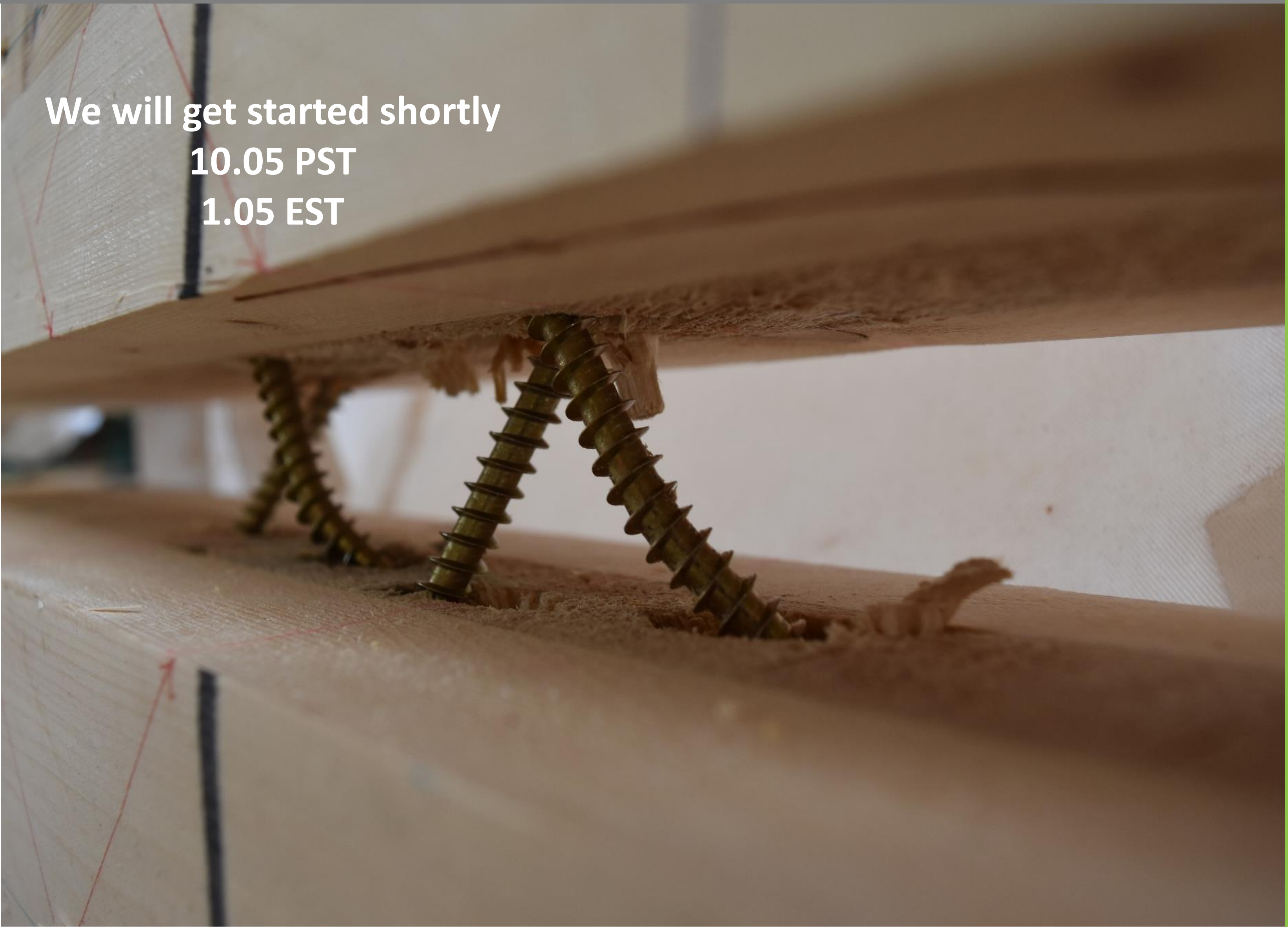
WELCOME and THANK YOU for joining

Performance of CLT Connections under Dynamic Loading

We will get started shortly
10.05 PST
1.05 EST



Performance of CLT Connections under Dynamic Loading

Presenter: **Max Closen**

Background: *Timber Engineering*

Performance of CLT Connections under Dynamic

The webinar outlook:

- Refresher: Performance of CLT connections under *Static* loading
- Performance of CLT connections under *Cyclic* loading
- Summary of proposed design procedures and design values

Outline

- Test Campaign #1 – Static Loading
  - Panel to Panel Connections
  - Surface Spline, Half Lapped & Butt Joint Connections

- Test Campaign #2 – Cyclic Loading
  - Panel to Panel Connections
  - Surface Spline, Half Lapped & Butt Joint Connections

- Test Data and Results
  - Statistics
  - Failure Modes
  - Proposed Design Methods/Values

Outline

- Test Campaign #1 – Static Loading
  - Panel to Panel Connections
  - Surface Spline, Half Lapped & Butt Joint Connections

- Test Campaign #2 – Cyclic Loading
  - Panel to Panel Connections
  - Surface Spline, Half Lapped & Butt Joint Connections

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- Test Campaign #1 – Static Loading
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  - Surface Spline, Half Lapped & Butt Joint Connections
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  - Failure Modes
  - Proposed Design Methods/Values

Disclaimer

Materials presented are for informational purpose only

but

Verification of existing or future code provisions for CLT connections through this small sample test series

Test Campaign #1

Static Loading

Surface Spline Joints

Half Lapped Joints

Butt Joints

Test Campaign #1 : Static Loading

Specimen List:

Label	Type	STS Ø [in]	STS Length [in]	Angle [º]	Replicates	# STS per Shear Plane	STS action
Series 1 – SS_90_3ply	Surface Spline Joint	5/16	3-1/8	90	6	8	Shear
Series 1 – SS_90_3ply_NF					3		
Series 2 – SS_90_5ply			4		6		
Series 3 – LJ_90_3ply	Half Lapped Joint	5/16	3-1/2	90	6	8	Shear
Series 3 – LJ_90_3ply_NF					3		
Series 4 – LJ_90_5ply			6-1/4		6		
Series 5 – LJ_45_3ply			5-1/2	45	6	12	Withdrawal
Series 5 – LJ_45_3ply_NF					3		
Series 6 – LJ_45_5ply			8-5/8		6	10	
Series 7 – LJ_45/90_3ply_WSSW			3-1/2 + 5-1/2	45 + 90	6	8	Shear + Withdrawal
Series 7 – LJ_45/90_3ply_WSSW_NF					3		
Series 8 – LJ_45/90_5ply_WSSW			6-1/4 + 220		6		
Series 9 – LJ_45/90_3ply_SWSWS			3-1/2 + 5-1/2			10	
Series 10 – LJ_45/90_5ply_SWSWS			6-1/4 + 8-5/8				
Series 11 – BJ_33/45_3ply	Butt Joint	5/16	7-1/8	33 + 45	6	8	Shear + Withdrawal
Series 11 – BJ_33/45_3ply_NF					3		
Series 12 – BJ_45_3ply			5-1/2	45	6		Shear

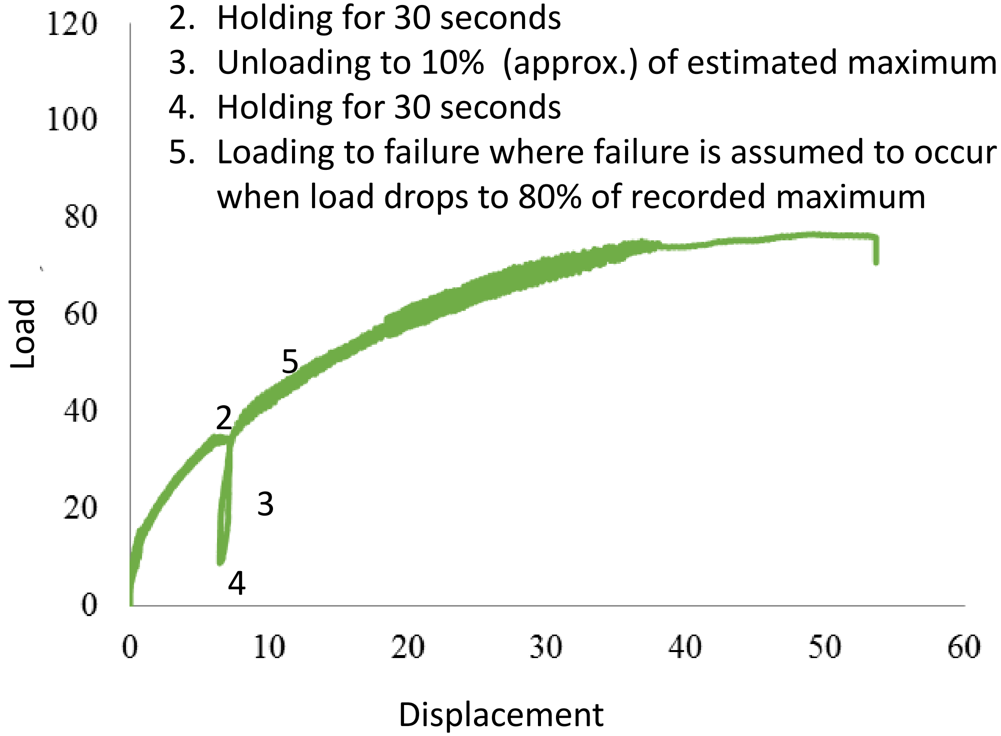
Notes:
SS=Surface Spline, LJ=Lap Joint, BJ=Butt Joint
WSSW = Screw arrangement within rows. Withdr. + Shear + Shear + Withdr.
SWSWS = Screw arrangement within rows. Shear + Withdr. + Shear + Withdr. + Shear

CrossLam® CLT Panels
V2M1 Grade

Test Campaign #1 : Static Loading

- Test setup as per DIN 26891
  - Actuator loading from top
  - Load control
  - Load rate: 5,000 lbf/min
  - *Brandner et al. (2013)*

1. Loading up to 40% (approx.) of estimated maximum
2. Holding for 30 seconds
3. Unloading to 10% (approx.) of estimated maximum
4. Holding for 30 seconds
5. Loading to failure where failure is assumed to occur when load drops to 80% of recorded maximum

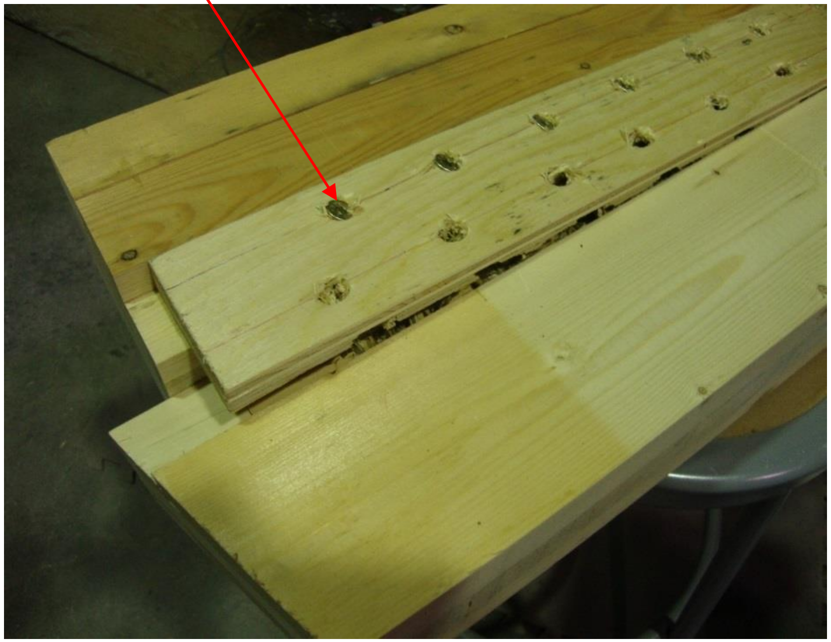


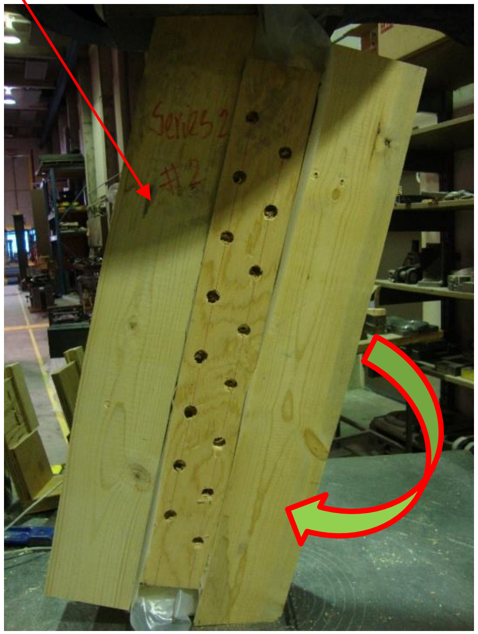
Test Campaign #1 : Static Loading

- Most commonly observed failure modes

- Surface Spline Joints:

Head pull-in of screws leads to out-of-plane rotation of specimens

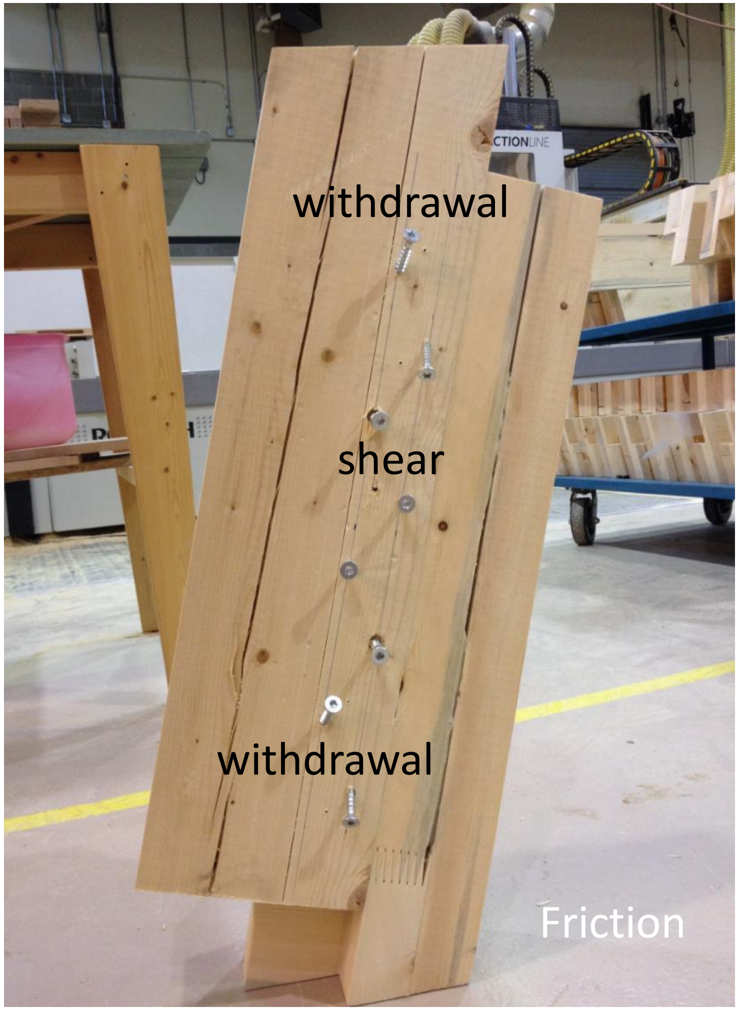




Test Campaign #1 : Static Loading

- Most commonly observed failure modes

- Half Lapped Joints with STS in Shear and Withdrawal:
Head pull-in of screws + out of plane rotation



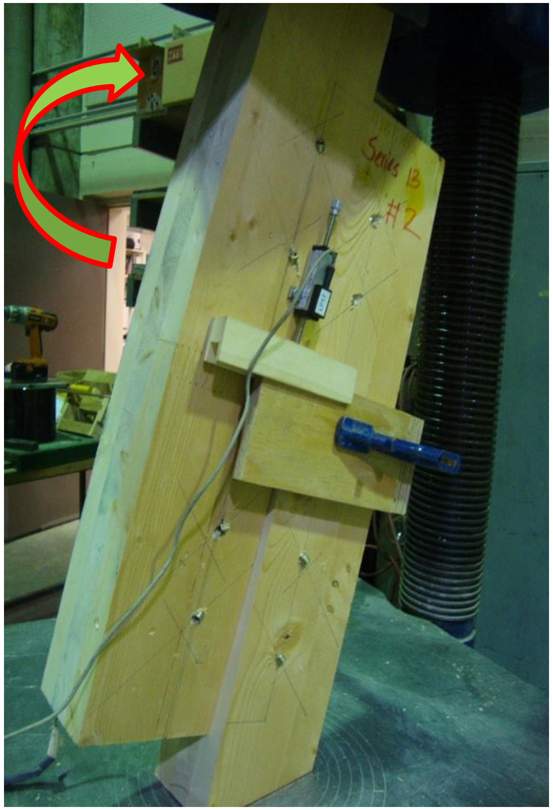
Test Campaign #1 : Static Loading

- Most commonly observed failure modes

- Half Lapped and Butt Joints with STS in Withdrawal:

-Half Lapped Joints:
withdrawal (head push-out and pull-in)

- Butt Joints:
Out of plane rotation



Test Campaign #1 : Static Test Results

Results for 3-ply Specimens:

Label	Type	Total F_{MAX} [lbf]	F_{MAX} [lbf]	F_Y [lbf]	Δ_{MAX} [in]	Δ_Y [in]	$K_{0.4}$ [lbf/in]	Ductility
Series 1 – SS_90_3ply	Surface Spline Joint	11,690	1,461	1,236	1.84	0.34	7,423	5.4
Series 1 – SS_90_3ply_NF		11,510	1,439	1,146	2.05	0.24	7,423	8.4
Series 3 – LJ_90_3ply	Half Lapped Joint	12,049	1,506	1,146	1.01	0.14	12,562	7.1
Series 3 – LJ_90_3ply_NF		13,668	1,708	1,259	1.18	0.17	14,846	7.1
Series 5 – LJ_45_3ply		19,423	1,619	1,439	0.16	0.05	82,223	3.4
Series 5 – LJ_45_3ply_NF		17,804	1,484	1,326	0.23	0.06	62,238	3.9
Series 7 – LJ_45/90_3ply_WSSW		12,049	1,506	1,326	0.77	0.04	65,093	19.5
Series 7 – LJ_45/90_3ply_WSSW_NF		12,049	1,506	1,214	0.67	0.04	127,902	17.0
Series 9 – LJ_45/90_3ply_SWSWS		11,015	1,102	944	0.97	0.06	47,392	17.6
Series 11 – BJ_33/45_3ply	Butt Joint	14,028	1,753	1,529	0.26	0.04	59,383	6.5
Series 11 – BJ_33/45_3ply_NF		13,128	1,641	1,416	0.30	0.04	51,960	7.5
Series 12 – BJ_45_3ply		12,229	1,529	1,394	1.54	0.40	5,710	3.8

- **Total F_{MAX} value is per shear plane ; All other values are per screw**
- Average measurements out of 6 specimens and 3 specimens for NF series
- F_{max}= Max. Force ; F_y= Yield Force ; Δ_{MAX}= Max Displ. ; Δ_y= Displ. at Yield ; μ= Ductility ; $K_{0.4}$= stiffness calculated at 10% - 40% of F_{max}
- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09

Test Campaign #1 : Static Test Results

Impact of Friction on 3ply Specimens:

Label	Type	Total F_{MAX} [lbf]	F_{MAX} [lbf]	F_Y [lbf]	Δ_{MAX} [in]	Δ_Y [in]	$K_{0.4}$ [lbf/in]	Ductility
Series 1 – SS_90_3ply	Surface Spline Joint	11,690	1,461	1,236	1.84	0.34	7,423	5.4
Series 1 – SS_90_3ply_NF		11,510	1,439	1,146	2.05	0.24	7,423	8.4
Series 3 – LJ_90_3ply	Half Lapped Joint	12,049	1,506	1,146	1.01	0.14	12,562	7.1
Series 3 – LJ_90_3ply_NF		13,668	1,708	1,259	1.18	0.17	14,846	7.1
Series 5 – LJ_45_3ply		19,423	1,619	1,439	0.16	0.05	82,223	3.4
Series 5 – LJ_45_3ply_NF		17,804	1,484	1,326	0.23	0.06	62,238	3.9
Series 7 – LJ_45/90_3ply_WSSW		12,049	1,506	1,326	0.77	0.04	65,093	19.5
Series 7 – LJ_45/90_3ply_WSSW_NF		12,049	1,506	1,214	0.67	0.04	127,902	17.0
Series 9 – LJ_45/90_3ply_SWSWS		11,015	1,102	944	0.97	0.06	47,392	17.6
Series 11 – BJ_33/45_3ply	Butt Joint	14,028	1,753	1,529	0.26	0.04	59,383	6.5
Series 11 – BJ_33/45_3ply_NF		13,128	1,641	1,416	0.30	0.04	51,960	7.5
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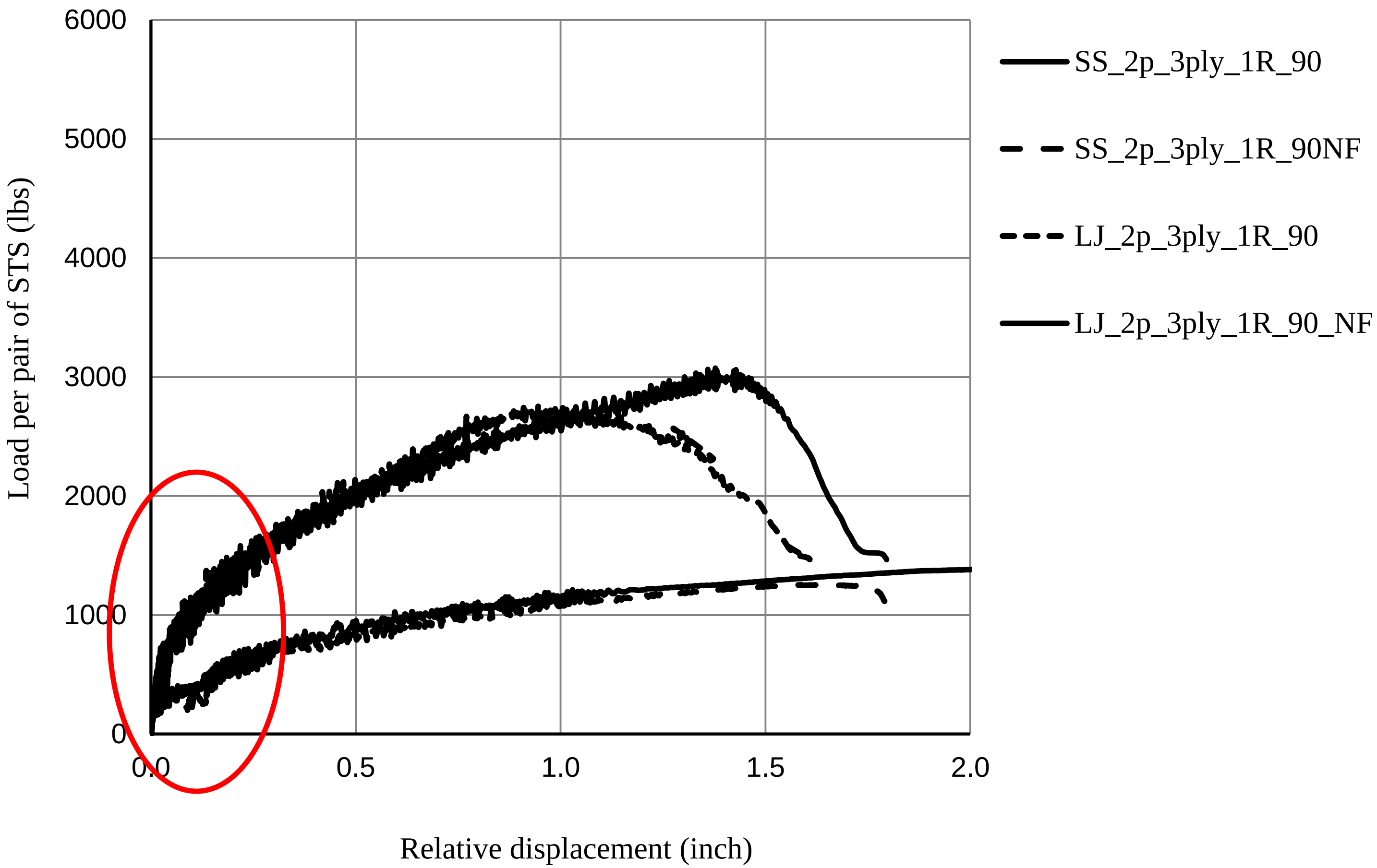
- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic (EEEP) Curves as per ASTM 2126-09

Impact of friction seems to be low!

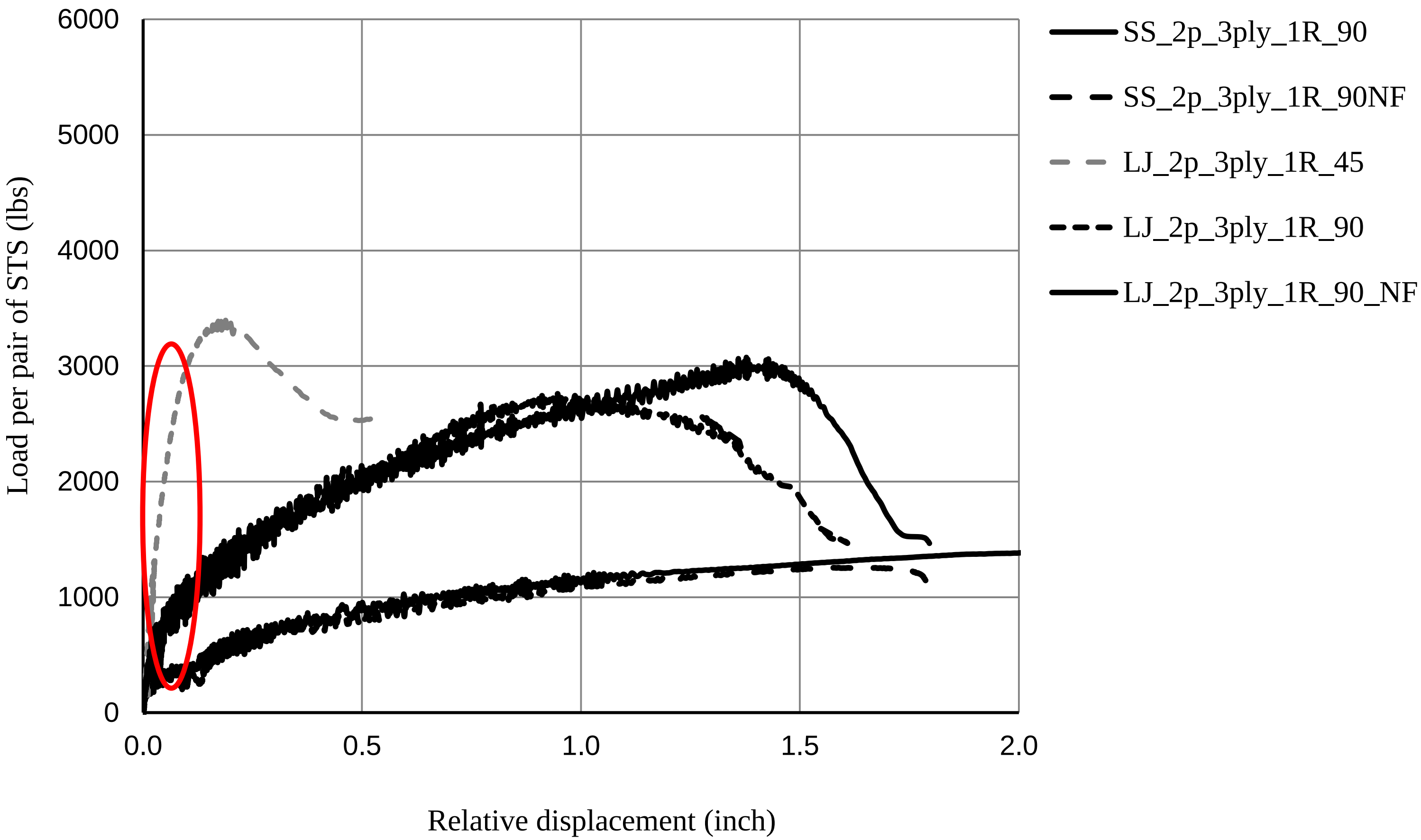
Test Campaign #1 : Static Test Results

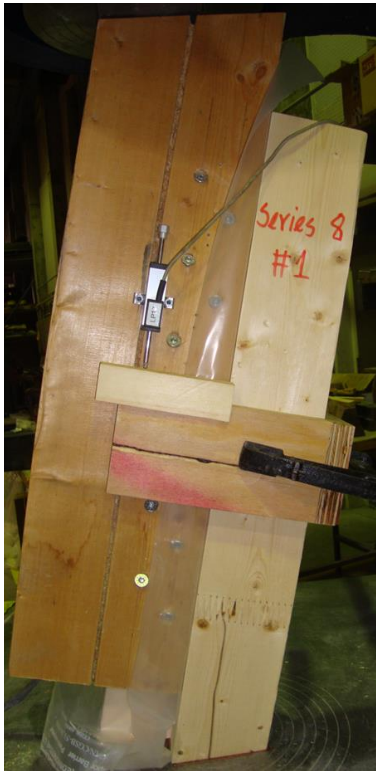
- Load-Displacement Curves



Test Campaign #1 : Static Test Results

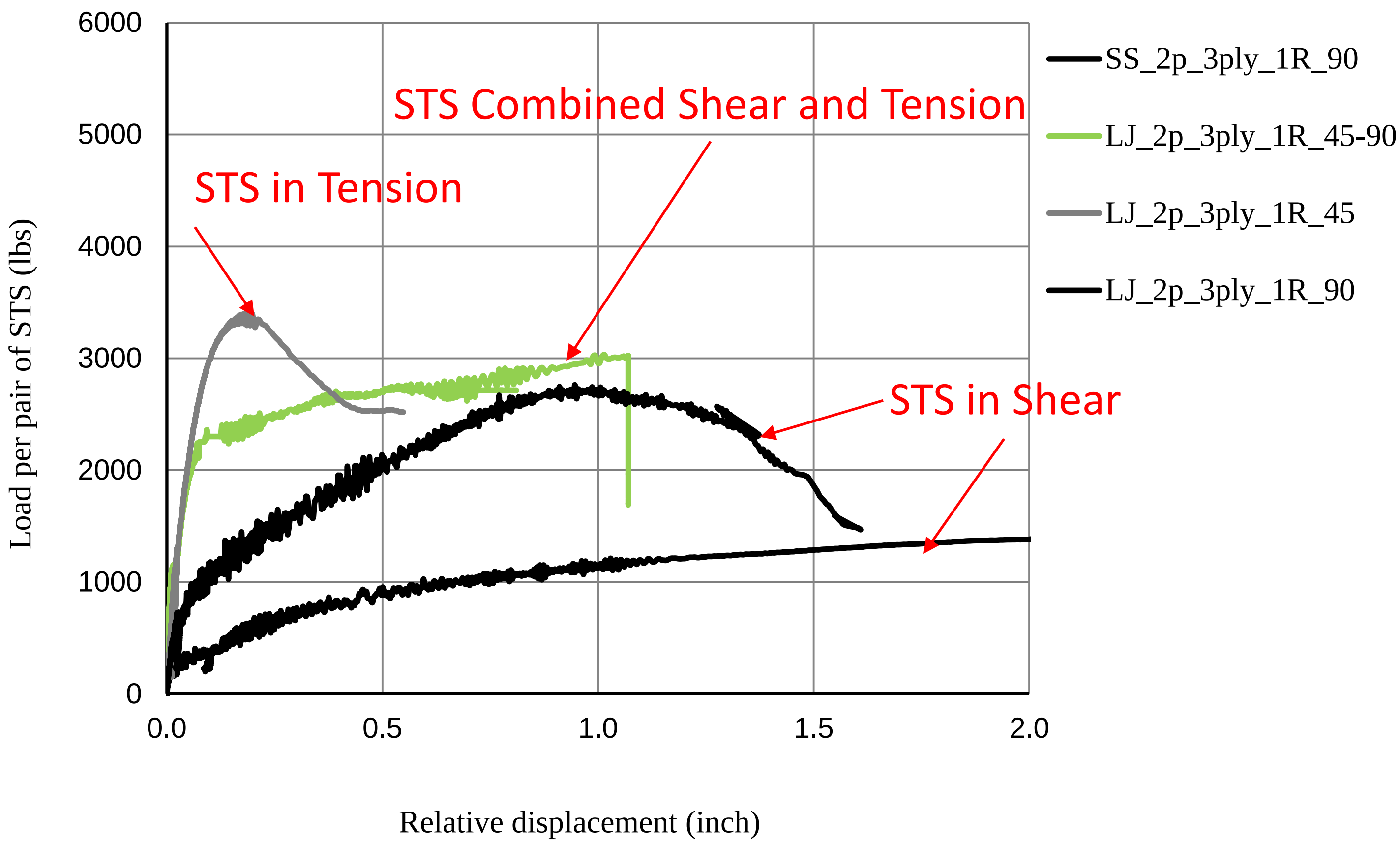
- Load-Displacement Curves





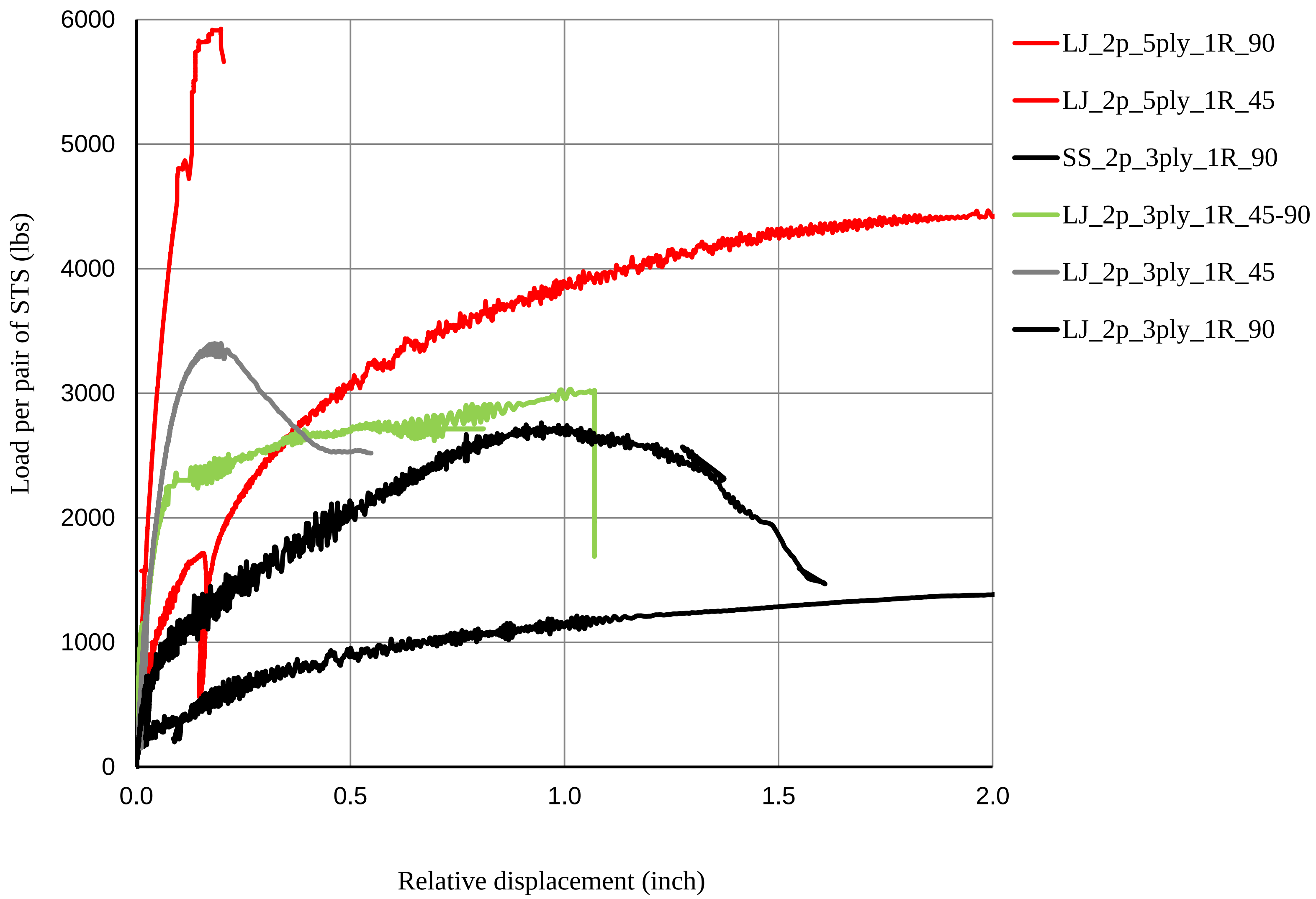
Test Campaign #1 : Static Test Results

- Load-Displacement Curves



Test Campaign #1 : Static Test Results

Load-Displacement Curves:



Test Campaign #1 : Static Test Results

Results for 3-ply Specimens:

Label	Type	Total F_{MAX} [lbf]	F_{MAX} [lbf]	F_Y [lbf]	Δ_{MAX} [in]	Δ_Y [in]	$K_{0.4}$ [lbf/in]	Ductility
Series 1 – SS_90_3ply	Surface Spline Joint	11,690	1,551	1,236	1.84	0.36	7,423	5.1
Series 3 – LJ_90_3ply	Half Lapped Joint	12,049	1,506	1,146	1.01	0.14	12,562	7.1
Series 5 – LJ_45_3ply		19,423	1,619	1,439	0.16	0.05	82,223	3.4
Series 7 – LJ_45/90_3ply_WSSW		11,690	1,461	1,326	0.77	0.04	65,093	19.5
Series 9 – LJ_45/90_3ply_SWSWS		10,611	1,057	944	0.97	0.06	47,392	17.6
Series 11 – BJ_33/45_3ply	Butt Joint	14,028	1,753	1,529	0.26	0.04	59,383	6.5
Series 12 – BJ_45_3ply		12,229	1,529	1,394	1.54	0.40	5,710	3.8

- **Total F_{MAX} value is per shear plane ; All other values are per screw**
- Average measurements out of 6 specimens and 3 specimens for NF series
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- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09

WHICH STIFFNESS VALUE SHOULD BE USED FOR DESIGN?

Test Campaign #1 : Static Test Results

Results for 3-ply Specimens:

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Series 3 – LJ_90_3ply	Half Lapped Joint	12,049	1,506	1,146	1.01	0.14	12,562	7.1
Series 5 – LJ_45_3ply		19,423	1,619	1,439	0.16	0.05	82,223	3.4
Series 7 – LJ_45/90_3ply_WSSW		11,690	1,461	1,326	0.77	0.04	65,093	19.5
Series 9 – LJ_45/90_3ply_SWSWS		10,611	1,057	944	0.97	0.06	47,392	17.6
Series 11 – BJ_33/45_3ply	Butt Joint	14,028	1,753	1,529	0.26	0.04	59,383	6.5
Series 12 – BJ_45_3ply		12,229	1,529	1,394	1.54	0.40	5,710	3.8

- **Total F_{MAX} value is per shear plane ; All other values are per screw**
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- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09

COMBINATION OF STS IN SHEAR AND WITHDRAWAL, BEST OF BOTH WORLDS?

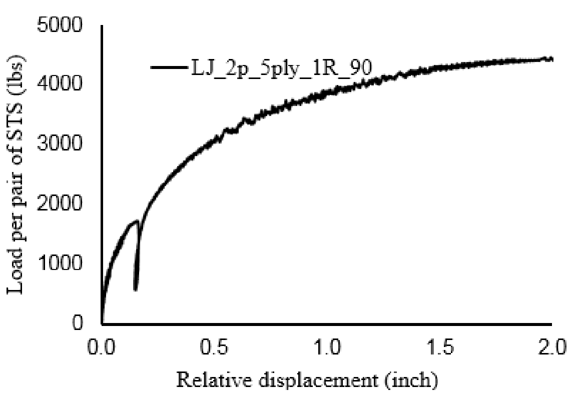
Test Campaign #1 : Static Test Results

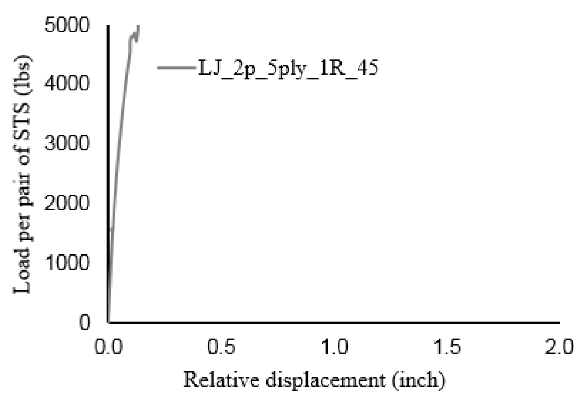
Results for 5-ply Specimens:

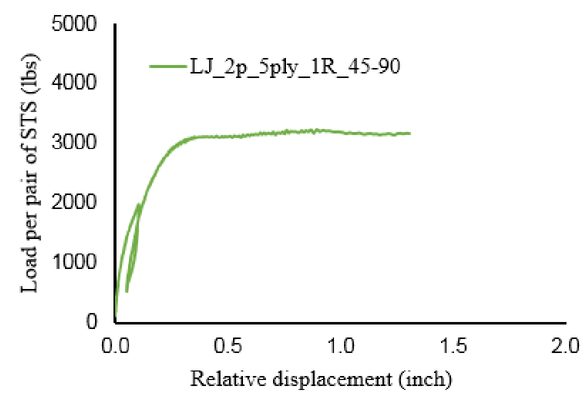
Label	Type	Total F_{MAX} [lbf]	F_{MAX} [lbf]	F_Y [lbf]	Δ_{MAX} [in]	Δ_Y [in]	$K_{0.4}$ [lbf/in]	Ductility
Series 2 – SS_90_5ply	Surface Spline Joint	12,769	1,596	1,259	1.80	0.29	8,565	6.3
Series 4 – LJ_90_5ply	Half Lapped Joint	21,401	2,675	2,136	2.53	0.35	8,565	7.1
Series 6 – LJ_45_5ply		29,224	2,922	2,585	0.19	0.07	60,525	2.6
Series 8 – LJ_45/90_5ply_WSSW		17,624	2,203	1,821	0.13	0.01	58,241	11.3
Series 10 – LJ_45/90_5ply_SWSWS		13,848	1,731	1,484	0.17	0.01	55,386	14.3

- **Total F_{MAX} value is per shear plane ; All other values are per screw**
- Average measurements out of 6 specimens and 3 specimens for NF series
- F_{max}= Max. Force ; F_y= Yield Force ; Δ_{MAX}= Max Displ. ; Δ_y= Displ. at Yield ; μ= Ductility ; $K_{0.4}$= stiffness calculated at 10% - 40% of F_{max}
- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09







Test Campaign #1 : Static Test Results

Comparison Between 3-ply & 5-ply:

Label	Type	F_{MAX} [lbf]	Δ_{MAX} [in]	$K_{0.4}$ [lbf/in]	**Increase** from 3-ply to 5-ply	
					F_{MAX}	$K_{0.4}$
Series 1 – SS_90_3ply	Surface Spline Joint	1,551	1.8	7,423	52%	15%
Series 2 – SS_90_5ply		2,360	2.3	8,565		
Series 3 – LJ_90_3ply	Half Lapped Joint	1,506	1.0	12,562	78%	-32%
Series 4 – LJ_90_5ply		2,675	2.5	8,565		
Series 5 – LJ_45_3ply		1,619	0.2	82,223	75%	-26%
Series 6 – LJ_45_5ply		2,832	0.2	60,525		
Series 7 – LJ_45/90_3ply_WSSW		1,461	0.8	65,093	20%	-11%
Series 8 – LJ_45/90_5ply_WSSW		1,753	0.1	58,241		
Series 9 – LJ_45/90_3ply_SWSWS		1,057	1.0	47,392	32%	17%
Series 10 – LJ_45/90_5ply_SWSWS		1,394	0.2	55,386		

Going to 5-ply = increase in connection capacity

Test Campaign #1 : Static Test Results

Comparison Between 3-ply & 5-ply:

Label	Type	F_{MAX} [lbf]	Δ_{MAX} [in]	$K_{0.4}$ [lbf/in]	**Increase** from 3-ply to 5-ply	
					F_{MAX}	$K_{0.4}$
Series 1 – SS_90_3ply	Surface Spline Joint	1,551	1.8	7,423	52%	15%
Series 2 – SS_90_5ply		2,360	2.3	8,565		
Series 3 – LJ_90_3ply	Half Lapped Joint	1,506	1.0	12,562	78%	-32%
Series 4 – LJ_90_5ply		2,675	2.5	8,565		
Series 5 – LJ_45_3ply		1,619	0.2	82,223	75%	-26%
Series 6 – LJ_45_5ply		2,832	0.2	60,525		
Series 7 – LJ_45/90_3ply_WSSW		1,461	0.8	65,093	20%	-11%
Series 8 – LJ_45/90_5ply_WSSW		1,753	0.1	58,241		
Series 9 – LJ_45/90_3ply_SWSWS		1,057	1.0	47,392	32%	17%
Series 10 – LJ_45/90_5ply_SWSWS		1,394	0.2	55,386		

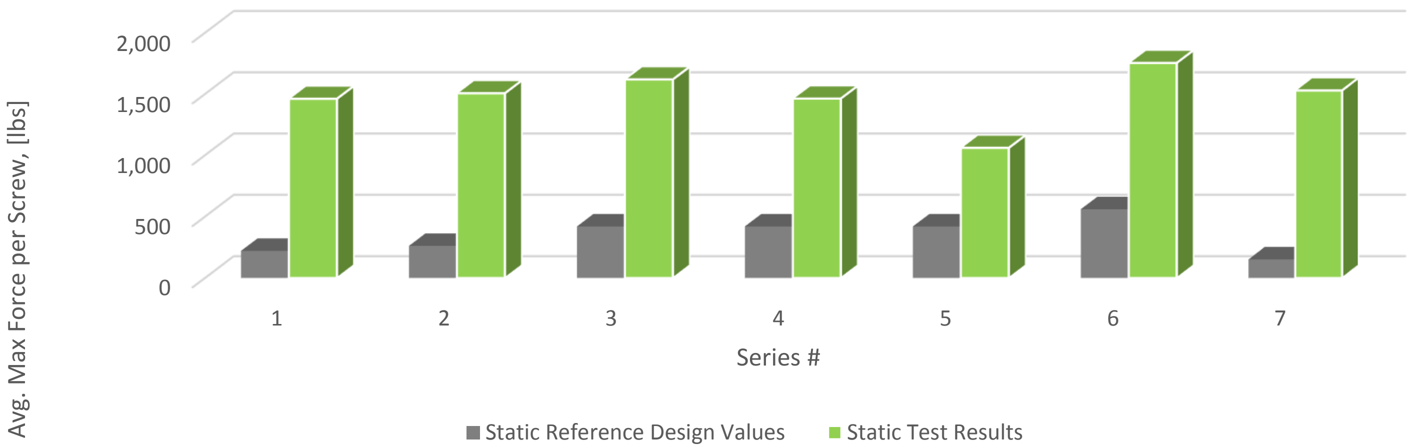
Going to 5-ply = not all tests show stiffness increase for 5-Ply

Test Campaign #1 : Static Test Results

Comparison Between Design & Test Data:

Label	Type	F_{MAX} [lbf]	Predicted* F_{MAX} [lbf]	Δ_{MAX} [in]	$K_{0.4}$ [lbf/in]	Over-Strength Ratio
Series 1 – SS_90_3ply	Surface Spline Joint	1,551	221	1.8	7,423	7.0
Series 2 – LJ_90_3ply	Half Lapped Joint	1506	262	1.0	12,562	5.8
Series 3 – LJ_45_3ply		1619	420	0.2	82,223	3.9
Series 4 – LJ_45/90_3ply_WSSW		1461		0.8	65,093	3.5
Series 5 – LJ_45/90_3ply_SWSWS		1057		1.0	47,392	2.5
Series 6 – BJ_33/45_3ply	Butt Joint	1,753	560	0.3	59,383	3.1
Series 7 – BJ_45_3ply		1,529	151	1.5	5,710	10.1

Connection Static Over-Strength Factors Estimate



Test Campaign #2
Cyclic Loading

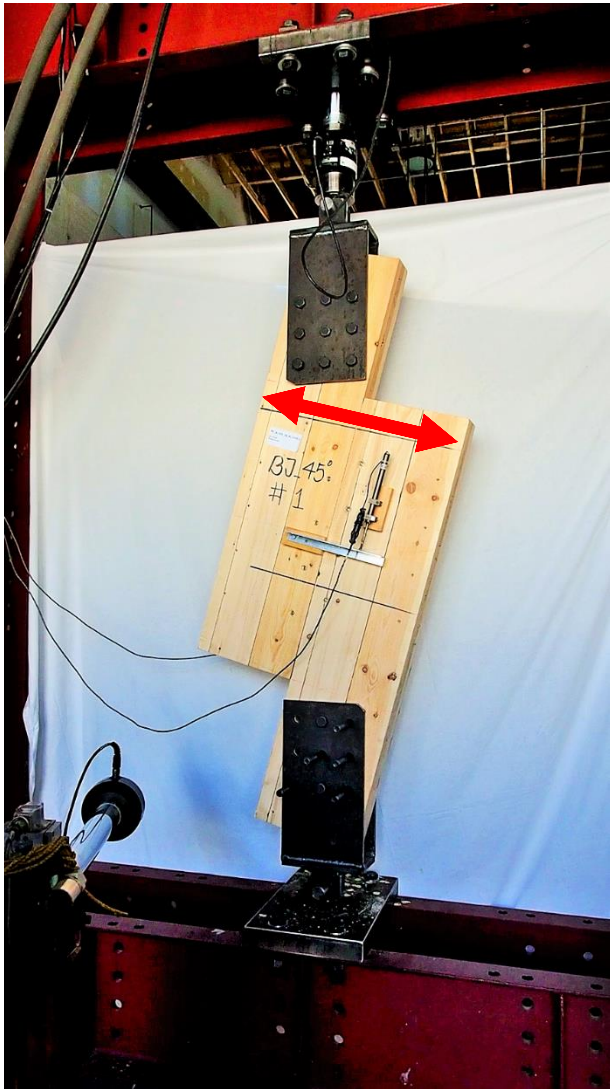
Surface Spline Joints

Half Lapped Joints

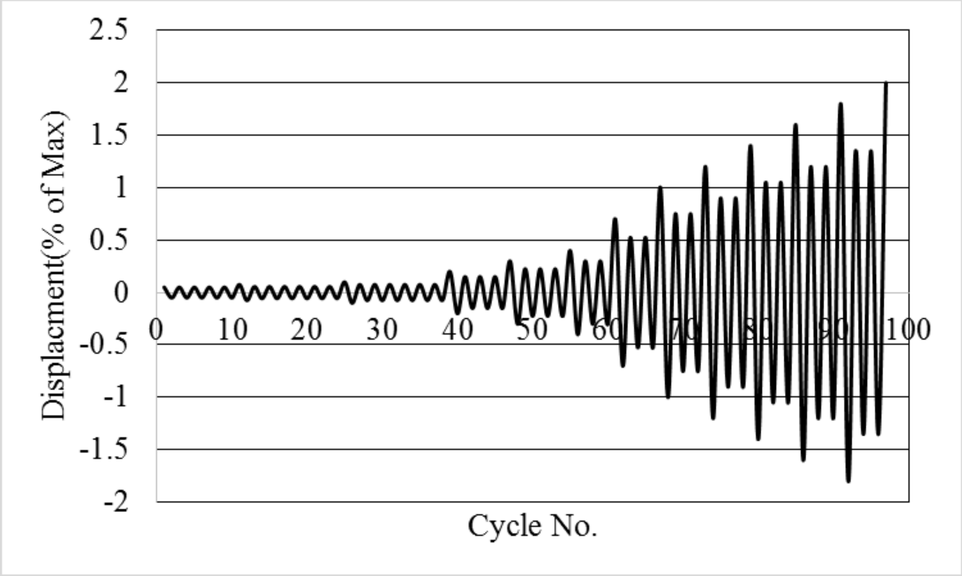
Butt Joints

Test Campaign #2 : Cyclic Loading

General Test Setup



CUREE Loading Protocol (ASTM 2126-09)



- Displacement Controlled
- Displacement Rate: 0.1”/sec
- Ductility calculations: EEEP – ASTM 2126-09
- Stiffness calculations: as per EN-26891 (10-40%)

Test Campaign #2 : Test Series

Label	Type	STS Ø [in]	STS Length [in]	Angle [º]	Replicates	# STS per Shear Plane	STS action
Series 1 – SS @ 90 - 3ply	Surface Spline Joint	5/16	3-1/8	90	6	8	Shear
Series 2 – LJ @ 90 - 3ply	Half Lapped Joint	5/16	3-1/2	90	6	8	Shear
Series 3 – LJ @ 45 - 3ply			5-1/2	45	6	12	Withdrawal
Series 4 – LJ @ 45&90 (1) - 3ply			3-1/2 + 5-1/2	45 + 90	6	8	Shear + Withdrawal
Series 5 – LJ @ 45&90 (2) - 3ply			3-1/2 + 5-1/2		6	10	
Series 6 – BJ @ 33&45 - 3ply	Butt Joint	5/16	7-1/8	33 + 45	6	8	Withdrawal
Series 7 – BJ @ 45 - 3ply				45	6		Shear

Notes:
SS=Surface Spline, LJ=Lap Joint, BJ=Butt Joint
WSSW = Screw arrangement within rows. Withdr. + Shear + Shear + Withdr.
SWSWS = Screw arrangement within rows. Shear + Withdr. + Shear + Withdr. + Shear


Surface Spline Joints


Half Lapped Joints

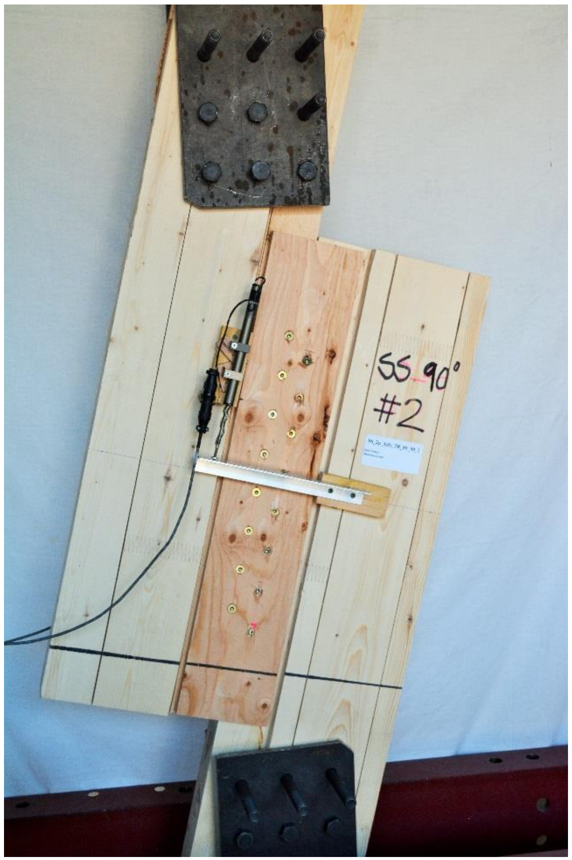

Butt Joints

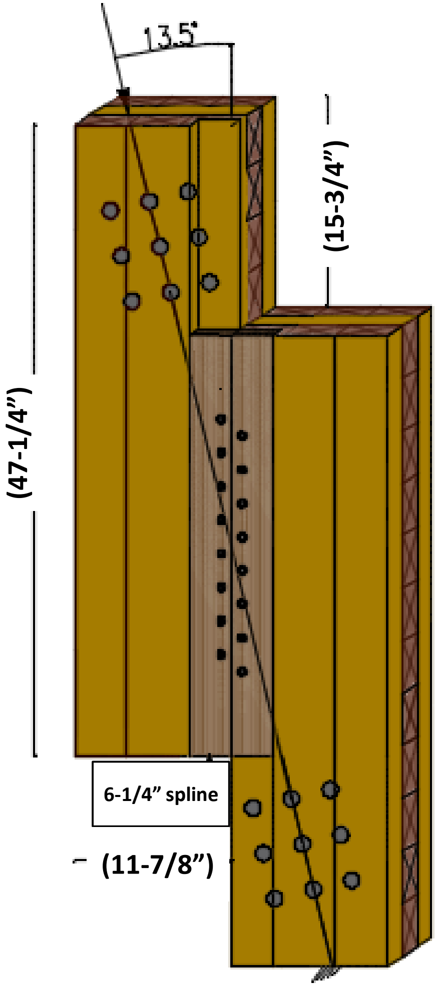
CrossLam® CLT Panels V2M1 Grade

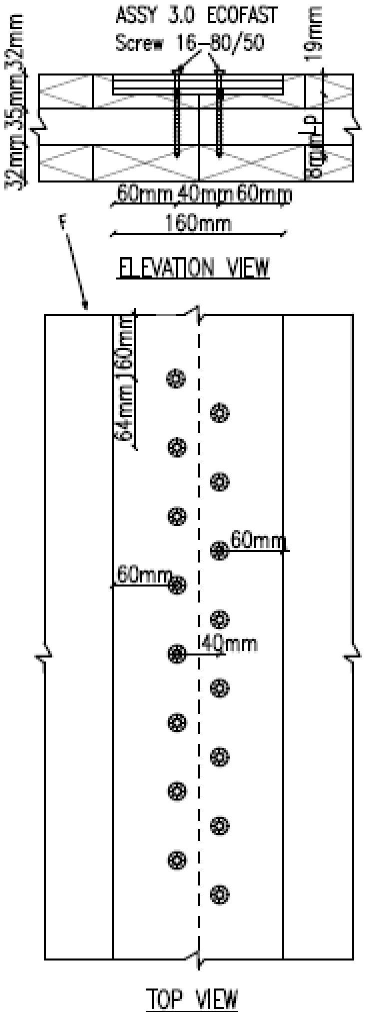
Test Series #1 : Configuration

1” = 25.4 mm

Surface Spline Joint with STS in Shear

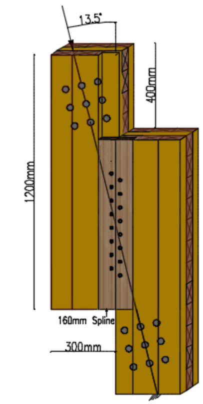






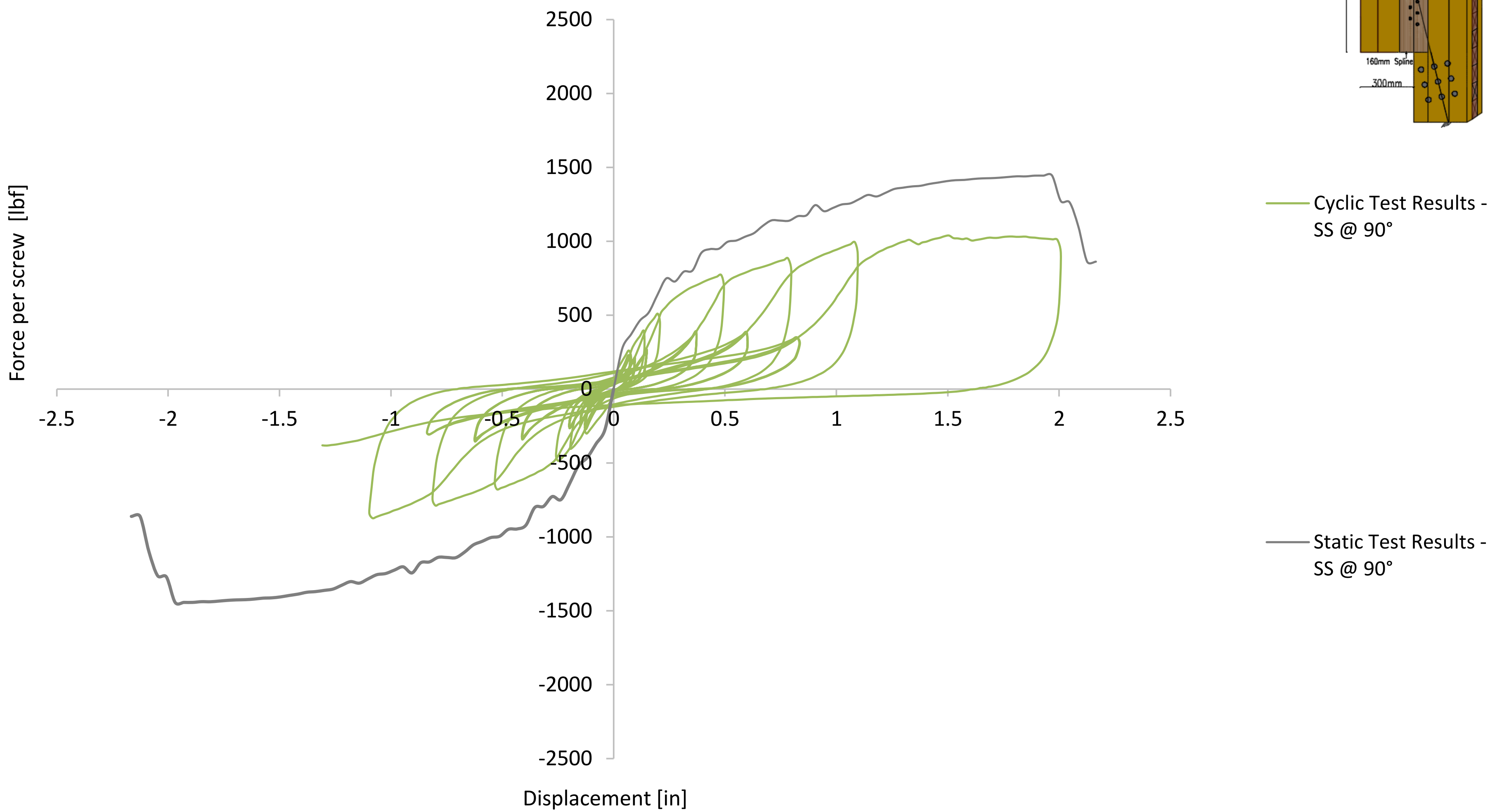
Courtesy of: Afrin Hossain©

Test Series #1 : Load-Displacement Curve

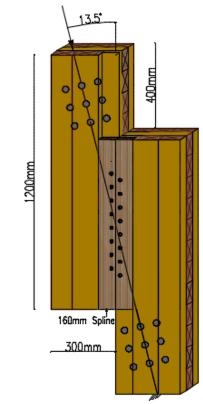


Static v Dynamic Testing

Series #1 = Surface Spline Joints with STS in Shear Action (α=90°)

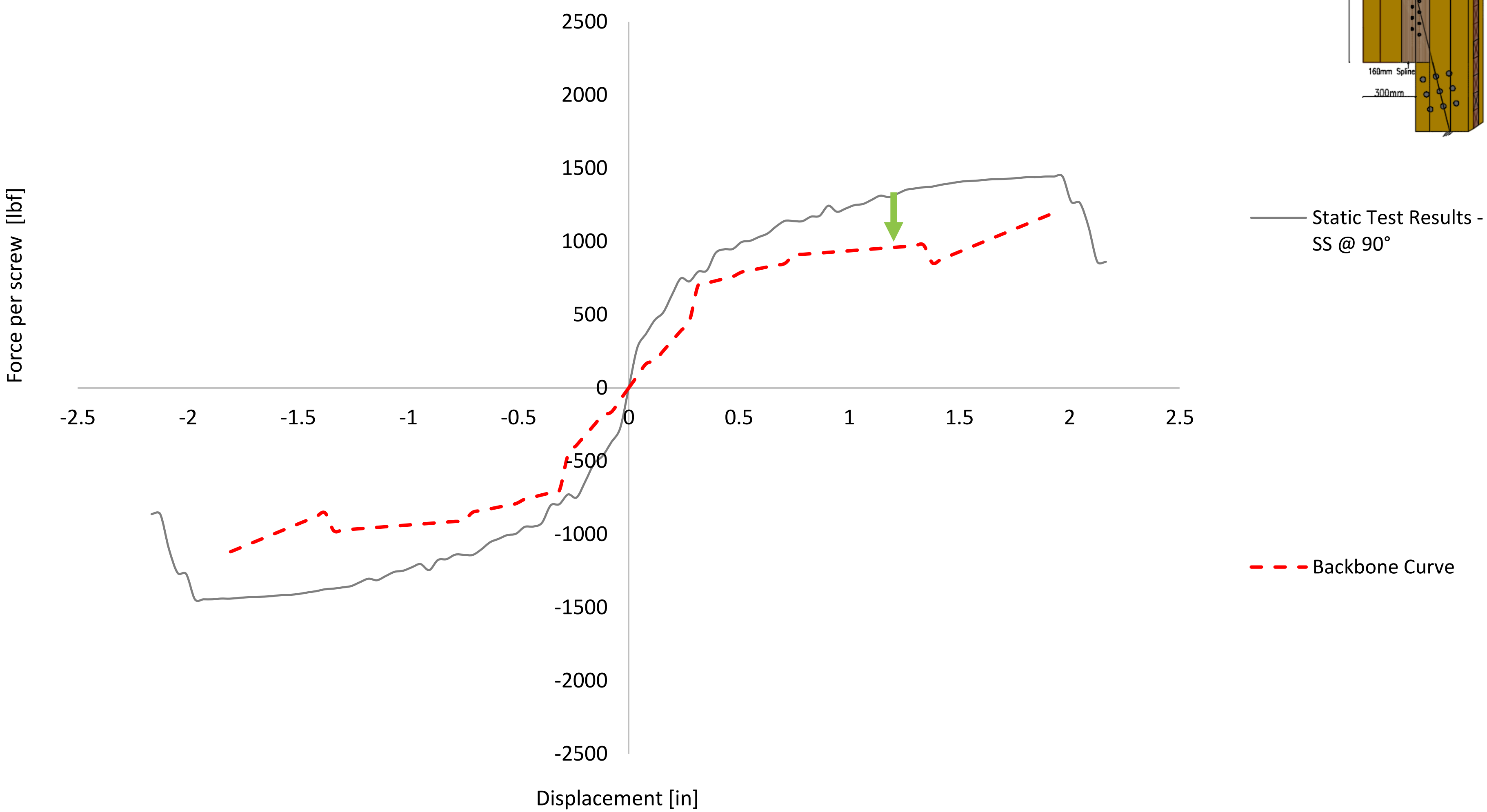


Test Series #1 : Backbone Curve



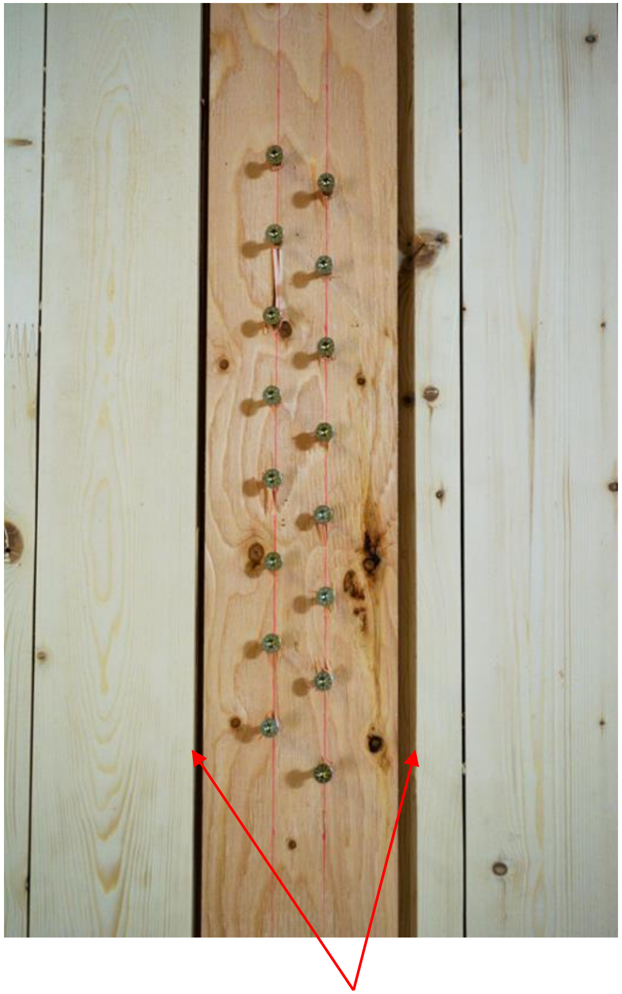
Static v Dynamic Testing

Series #1 = Surface Spline Joints with STS in Shear Action (α=90°)

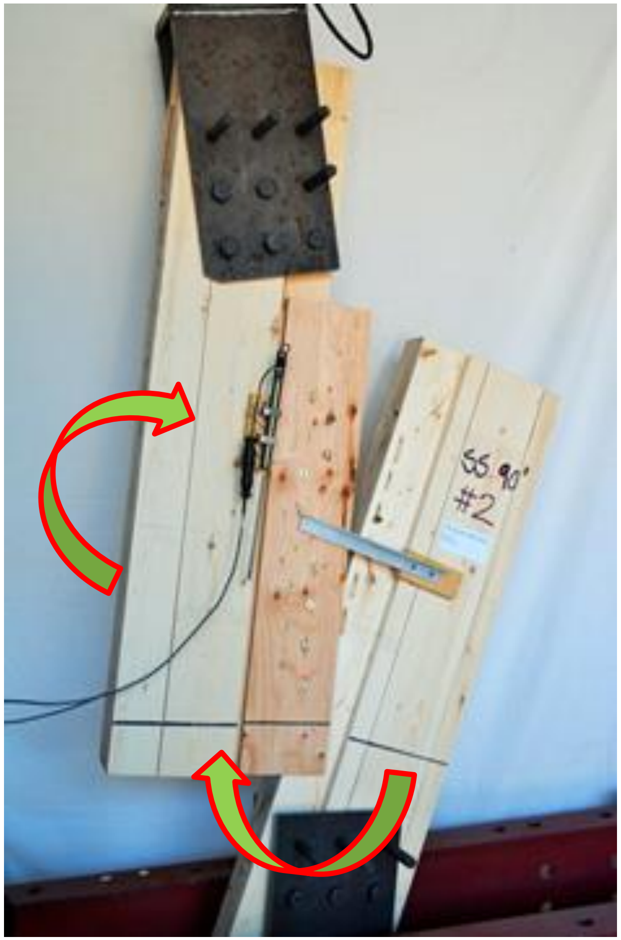


Test Series #1 : Connection Performance

Overall Connection Behaviour at Failure



Separation of members in ultimate state



In and out-of-plane rotation

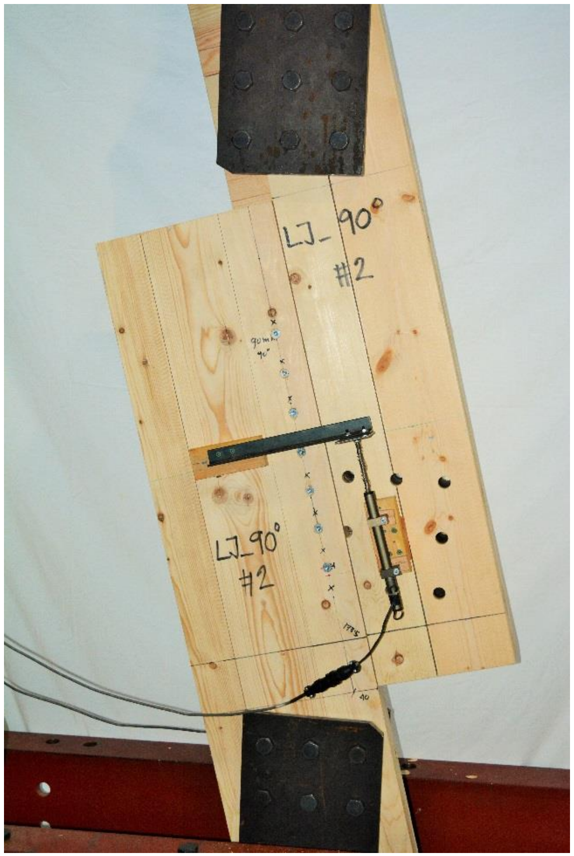
Test Series #1 : Connection Performance

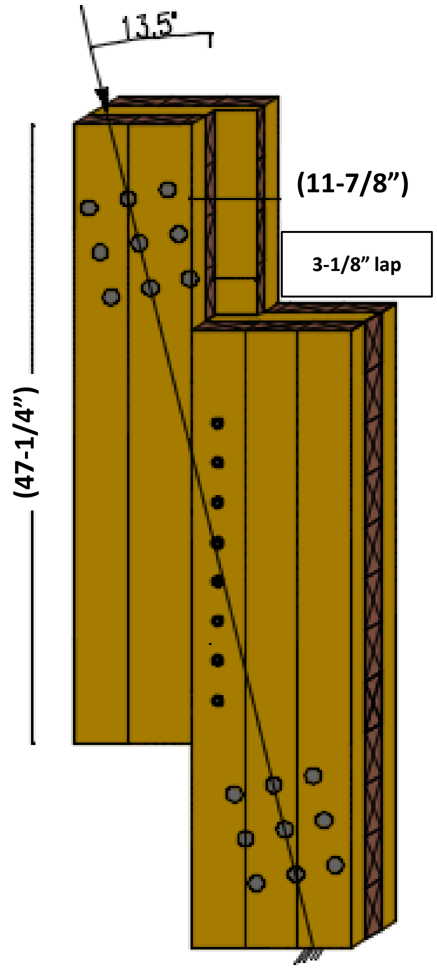
STS Behaviour at Failure

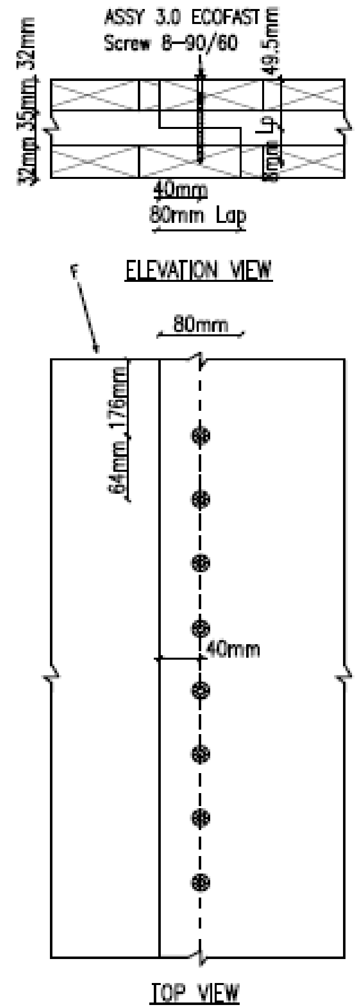
Test Series #2 : Configuration

1” = 25.4 mm

Half Lapped Joint with STS in Shear

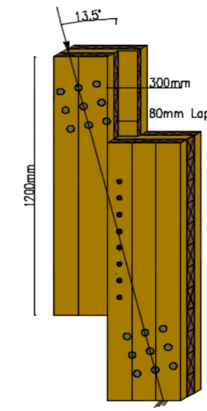






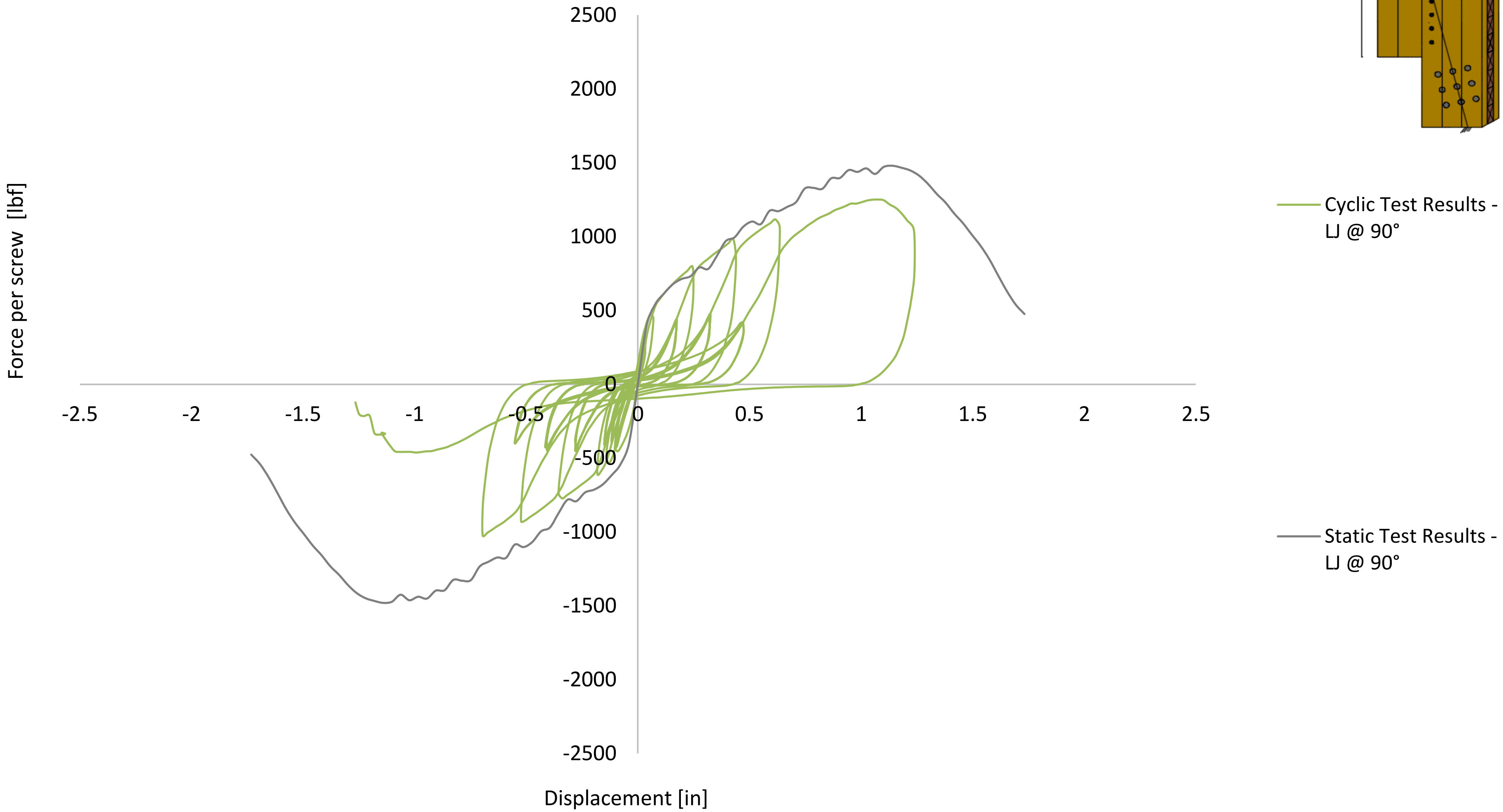
Courtesy of: Afrin Hossain©

Test Series #2 : Load-Displacement Curve



Static v Dynamic Testing

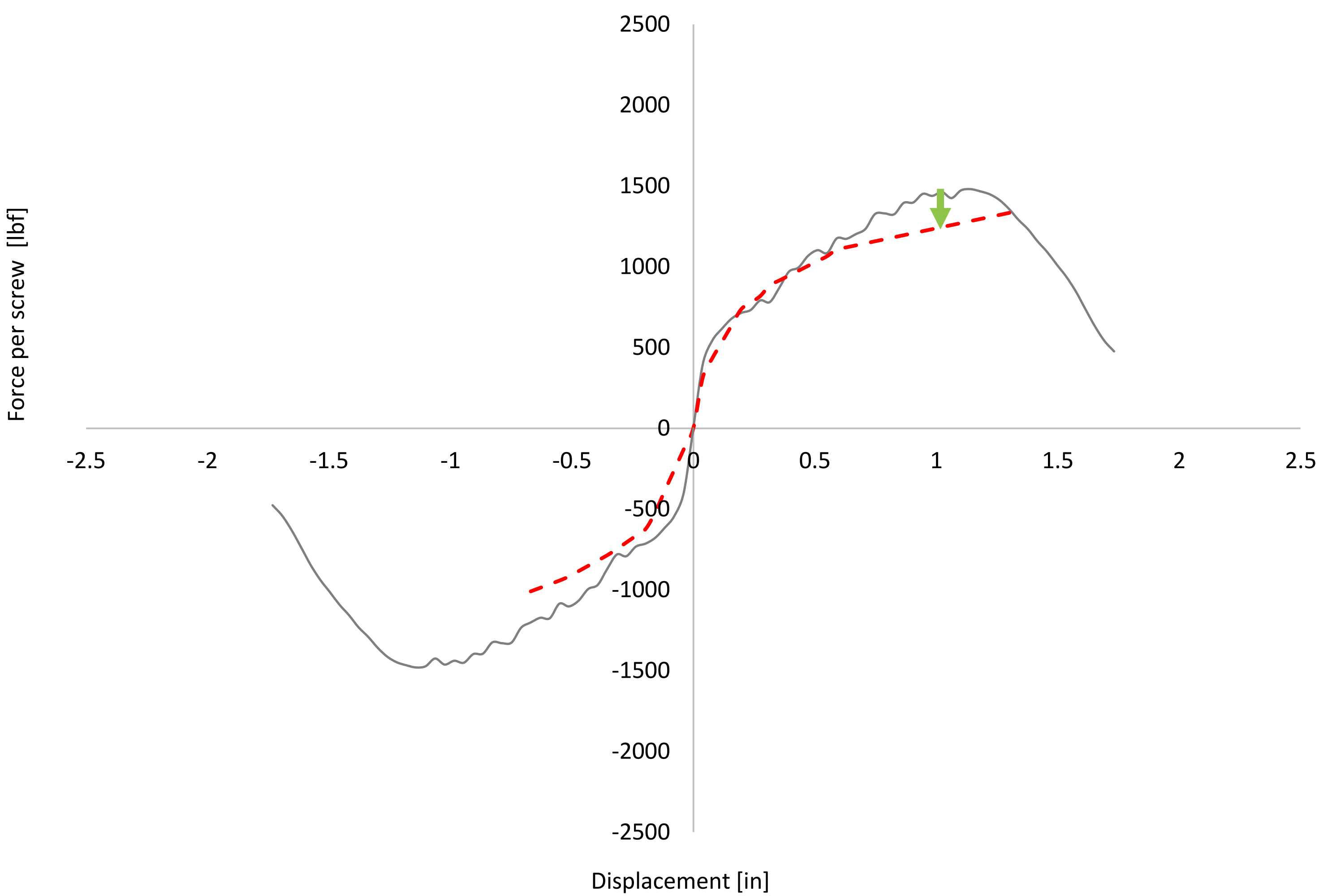
Series #2 = Half Lap Joint with STS in Shear Action (α=90°)

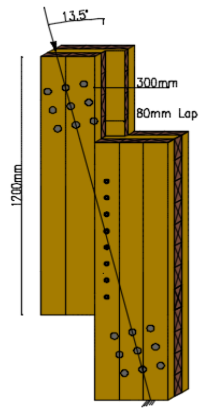


Test Series #2 : Backbone Curve

Static v Dynamic Testing

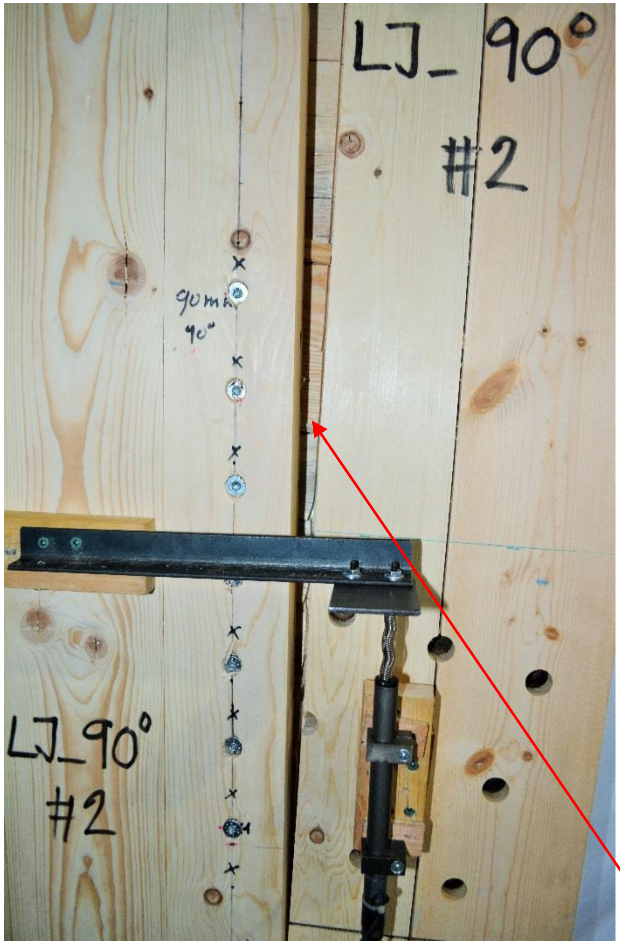
Series #2 = Half Lap Joint with STS in Shear Action (α=90°)

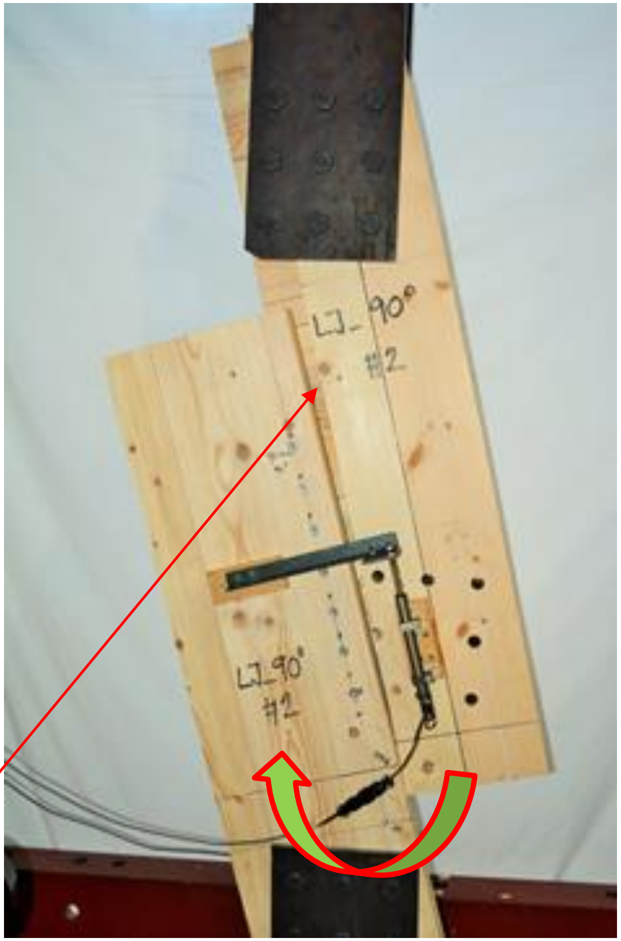




Test Series #2 : Connection Performance

Overall Connection Behaviour at Failure

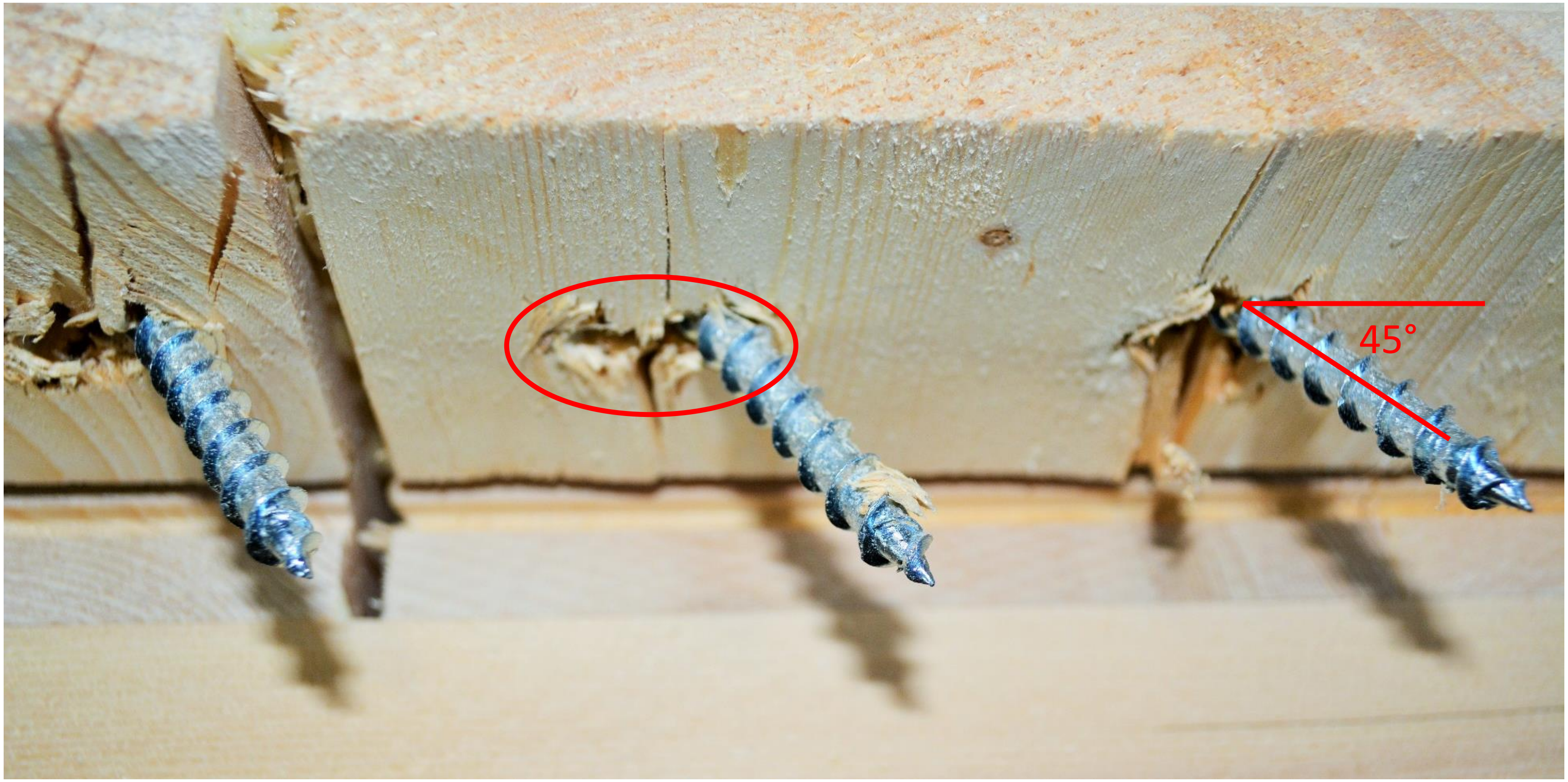




Large displacement and separation of members and specimen rotation

Test Series #2 : Connection Performance

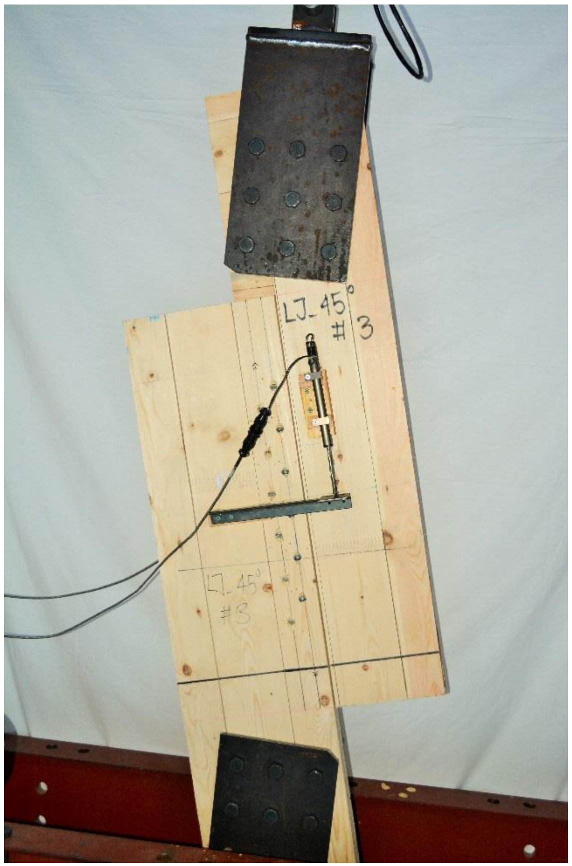
STS Behaviour at Failure

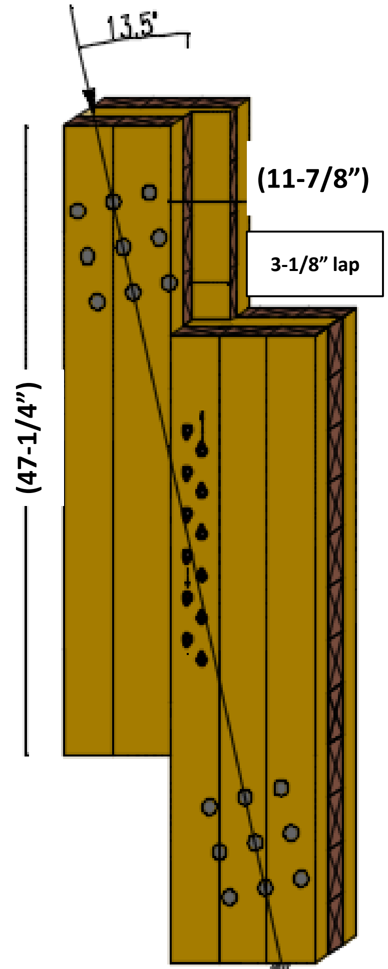


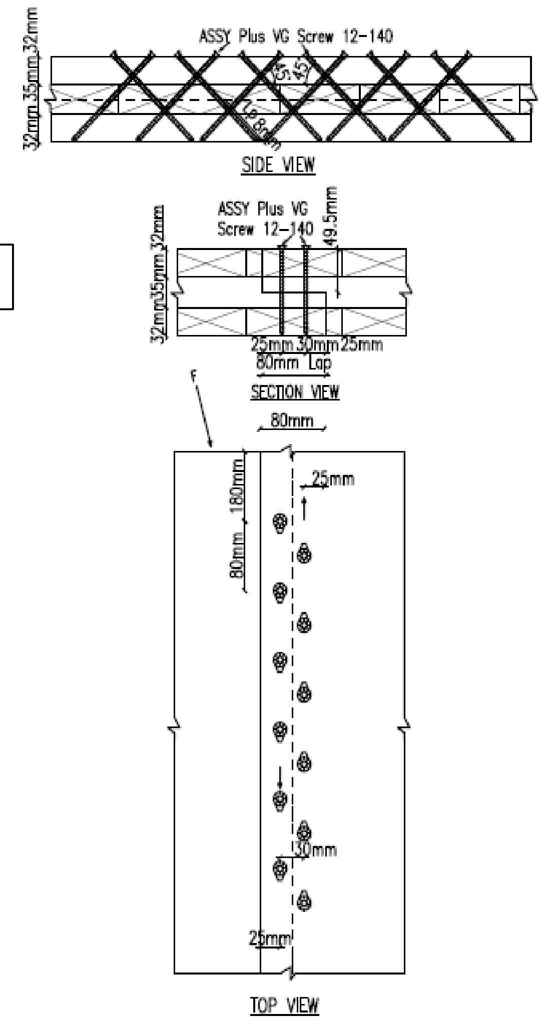
Test Series #3 : Configuration

1" = 25.4 mm

Half Lapped Joint with STS in Tension

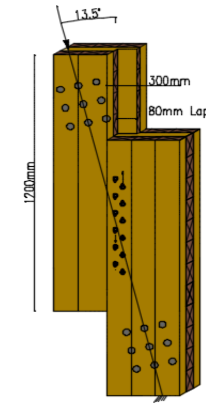


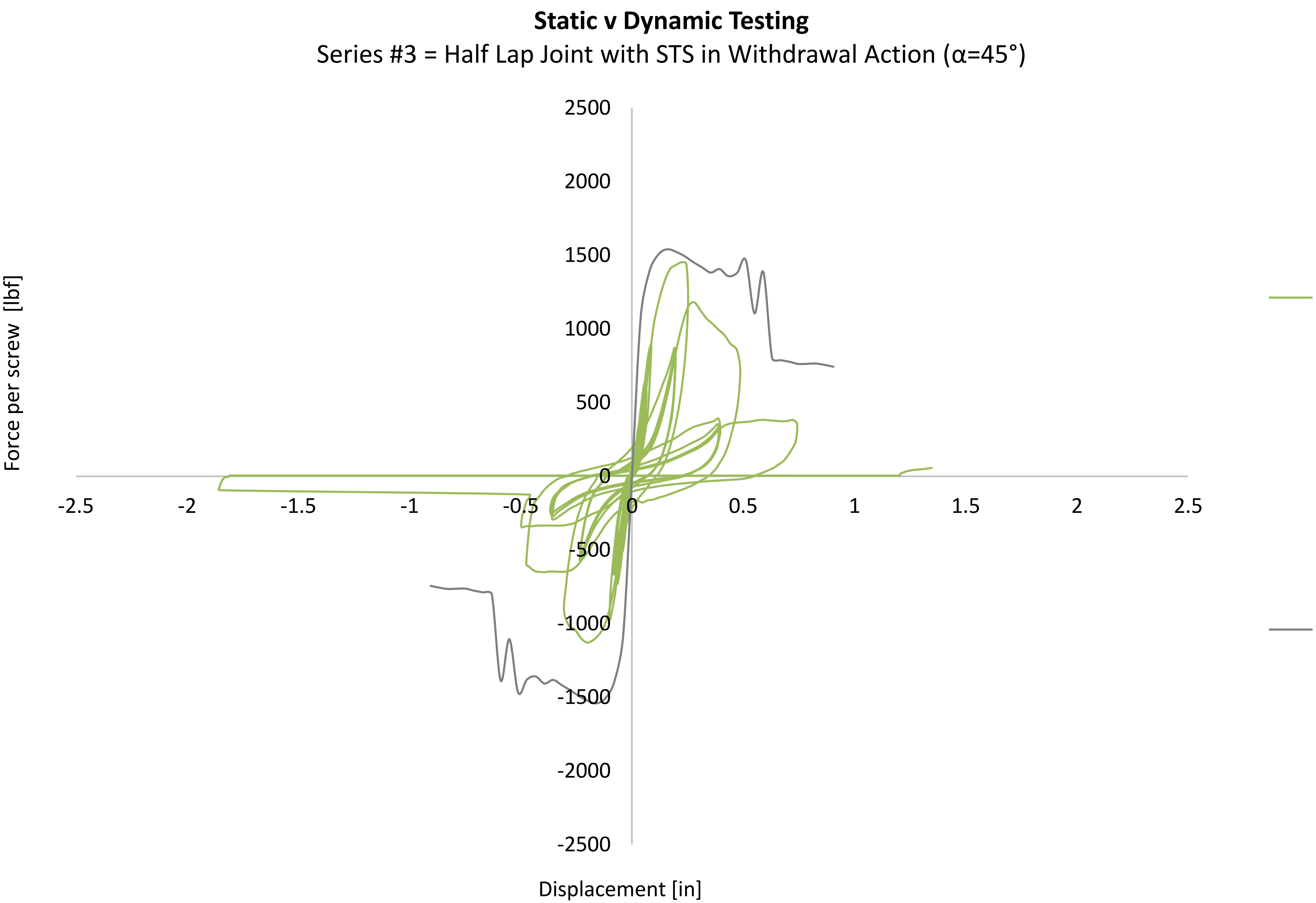




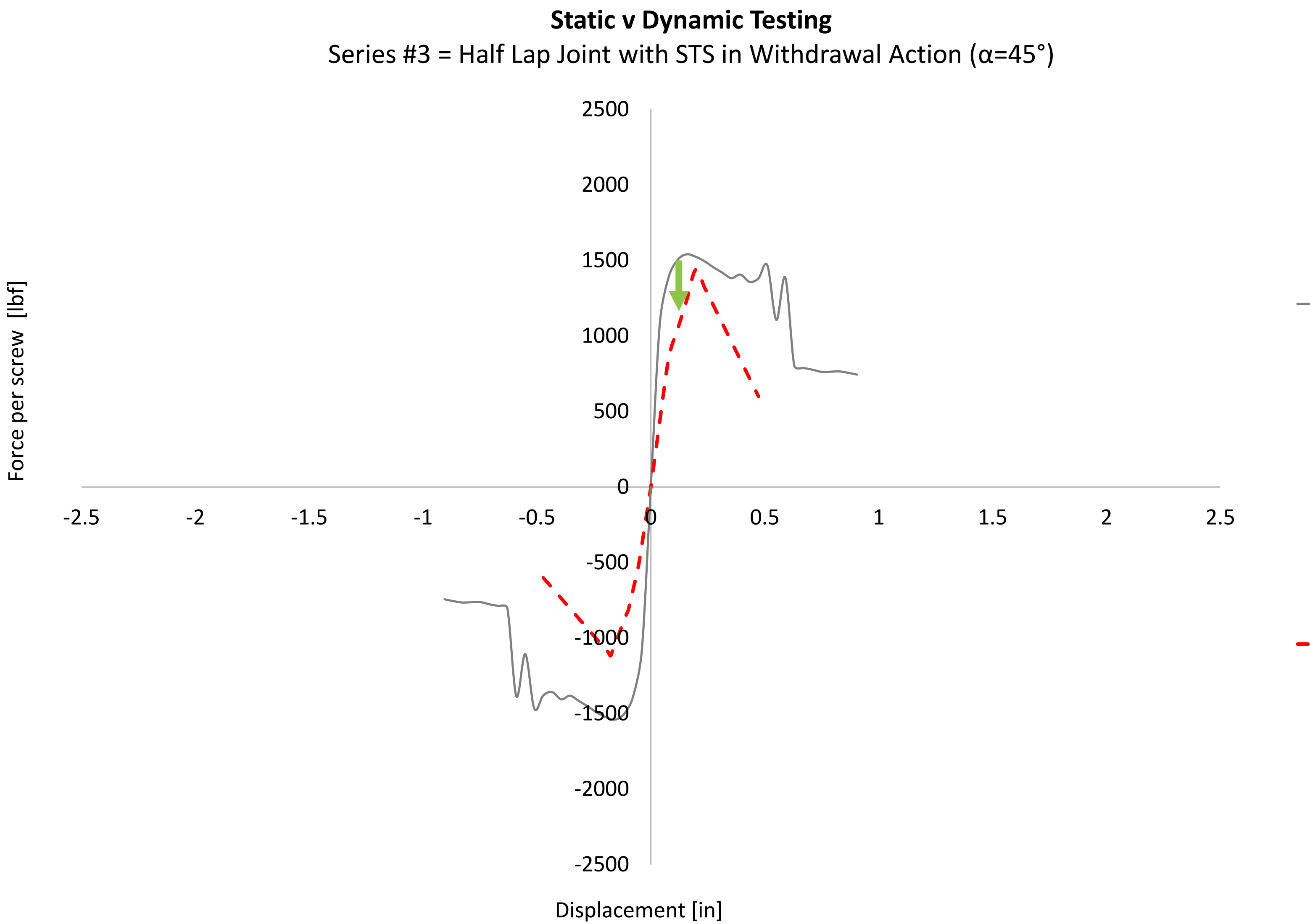
Courtesy of: Afrin Hossain©

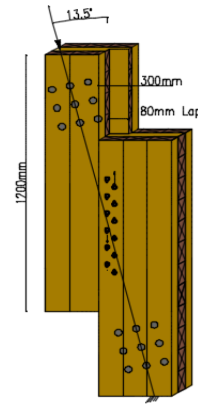
Test Series #3 : Load-Displacement Curve





Test Series #3 : Backbone Curve





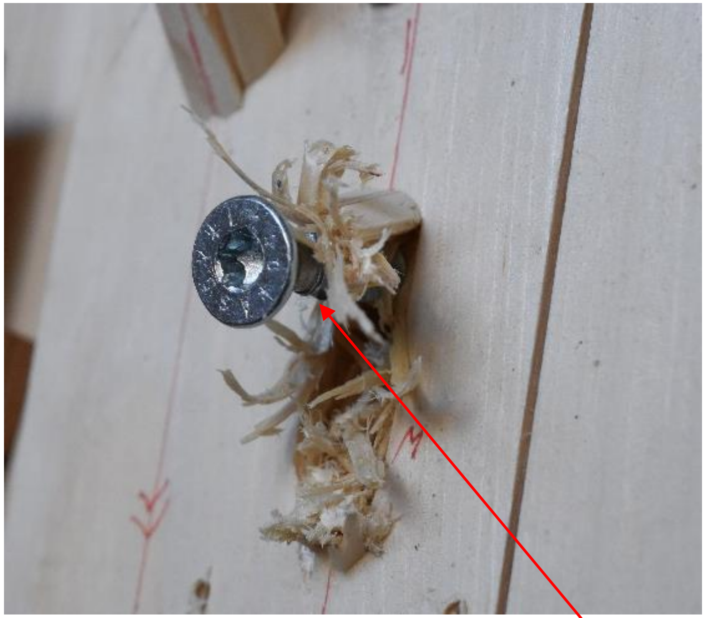
Test Series #3 : Connection Performance

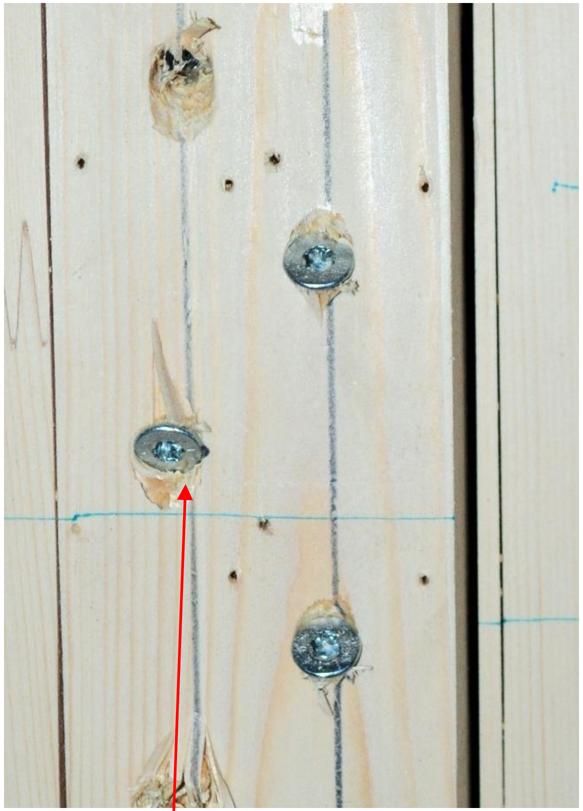
Overall Connection Behaviour at Failure

Small displacement and specimen separation

Minimal in plane and out-of-plane rotation

STS Behaviour at Failure



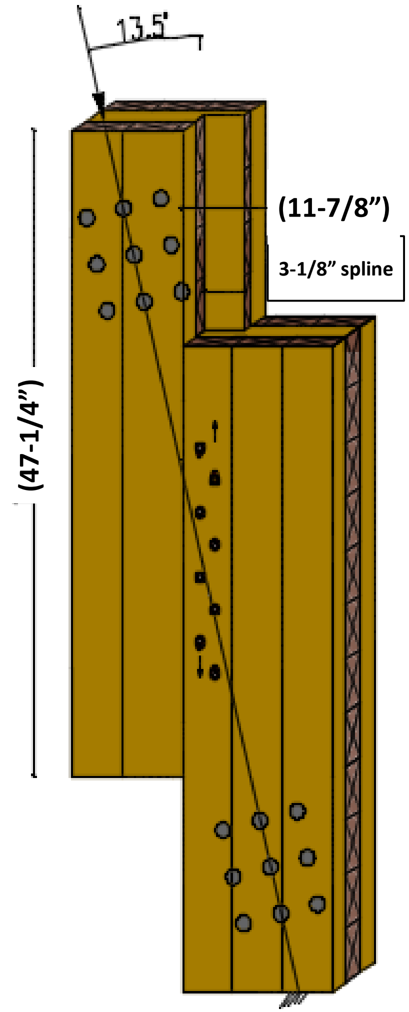


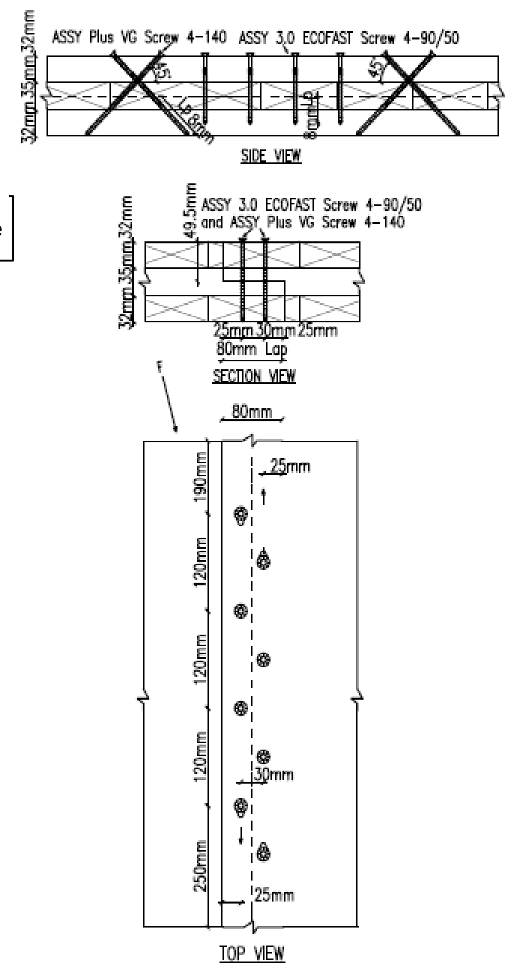
Head push-out and head pull-in

Test Series #4 : Configuration

1" = 25.4 mm

Half Lapped Joint with STS in Shear and Tension

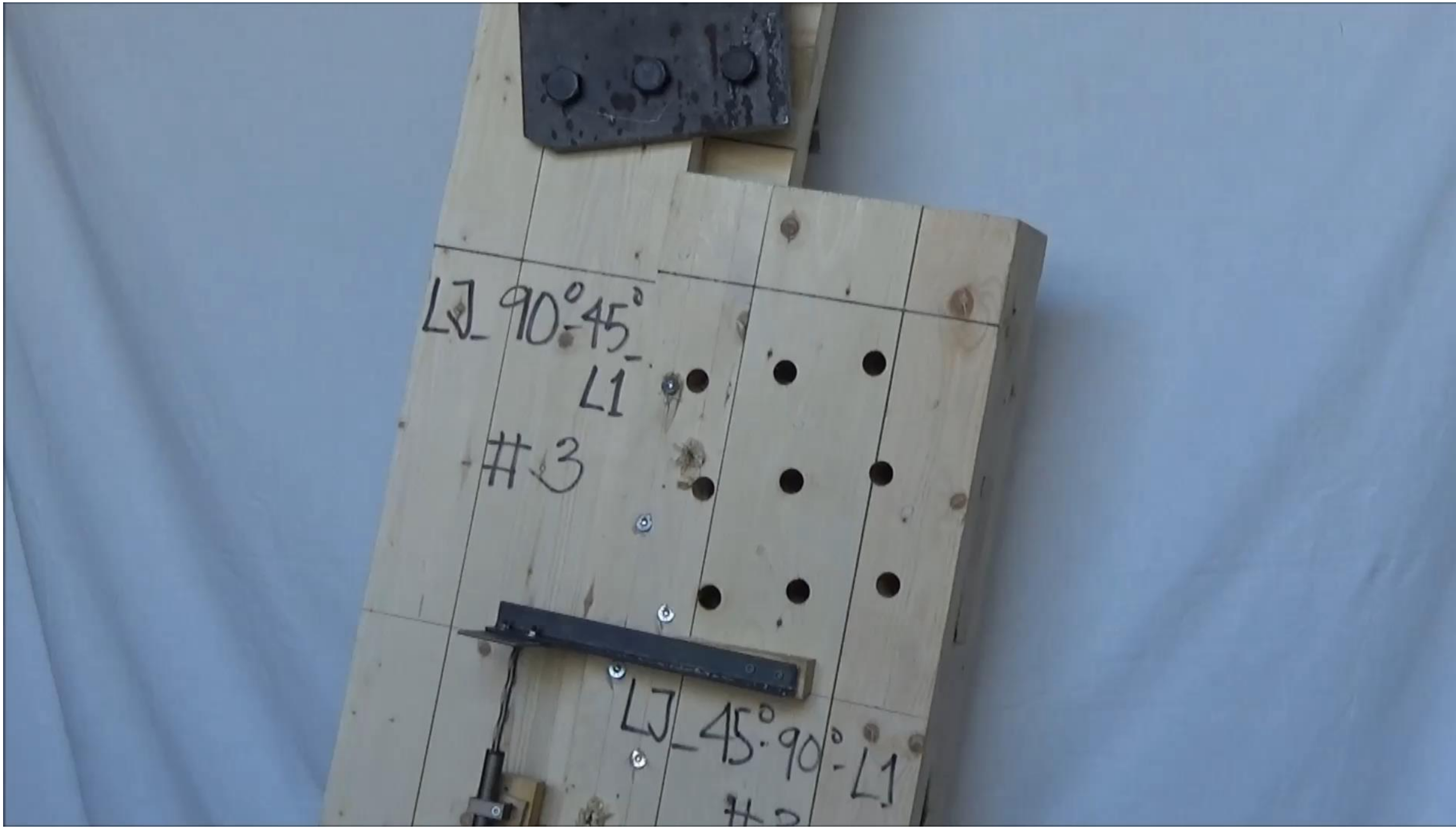




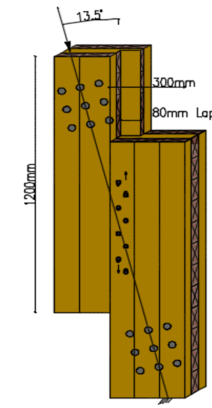
Courtesy of: Afrin Hossain©

Test Series #4 : Testing Video

Half Lapped Joint with STS in Shear and Tension

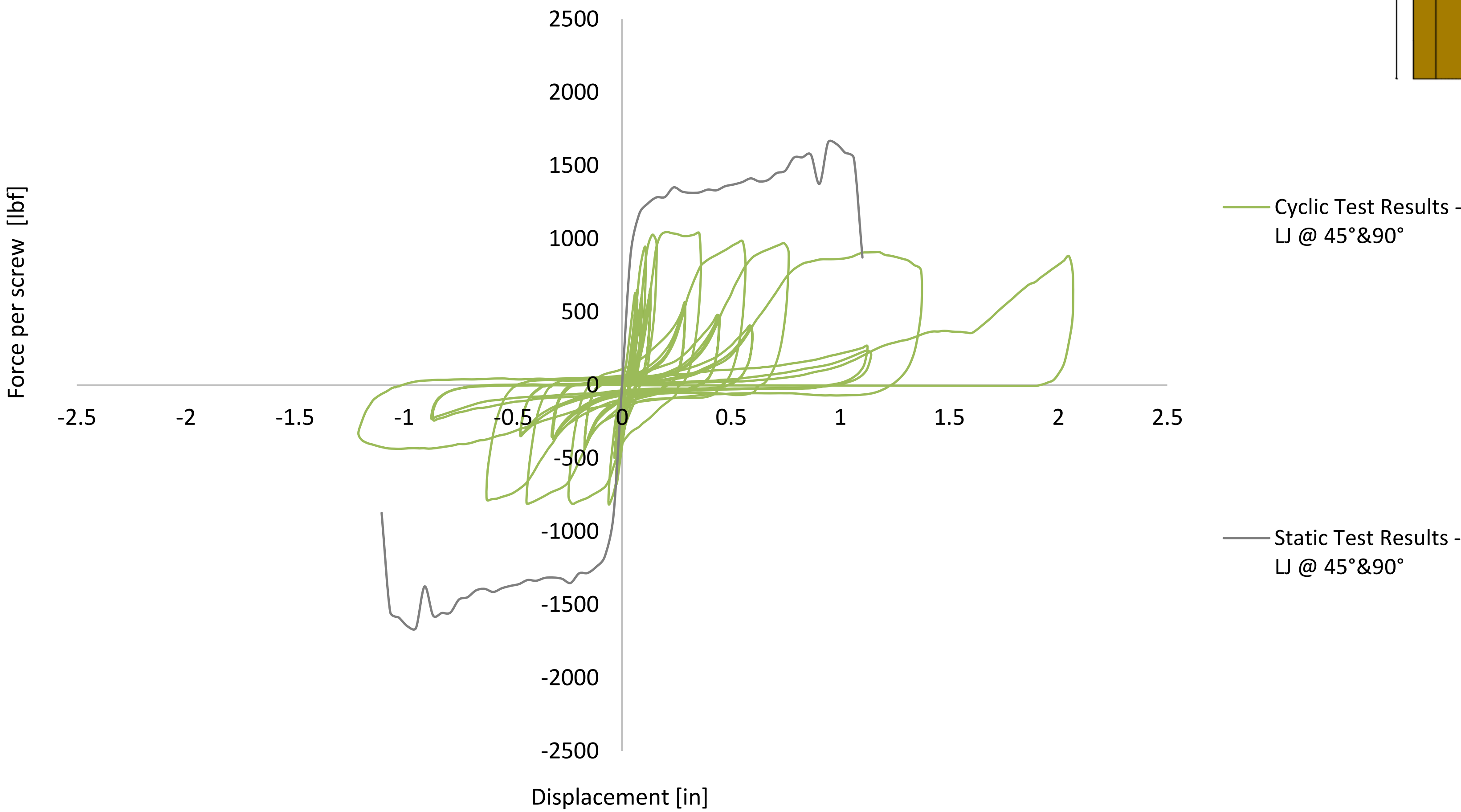


Test Series #4 : Load-Displacement Curve

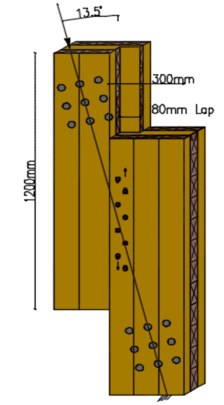


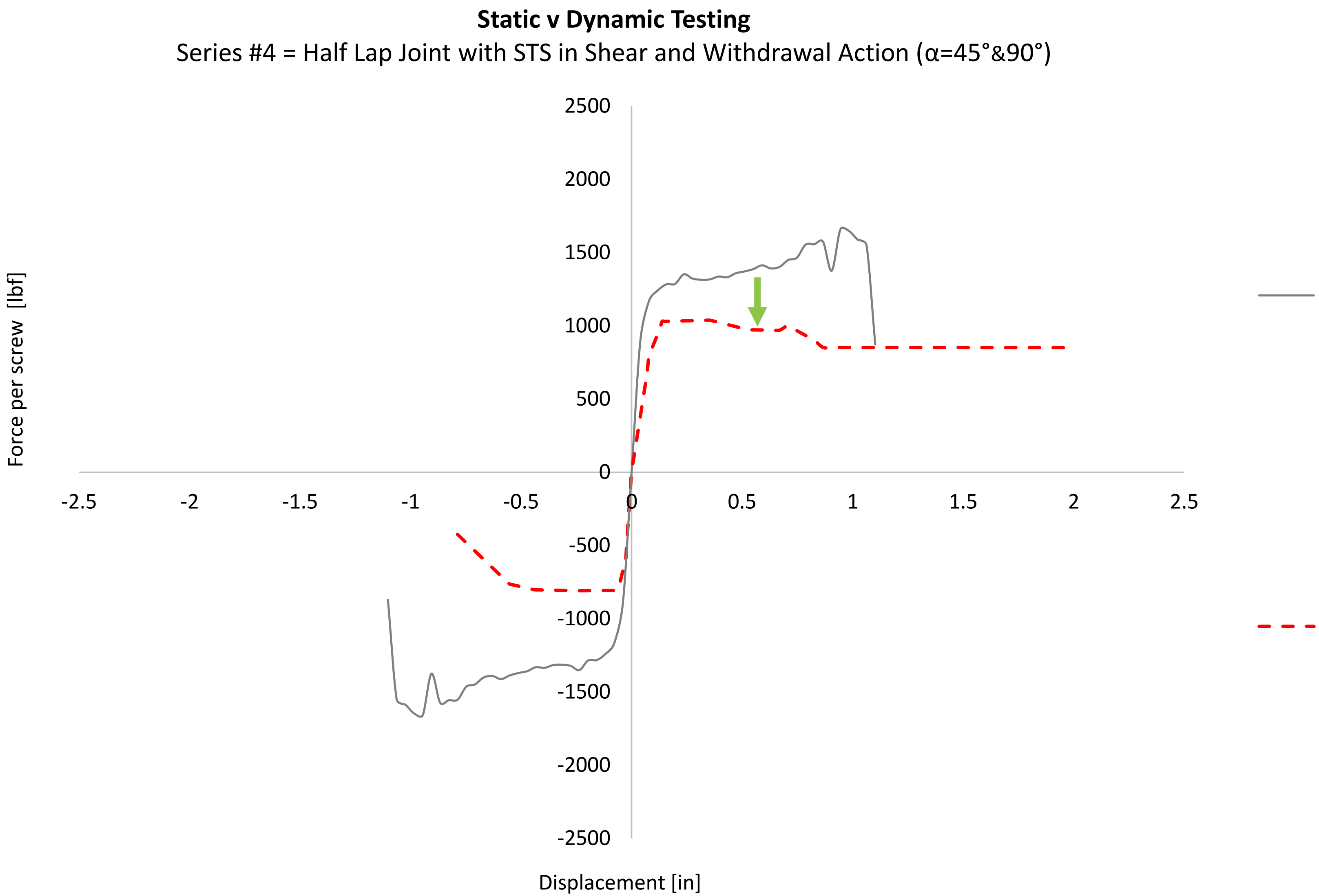
Static v Dynamic Testing

Series #4 = Half Lap Joint with STS in Shear and Withdrawal Action (α=45°&90°)



Test Series #4 : Backbone Curve



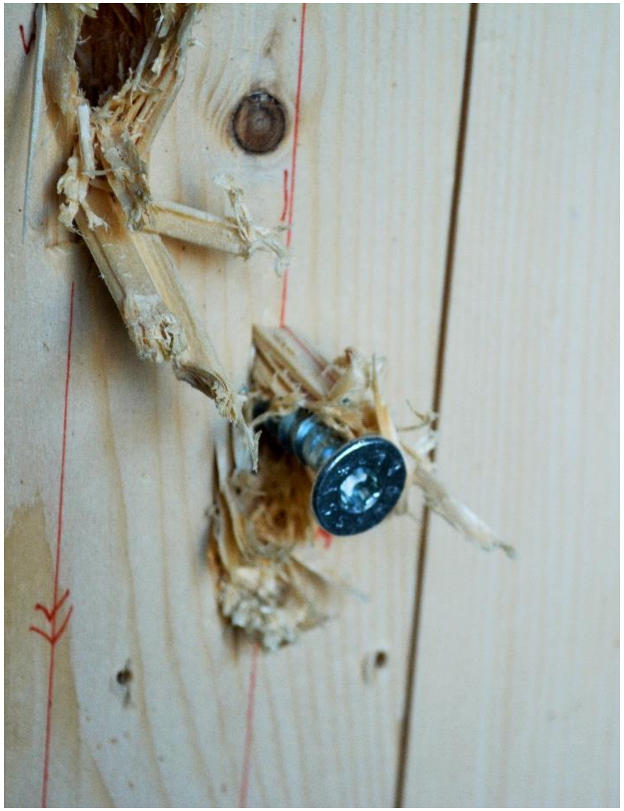


Test Series #4 : Connection Performance

Overall Connection Behaviour at Failure

Test Series #4 : Connection Performance

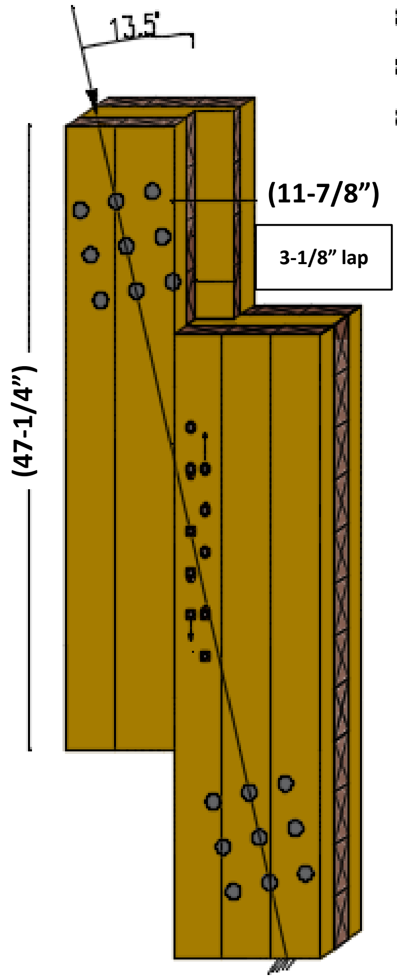
STS Behaviour at Failure

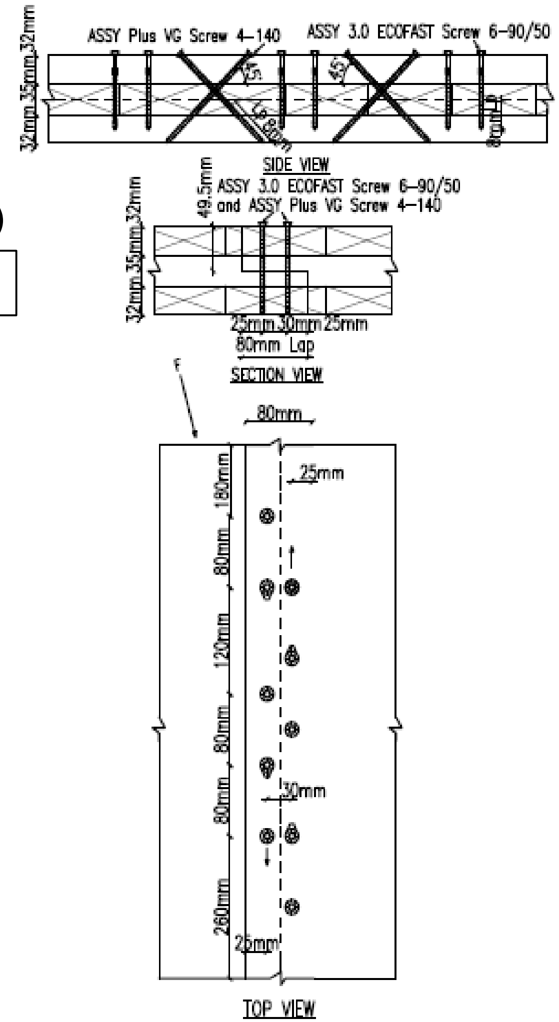


Test Series #5 : Configuration

1” = 25.4 mm

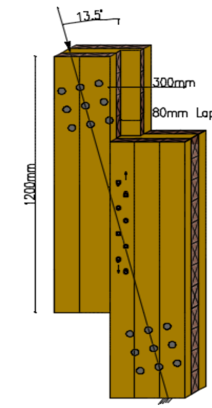
Half Lapped Joint with STS in Shear and Tension





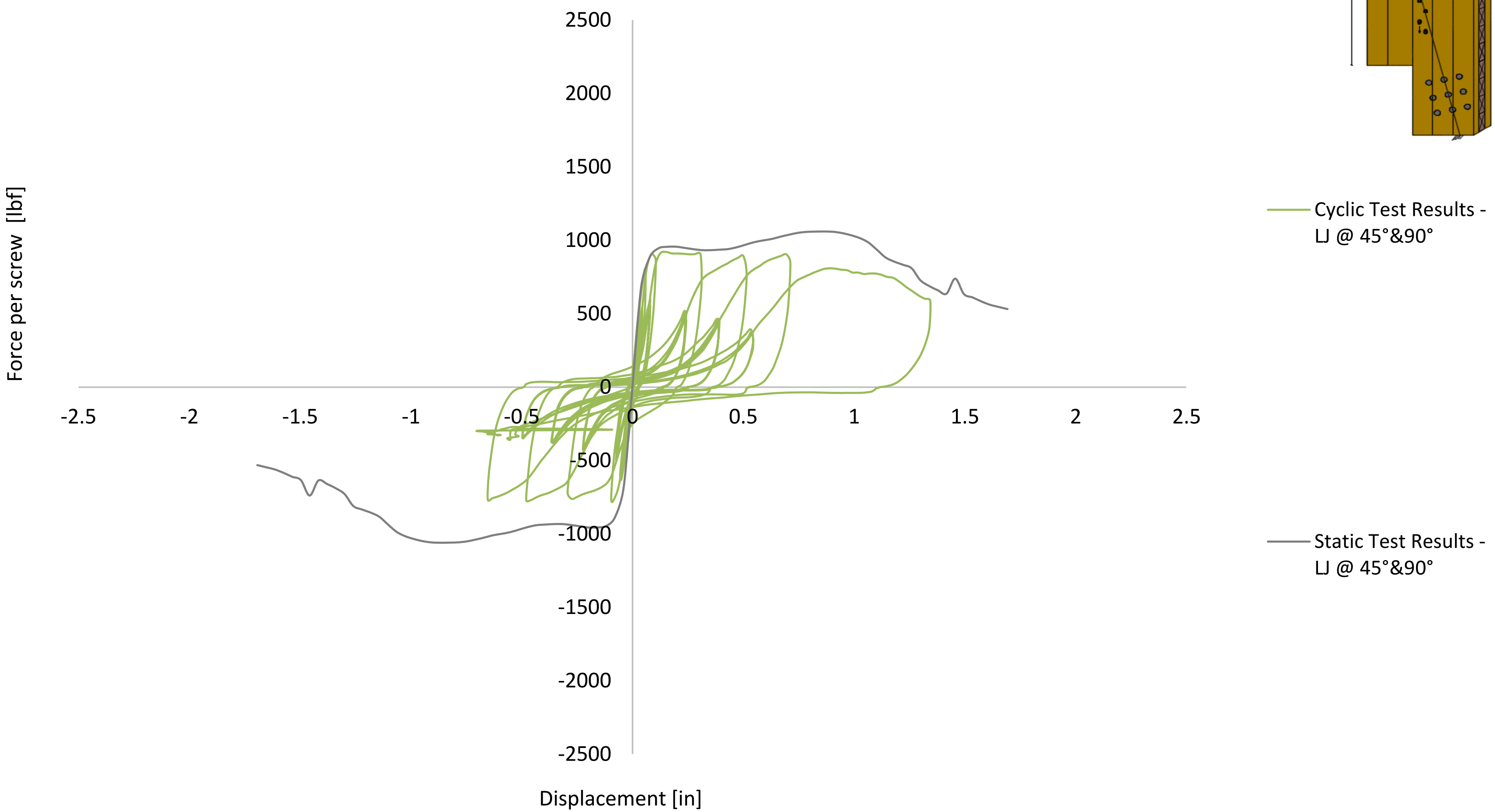
Courtesy of: Afrin Hossain©

Test Series #5 : Load-Displacement Curve

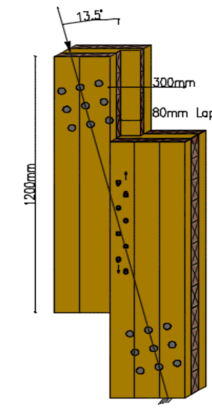


Static v Dynamic Testing

Series #5 = Half Lap Joint with STS in Shear and Withdrawal Action (α=45°&90°)

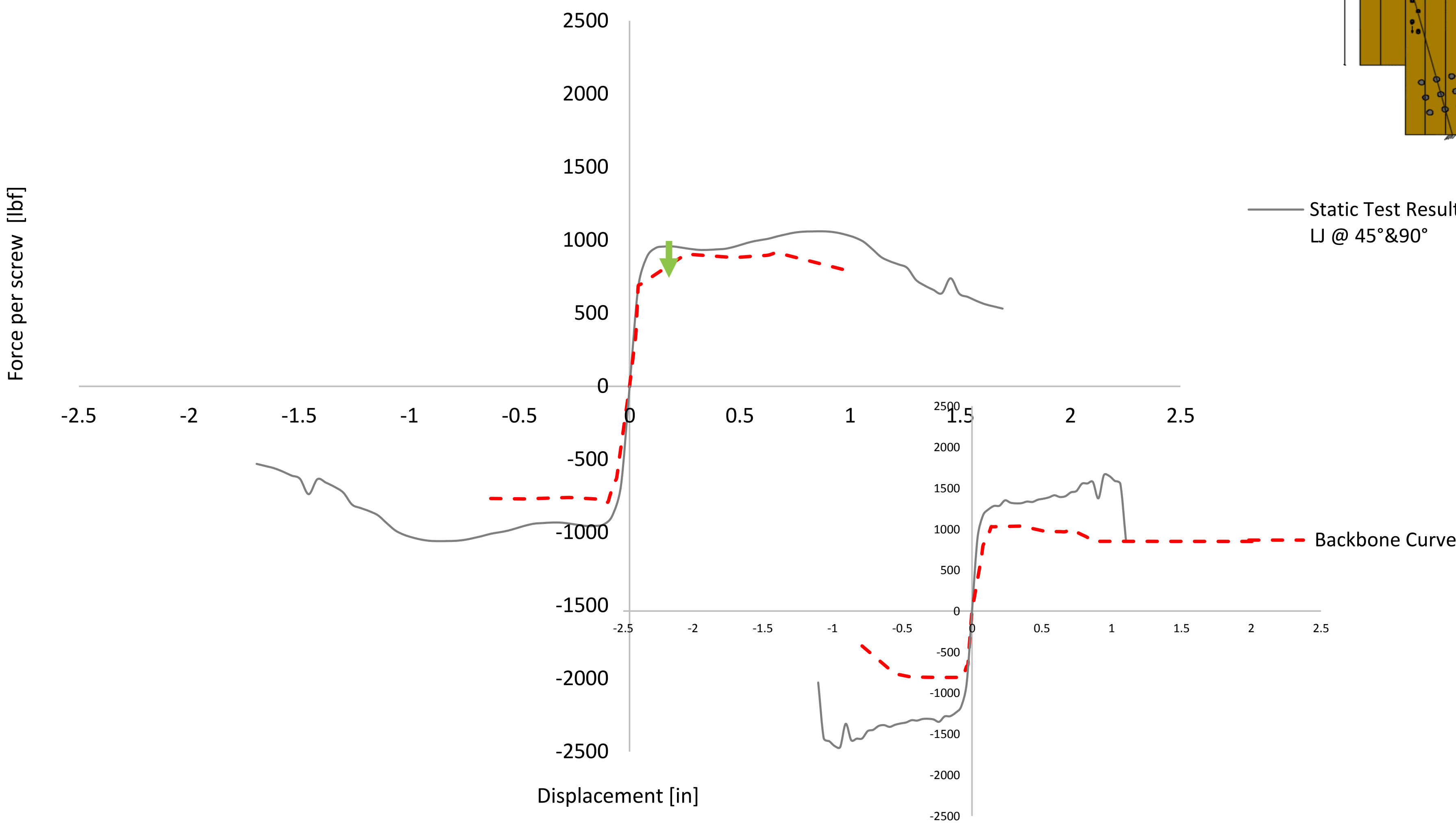


Test Series #5 : Backbone Curve



Static v Dynamic Testing

Series #5 = Half Lap Joint with STS in Shear and Withdrawal Action (α=45°&90°)

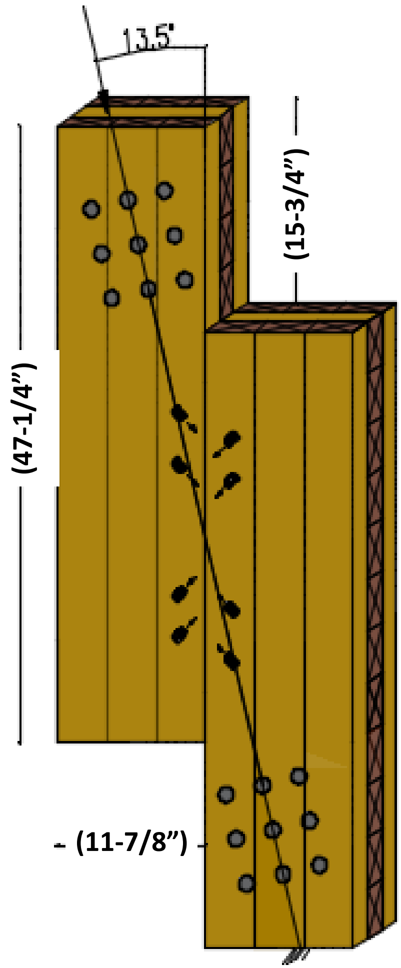


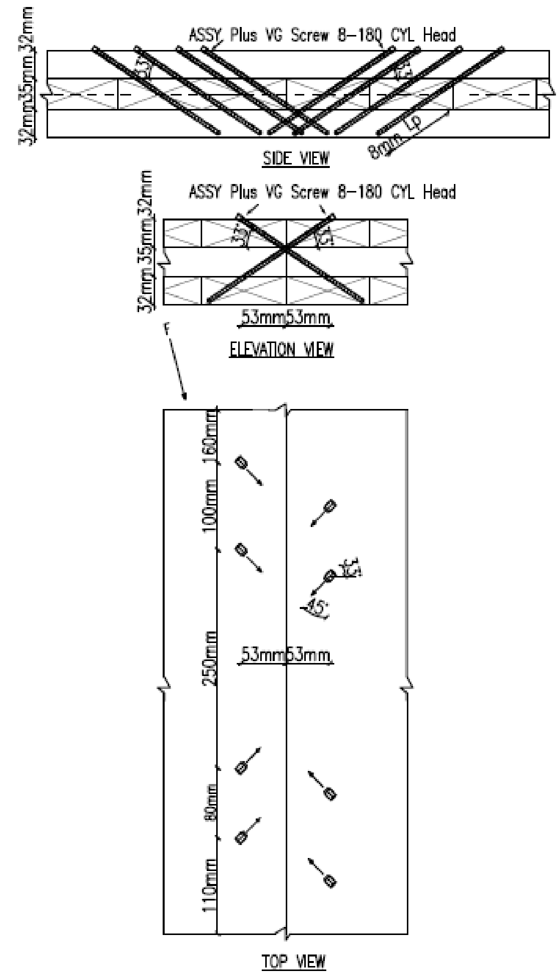
Test Series #5 : Connection Performance

Overall Connection Behaviour at Failure

1" = 25.4 mm

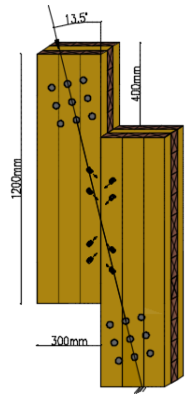
Butt Joint with STS in Shear and Tension

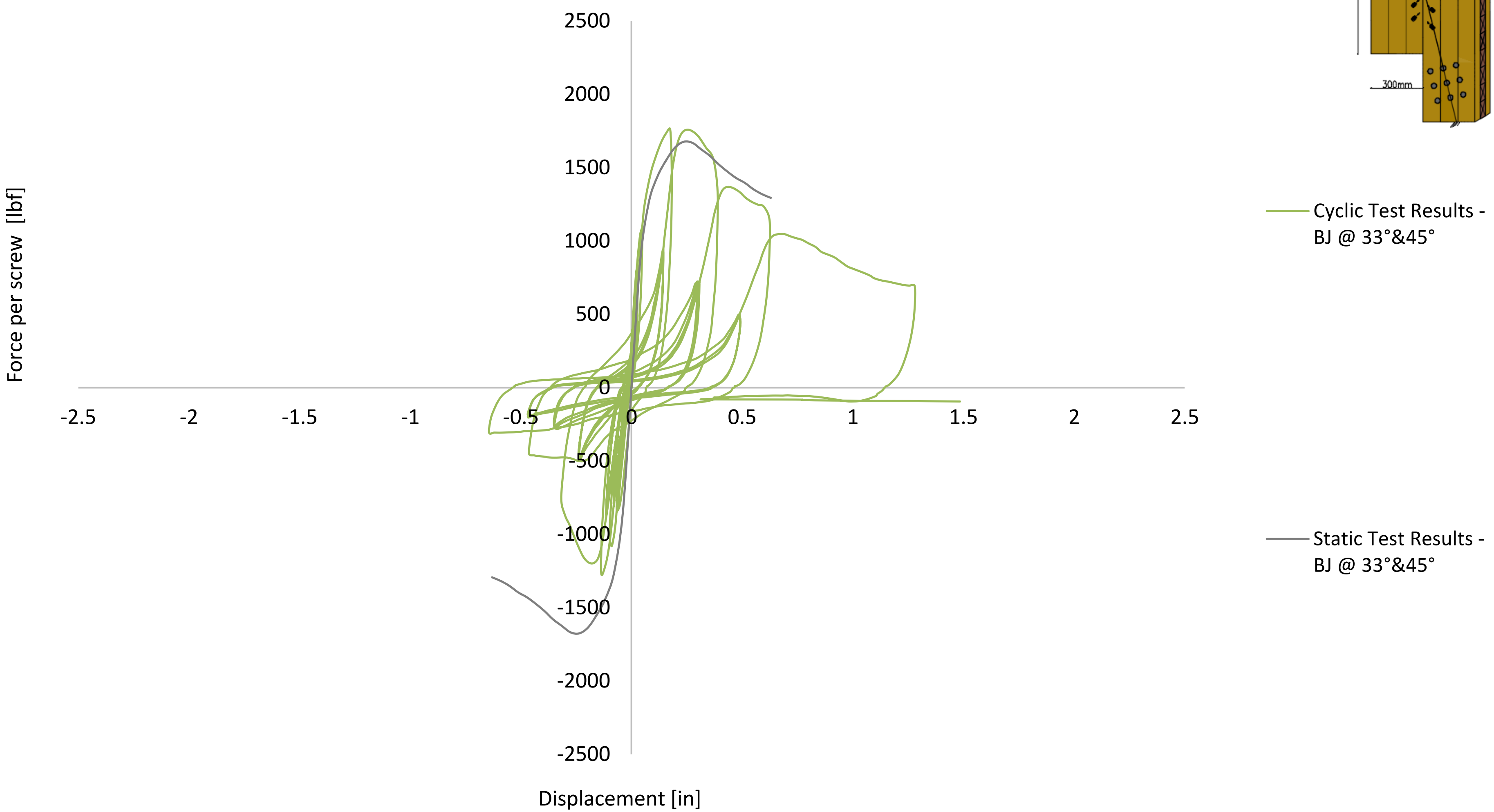




Courtesy of: Afrin Hossain©

Test Series #6 : Load-Displacement Curve

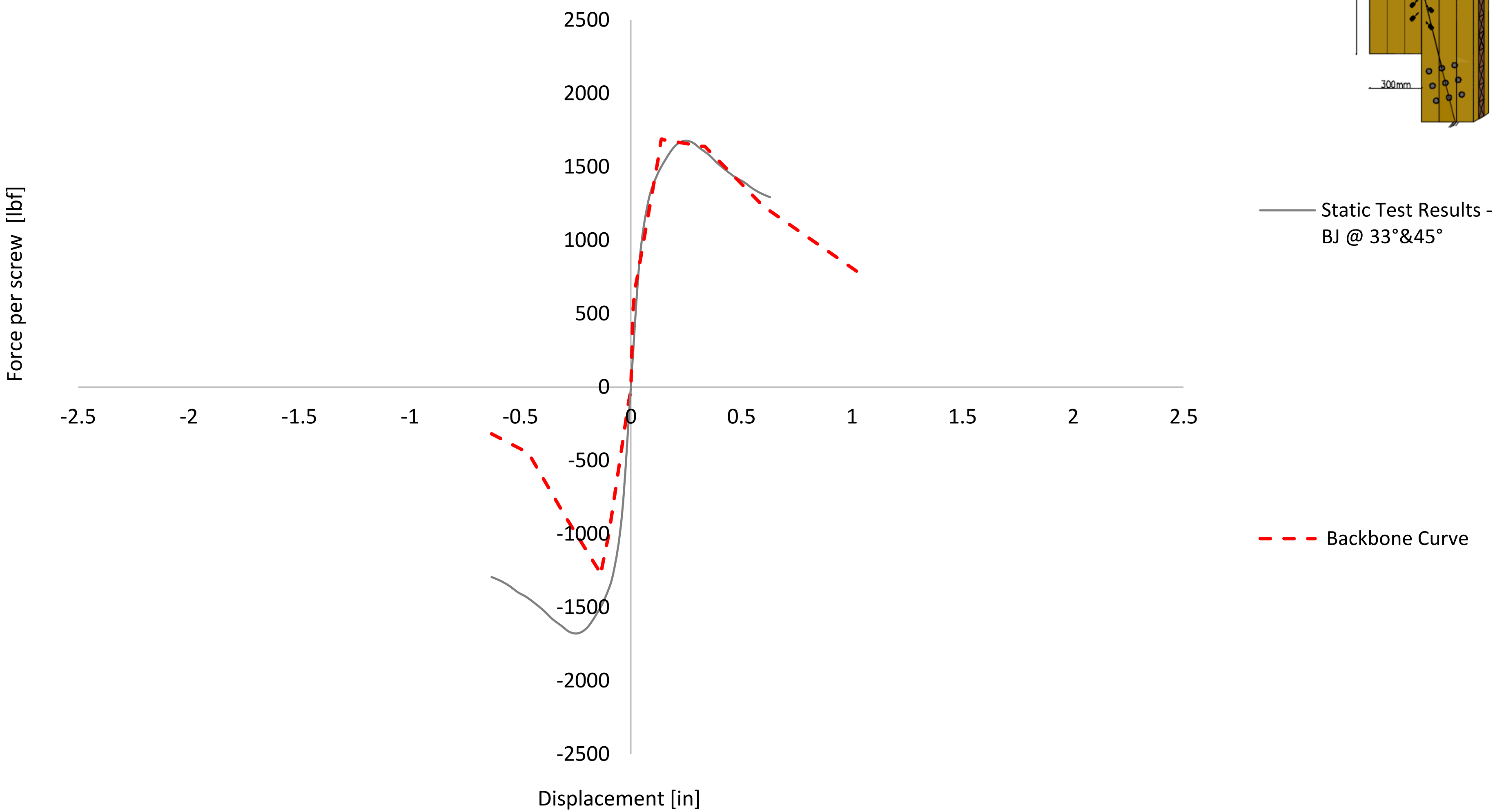


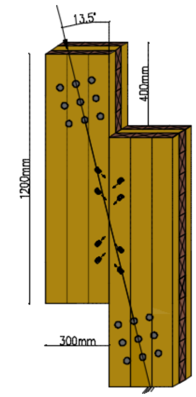


Test Series #6 : Backbone Curve

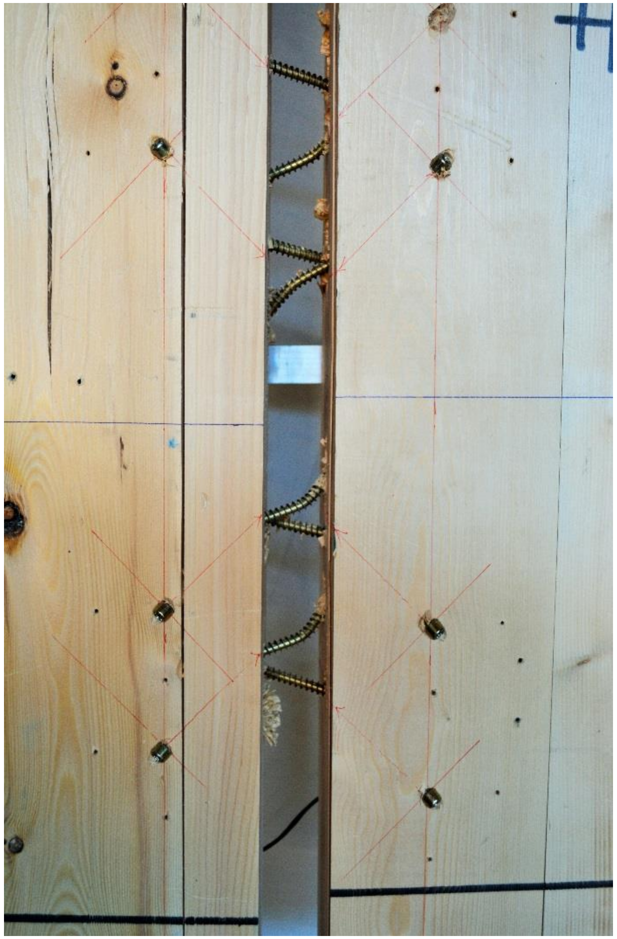
Static v Dynamic Testing

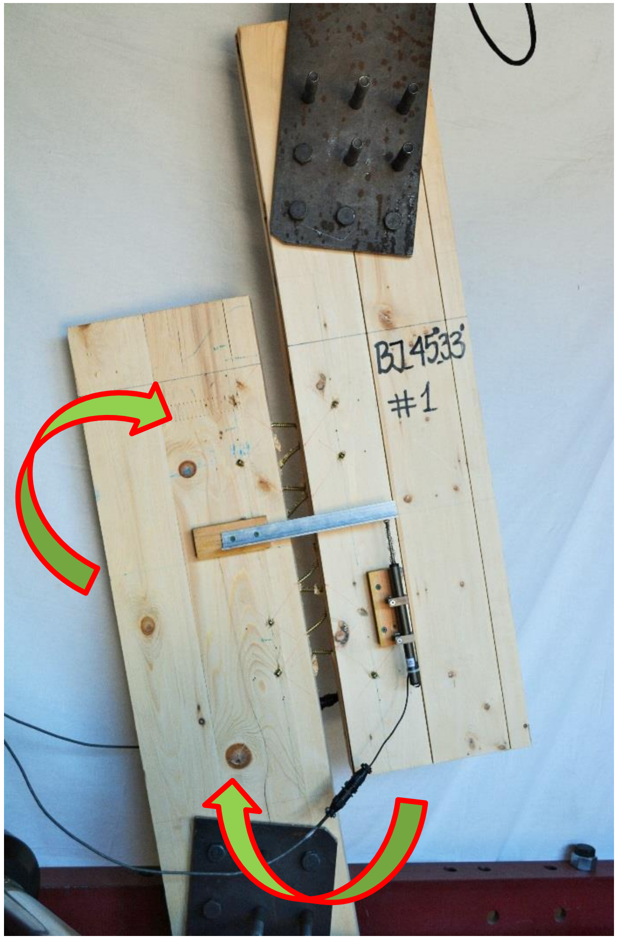
Series #6 = Butt Joint with STS in Withdrawal Action (α=45°&33°)





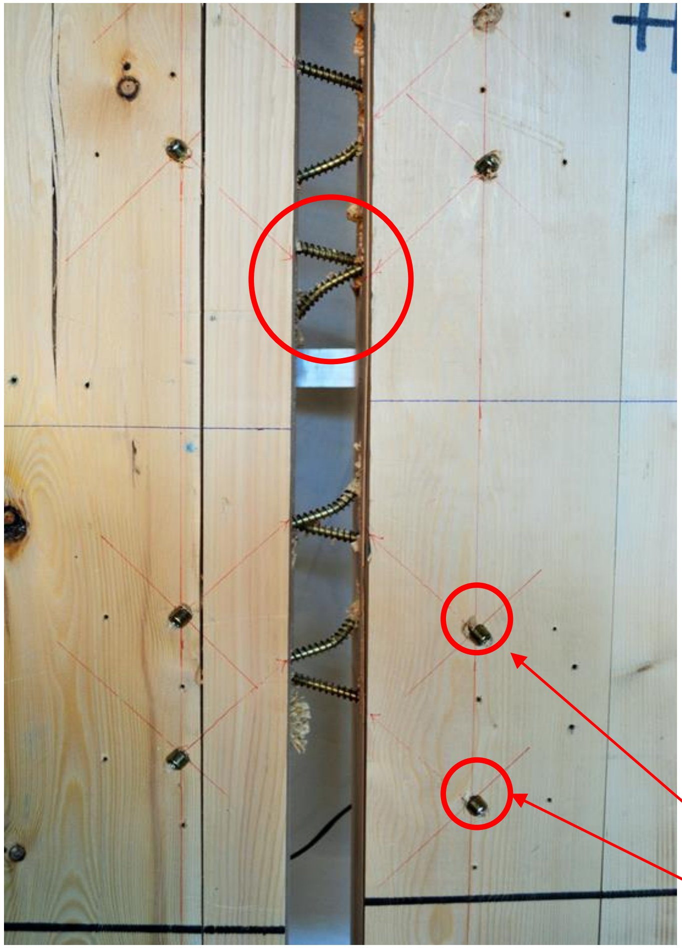
Overall Connection Behaviour at Failure





Test Series #6 : Connection Performance

STS Behaviour at Failure



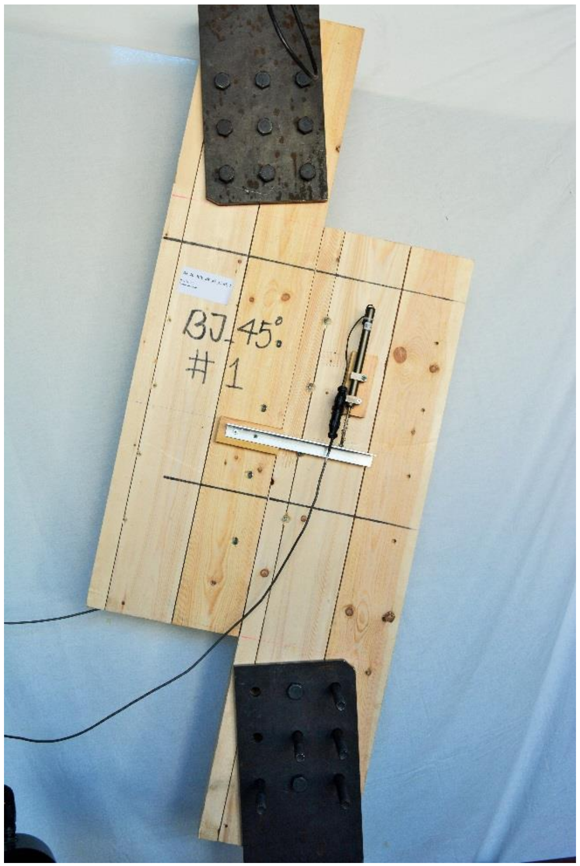
Connection exhibits large degree of ductility

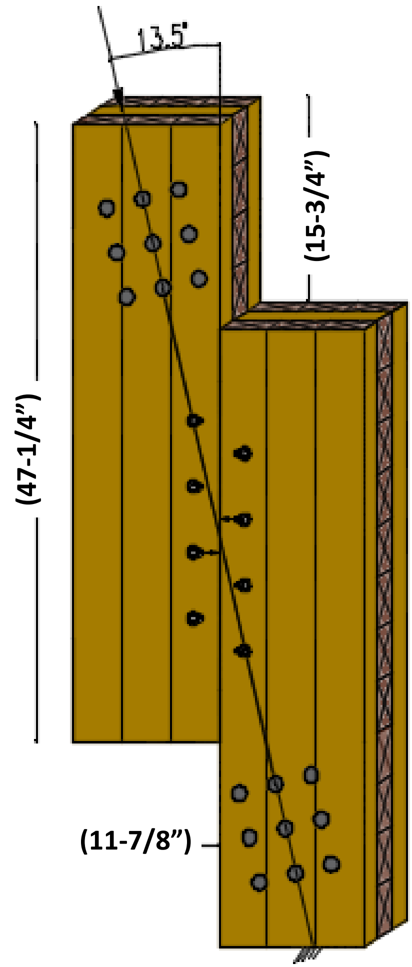
STS failed in withdrawal first, subsequent yielding towards ultimate state

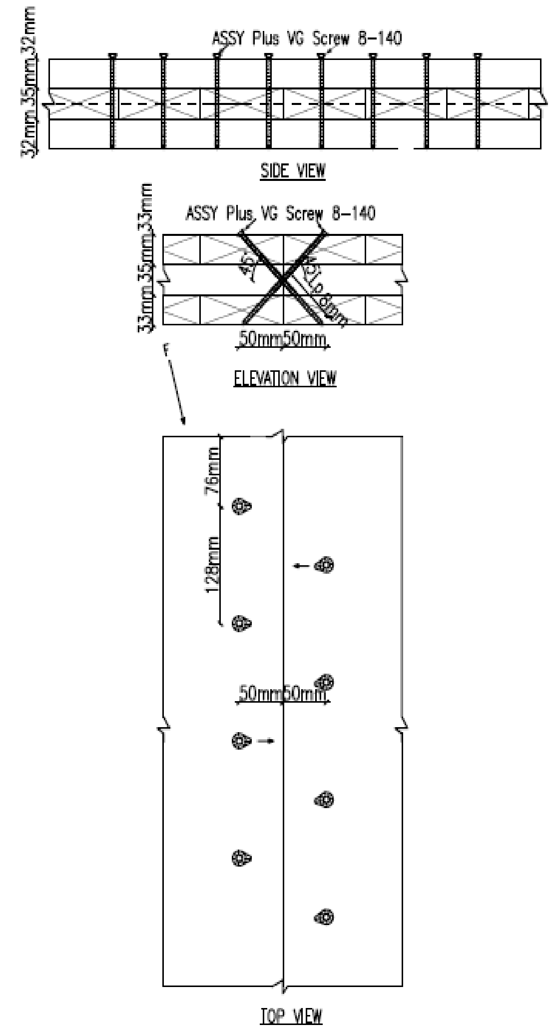
Test Series #7 : Configuration

1" = 25.4 mm

Butt Joint with STS in Shear

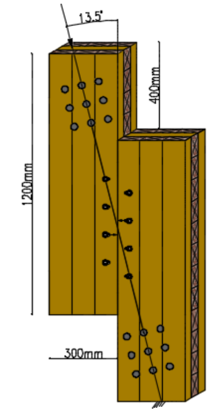


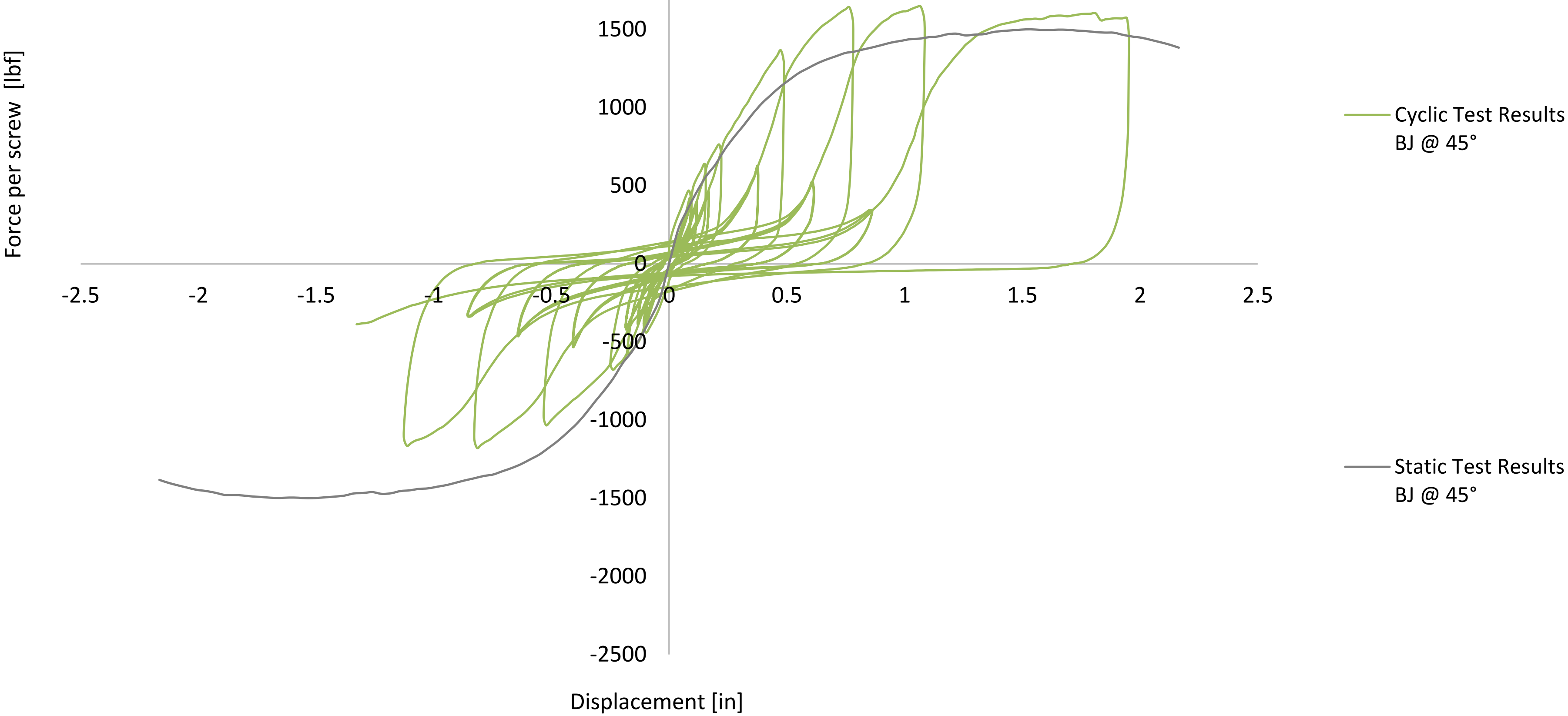




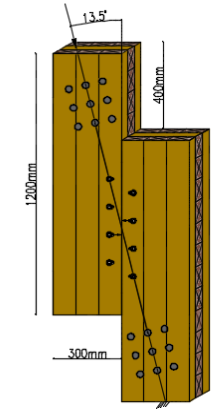
Courtesy of: Afrin Hossain©

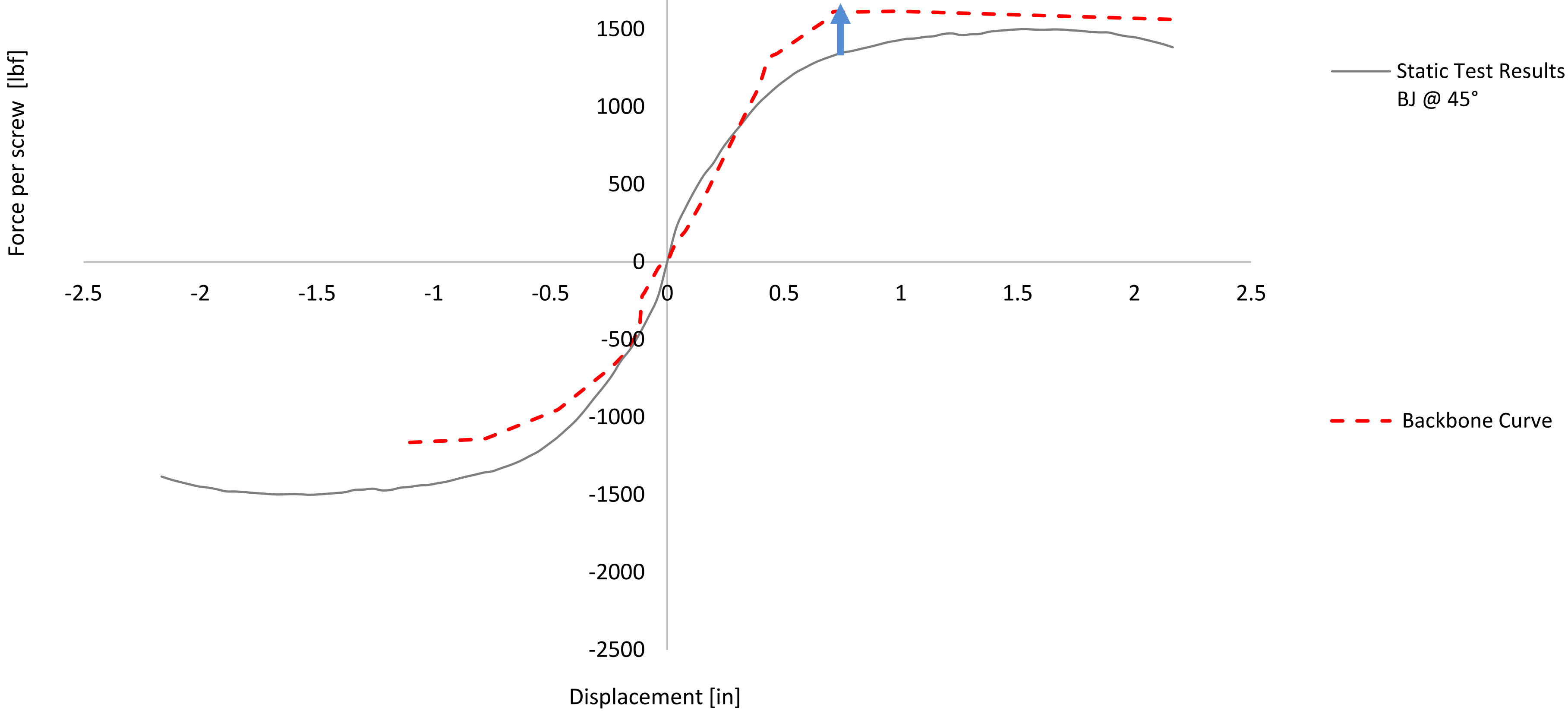
Test Series #7 : Load-Displacement Curve





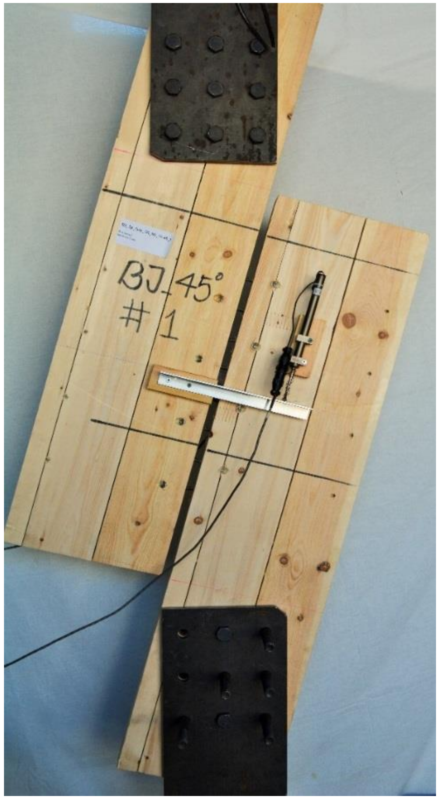
Test Series #7 : Backbone Curve



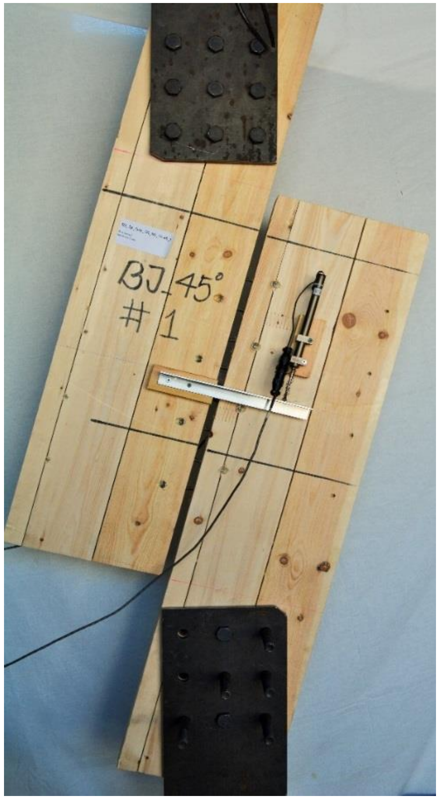


Test Series #7 : Connection Performance

Overall Connection Behaviour at Failure



Overall Connection Behaviour at Failure

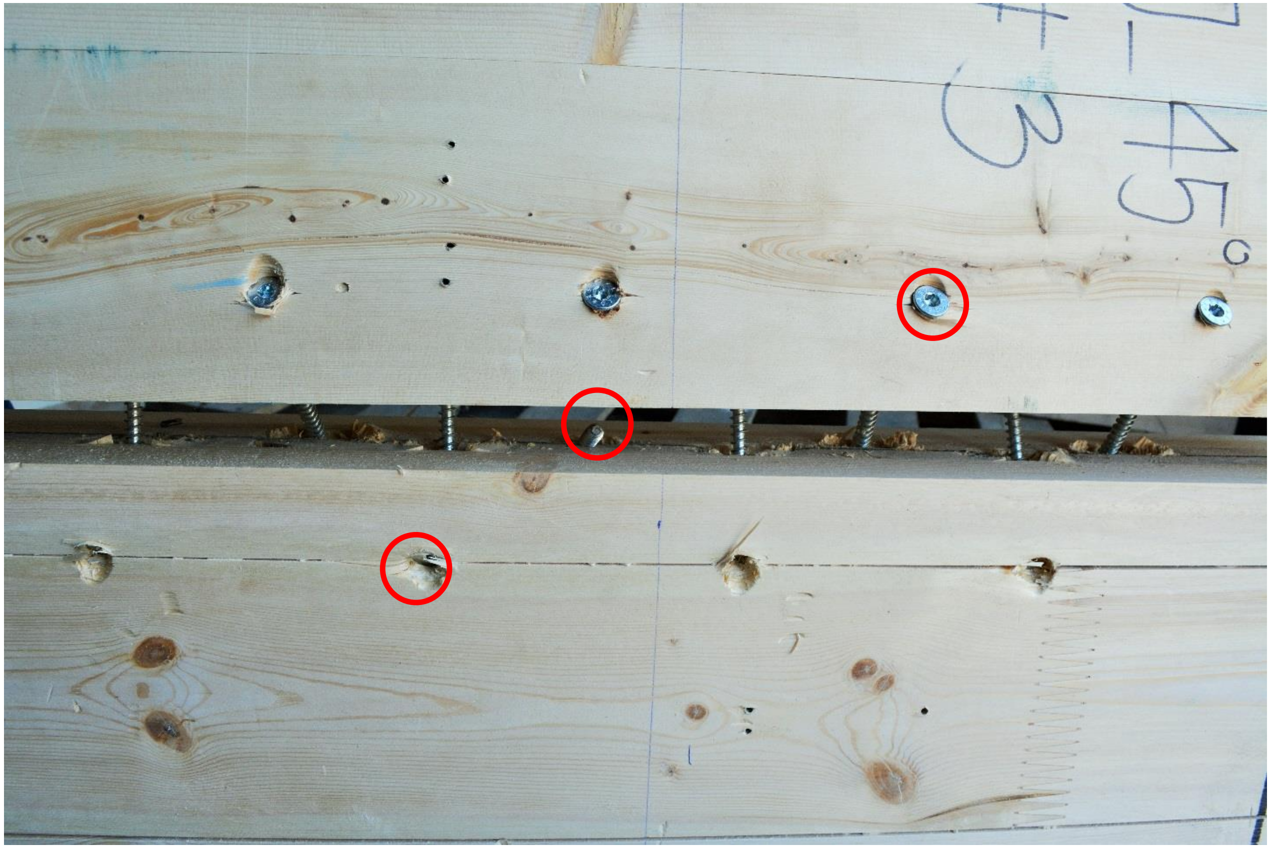


Large displacement visible

In-plane and out-of-plane rotation in ultimate state

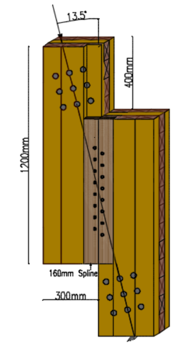
Test Series #7 : Connection Performance

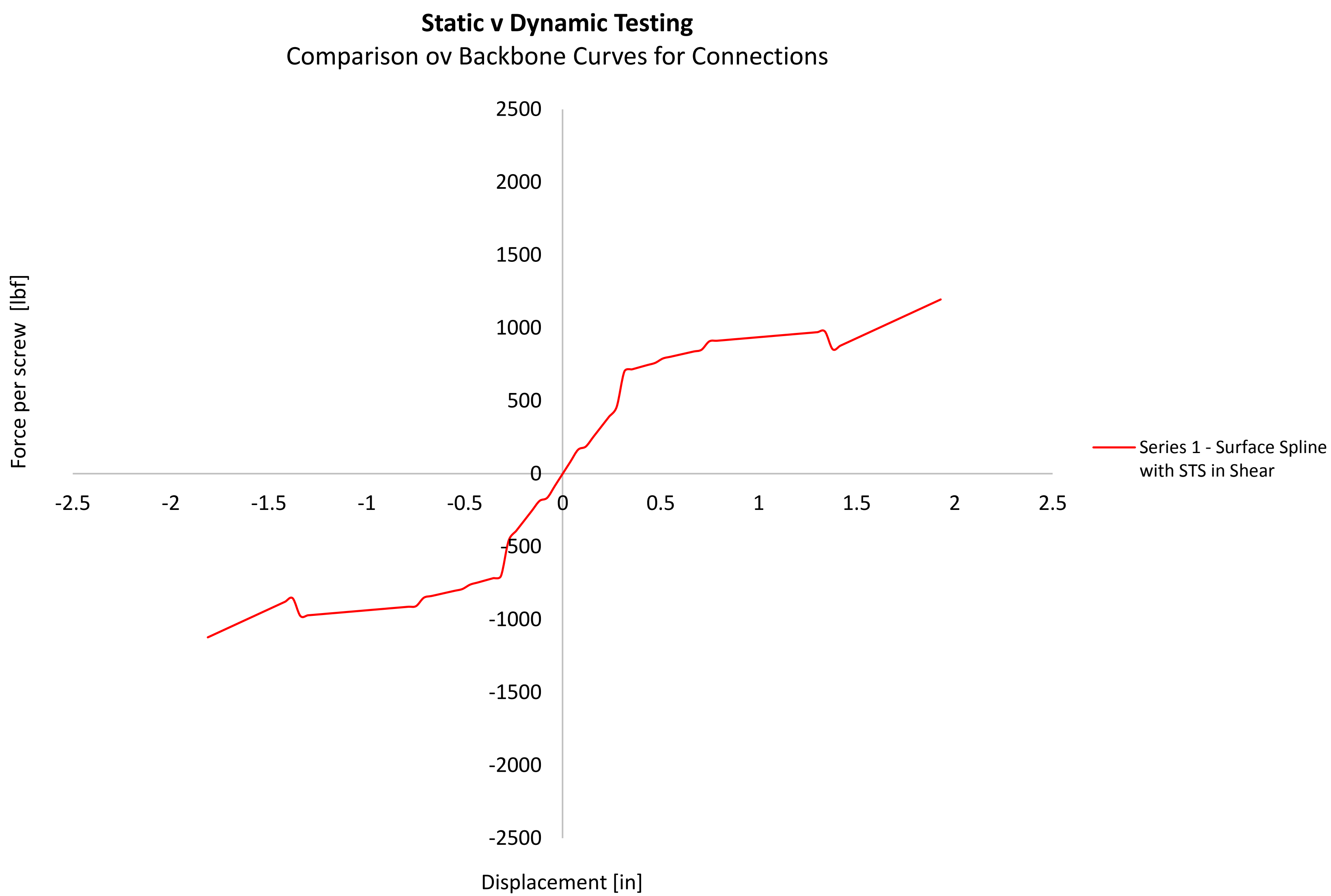
STS Behaviour at Failure



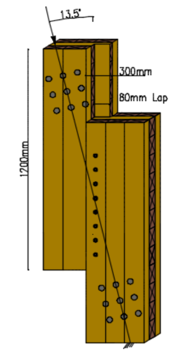
Head push-out and head pull-in failures
Screw breakage at ultimate level

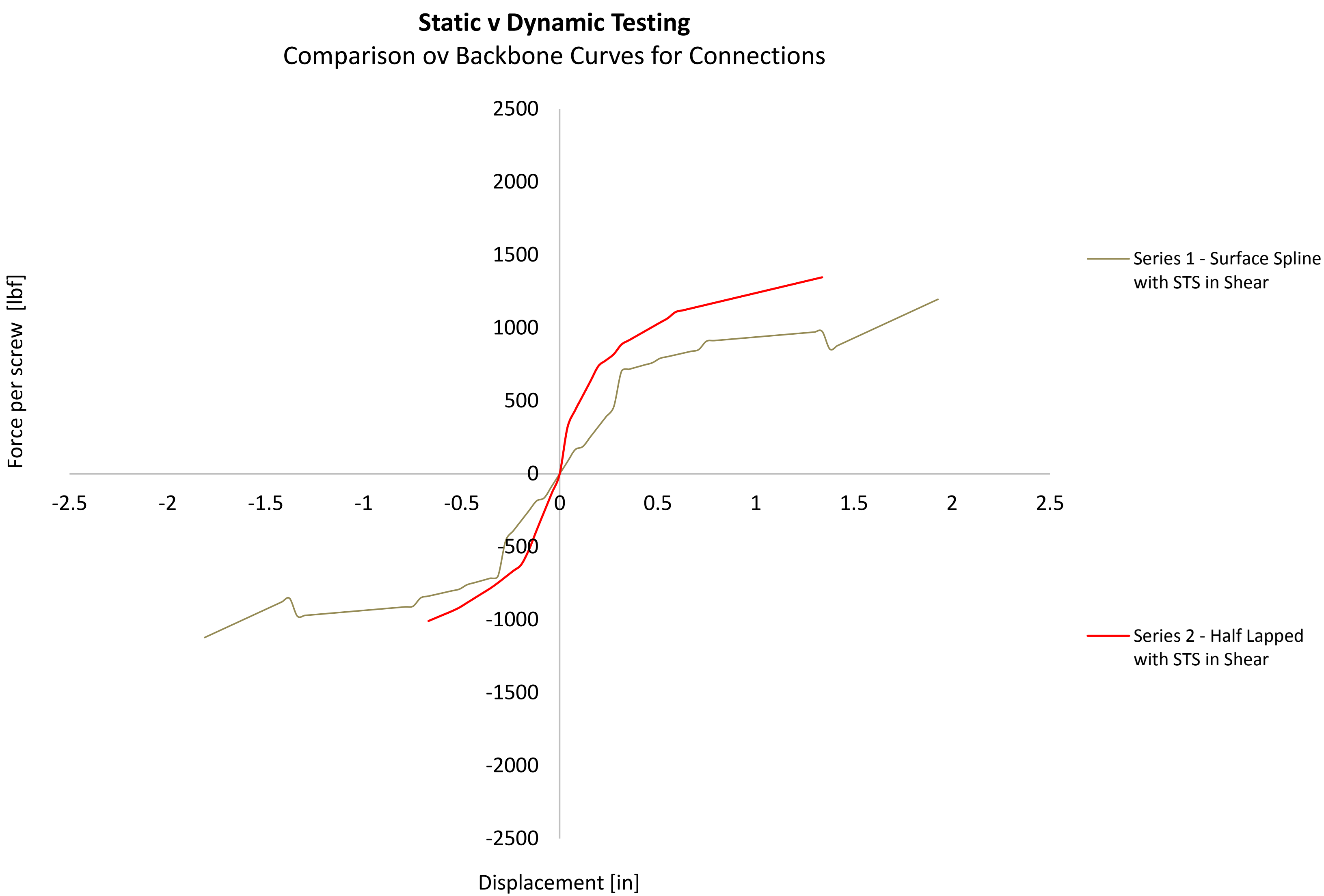
Cyclic Backbone Curve Comparison



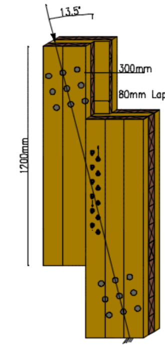


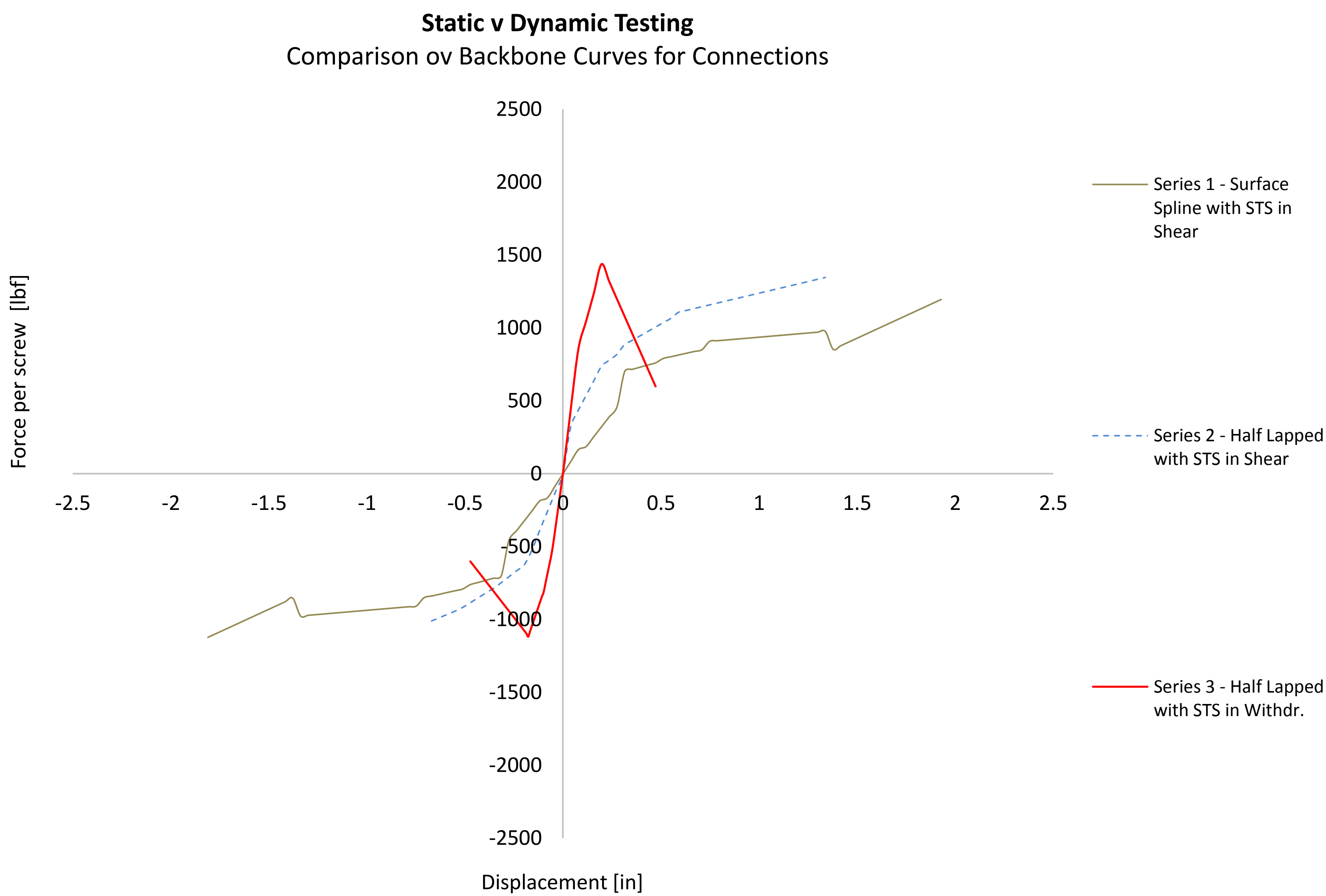
Cyclic Backbone Curve Comparison



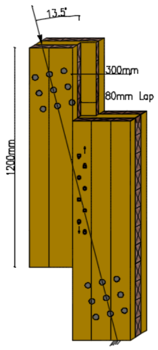


Cyclic Backbone Curve Comparison



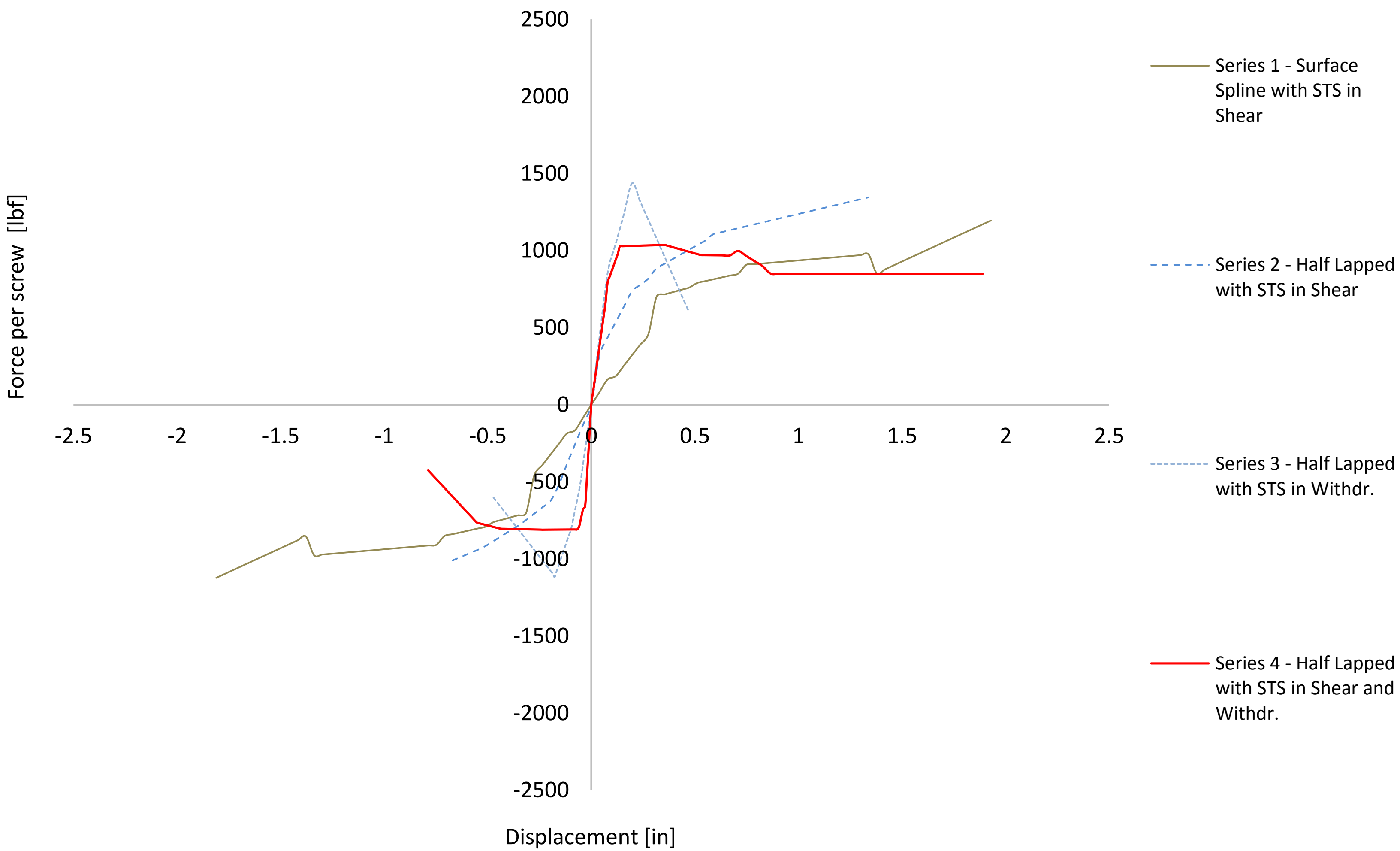


Cyclic Backbone Curve Comparison

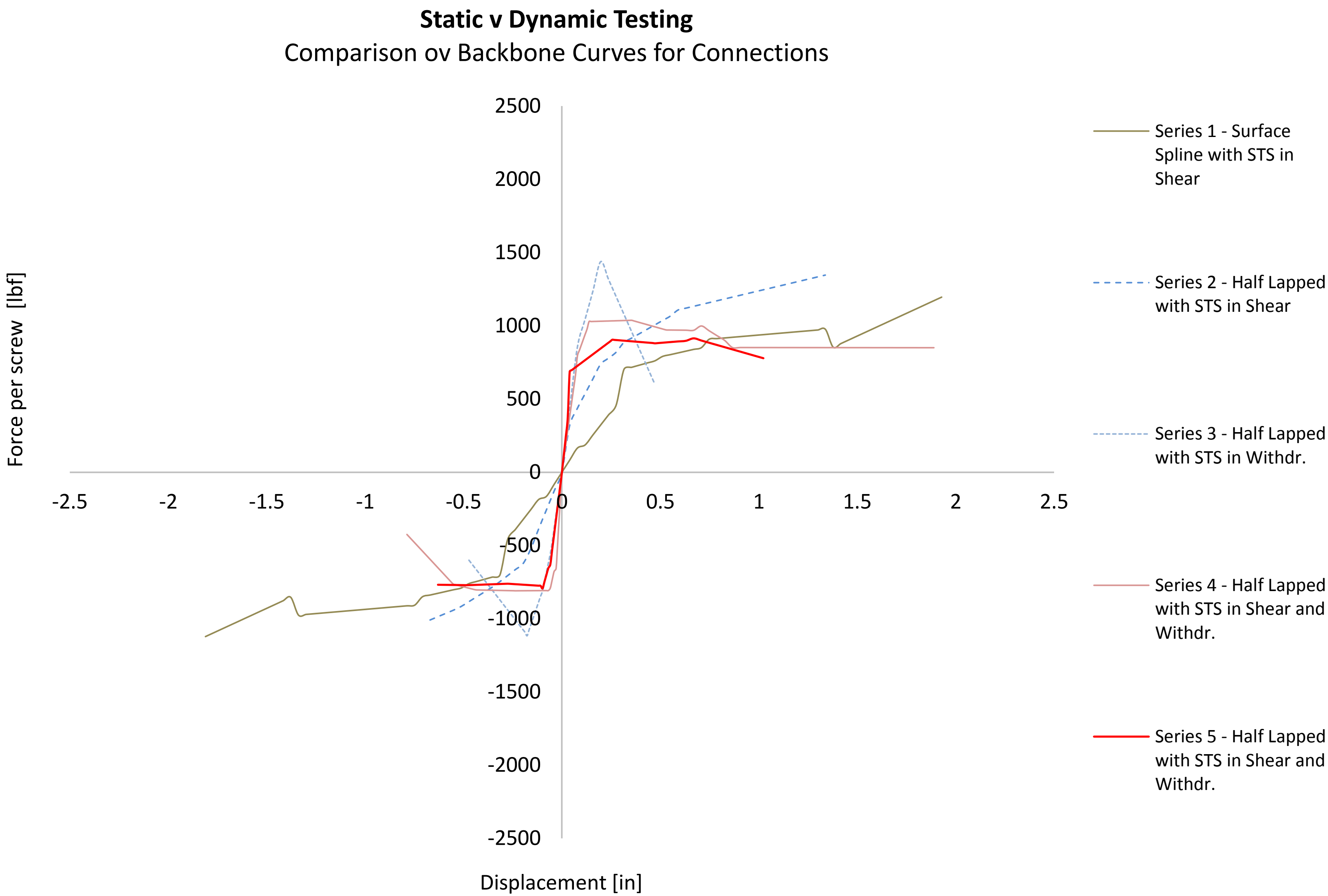


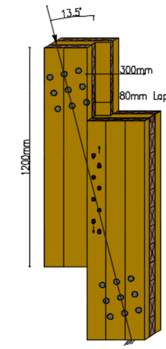
Static v Dynamic Testing

Comparison ov Backbone Curves for Connections

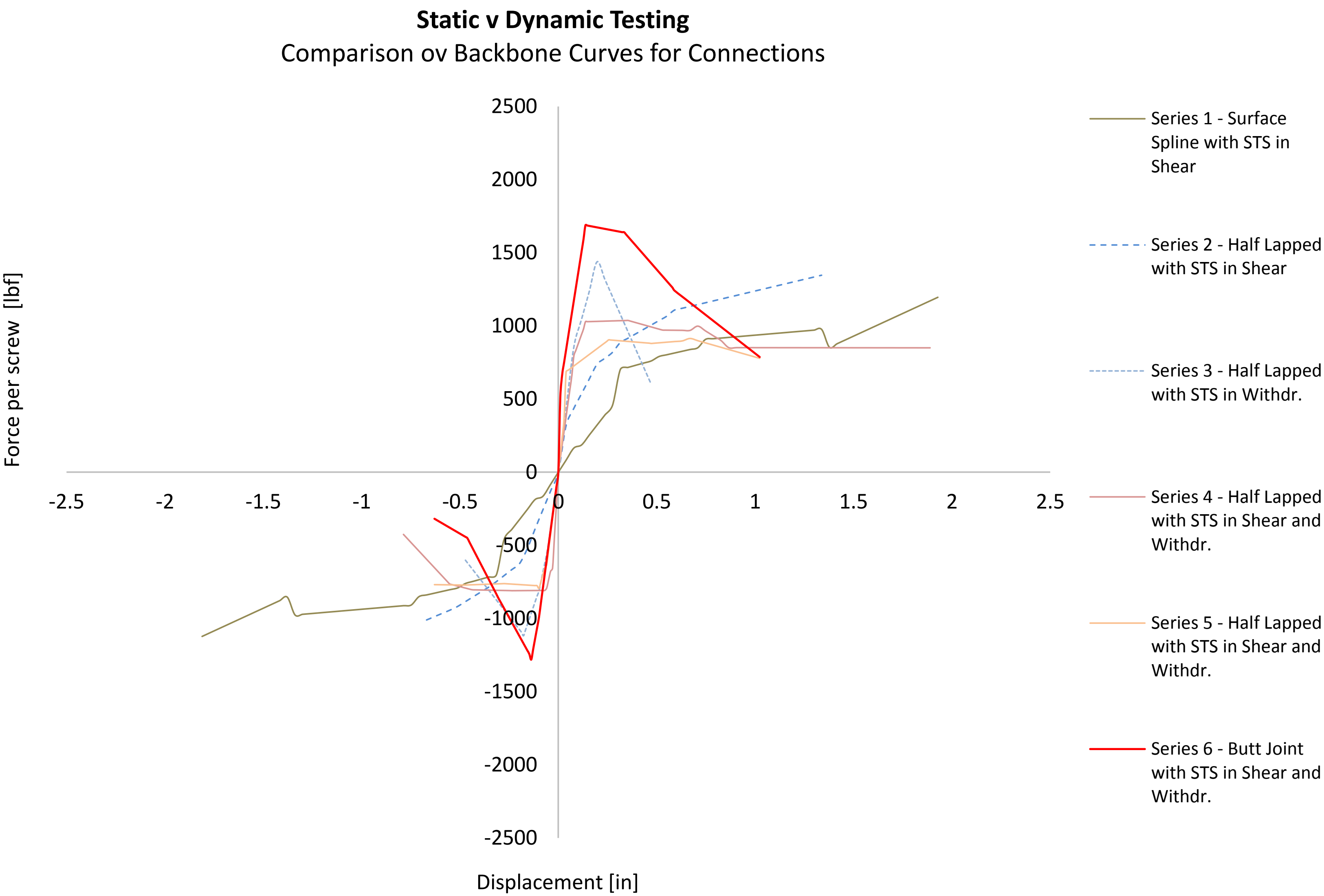


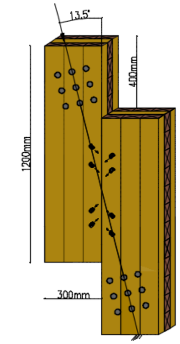
Cyclic Backbone Curve Comparison



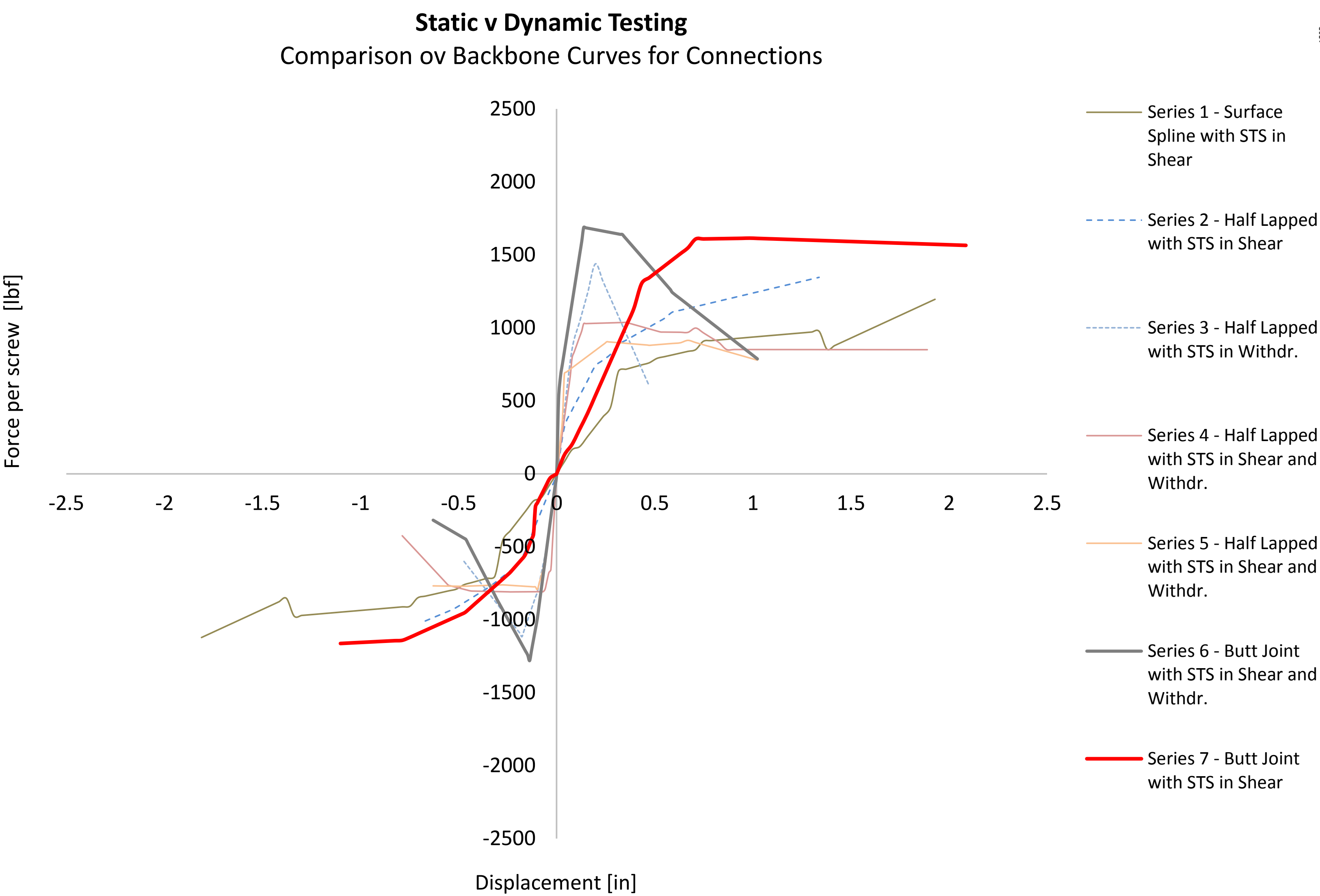


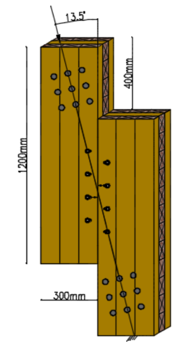
Cyclic Backbone Curve Comparison





Cyclic Backbone Curve Comparison





Test Campaign #2 : Cyclic Test Results

Average Test Results for POSITIVE envelope

Series	Total Max Force F_{MAX} [lbf]	Max Force F_{MAX} [lbf]	Yield Force F_Y [lbf]	Max. Displacement Δ_{MAX} [in]	Disp. @ Yield Δ_Y [in]	Ductility μ	Stiffness (10%-90%) F_Y [lbf/in]	Stiffness $K_{0.4}$ (10%-40%) F_{MAX} [lbf/in]
Series 1 – SS @ 90 - 3ply	9,172	1,146	967	1.38	0.24	5.6	2,284	5,139
Series 2 – LJ @ 90 - 3ply	9,891	1,236	877	1.00	0.14	7.2	2,855	3,426
Series 3 – LJ @ 45 - 3ply	17,265	1,439	1,281	0.17	0.11	1.6	10,278	11,991
Series 4 – LJ @ 45&90 (1) - 3ply	8,632	1,079	967	0.83	0.06	13.1	12,562	12,562
Series 5 – LJ @ 45&90 (2) - 3ply	9,442	944	854	0.45	0.05	8.8	15,417	19,414
Series 6 – BJ @ 33&45 - 3ply	14,207	1,776	1,574	0.22	0.08	2.8	11,991	15,417
Series 7 – BJ @ 45 - 3ply	13,308	1,664	1,461	1.33	0.41	3.3	2,855	3,997

- **Total F_{MAX} value is per shear plane ; All other values are per screw**
- Average measurements out of 3 specimens
- F_{max}= Max. Force ; F_y= Yield Force ; Δ_{MAX}= Max Displ. ; Δ_y= Displ. at Yield ; μ= Ductility ; $K_{0.4}$= stiffness calculated at 10% - 40% of F_{max}
- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09

Test Campaign #2 : Cyclic Test Results

Average Test Results for NEGATIVE envelope

Series	Total Max Force F_{MAX} [lbf]	Max Force F_{MAX} [lbf]	Yield Force F_Y [lbf]	Max. Displacement Δ_{MAX} [in]	Disp. @ Yield Δ_Y [in]	Ductility μ	Stiffness (10%-90%) F_Y [lbf/in]	Stiffness $K_{0.4}$ (10%-40%) F_{MAX} [lbf/in]
Series 1 – SS @ 90 - 3ply	6,834	854	697	0.91	0.26	3.5	1,713	2,855
Series 2 – LJ @ 90 - 3ply	7,913	989	809	0.71	0.19	3.8	2,284	3,997
Series 3 – LJ @ 45 - 3ply	14,028	1,169	1,057	0.15	0.06	2.4	15,417	13,704
Series 4 – LJ @ 45&90 (1) - 3ply	7,194	899	764	0.55	0.04	12.7	16,559	22,269
Series 5 – LJ @ 45&90 (2) - 3ply	7,868	787	719	0.55	0.05	10.8	10,278	9,136
Series 6 – BJ @ 33&45 - 3ply	8,992	1,236	1,012	0.11	0.06	1.8	11,991	13,133
Series 7 – BJ @ 45 - 3ply	9,352	1,169	944	1.06	0.28	3.9	2,284	3,997

- **Total F_{MAX} value is per shear plane ; All other values are per screw**
- Average measurements out of 3 specimens
- F_{max}= Max. Force ; F_y= Yield Force ; Δ_{MAX}= Max Displ. ; Δ_y= Displ. at Yield ; μ= Ductility ; $K_{0.4}$= stiffness calculated at 10% - 40% of F_{max}
- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09

Test Campaign #2 : Cyclic Test Results

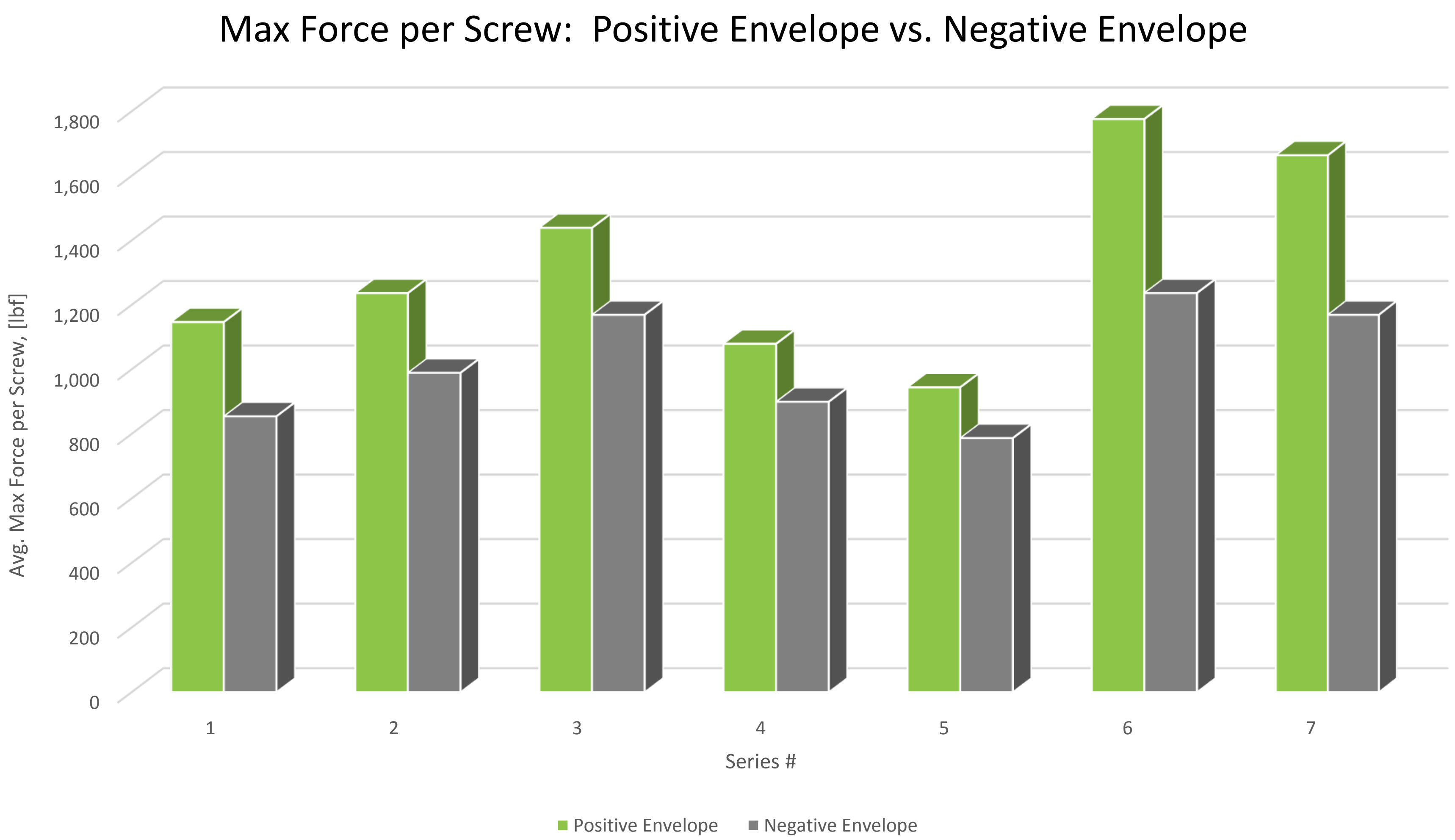
AVERAGE Test Results

Series	Total Max Force F_{MAX} [lbf]	Max Force F_{MAX} [lbf]	Yield Force F_Y [lbf]	Max. Displacement Δ_{MAX} [in]	Disp. @ Yield Δ_Y [in]	Ductility μ	Stiffness (10%-90%) F_Y [lbf/in]	Stiffness $K_{0.4}$ (10%-40%) F_{MAX} [lbf/in]
Series 1 – SS @ 90 - 3ply	8,003	1,000	832	1.14	0.25	4.6	1,998	3,997
Series 2 – LJ @ 90 - 3ply	8,992	1,113	843	0.85	0.16	5.2	2,569	3,711
Series 3 – LJ @ 45 - 3ply	15,646	1,304	1,169	0.16	0.08	1.9	12,847	12,847
Series 4 – LJ @ 45&90 (1) - 3ply	7,913	989	865	0.69	0.05	13.0	14,560	17,415
Series 5 – LJ @ 45&90 (2) - 3ply	8,542	854	787	0.50	0.05	9.8	12,847	14,275
Series 6 – BJ @ 33&45 - 3ply	12,049	1,506	1,293	0.17	0.07	2.3	11,991	14,275
Series 7 – BJ @ 45 - 3ply	11,330	1,416	1,203	1.19	0.34	3.5	2,569	3,997

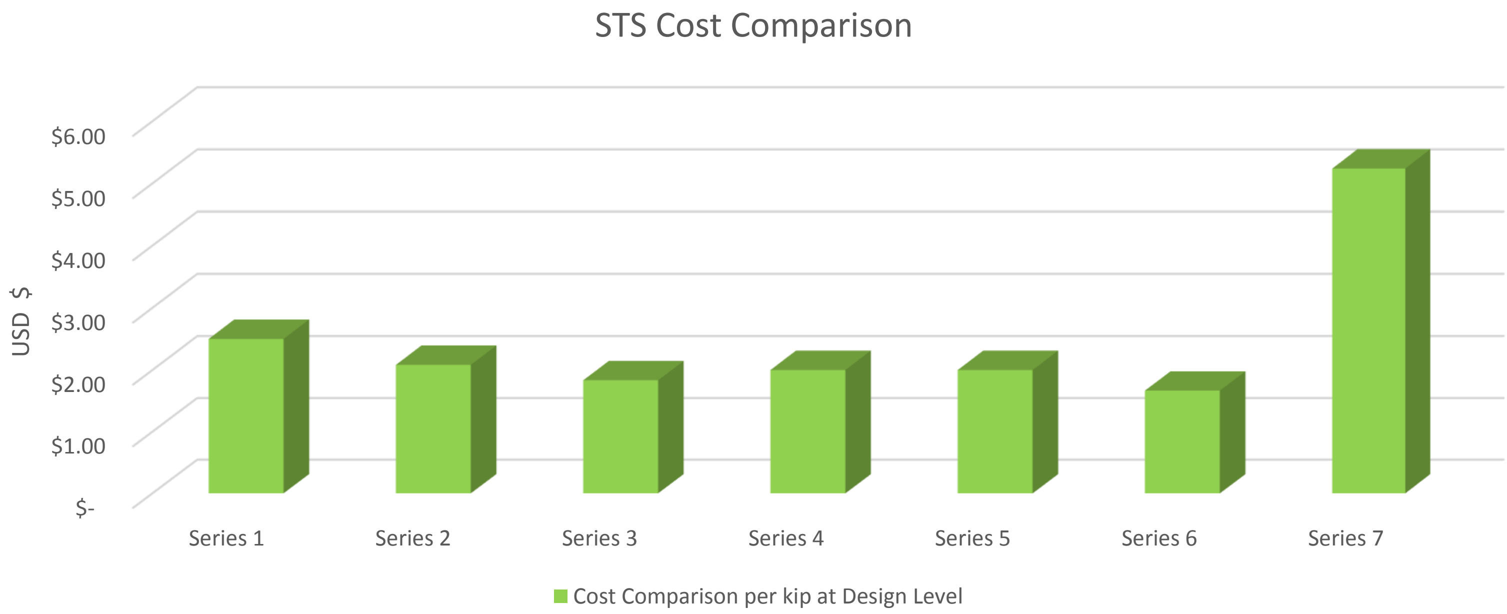
- **Total F_{MAX} value is per shear plane ; All other values are per screw**
- Average measurements out of 6 specimens
- F_{max}= Max. Force ; F_y= Yield Force ; Δ_{MAX}= Max Displ. ; Δ_y= Displ. at Yield ; μ= Ductility ; $K_{0.4}$= stiffness calculated at 10% - 40% of F_{max}
- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09

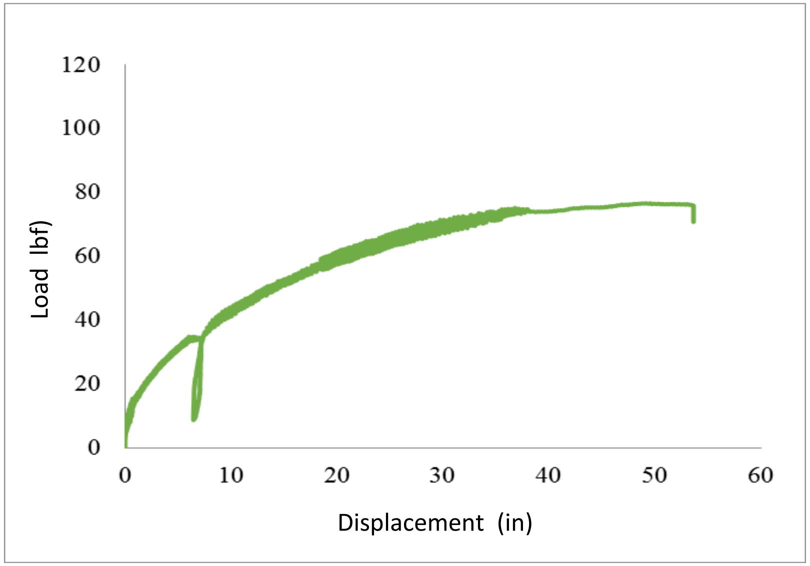
Test Campaign #2 : Cyclic Test Results



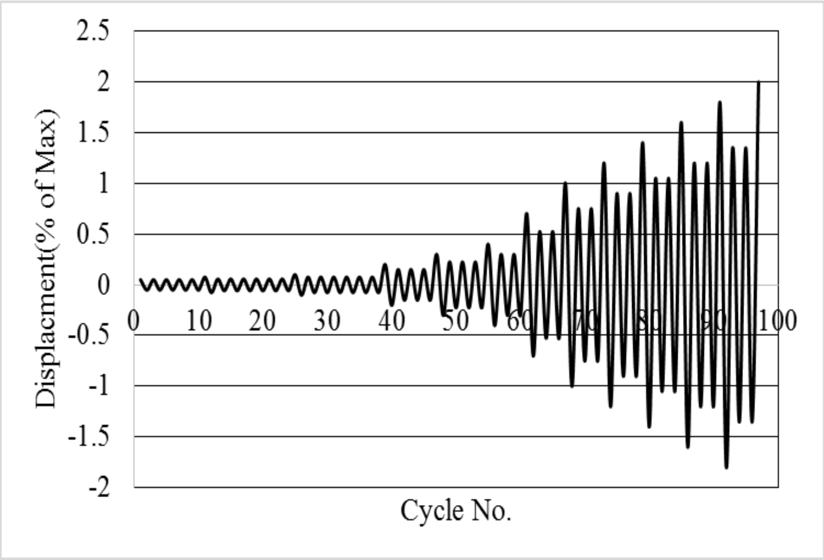
Test Campaign #2: STS Cost Analysis



Static vs Cyclic Performance



vs



Test Campaign #2 : Static vs Cyclic

Comparison of Connection Capacity

Series	STATIC LOADING			CYCLIC LOADING			**Reduction** of Capacity due to Cyclic Loading	
	Total Max Force F_{MAX} [lbf]	Max Force F_{MAX} [lbf]	Yield Force F_Y [lbf]	Total Max Force F_{MAX} [lbf]	Max Force F_{MAX} [lbf]	Yield Force F_Y [lbf]	F_{MAX}	F_Y
Series 1 – SS @ 90 - 3ply	11,690	1,461	1,236	8,003	1,012	832	31%	33%
Series 2 – LJ @ 90 - 3ply	12,049	1,529	1,124	8,902	1,124	854	26%	24%
Series 3 – LJ @ 45 - 3ply	19,423	1,619	1,304	15,646	1,304	1,169	19%	10%
Series 4 – LJ @ 45&90 (1) - 3ply	12,049	1,506	989	7,913	989	877	34%	11%
Series 5 – LJ @ 45&90 (2) - 3ply	11,015	1,102	854	8,655	854	787	22%	8%
Series 6 – BJ @ 33&45 - 3ply	14,028	1,753	1,506	12,049	1,506	1,304	14%	13%
Series 7 – BJ @ 45 - 3ply	12,229	1,529	1,461	11,330	1,416	1,214	7%	17%

- **Total F_{MAX} value is per shear plane ; All other values are per screw**
- Average measurements out of 6 specimens and 3 specimens for cyclic
- F_{max}= Max. Force ; F_y= Yield Force ; Δ_{MAX}= Max Displ. ; Δ_y= Displ. at Yield ; μ= Ductility ; $K_{0.4}$= stiffness calculated at 10% - 40% of F_{max}
- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09

Test Campaign #2 : Static vs Cyclic

Comparison of Connection Capacity

Series	STATIC LOADING			CYCLIC LOADING			Reduction of Capacity due to Cyclic Loading	
	Total Max Force F_{MAX} [lbf]	Max Force F_{MAX} [lbf]	Yield Force F_Y [lbf]	Total Max Force F_{MAX} [lbf]	Max Force F_{MAX} [lbf]	Yield Force F_Y [lbf]	F_{MAX}	F_Y
Series 1 – SS @ 90 - 3ply	11,690	1,461	1,236	8,003	1,012	832	31%	33%
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Series 3 – LJ @ 45 - 3ply	19,423	1,619	1,304	15,646	1,304	1,169	19%	10%
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Series 6 – BJ @ 33&45 - 3ply	14,028	1,753	1,506	12,049	1,506	1,304	14%	13%
Series 7 – BJ @ 45 - 3ply	12,229	1,529	1,461	11,330	1,416	1,214	7%	17%

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- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09

Test Campaign #2 : Static vs Cyclic

Comparison of Connection Performance

Series	STATIC LOADING			CYCLIC LOADING			**Reduction** of Ductility and Stiffness due to Cyclic Loading	
	Max. Displacement Δ_{MAX} [in]	Ductility μ	Stiffness $K_{0.4}$ (10%-40%) F_{MAX} [lbf/in]	Max. Displacement Δ_{MAX} [in]	Ductility μ	Stiffness $K_{0.4}$ (10%-40%) F_{MAX} [lbf/in]	Ductility	$K_{0.4}$
Series 1 – SS @ 90 - 3ply	1.84	5.4	7,423	1.14	4.6	3,997	15%	46%
Series 2 – LJ @ 90 - 3ply	1.01	7.1	12,562	0.85	5.5	3,711	23%	70%
Series 3 – LJ @ 45 - 3ply	0.16	3.4	82,223	0.16	2.0	12,847	41%	84%
Series 4 – LJ @ 45&90 (1) - 3ply	0.77	19.5	65,093	0.69	12.8	17,415	34%	73%
Series 5 – LJ @ 45&90 (2) - 3ply	0.97	17.6	47,392	0.50	9.7	14,275	45%	70%
Series 6 – BJ @ 33&45 - 3ply	0.26	6.5	59,383	0.17	2.3	14,275	65%	76%
Series 7 – BJ @ 45 - 3ply	1.54	3.8	5,710	1.19	3.6	3,997	5%	30%

- **Total F_{MAX} value is per shear plane ; All other values are per screw**
- Average measurements out of 6 specimens and 3 specimens for cyclic
- F_{max}= Max. Force ; F_y= Yield Force ; Δ_{MAX}= Max Displ. ; Δ_y= Displ. at Yield ; μ= Ductility ; $K_{0.4}$= stiffness calculated at 10% - 40% of F_{max}
- Ductility = (Displ. @ F_{max}) / (Displ. @ F_y)
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09

Test Campaign #2 : Static vs Cyclic

Comparison of Connection Performance

Series	STATIC LOADING			CYCLIC LOADING			**Reduction** of Ductility and Stiffness due to Cyclic Loading	
	Max. Displacement Δ_{MAX} [in]	Ductility μ	Stiffness $K_{0.4}$ (10%-40%) F_{MAX} [lbf/in]	Max. Displacement Δ_{MAX} [in]	Ductility μ	Stiffness $K_{0.4}$ (10%-40%) F_{MAX} [lbf/in]	Ductility	$K_{0.4}$
Series 1 – SS @ 90 - 3ply	1.84	5.4	7,423	1.14	4.6	3,997	15%	46%
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Series 3 – LJ @ 45 - 3ply	0.16	3.4	82,223	0.16	2.0	12,847	41%	84%
Series 4 – LJ @ 45&90 (1) - 3ply	0.77	19.5	65,093	0.69	12.8	17,415	34%	73%
Series 5 – LJ @ 45&90 (2) - 3ply	0.97	17.6	47,392	0.50	9.7	14,275	45%	70%
Series 6 – BJ @ 33&45 - 3ply	0.26	6.5	59,383	0.17	2.3	14,275	65%	76%
Series 7 – BJ @ 45 - 3ply	1.54	3.8	5,710	1.19	3.6	3,997	5%	30%

- **Total F_{MAX} value is per shear plane ; All other values are per screw**
- Average measurements out of 6 specimens and 3 specimens for cyclic
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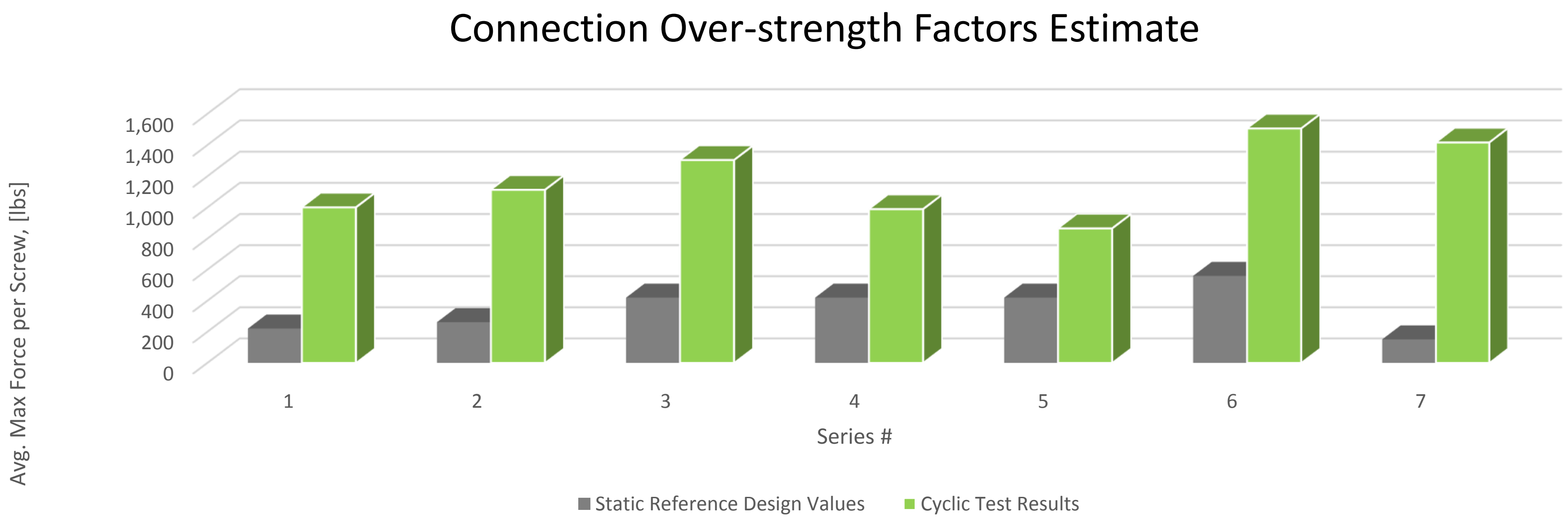
- Yield Force and ductility were calculated following Equivalent Energy Elastic-Plastic

(EEEP) Curves as per ASTM 2126-09

Test Campaign #2 : Static vs Cyclic

Comparison between Design & Cyclic Test Data:

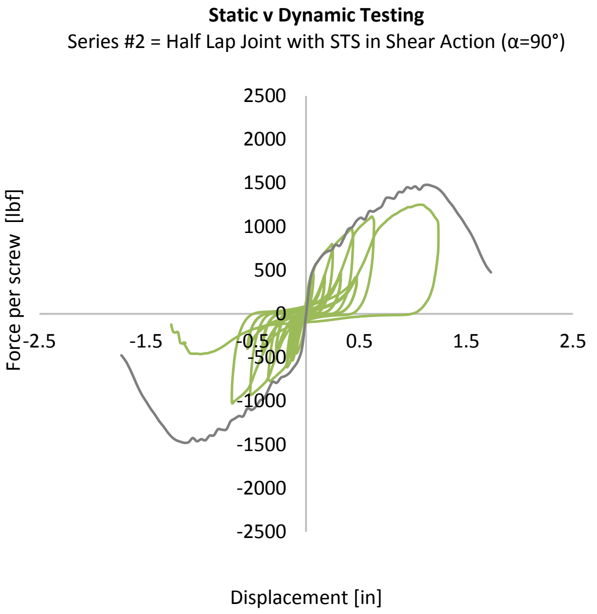
Label	Type	F_{MAX} [lbf]	Predicted* F_{MAX} [lbf]	Δ_{MAX} [in]	$K_{0.4}$ [lbf/in]	Over-Strength Ratio
Series 1 – SS_90_3ply	Surface Spline Joint	1,000	221	1.8	3,997	4.5
Series 2 – LJ_90_3ply	Half Lapped Joint	1,113	262	1.0	3,711	4.3
Series 3 – LJ_45_3ply		1,304	420	0.2	12,847	3.1
Series 4 – LJ_45/90_3ply_WSSW		989	420	0.8	17,415	2.4
Series 5 – LJ_45/90_3ply_SWSWS		865	420	1.0	14,275	2.1
Series 6 – BJ_33/45_3ply	Butt Joint	1,506	560	0.3	14,275	2.7
Series 7 – BJ_45_3ply		1,416	151	1.5	3,997	9.4

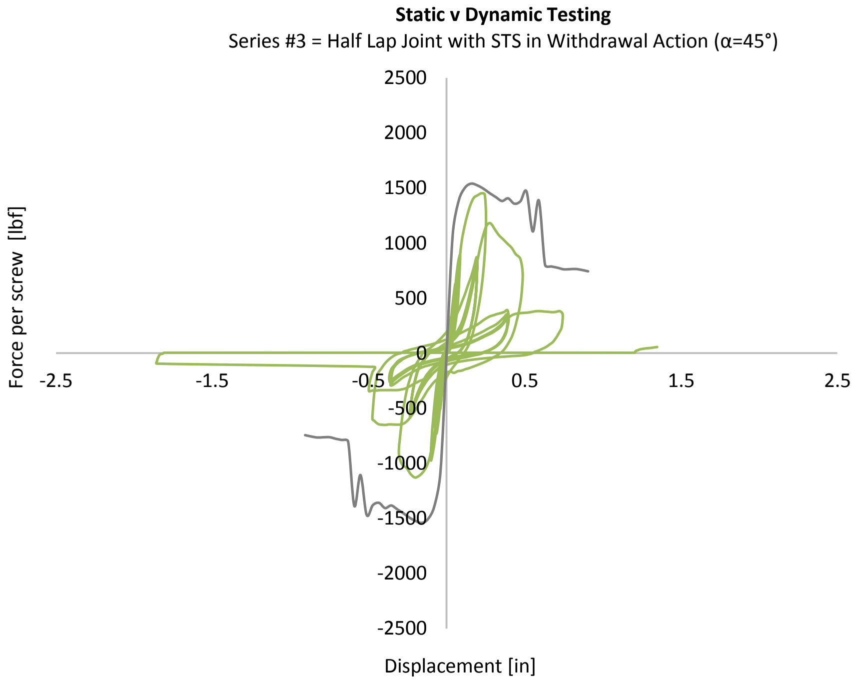


Conclusions

1. Tests indicate ductile performance with STS in shear action

2. Tests indicate brittle performance with STS in withdrawal, higher initial stiffness and ultimate capacity



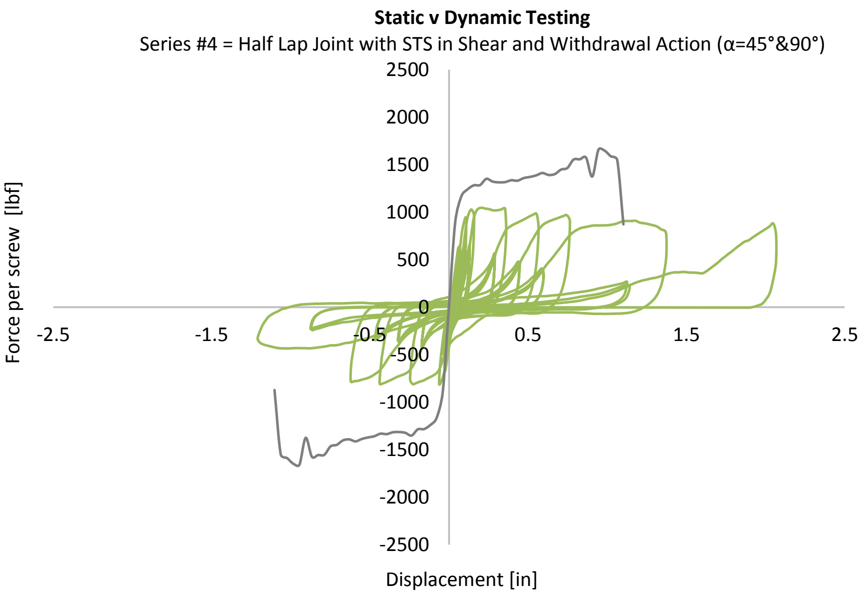


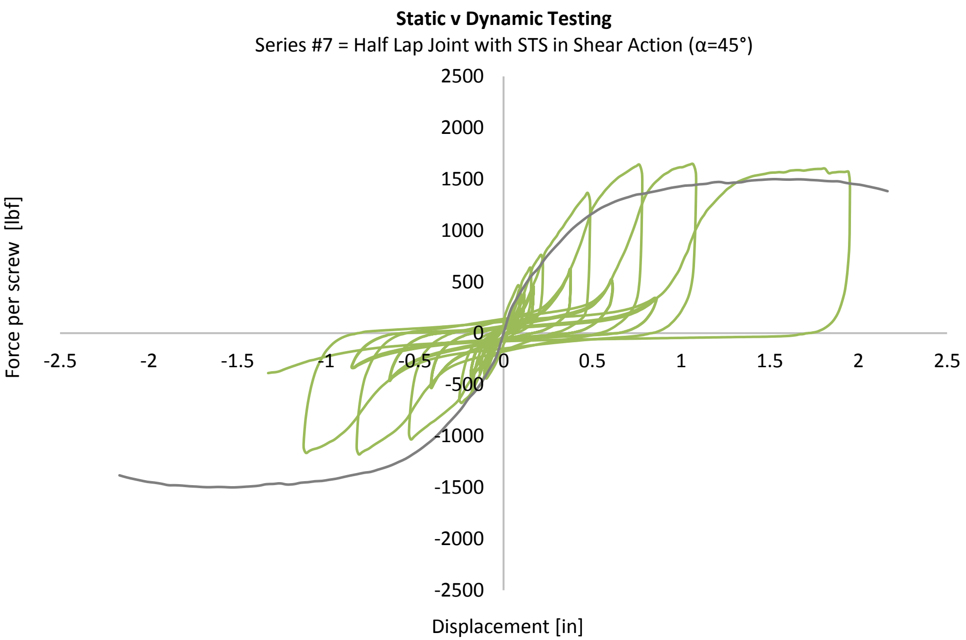
Conclusions

3. Tests indicate moderate performance with STS in combined action

4. Tests indicate reduction in capacity and stiffness in cyclic tests

5. Tests indicate Butt Joints exhibit good performance under cyclic loading

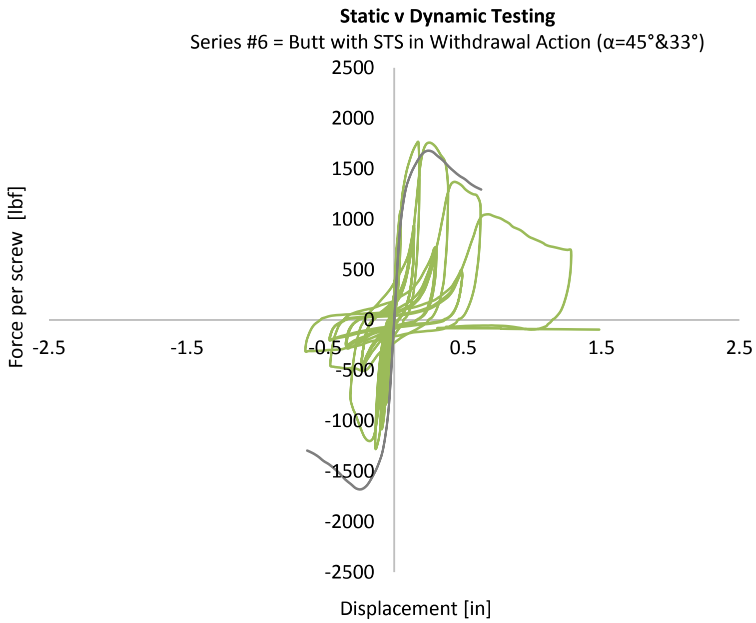


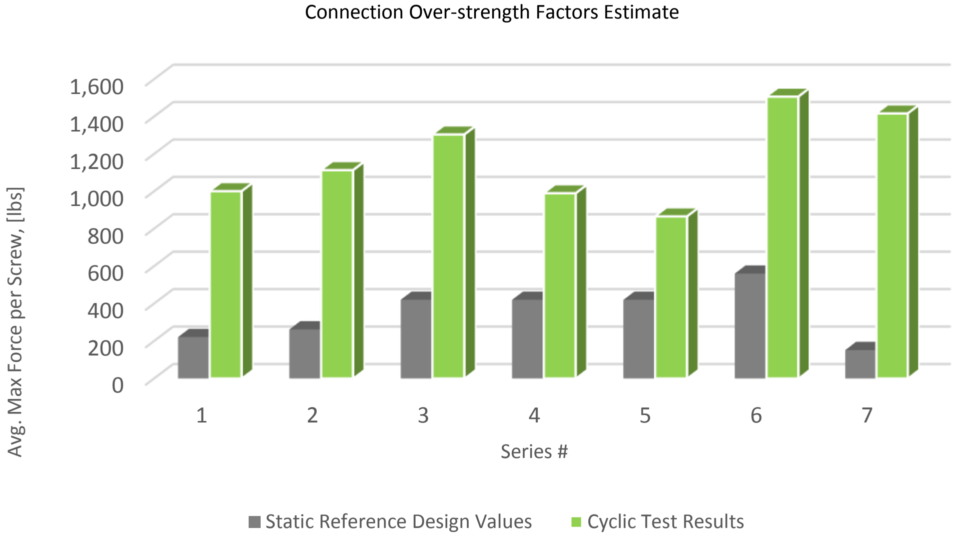


Conclusions

6. In addition, Butt Joints exhibited minimal reduction of capacity and stiffness from static results in linear elastic range

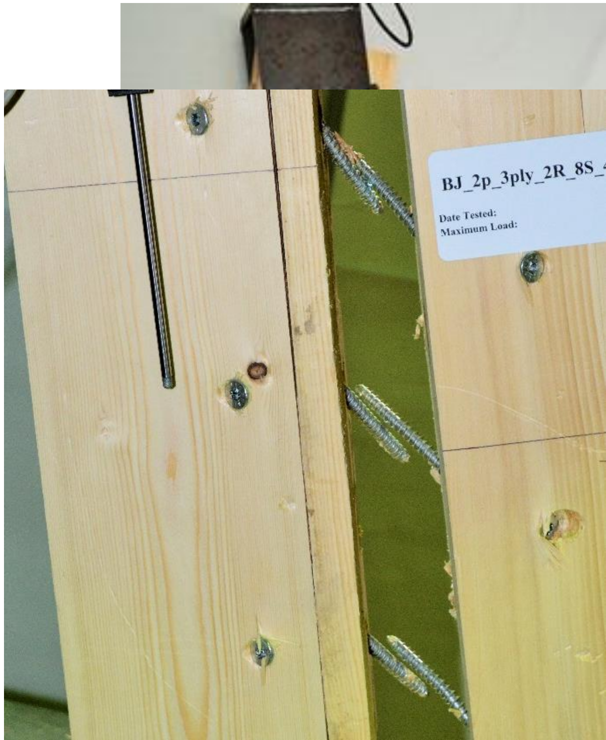
7. Testing indicates the conservative nature of over-strength factors even between static design approach and cyclic results





Outlook

1. Group action factors need more testing - no conclusive results
2. Dynamic confirmation testing needs to address the created perpendicular force component and its impact
3. Impact of difference in fasteners to butt joint performance, partially threaded or fully threaded, to be investigated
4. Medium scale testing with 4’x8’ CLT panels i.e. shear wall
5. Investigating fastener diameter influence



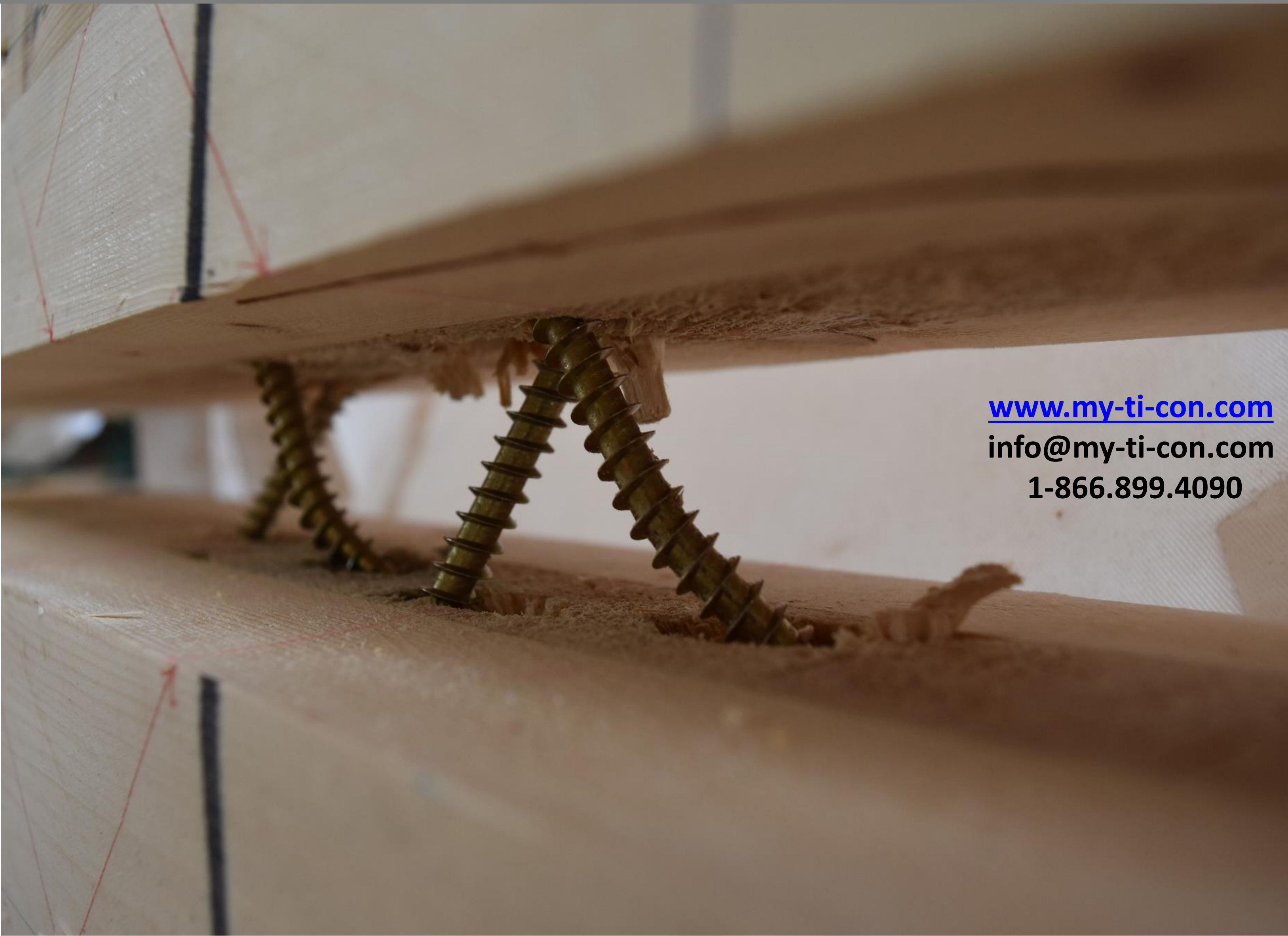
Special thanks to:

- Prof. Dr. Thomas Tannert, Univ. of British Columbia
- Afrin Hossain, PhD. candidate Univ. of British Columbia

THANK YOU for attending

MyTiCon Timber Connectors

Performance of CLT Connections under Dynamic Loading



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