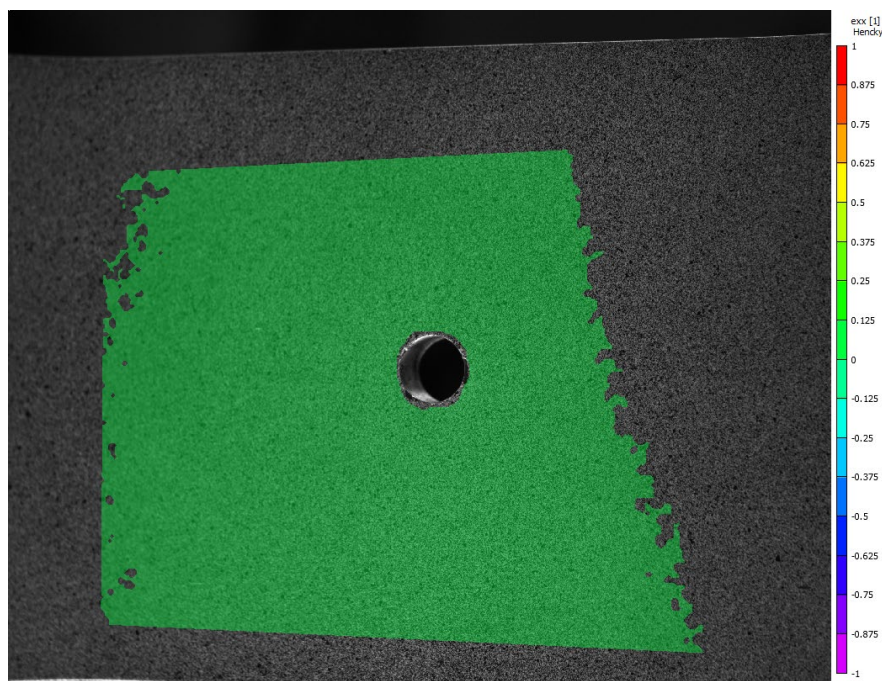
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DIC after to pin installation



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Global results



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Local results

