Can U-wraps Concurrently Serve as Supplemental Shear Reinforcement and Anchorage of Flexural CFRP in Shear-Deficient Reinforced Concrete Beams?

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Overview

- Objectives and Scope
- Specimen Design
- Test Matrix
- Test Setup
- Experimental Results
- Conclusions
- Future Work and Recommendations

Objectives

- Investigate combined shear and anchorage effect of U-wraps on RC beams strengthened with externally bonded CFRP laminates.
- Make design recommendations for the use of U-wraps.

Scope

- Tested six (6) Large-Scale Control Beams: Three (3) Unstrengthened and Three (3) Strengthened with 2-ply of unanchored longitudinal CFRP.
- Tested six (6) Large-Scale Strengthened Beams Anchored with 1-ply and 2-ply U-Wraps.

Specimen Design

Materials:

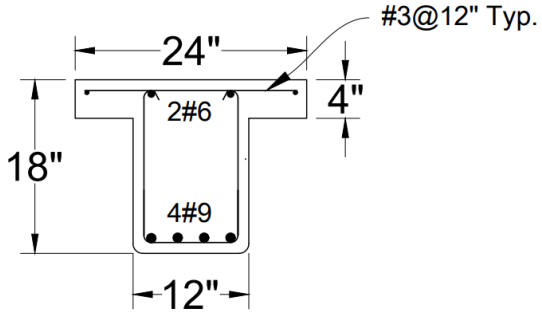
Actual Concrete Compressive Strength = 4,500-5000 psi

Actual Yield Strength of Steel (f_y) = 61,000 psi (#2)

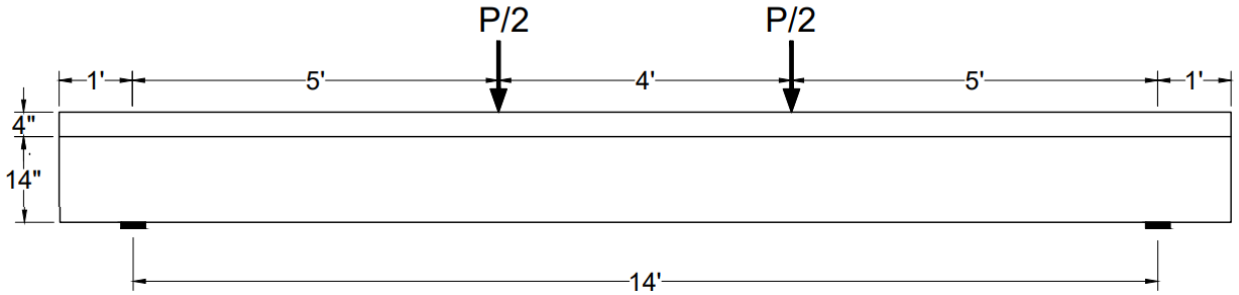
Actual Yield Strength of Steel (f_y) = 70,000 psi

Longitudinal Steel Reinforcement Ratio (ρ) = 2.20 %

Shear Span-to-Depth Ratio (a/d)=3.90



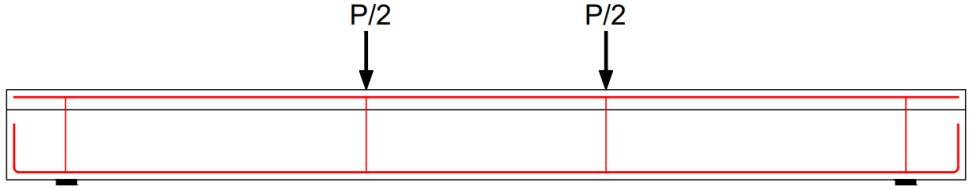
Cross-Section View



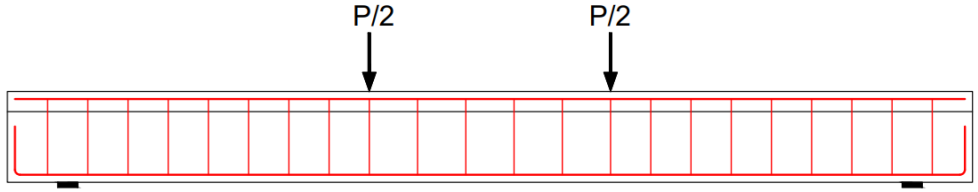
Elevation View

Unstrengthened Control Beams

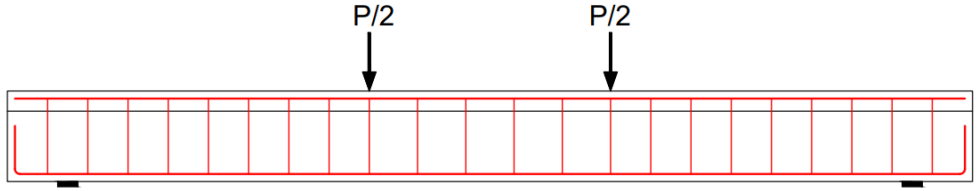
0S0: No Stirrups



2S8: #2@8” c/c (A_v=0.09 in^2)
(ACI $A_{v,min}$=0.08 in^2)



4S8: #4@8” c/c (A_v=0.40 in^2)



Strengthened Control Beam

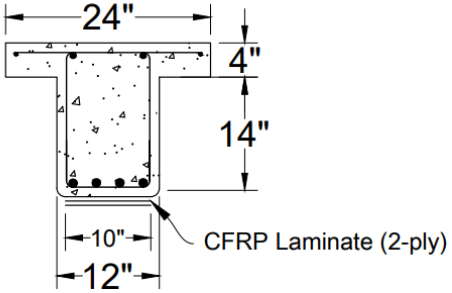
CFRP: CSS-CUCF22

Modulus of Elasticity (E_f)= 14,800 ksi

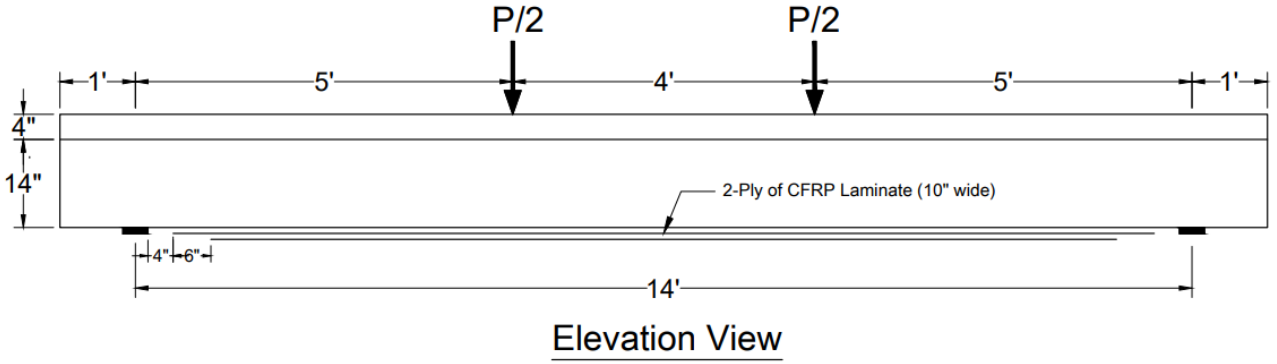
Rupture Strength (f_{fu}) = 195 ksi

Rupture Strain (ε_{fu}) = 1.3 %

Nominal Thickness = 0.04 in



Cross-Section View



Elevation View

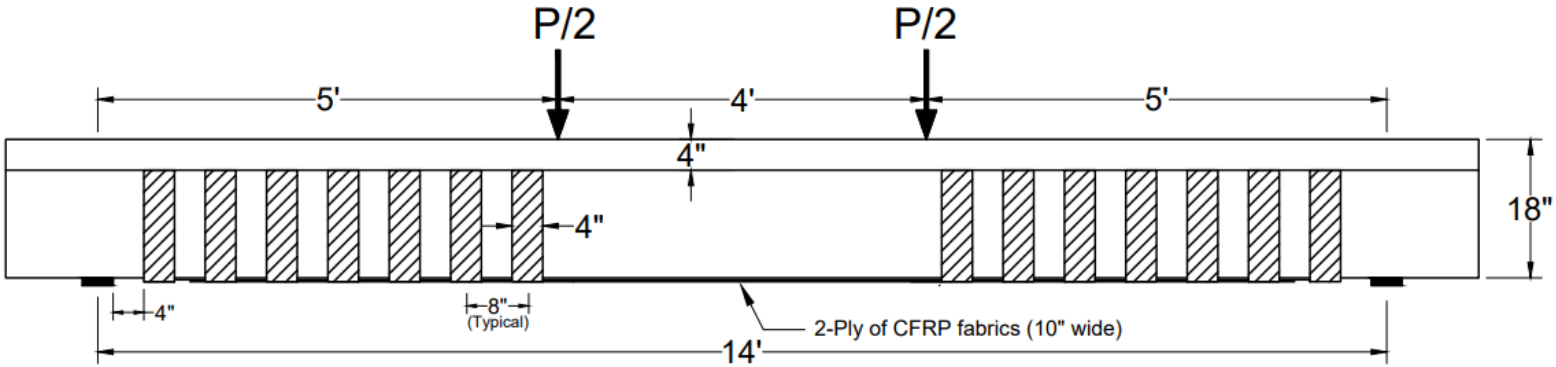
Beam Nomenclature

2L1U-2S8

Number of Plies in **L**ongitudinal CFRP

Number of Plies in 4” Wide **U**-Wraps

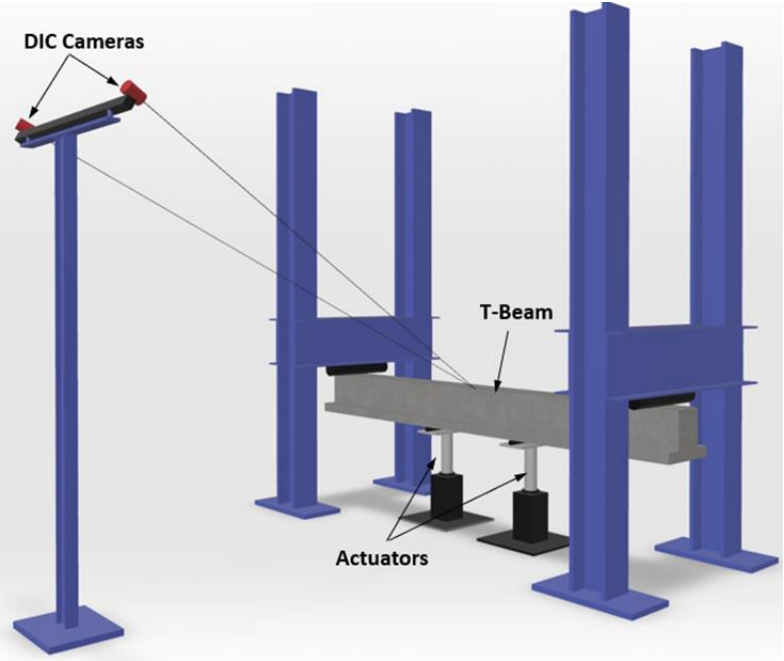
Diameter and Spacing of **S**tirrups in Shear Span (in)

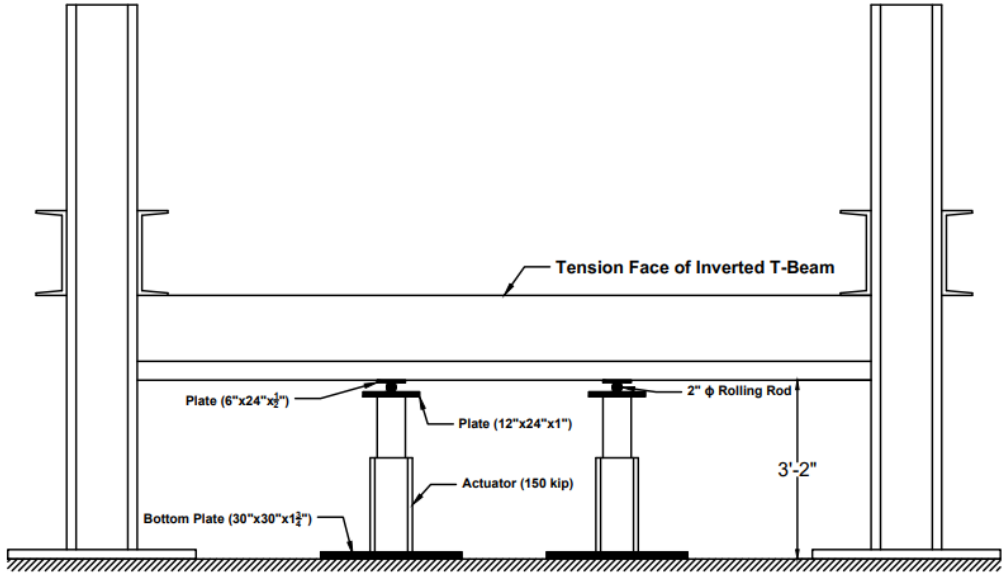


Test Matrix

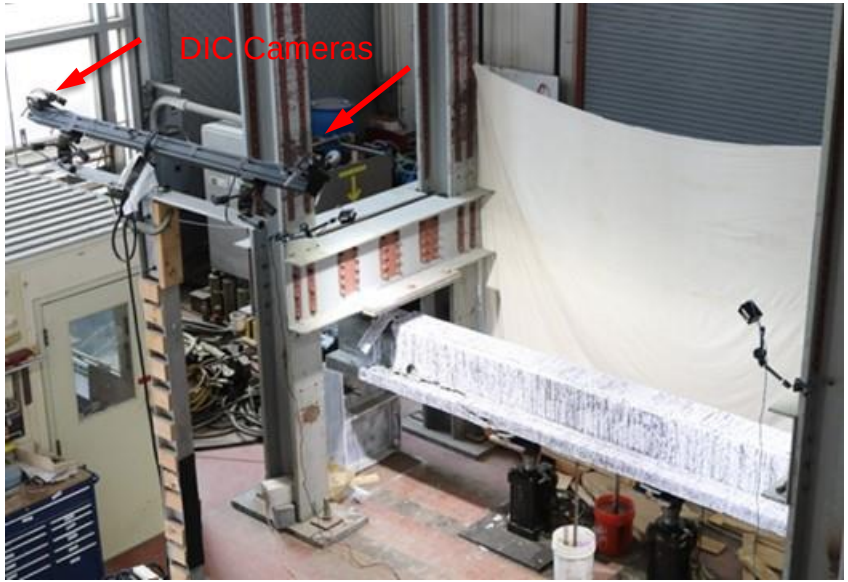
Group No.	Beam No.	Beam Designation	Type	Shear Steel Reinforcement	Shear Steel Ratio (ρv)	Predicted Ultimate Load		Remarks
						Flexure (Kip)	Shear (Kip)	
A	1	0L0U-0S0	Unstrengthened Control	No Stirrups	0	136	68	Shear-Controlled
	2	2L0U-0S0	Strengthened Control	No Stirrups	0	169	68	Shear-Controlled
	3	2L1U-0S0	Strengthened (With U-wraps)	No Stirrups	0	185	100	Shear-Controlled
	4	2L2U-0S0	Strengthened (With U-wraps)	No Stirrups	0	194	112	Shear-Controlled
	5	2L1UA-0S0	Strengthened (With U-wraps+Spike Anchors)	No Stirrups	0	201	120	Shear-Controlled
	6	2L2UA-0S0	Strengthened (With U-wraps+Spike Anchors)	No Stirrups	0	201	172	Shear-Controlled
B	7	0L0U-2S8	Unstrengthened Control	#2@8"	0.0011	136	95	Shear-Controlled
	8	2L0U-2S8	Strengthened Control	#2@8"	0.0011	169	95	Shear-Controlled
	9	2L1U-2S8	Strengthened (With U-wraps)	#2@8"	0.0011	185	127	Shear-Controlled
	10	2L2U-2S8	Strengthened (With U-wraps)	#2@8"	0.0011	194	139	Shear-Controlled
	11	2L1UA-2S8	Strengthened (With U-wraps+Spike Anchors)	#2@8"	0.0011	201	147	Shear-Controlled
	12	2L2UA-2S8	Strengthened (With U-wraps+Spike Anchors)	#2@8"	0.0011	201	202	Flexure-Controlled
C	13	0L0U-4S8	Unstrengthened Control	#4@8"	0.0042	136	218	Flexure-Controlled
	14	2L0U-4S8	Strengthened Control	#4@8"	0.0042	169	218	Flexure-Controlled
	15	2L1U-4S8	Strengthened (With U-wraps)	#4@8"	0.0042	185	250	Flexure-Controlled
	16	2L2U-4S8	Strengthened (With U-wraps)	#4@8"	0.0042	194	262	Flexure-Controlled
	17	2L2U-4S8	Strengthened (With 24" U-wrap)	#4@8"	0.0042	194	270	Flexure-Controlled
	18	2L2UA-4S8	Strengthened (With 24" U-wrap+Spike Anchors)	#4@8"	0.0042	201	280	Flexure-Controlled

Test Setup

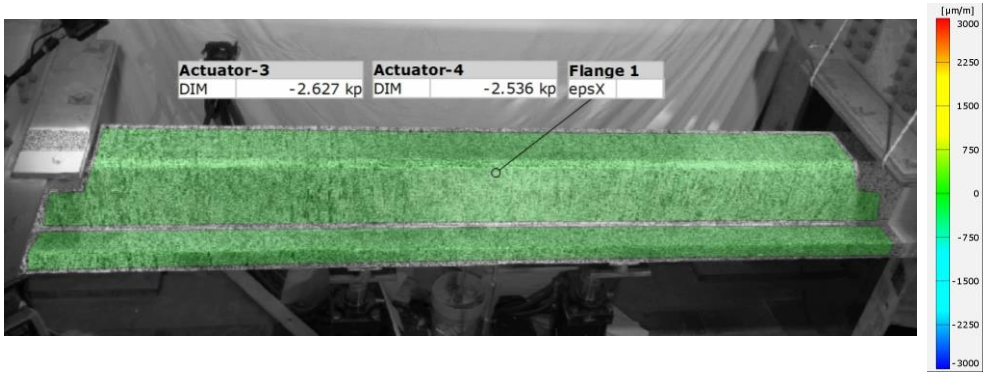

DIC Cameras
T-Beam
Actuators


Tension Face of Inverted T-Beam
Plate (6"x24"x½")
Plate (12"x24"x1")
2" ϕ Rolling Rod
Actuator (150 kip)
Bottom Plate (30"x30"x1¾")
3'-2"

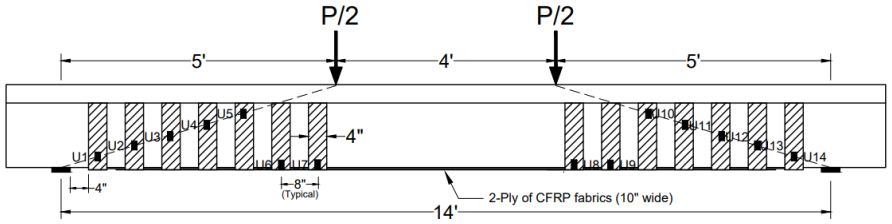
Test Setup – DIC System



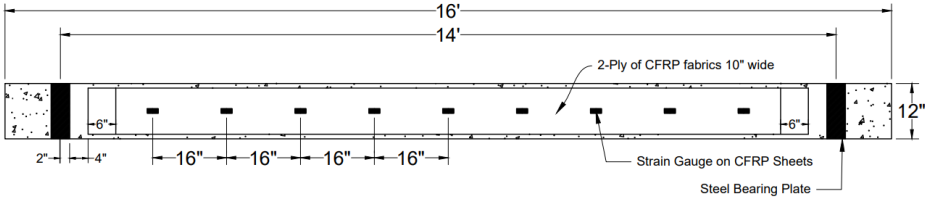
2L1U-2S8



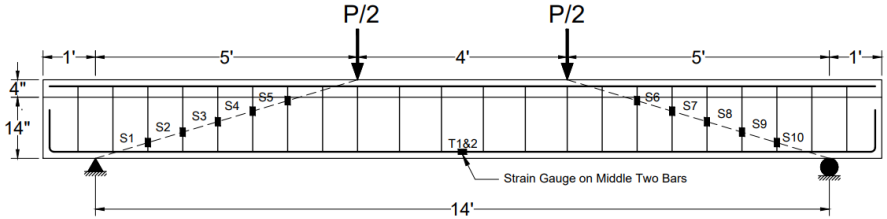
Beam Instrumentation



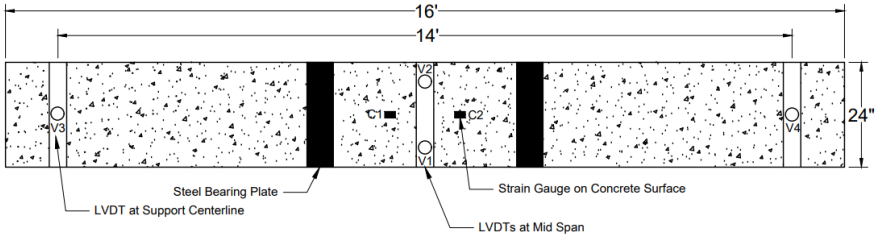
Strain Gauges on U-Wraps



Plan View (Tension Face)

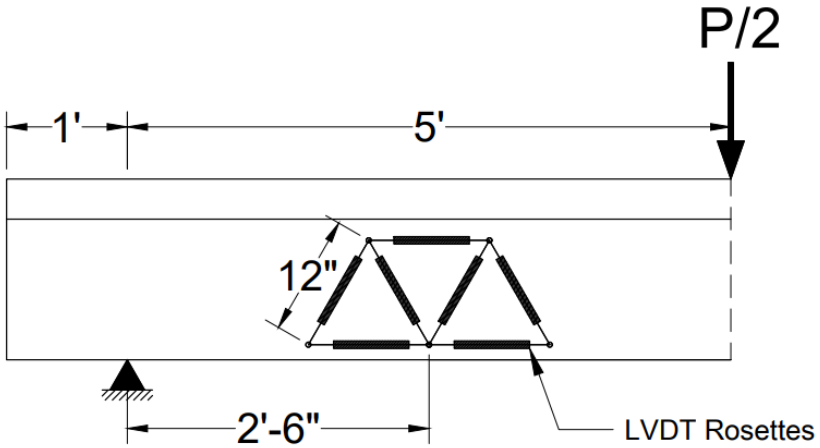


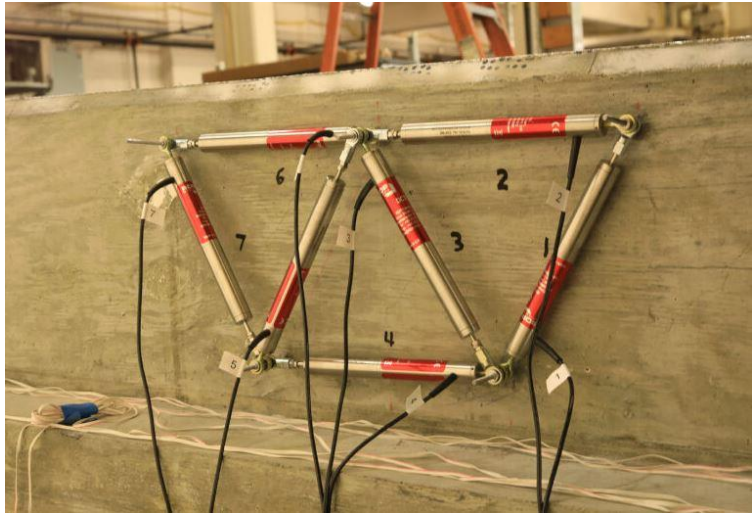
Strain Gauges on Internal Steel



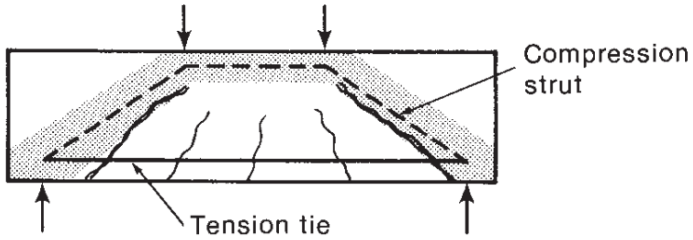
Plan View (Compression Face)

Beam Instrumentation

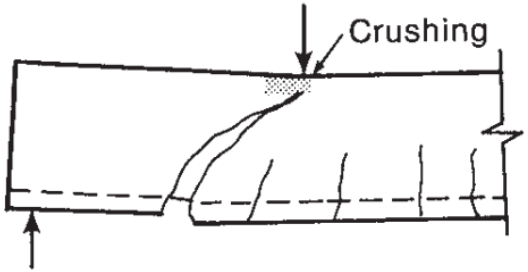




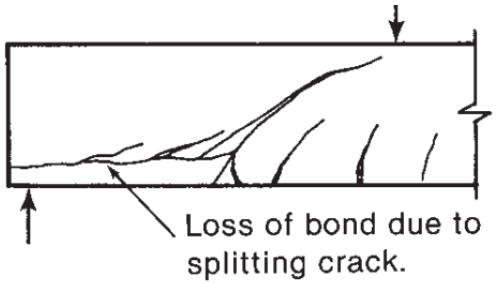
Expected Shear Failure Type



(i) Deep Beam Failure (a/d < 1)



(ii) Shear-Compression Failure (1 < a/d < 2.5)

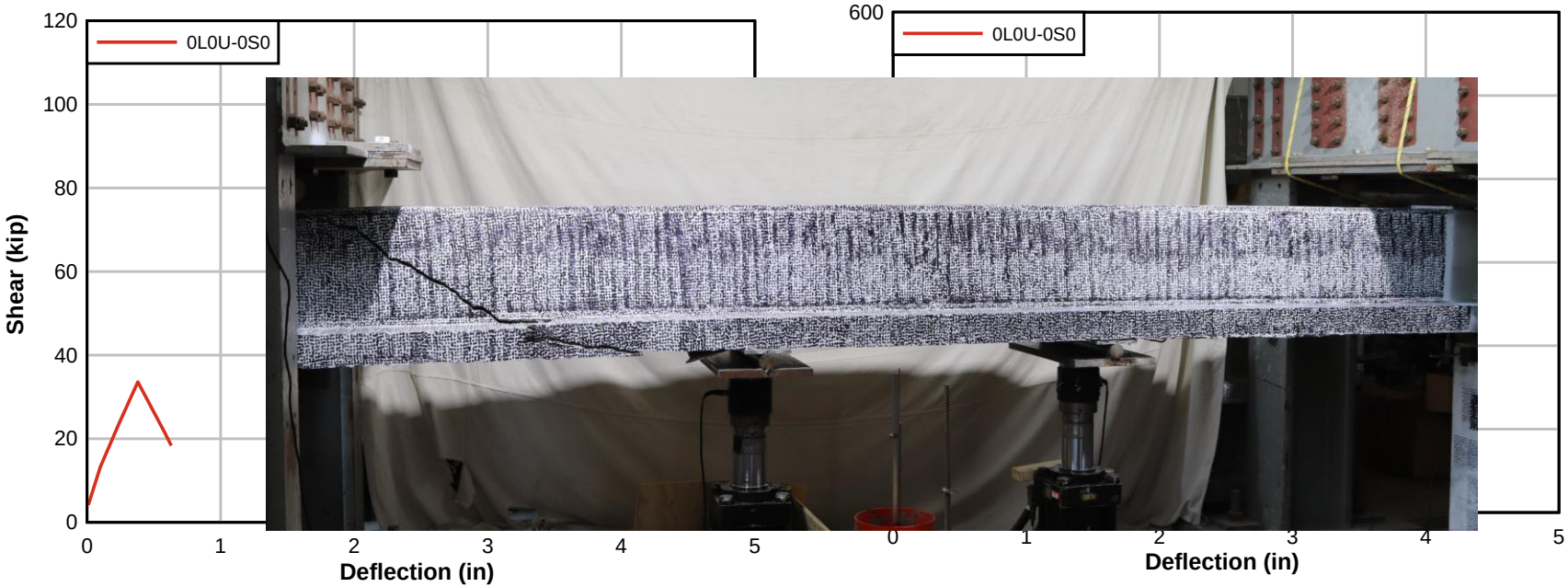


(iii) Shear-Tension Failure (2.5 < a/d < 6)

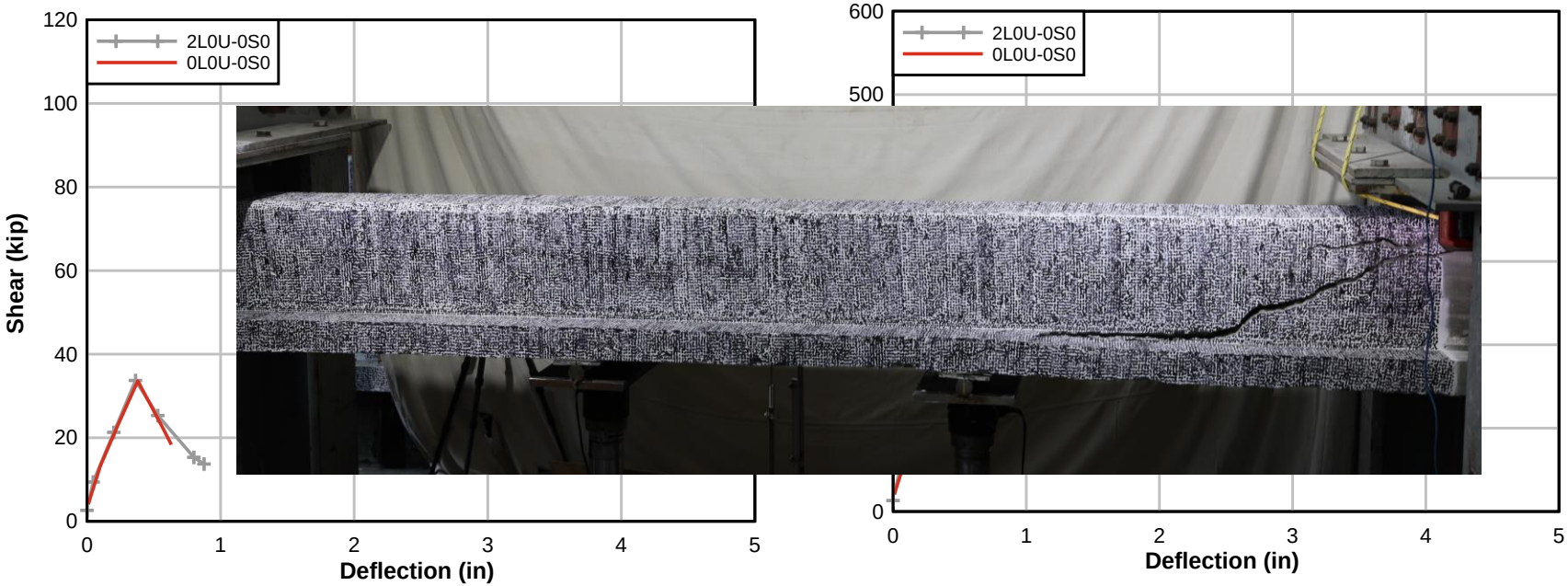
Diagonal-tension failure was anticipated due to a shear Span-to-depth ratio (a/d = 3.90) for all shear-critical beams.

(Adopted from Wight and MacGregor, 2012)

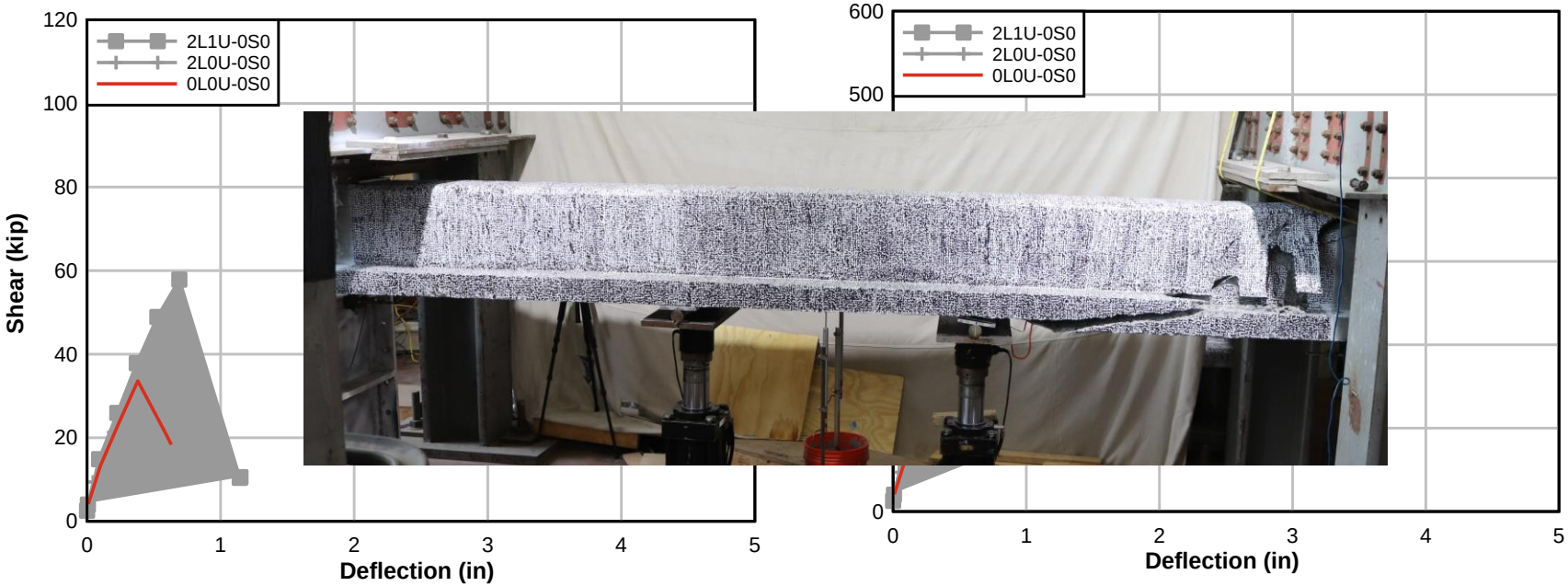
Experimental Results: Group A



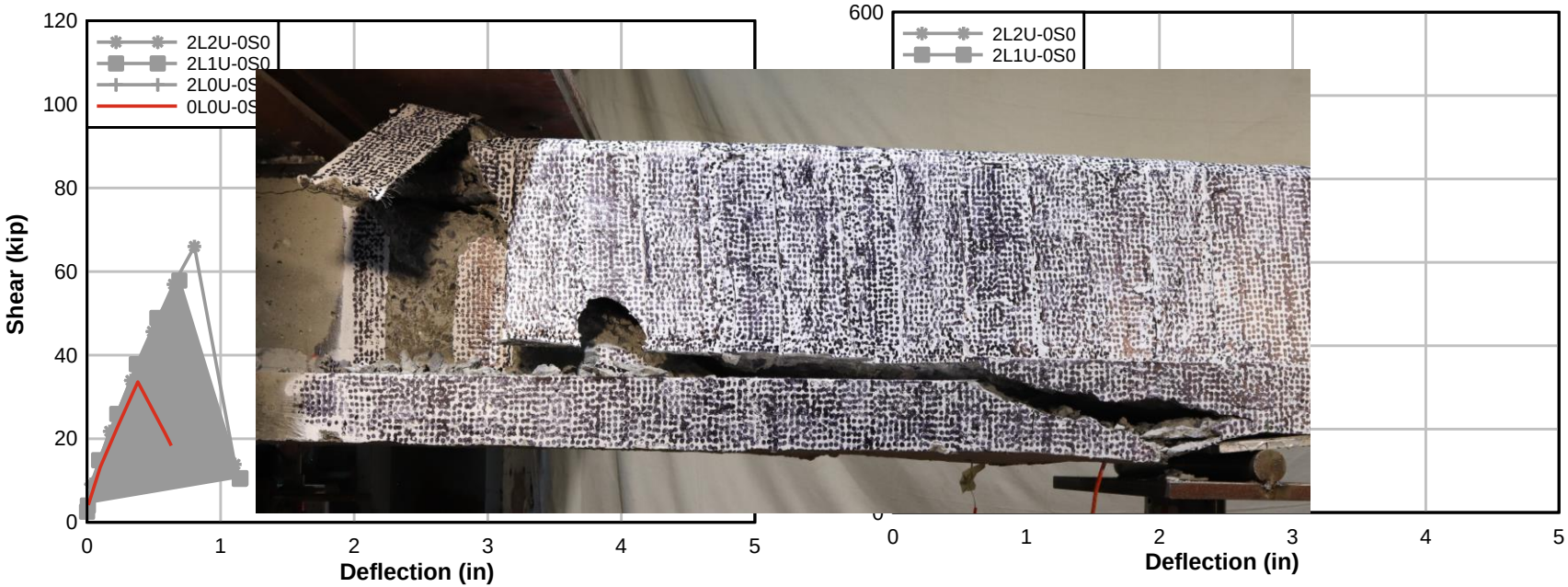
Experimental Results: Group A



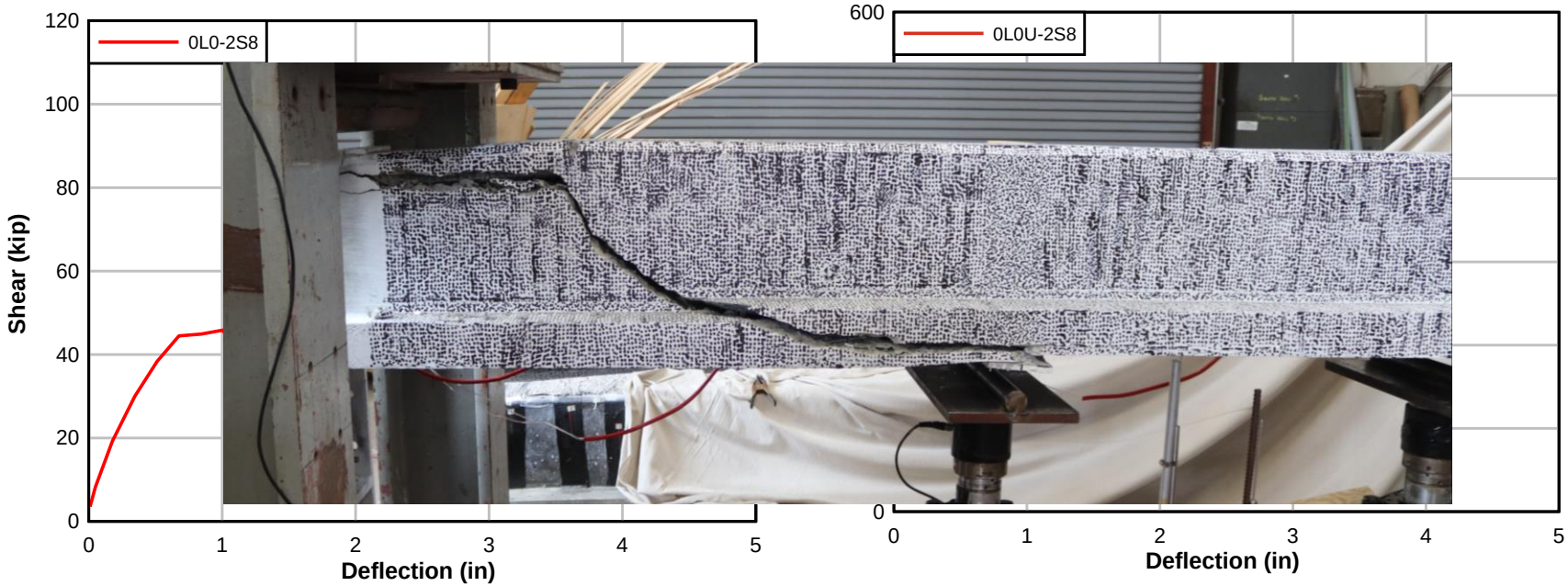
Experimental Results: Group A



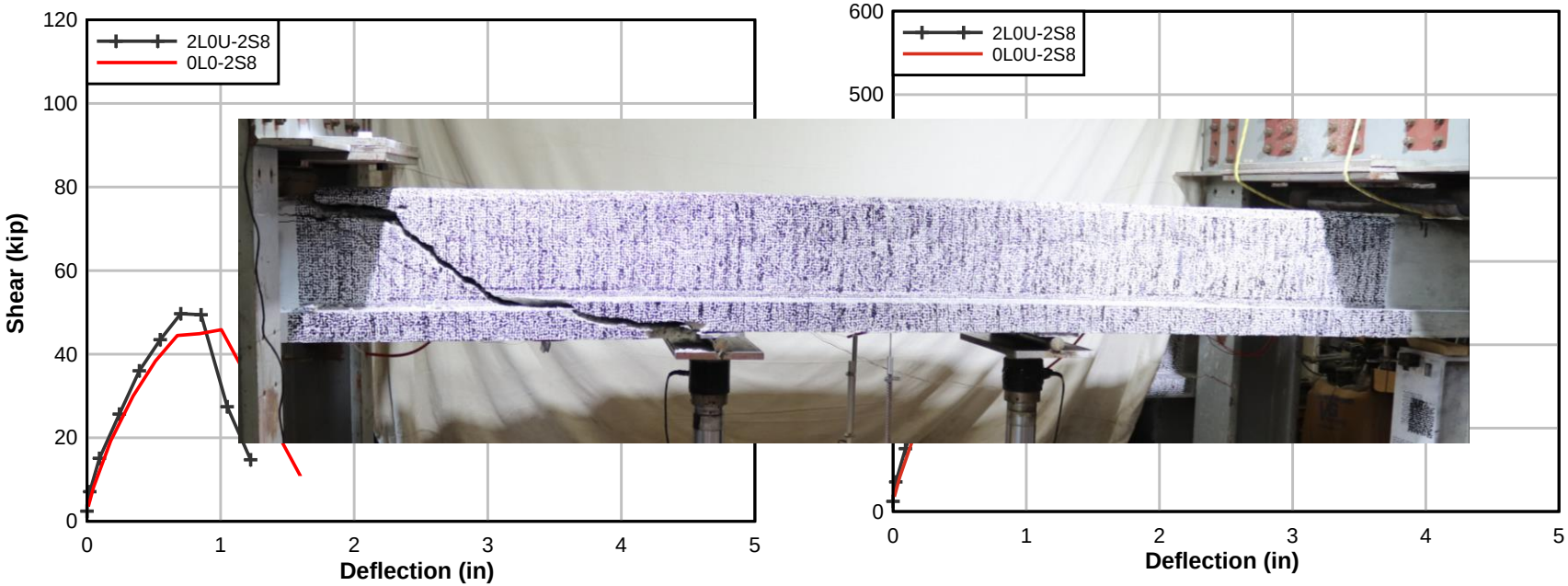
Experimental Results: Group A



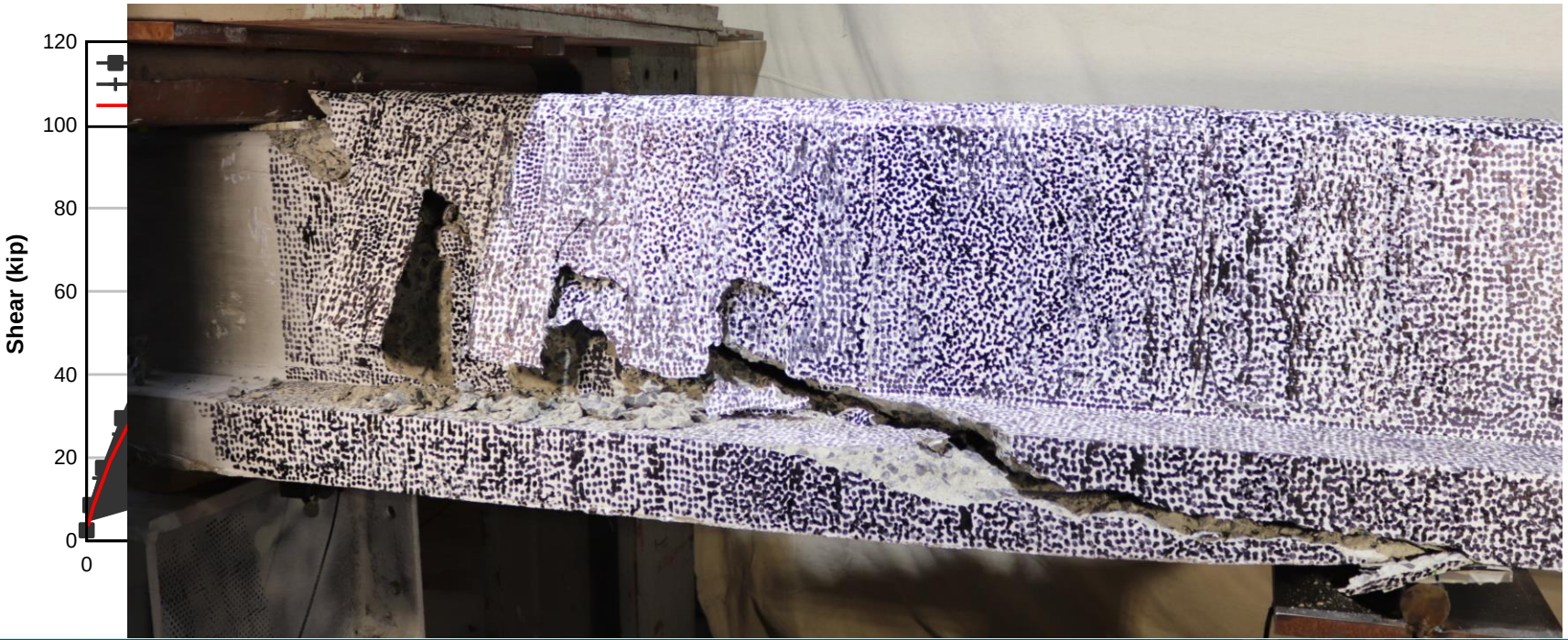
Experimental Results: Group B



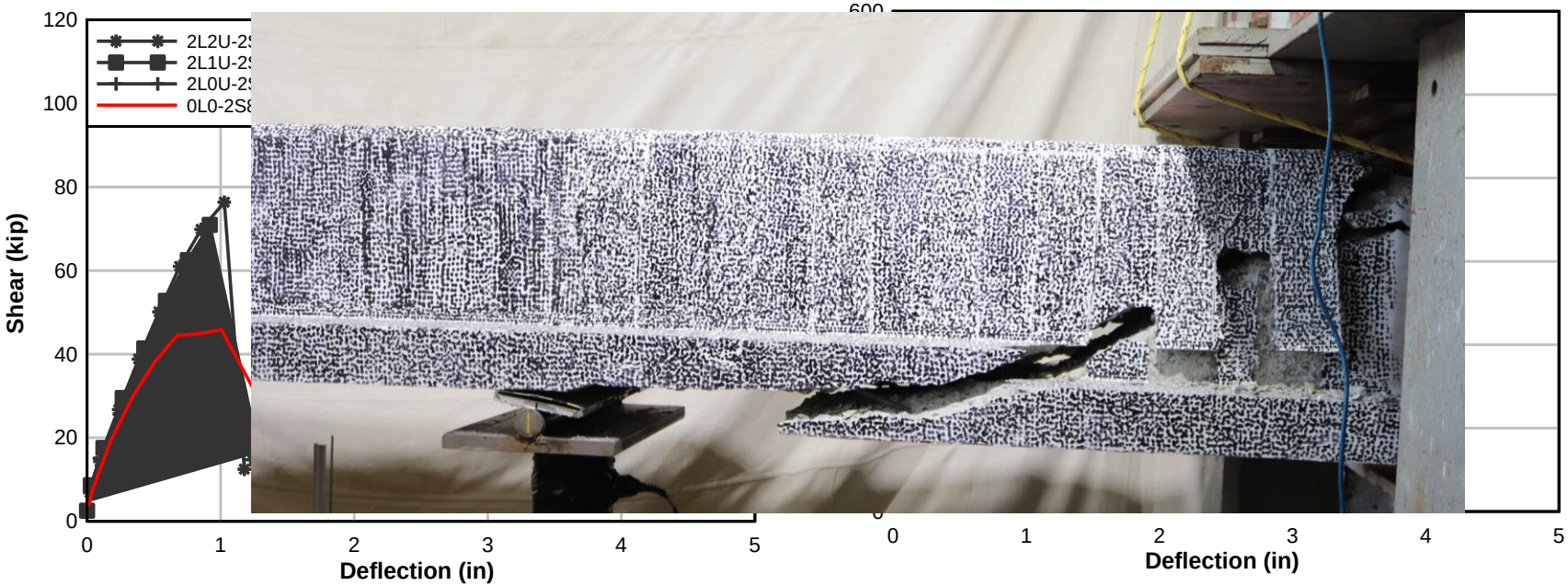
Experimental Results: Group B



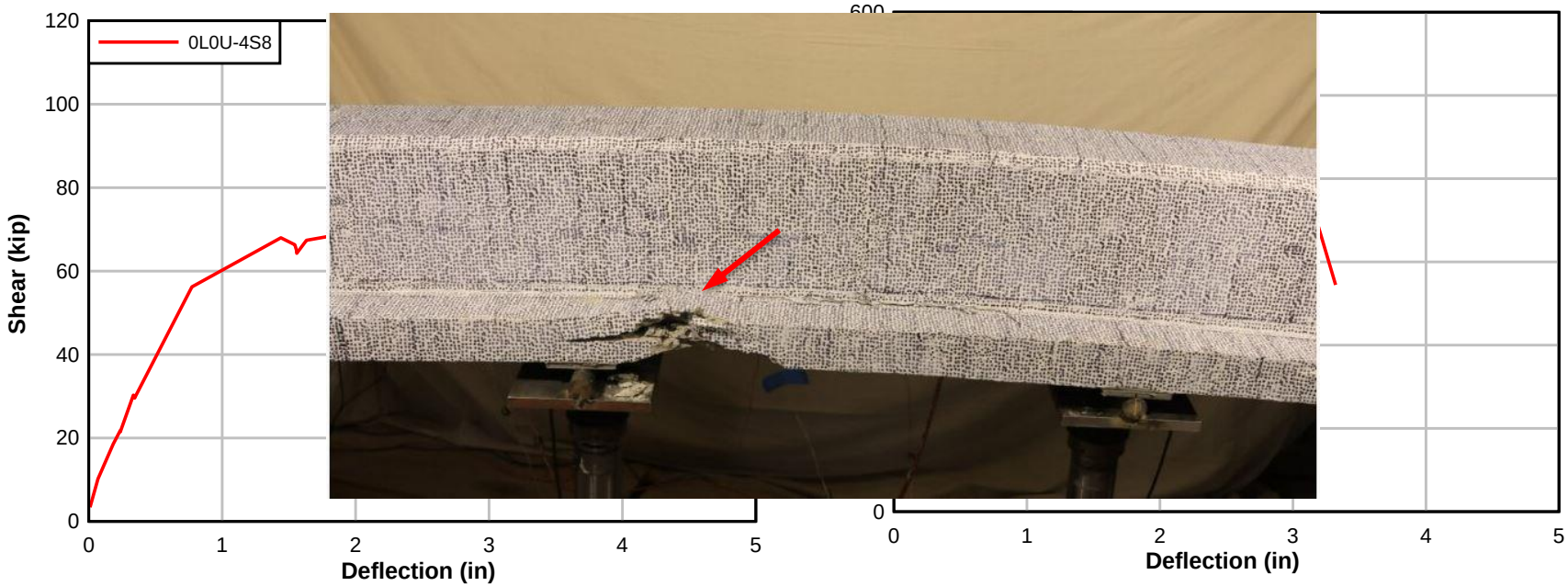
Experimental Results: Group B



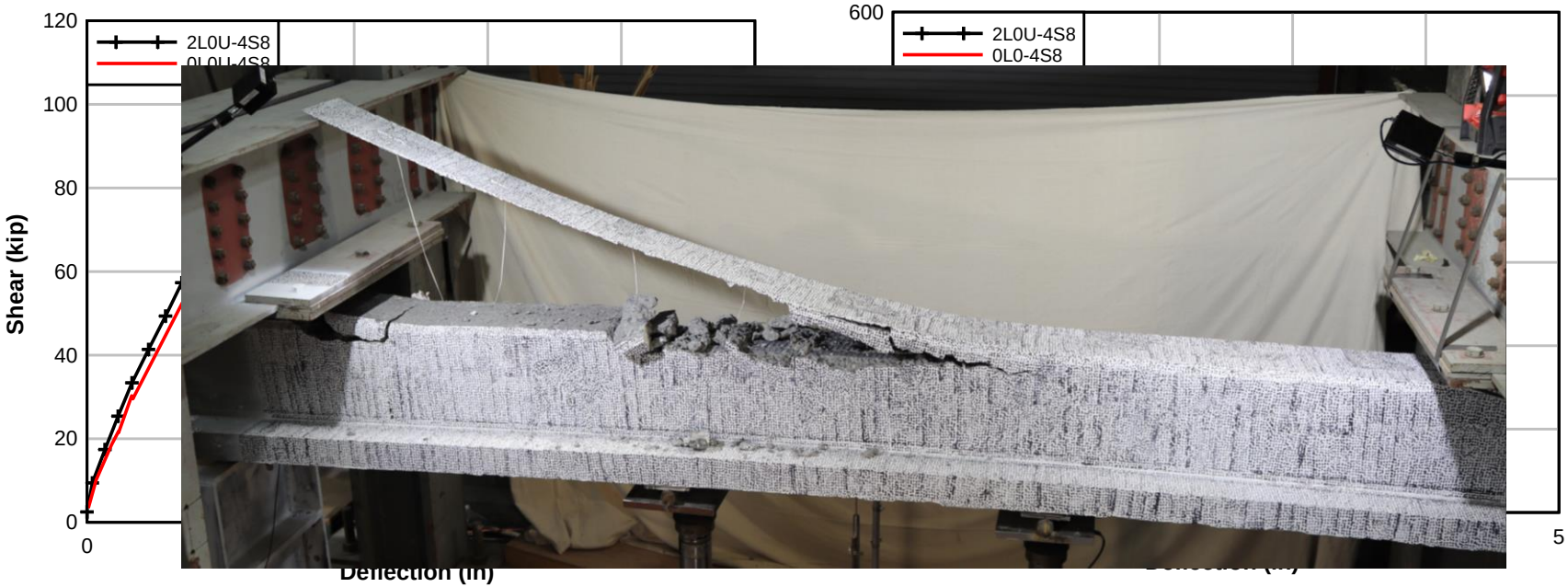
Experimental Results: Group B



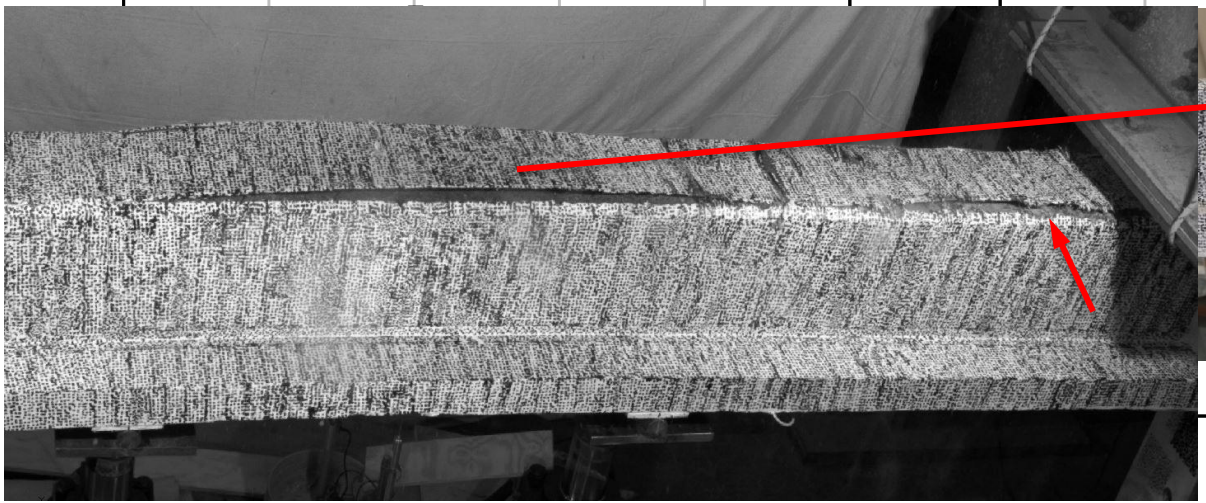
Experimental Results: Group C

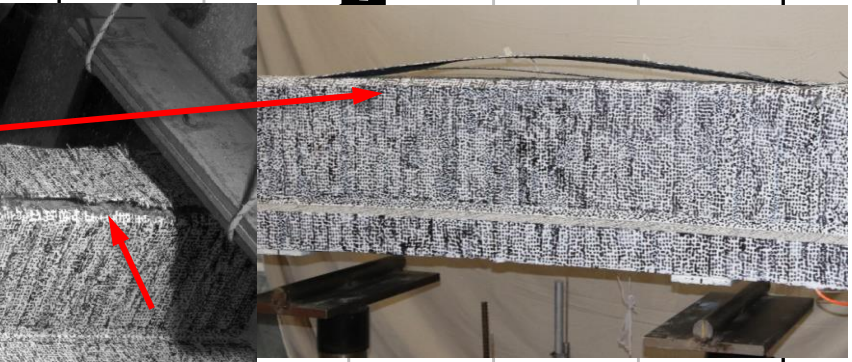


Experimental Results: Group C

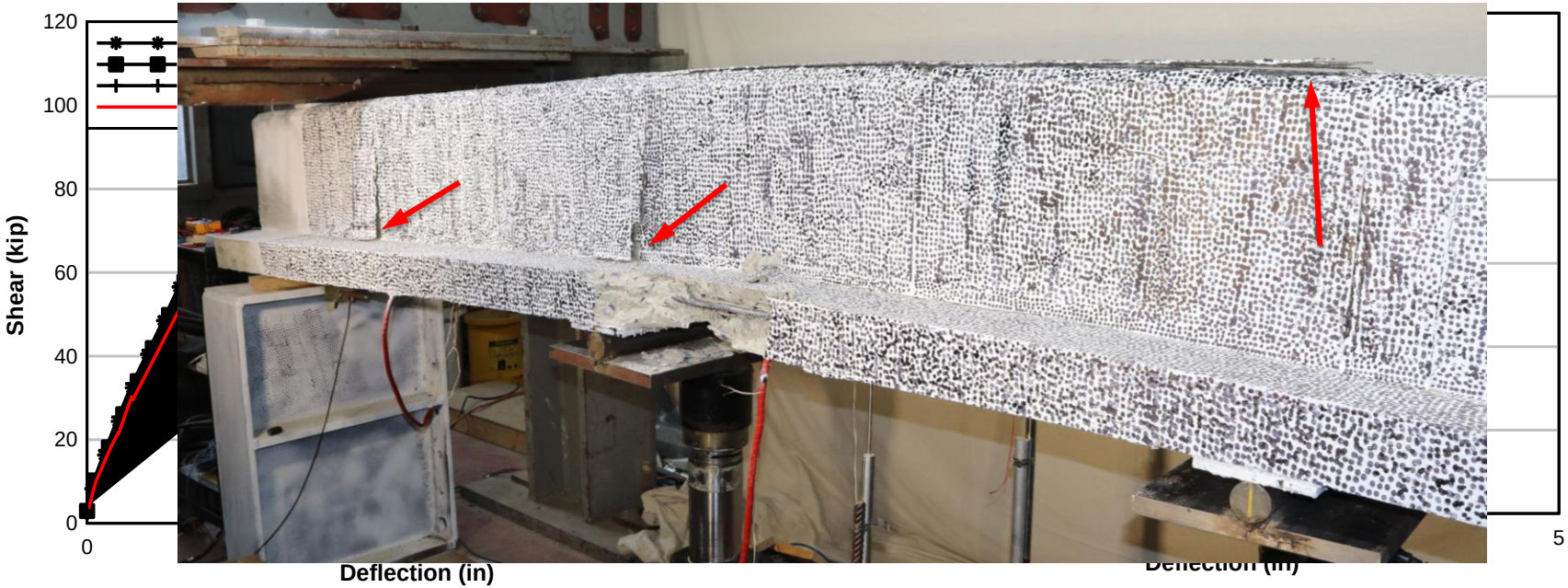


Experimental Results: Group C



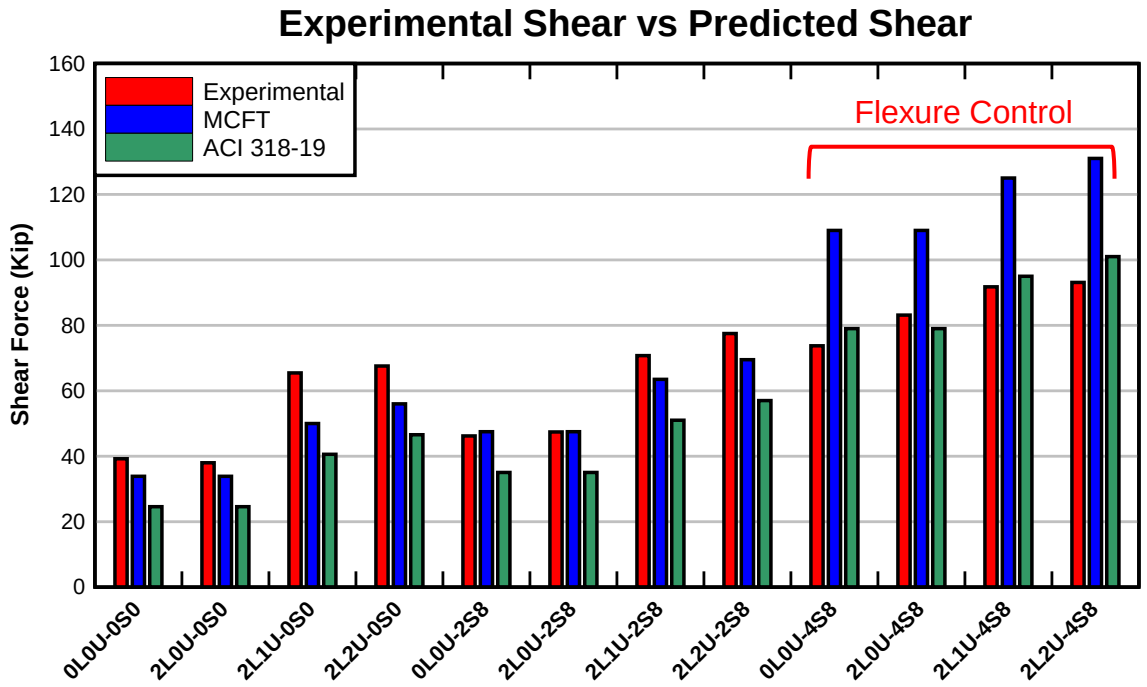


Experimental Results: Group C



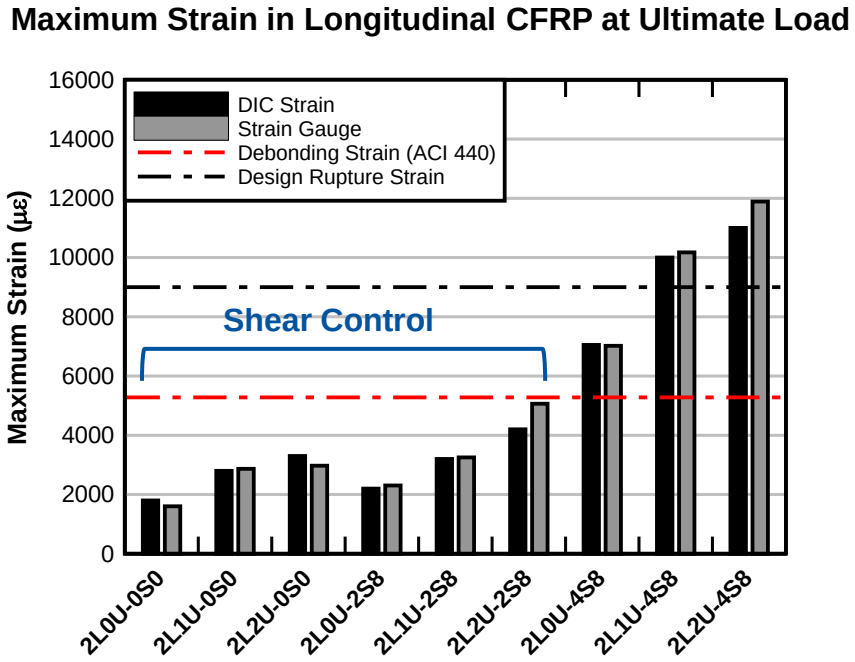
Experimental Results

- The experimental shear capacity of all specimens is greater than the theoretically calculated value.
- ACI predicted values are more conservative compared to experimental and MCFT values.
- MCFT values are close to experimental values.



Experimental Results

- U-Wraps allowed longitudinal CFRP to exceed the ACI debonding strain
- Increase in strain with the increase in the number of plies in the U-Wraps
- Shear-Control specimen experience low strain in longitudinal CFRP



Experimental Results

Maximum Strain in Longitudinal CFRP at Ultimate Load

Beam	Experimental (με)	Back Calculated (με)*	Exp./Calculated
2L0U-0S0	1602	1440	1.11
2L1U-0S0	2868	2675	1.07
2L2U-0S0	2973	2835	1.05
2L0U-2S8	2305	2106	1.09
2L1U-2S8	3252	2969	1.10
2L2U-2S8	5064	4085	1.24
2L0U-4S8	7021	6776	1.04
2L1U-4S8	10175	9567	1.06
2L2U-4S8	11890	10100	1.18

*Back calculated strains are computed from ACI 440 equations using experimental moment values

Experimental Results

U-wraps Shear Contributions in Shear-Critical Beams (kip)

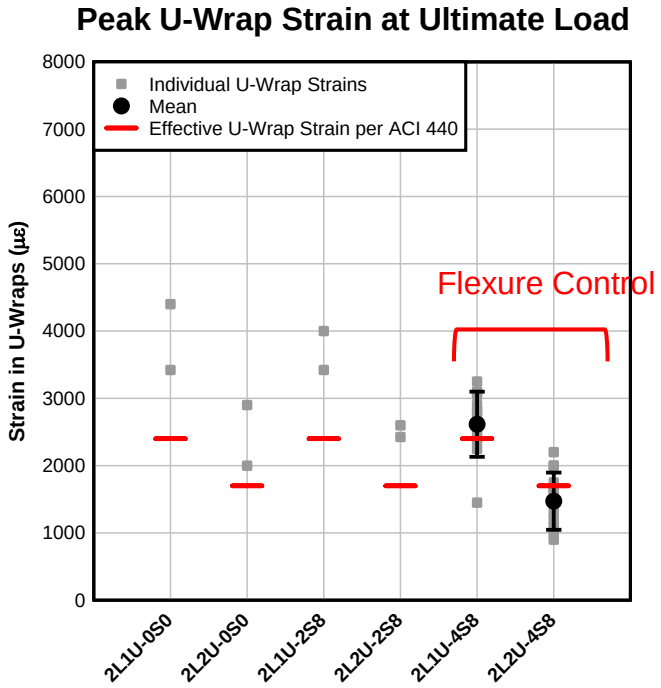
Beam	Experimental ($V_{f,exp}$)	ACI 440 ($V_{f,th}$)	$V_{f,exp}/V_{f,th}$
2L1U-0S0	26	16	1.63
2L2U-0S0	29	22	1.32
2L1U-2S8	25	16	1.56
2L2U-2S8	31	22	1.41

U-Wrap Strain in Shear-Critical Beams (με)

Beam	Experimental (Mean)*	Back Calculated**	Exp./Back Calculated
2L1U-0S0	3911	4049	0.97
2L2U-0S0	2450	2188	1.12
2L1U-2S8	3710	3758	0.99
2L2U-2S8	2512	2396	1.05

*Experimental strains are the average of the two U-wrap strain engaged at the shear failure plane.

**Back calculated strains are computed from ACI 440 equation using experimental shear contribution of U-wraps



Conclusions

- U-Wrap increases beam shear strength by 70% in shear-critical beams and moment strength by 28% in flexural control specimens.
- U-wraps resulted in an increase of maximum strain in the longitudinal CFRP by 137 % compared ACI 440 debonding strain.
- Shear contribution of 2-ply U-wraps was not significant compared to 1-ply; however, the failure mode changes from U-wrap rupture to debonding.
- U-Wraps shift failure mode from flexure CFRP debonding to rupture or U-wrap debonding in flexure control group.
- Strains in U-Wraps exceeded the ACI 440 effective strain in all shear critical beams.

Future Work and Recommendations

- To investigate the effect of inclined U-wrap configuration
- To investigate the performance of pre-cured CFRP plates
- To investigate the effect of different CFRP properties for U-wrap and flexure reinforcement

Acknowledgements

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NEX
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University of Delaware

SIMPSON
Strong-Tie