

**STRENGTH AND DURABILITY OF
NEAR-SURFACE MOUNTED CFRP BARS
FOR SHEAR STRENGTHENING
REINFORCED CONCRETE BRIDGE
GIRDERS**

Final Report

**SPR 712
APPENDICES**



Oregon Department of Transportation

APPENDIX A:

DEFINITIONS

Carbon Fiber Reinforcing Polymer (CFRP): A composite material made from carbon fibers and resin. It can be manufactured into strips, rods, or sheets.

CFRP bar: A thin piece of carbon fiber reinforcing of any cross-section with fibers oriented in the uniaxial direction.

CFRP rod: A round cross-section reinforcing bar with fibers oriented in the uniaxial direction.

CFRP sheet: Woven reinforcing used as external concrete reinforcing with fibers oriented in a biaxial or uniaxial direction.

CFRP strip or tape: A primarily rectangular cross-section reinforcing bar with fibers oriented in the uniaxial direction.

Externally Bonded Reinforcement (EBR): Method used to bond supplemental reinforcing to the surface of concrete with an adhesive. It is commonly done by wrapping sheets of reinforcement in a U-shape around the outside of a girder.

Near-Surface Mounted (NSM): A technique used to attach supplemental reinforcing to the concrete substrate that consists of cutting rectangular grooves into the surface of a concrete member and filling them with adhesive and a retrofitting material.

APPENDIX B:
EXPERIMENTAL DATA

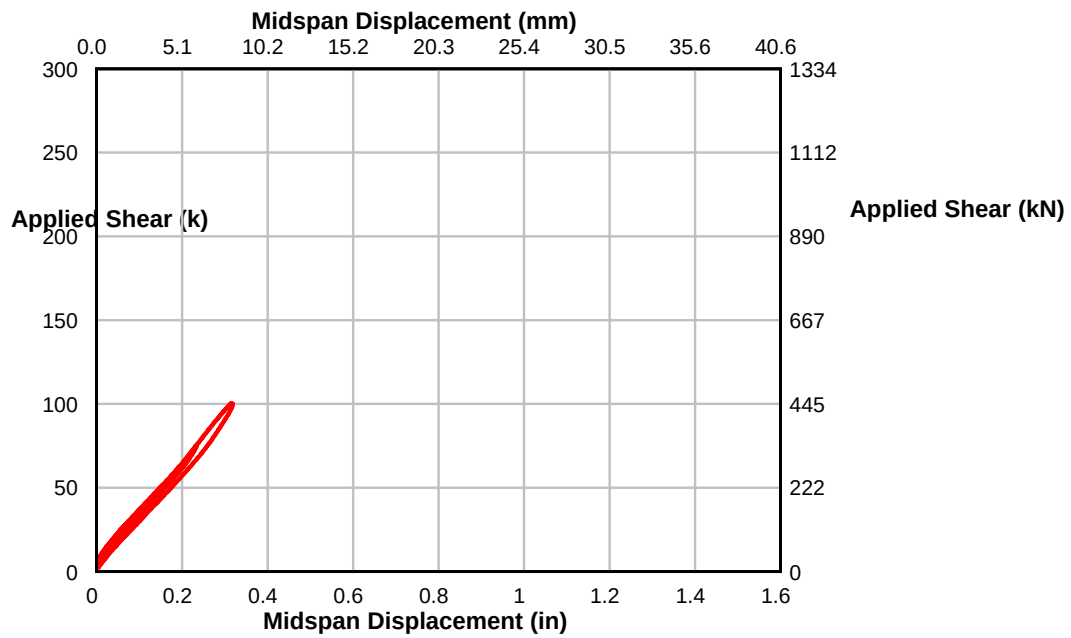


Figure B-1: Specimen T.6.18.6.S applied shear - midspan disp. (precrack test)

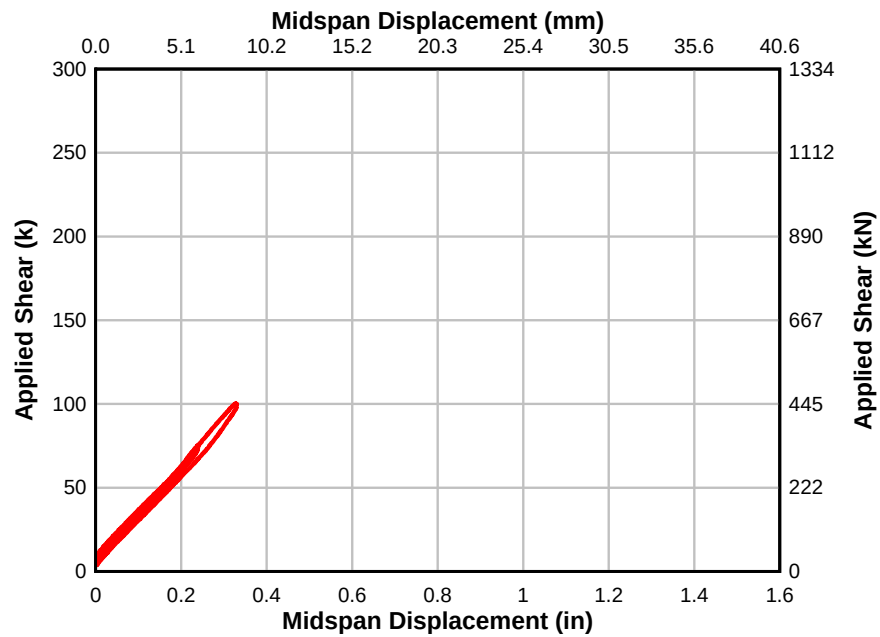


Figure B-2: Specimen T.6.18.12.S applied shear - midspan disp. (precrack test)

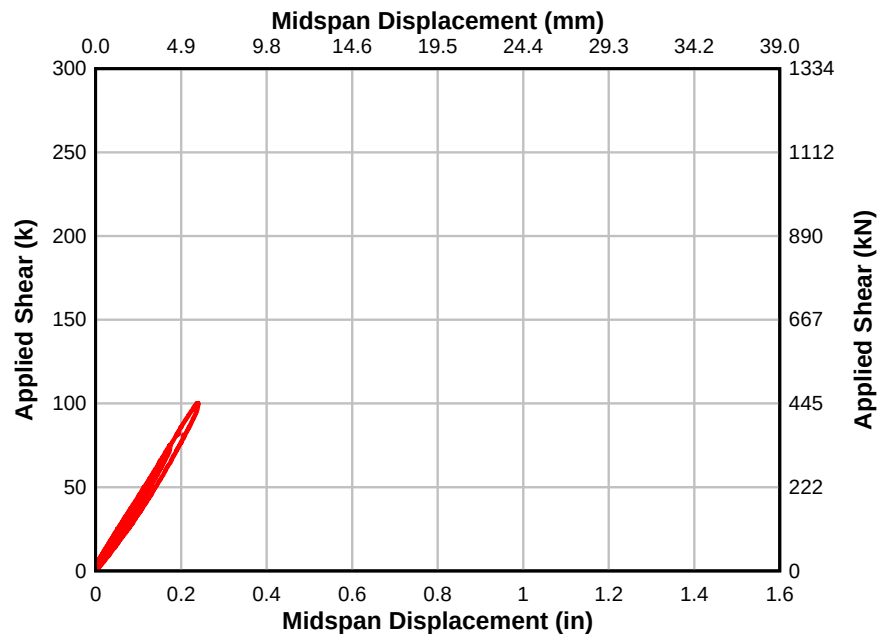


Figure B-3: Specimen IT.7.18.6.S applied shear - midspan disp. (precrack test)

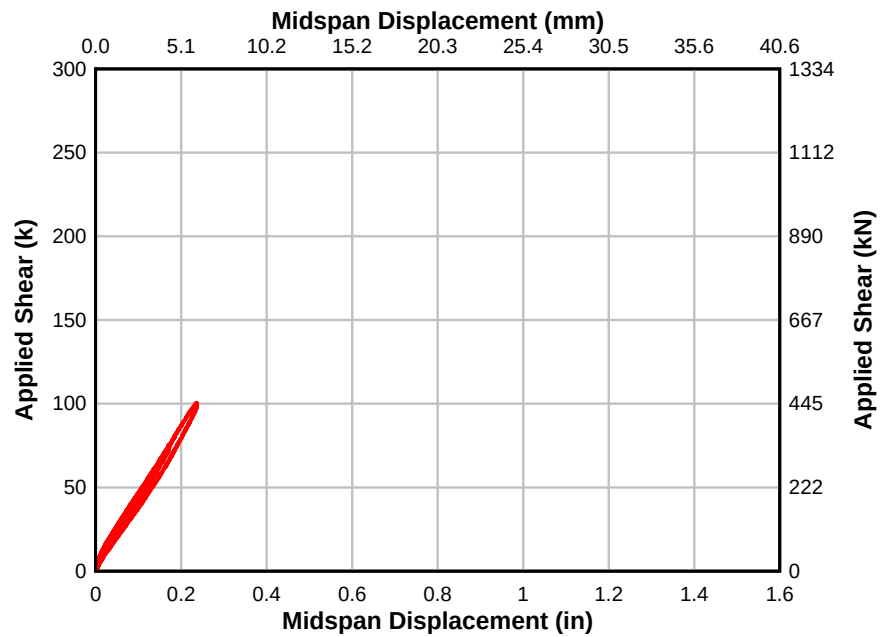


Figure B-4: Specimen IT.7.18.12.S applied shear - midspan disp. (precrack test)

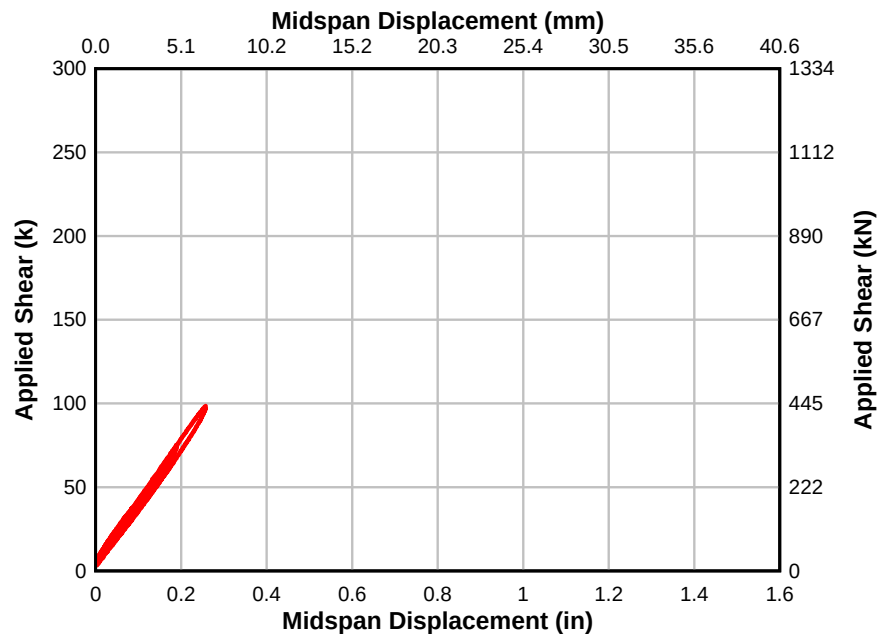


Figure B-5: Specimen IT.5.22.12*.S applied shear - midspan disp. (precrack test)

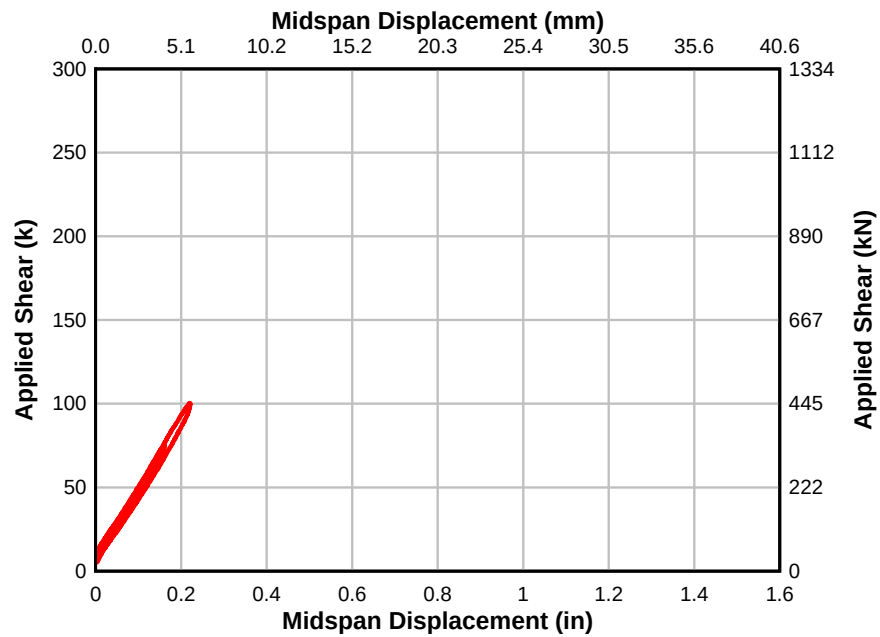


Figure B-6: Specimen IT.7.22.6.S applied shear - midspan disp. (precrack test)

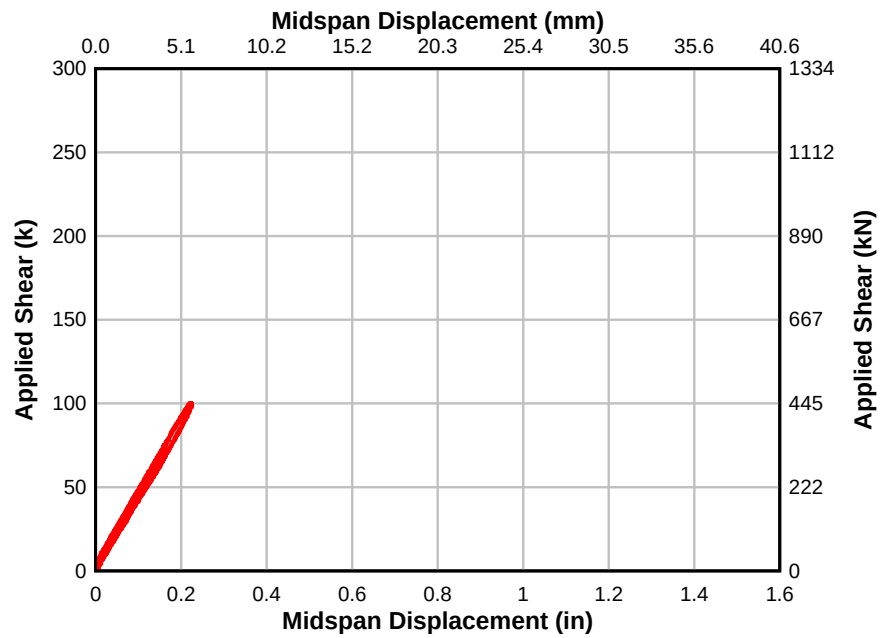


Figure B-7: Specimen IT.7.22.6.FTG applied shear - midspan disp. (precrack test)

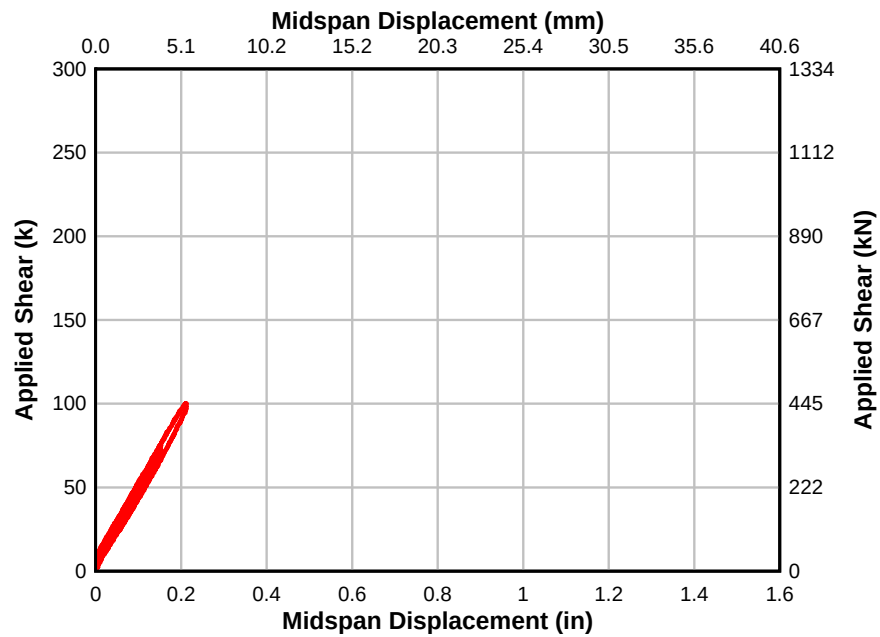


Figure B-8: Specimen IT.7.22.6.FT/FTG applied shear - midspan disp. (precrack test)

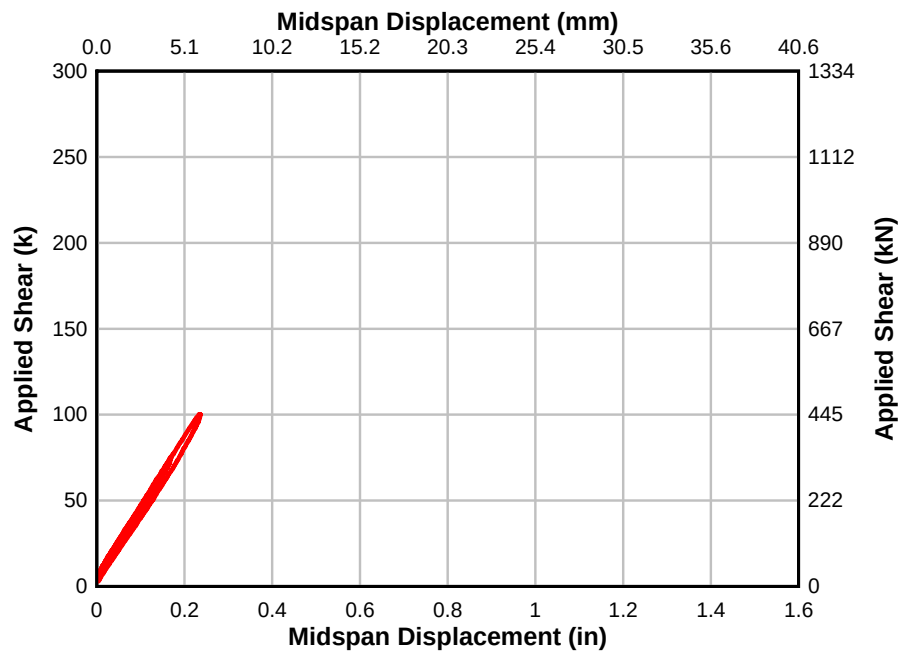


Figure B-9: Specimen IT.7.18.6.M applied shear vs. midspan disp. (baseline test)

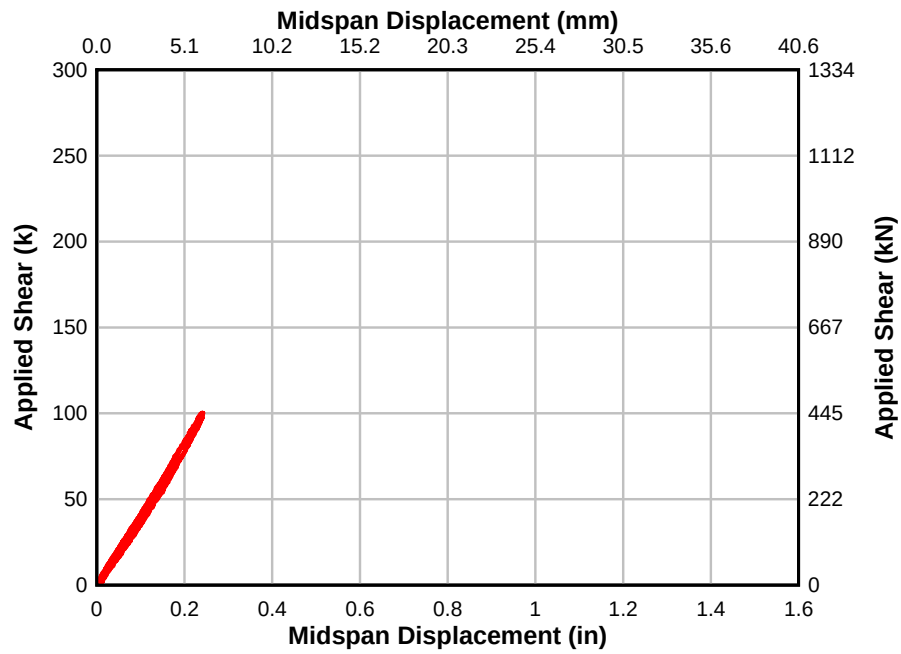


Figure B-10: Specimen IT.7.22.6.FT applied shear vs. midspan disp. (baseline test)

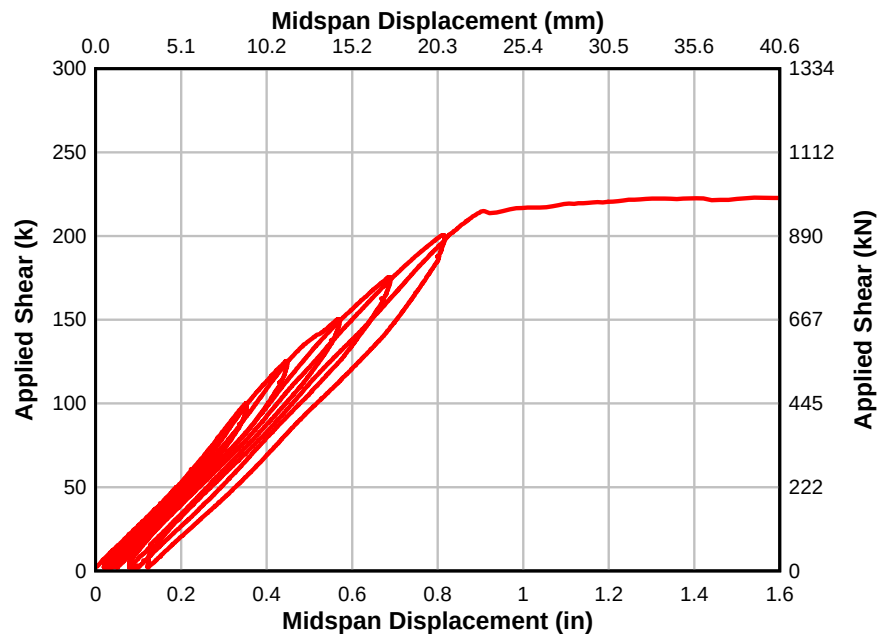


Figure B-11: Specimen T.6.18.6.S applied shear - midspan disp. (failure test)

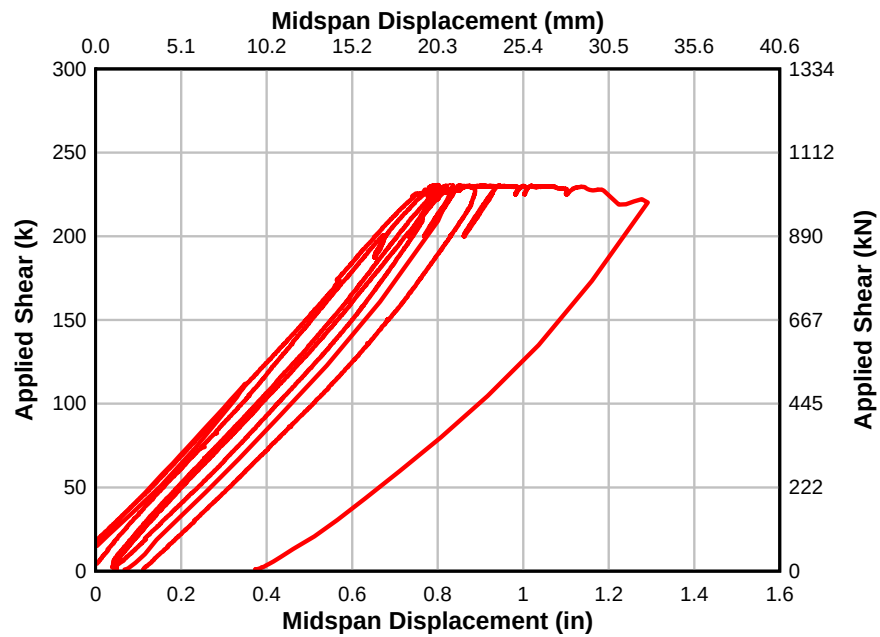


Figure B-12: Specimen T.6.18.12.S applied shear - midspan disp. (failure test)

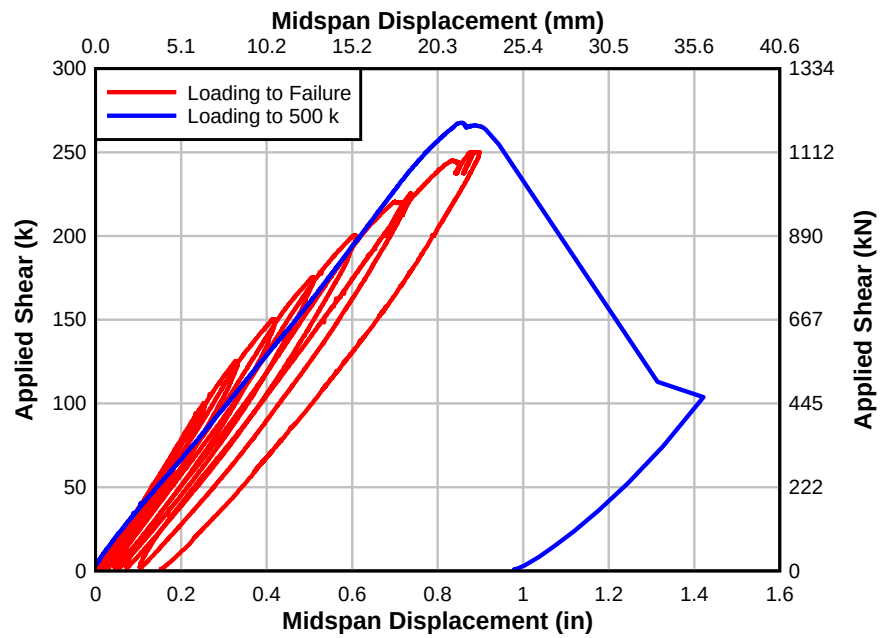


Figure B-13: Specimen IT.7.18.6.S applied shear - midspan disp. (failure test)

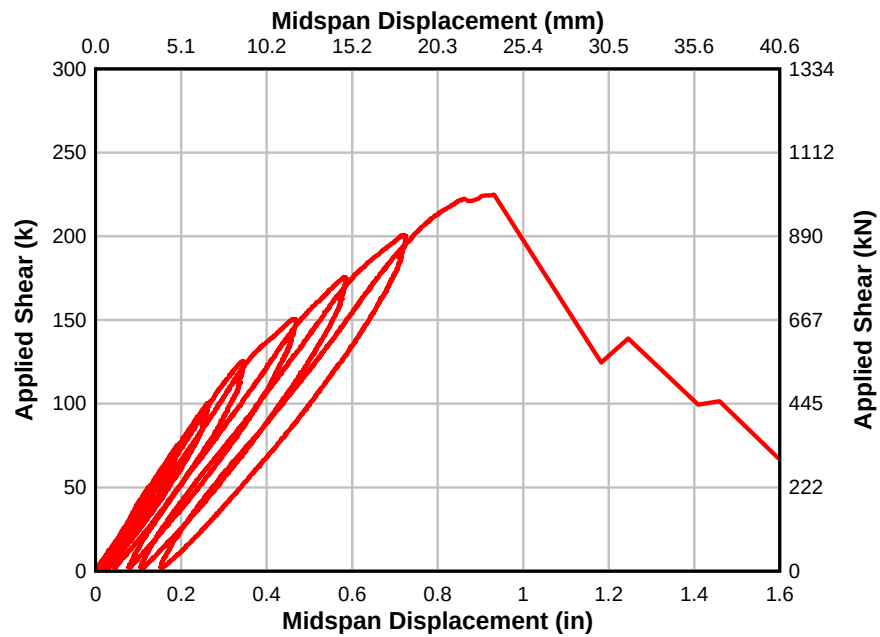


Figure B-14: Specimen IT.7.18.12.S applied shear - midspan disp. (failure test)

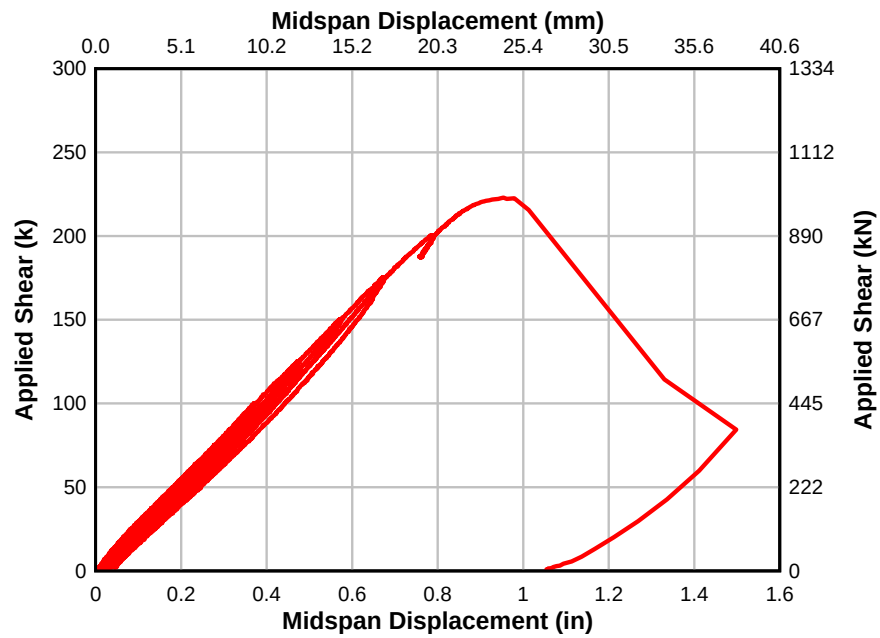


Figure B-15: Specimen IT.5.22.12*.S applied shear - midspan disp. (failure test)

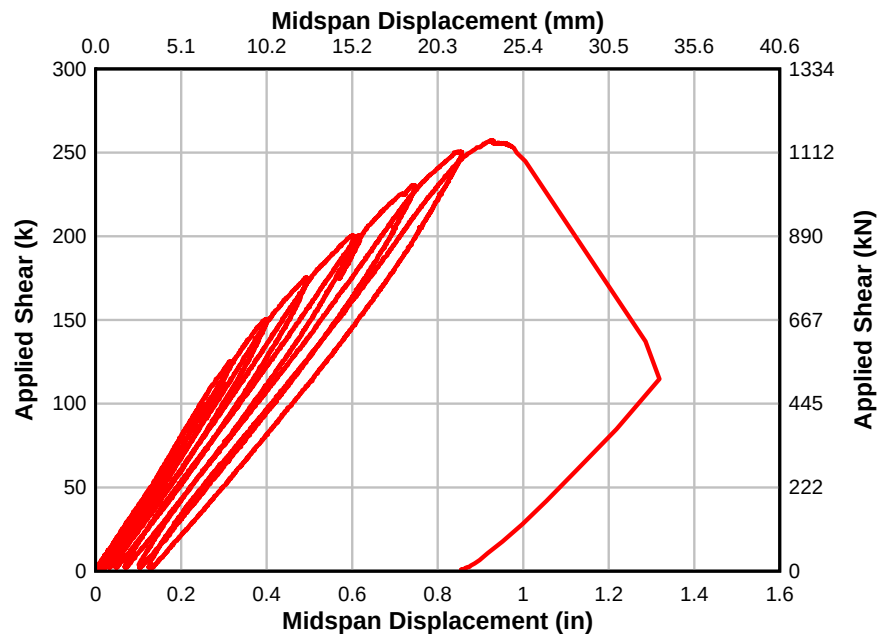


Figure B-16: Specimen IT.7.22.6.S applied shear - midspan disp. (failure test)

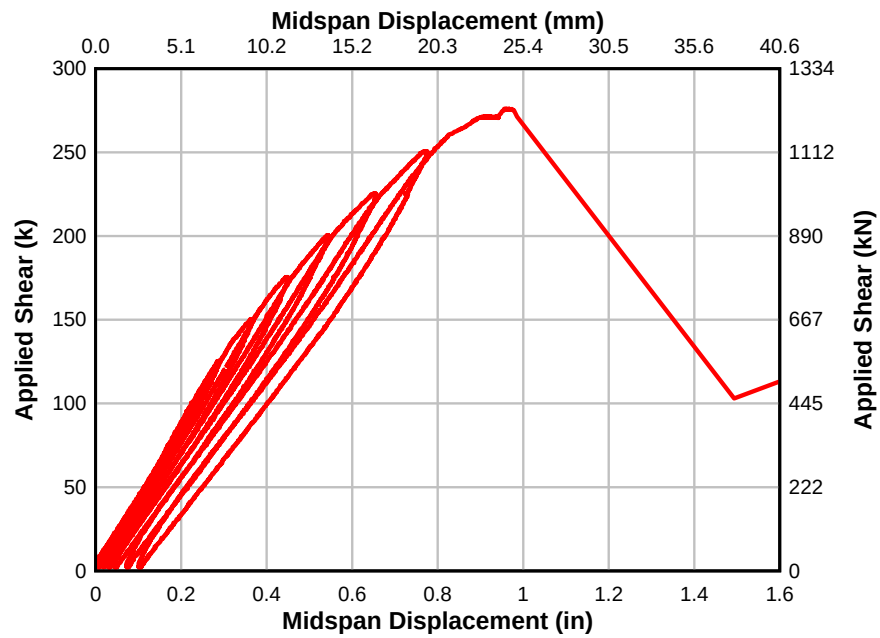


Figure B-17: Specimen IT.7.22.6.FTG applied shear - midspan disp. (failure test)

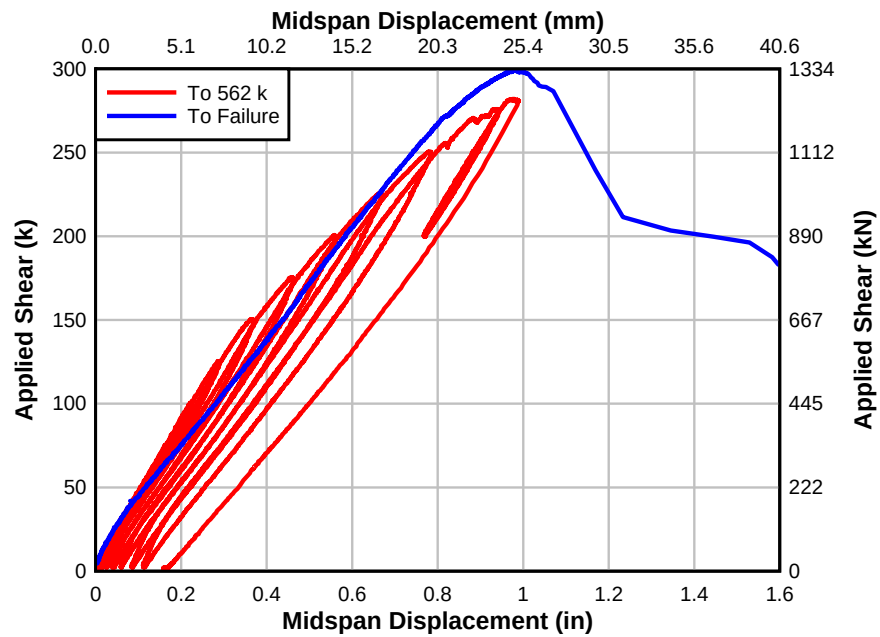


Figure B-18: Specimen IT.7.22.6.FT/FTG applied shear - midspan disp. (failure test)

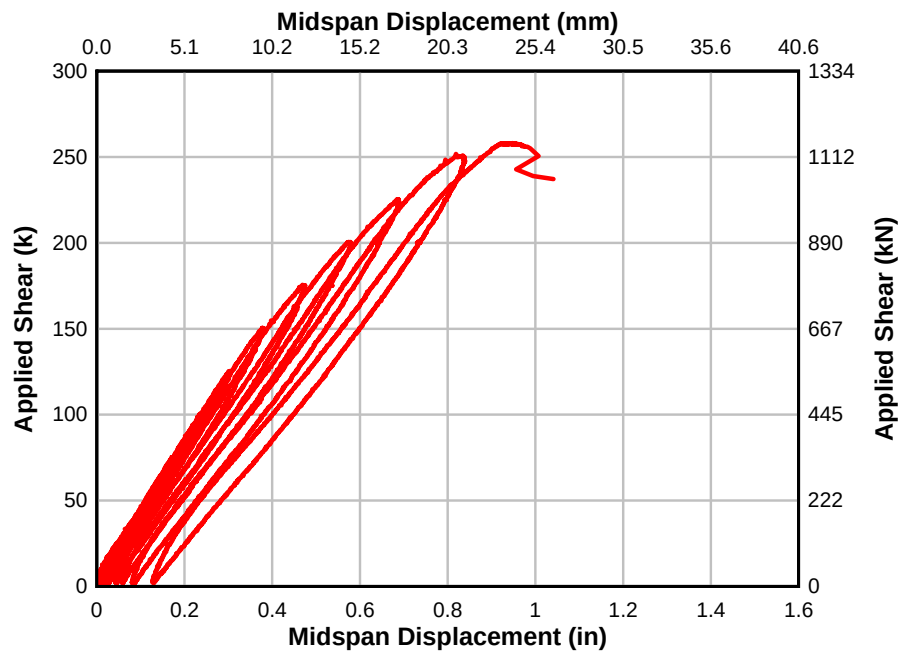


Figure B-19: Specimen IT.7.18.6.M applied shear vs. midspan disp. (failure test)

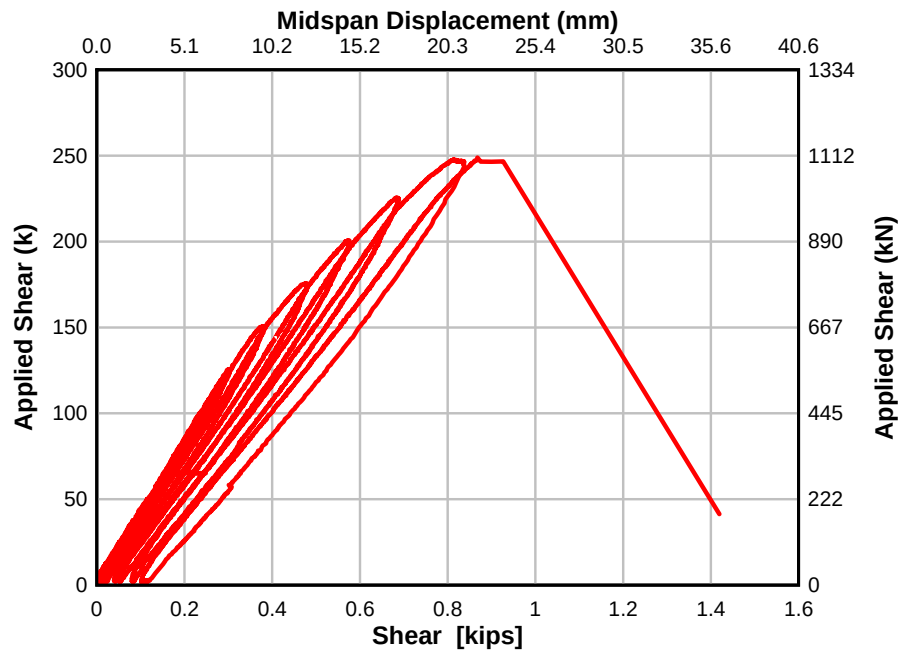


Figure B-20: Specimen IT.7.22.6.FT applied shear vs. midspan disp. (failure test)

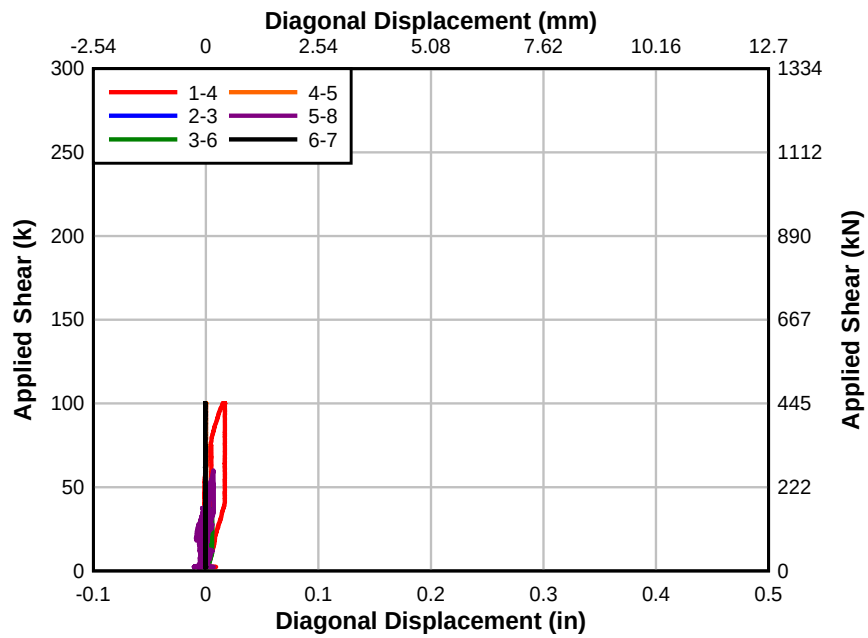


Figure B-21: Specimen T.6.18.6.S applied shear - diagonal disp. (precrack test)

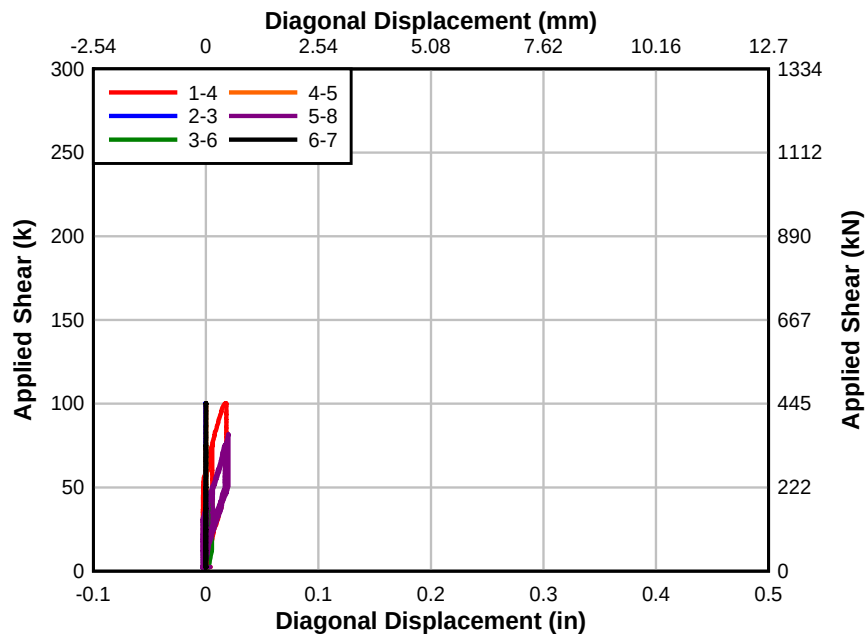


Figure B-22: Specimen T.6.18.12.S applied shear - diagonal disp. (precrack test)

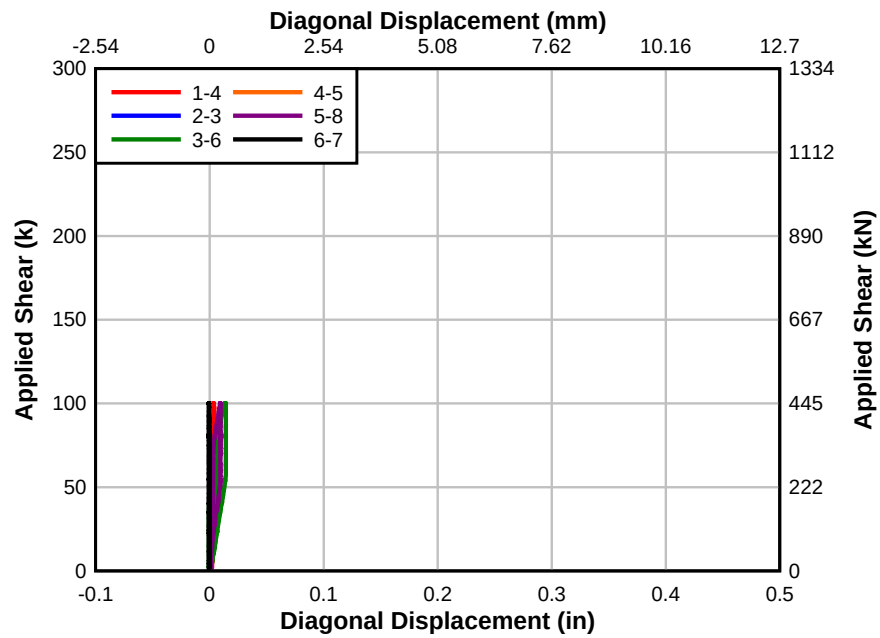


Figure B-23: Specimen IT.7.18.6.S applied shear - diagonal disp. (precrack test)

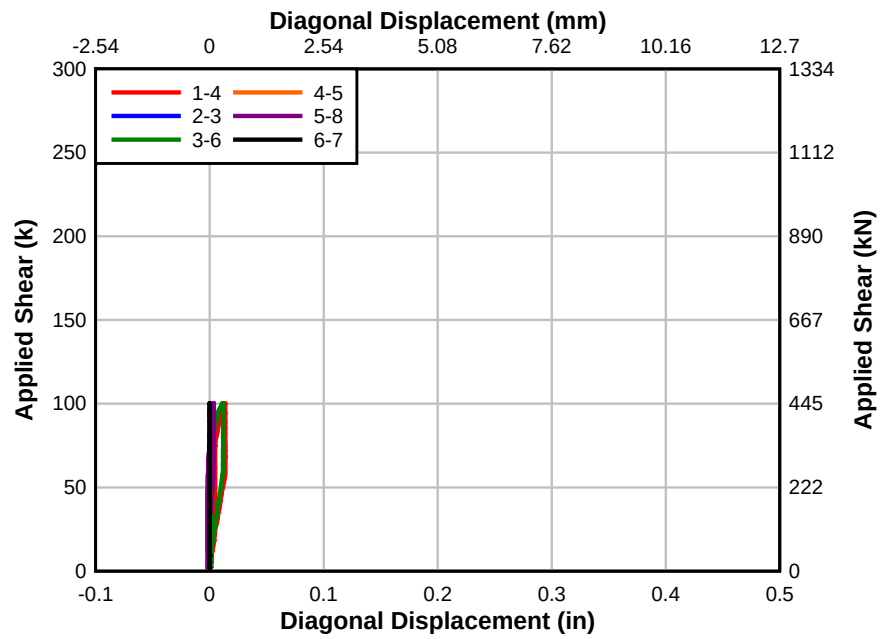


Figure B-24: Specimen IT.7.18.12.S applied shear - diagonal disp. (precrack test)

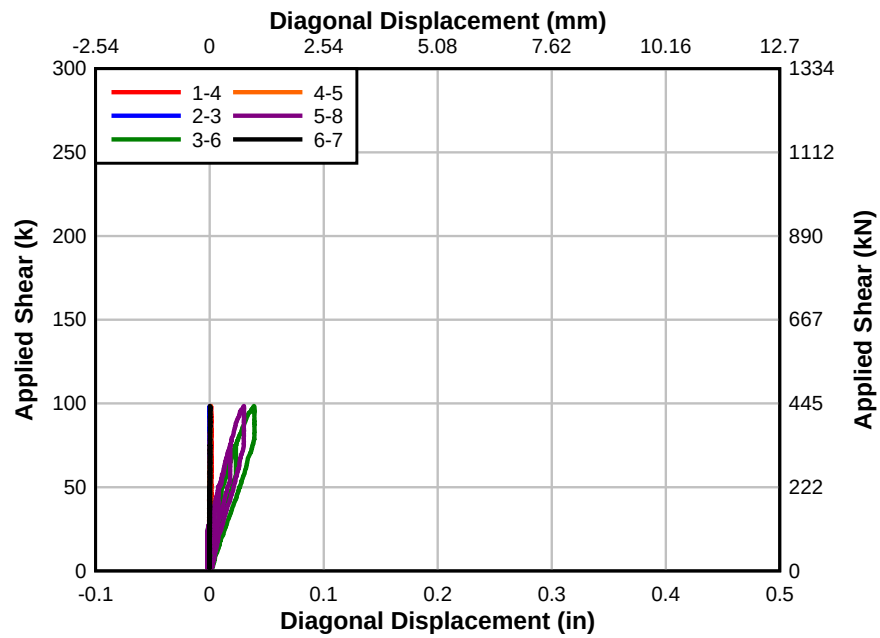


Figure B-25: Specimen IT.5.22.12*.S applied shear - diagonal disp. (precrack test)

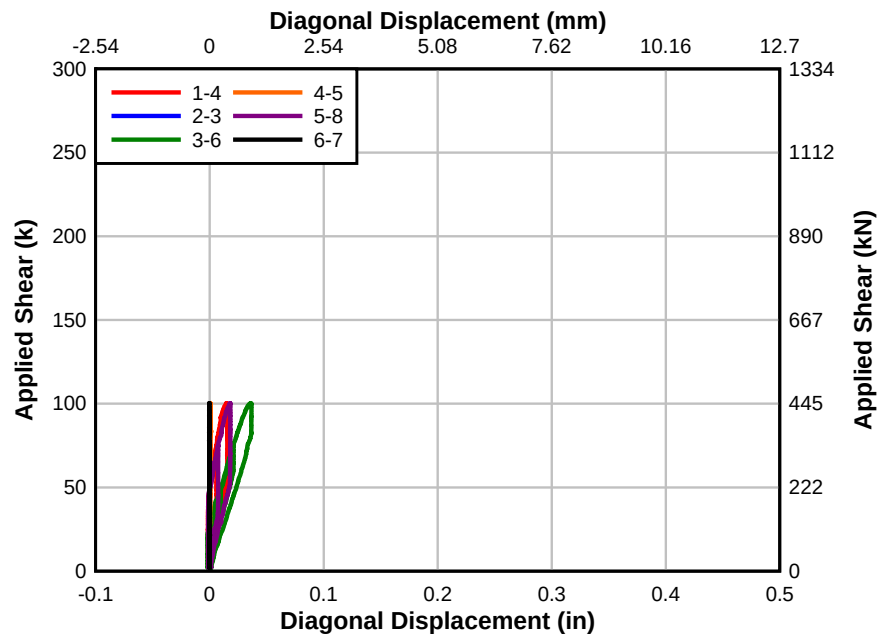


Figure B-26: Specimen IT.7.22.6.S applied shear - diagonal disp. (precrack test)

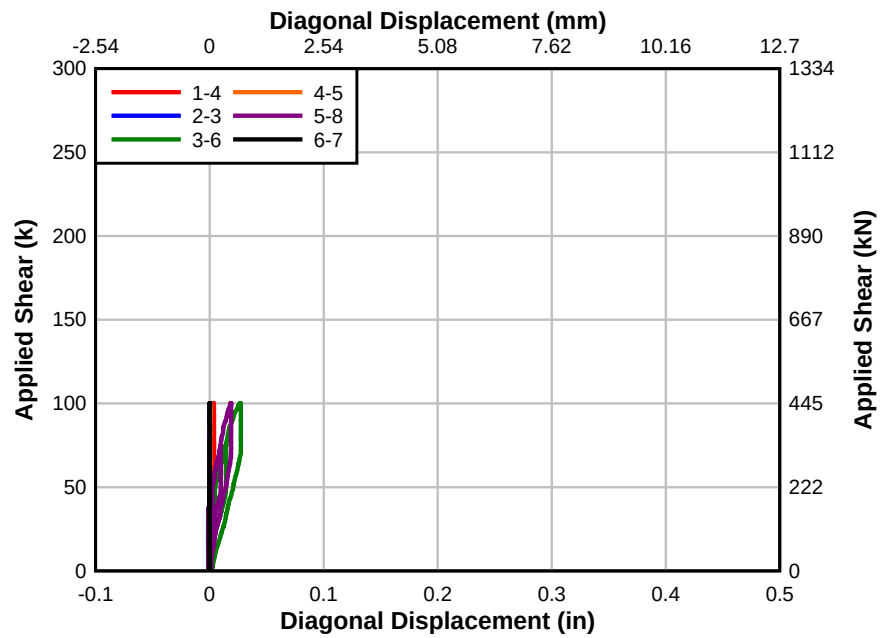


Figure B-27: Specimen IT.7.22.6.FTG applied shear - diagonal disp. (precrack test)

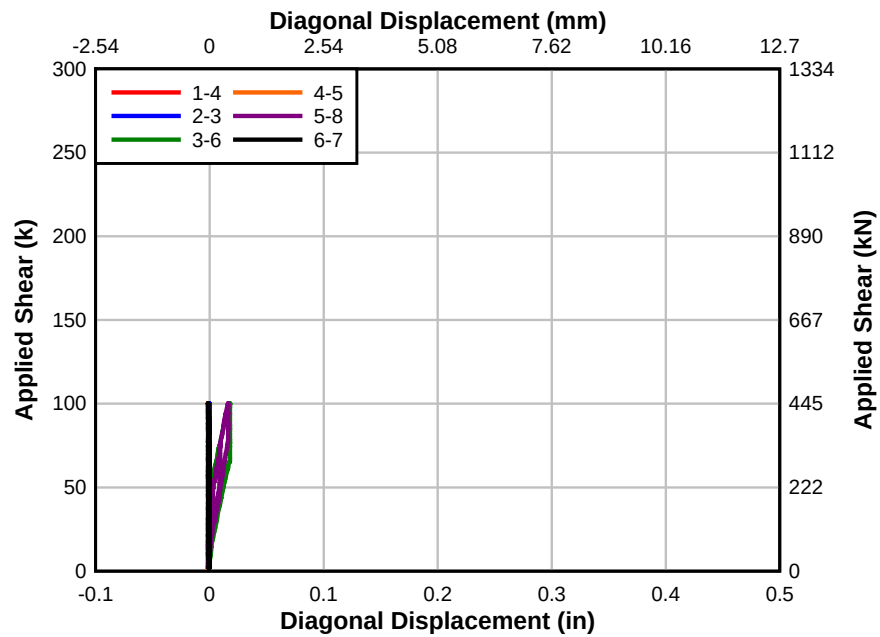


Figure B-28: Specimen IT.7.22.6.FT/FTG applied shear - diagonal disp. (precrack test)

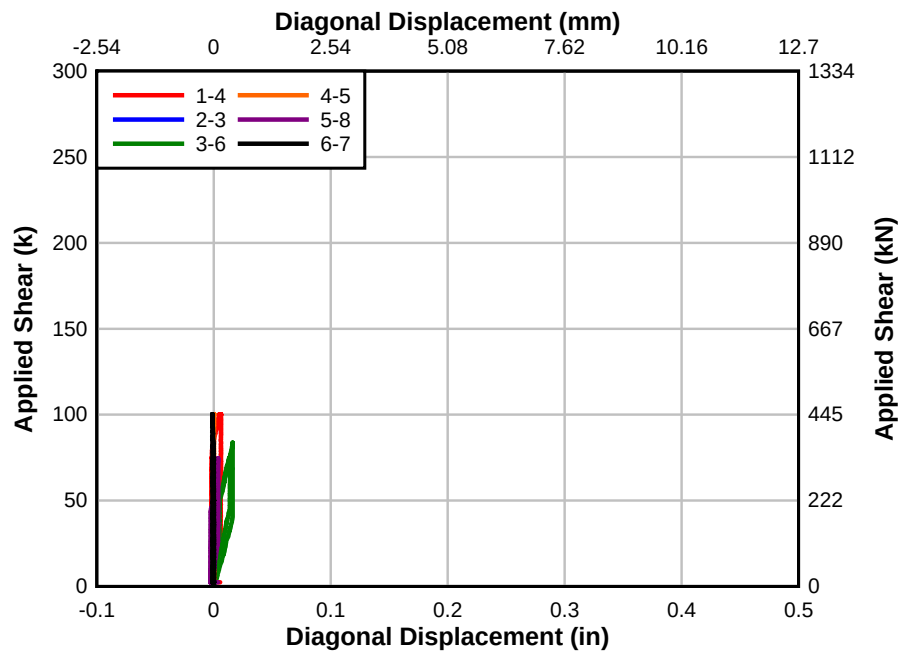


Figure B-29: Specimen IT.7.18.6.M applied shear vs. diagonal disp. (precrack test)

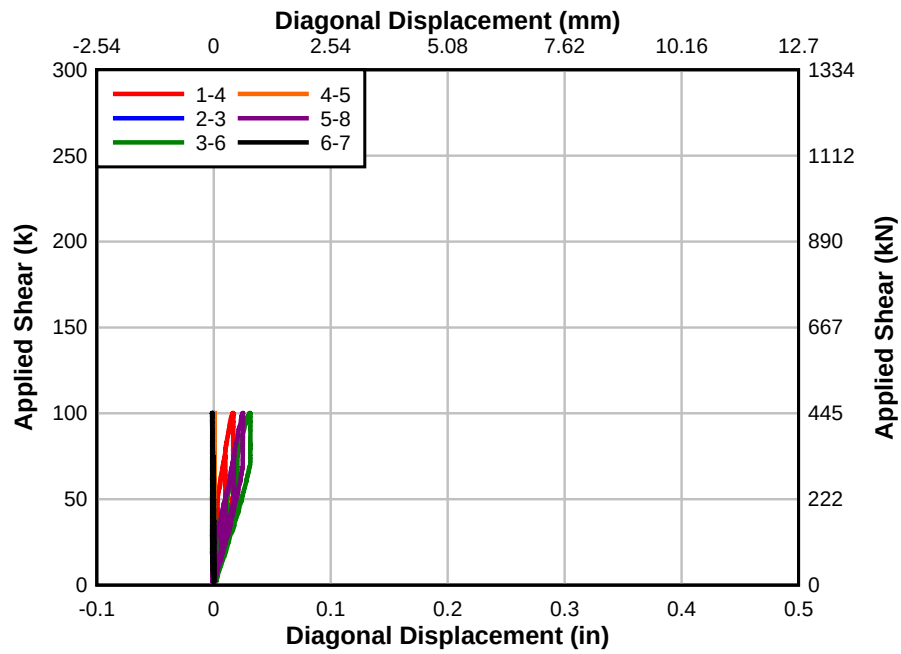


Figure B-30: Specimen IT.7.22.6.FT applied shear vs. diagonal disp. (precrack test)

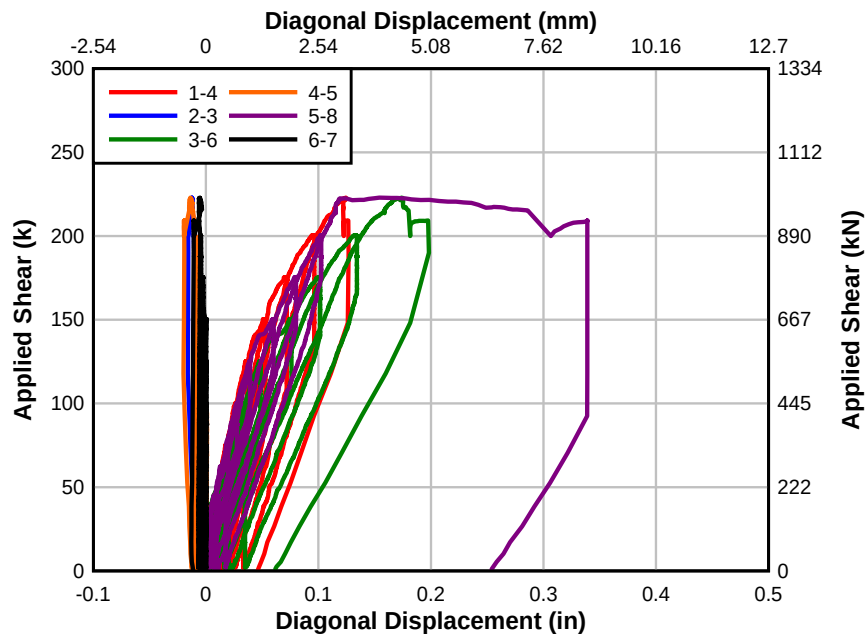


Figure B-31: Specimen T.6.18.6.S applied shear - diagonal disp. (failure test)

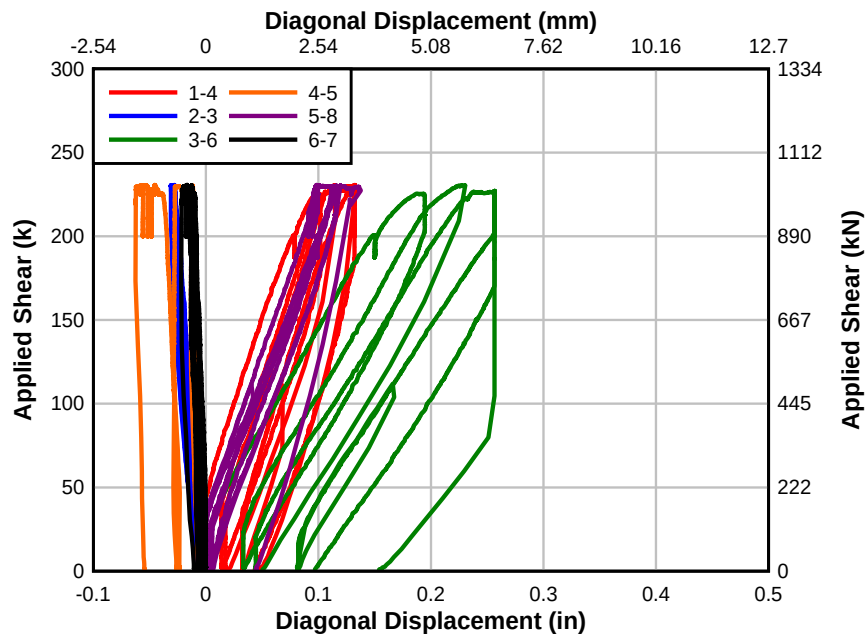


Figure B-32: Specimen T.6.18.12.S applied shear - diagonal disp. (failure test)

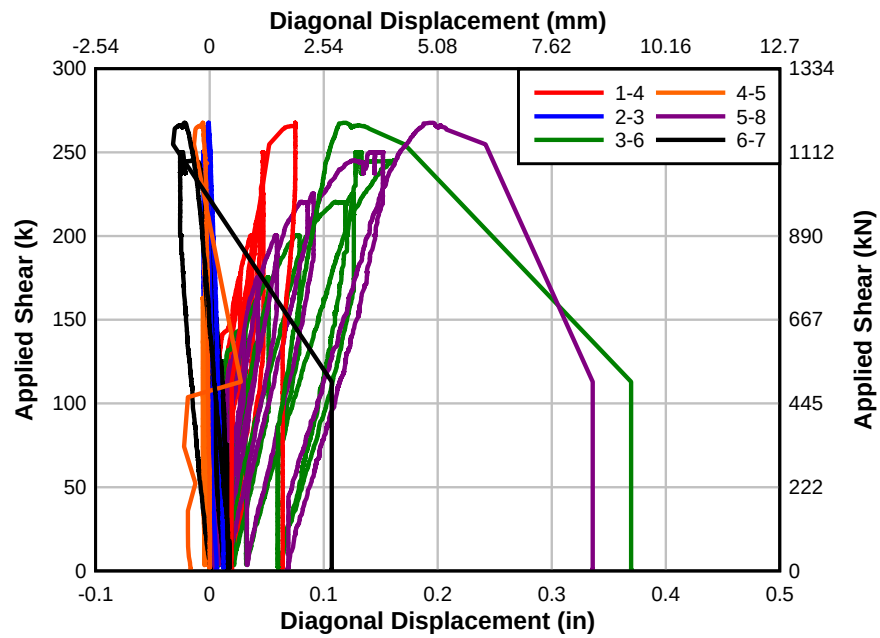


Figure B-33: Specimen IT.7.18.6.S applied shear - diagonal disp. (failure test)

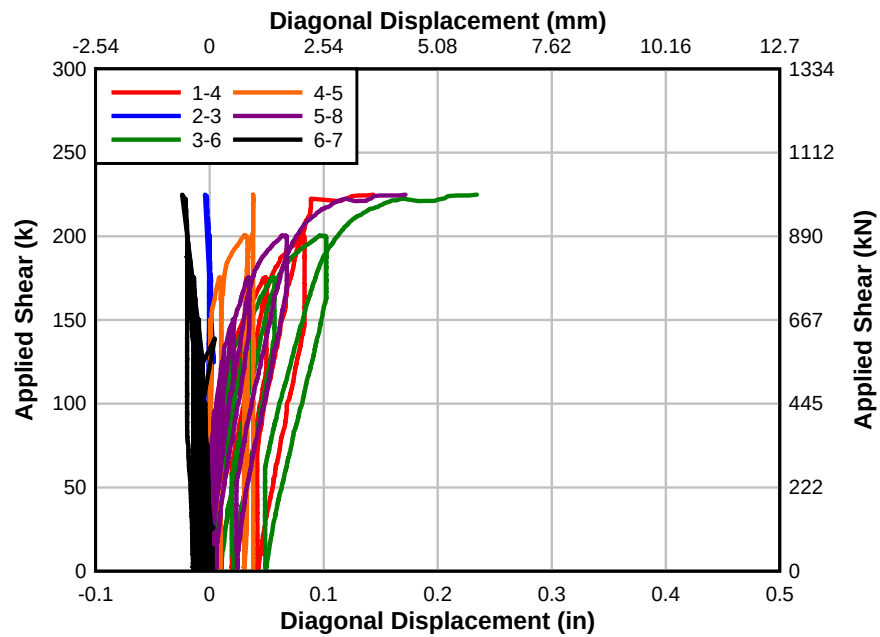


Figure B-34: Specimen IT.7.18.12.S applied shear - diagonal disp. (failure test)

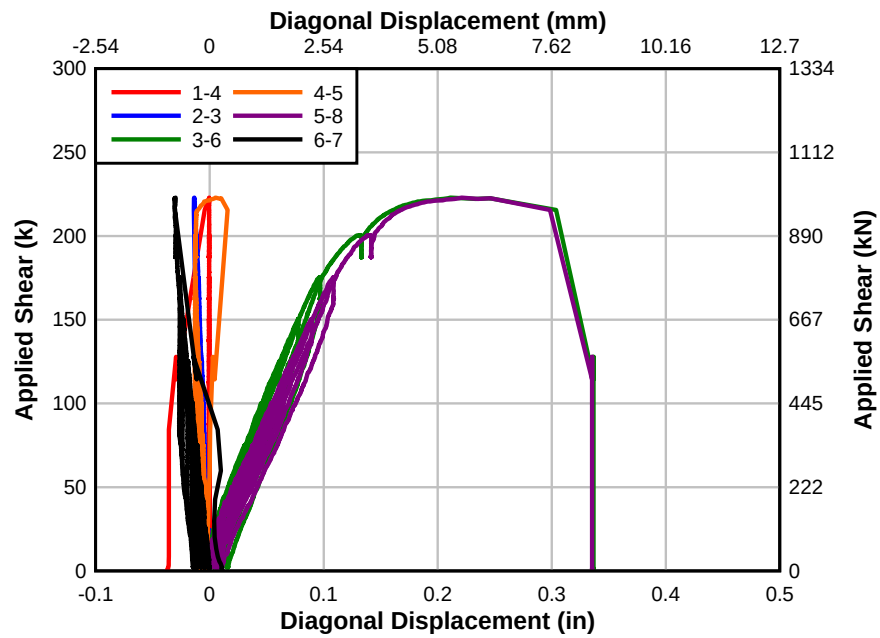


Figure B-35: Specimen IT.5.22.12*.S applied shear - diagonal disp. (failure test)

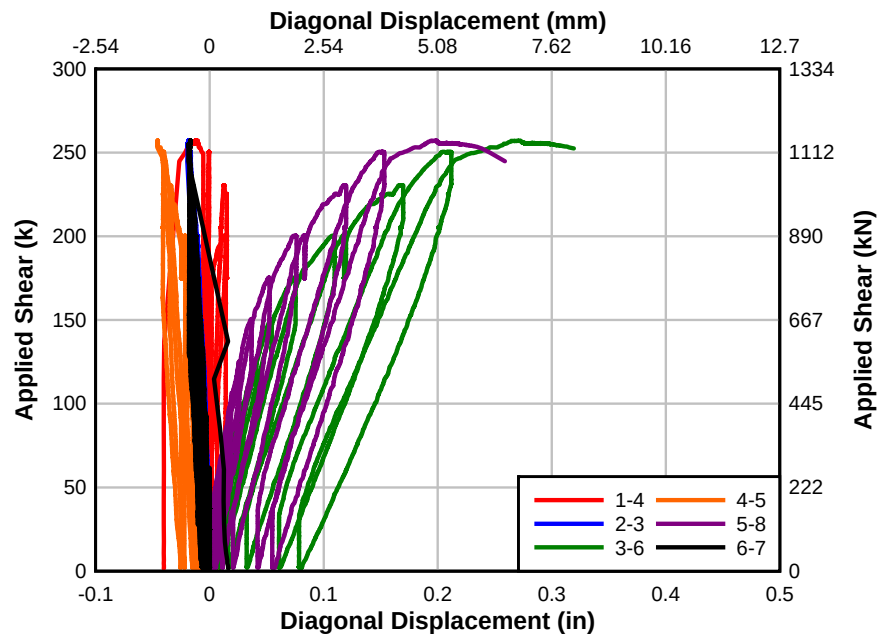


Figure B-36: Specimen IT.7.22.6.S applied shear - diagonal disp. (failure test)

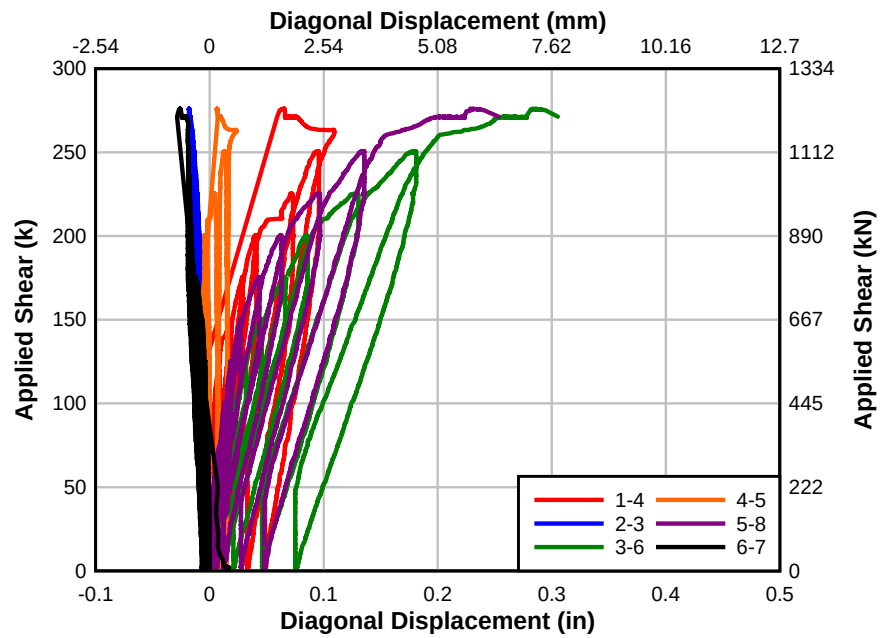


Figure B-37: Specimen IT.7.22.6.FTG applied shear - diagonal disp. (failure test)

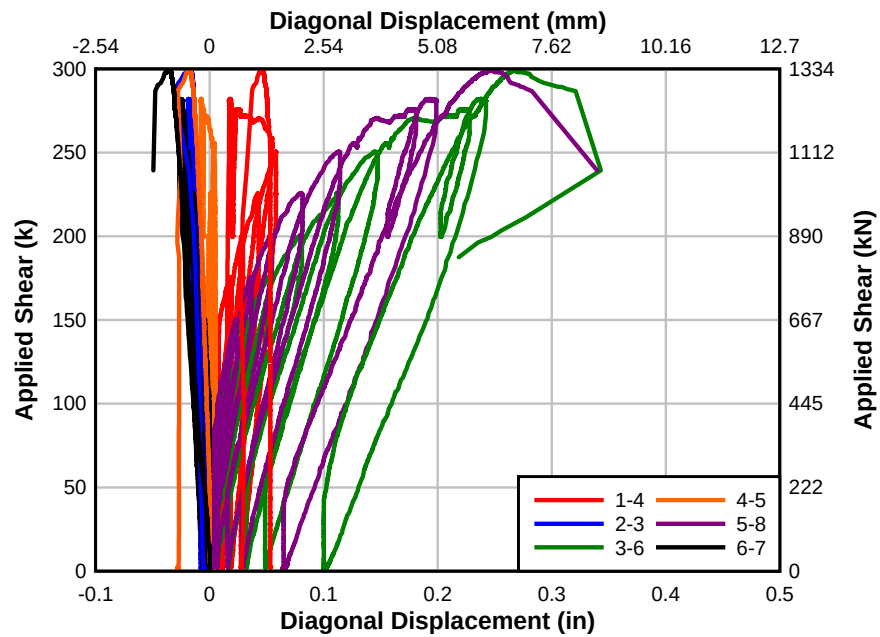


Figure B-38: Specimen IT.7.22.6.FT/FTG applied shear - diagonal disp. (failure test)

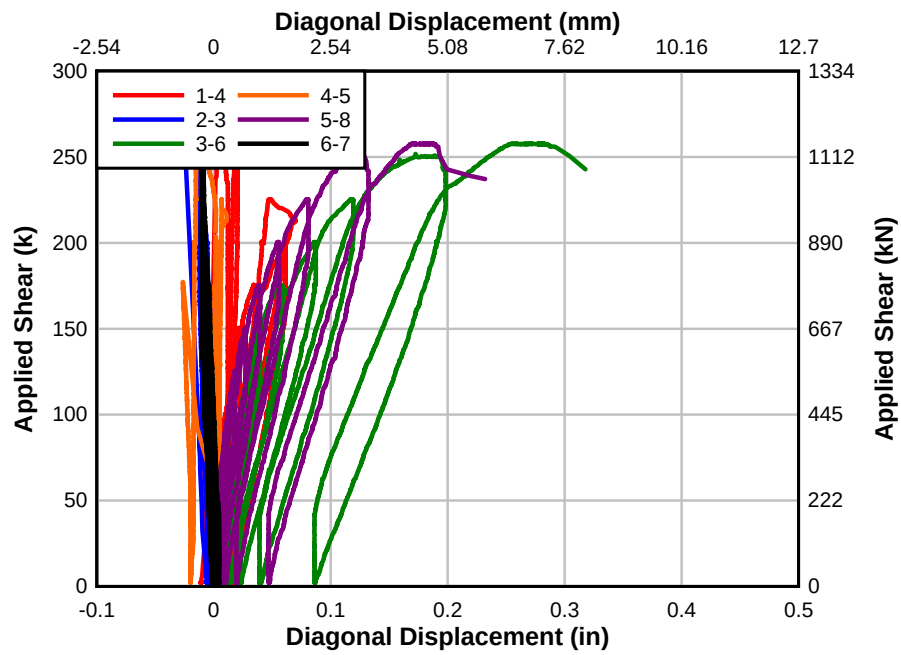


Figure B-39: Specimen IT.7.18.6.M applied shear vs. diagonal disp. (failure test)

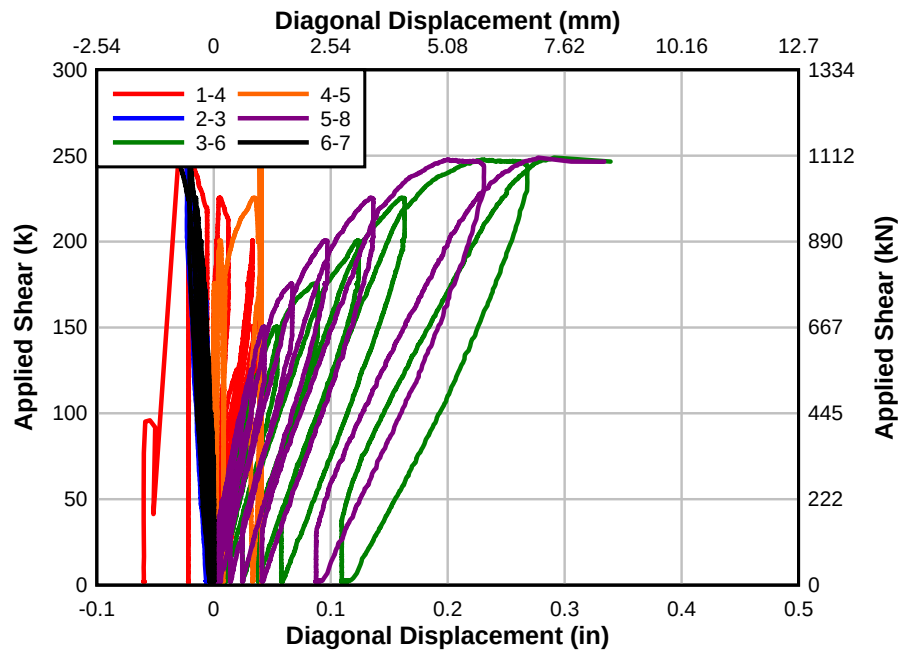


Figure B-40: Specimen IT.7.22.6.FT applied shear vs. diagonal disp. (failure test)

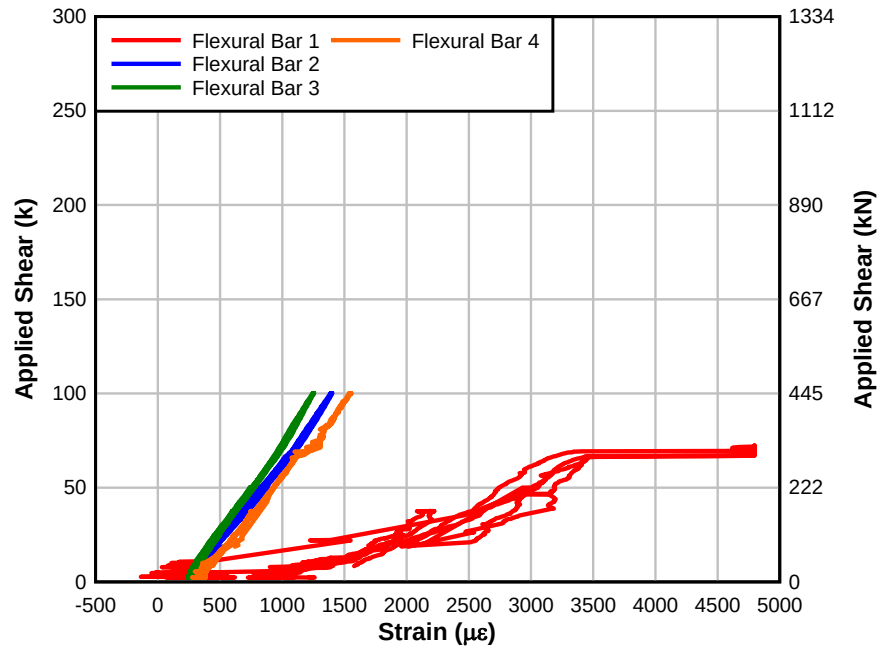


Figure B-41: Specimen T.6.18.6.S applied shear – flexural strain (precrack test)

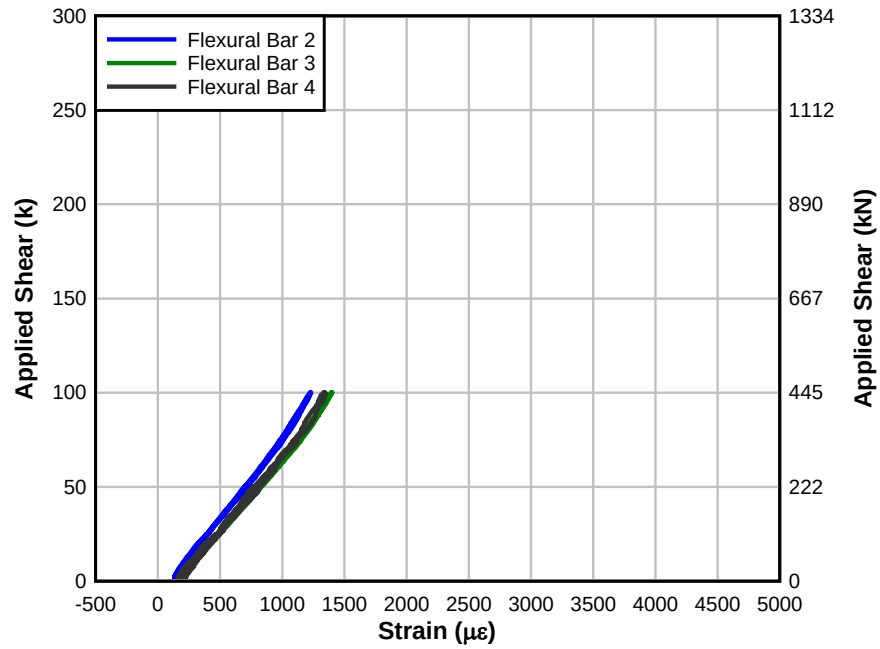


Figure B-42: Specimen T.6.18.12.S applied shear – flexural strain (precrack test)

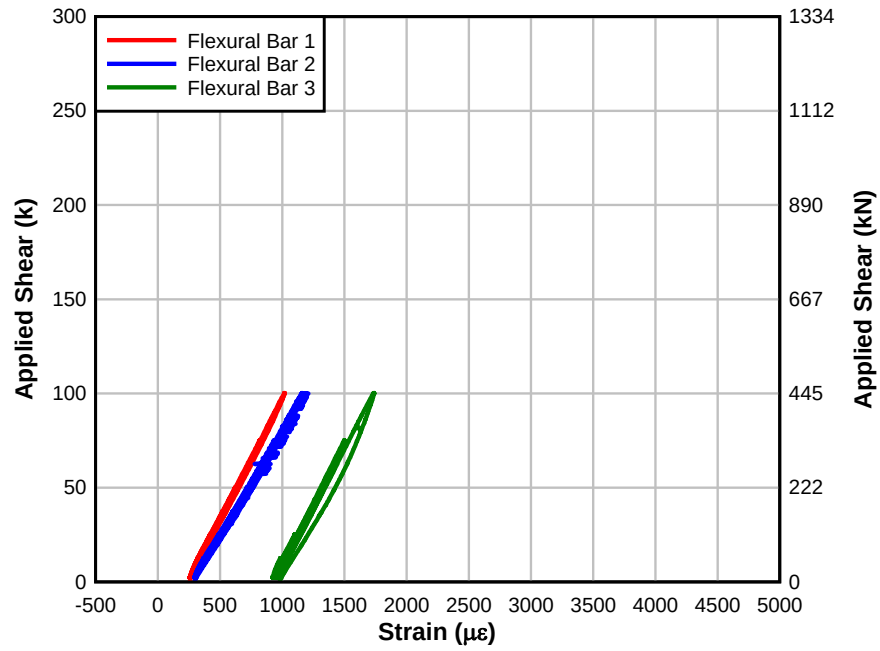


Figure B-43: Specimen IT.7.18.6.S applied shear – flexural strain (precrack test)

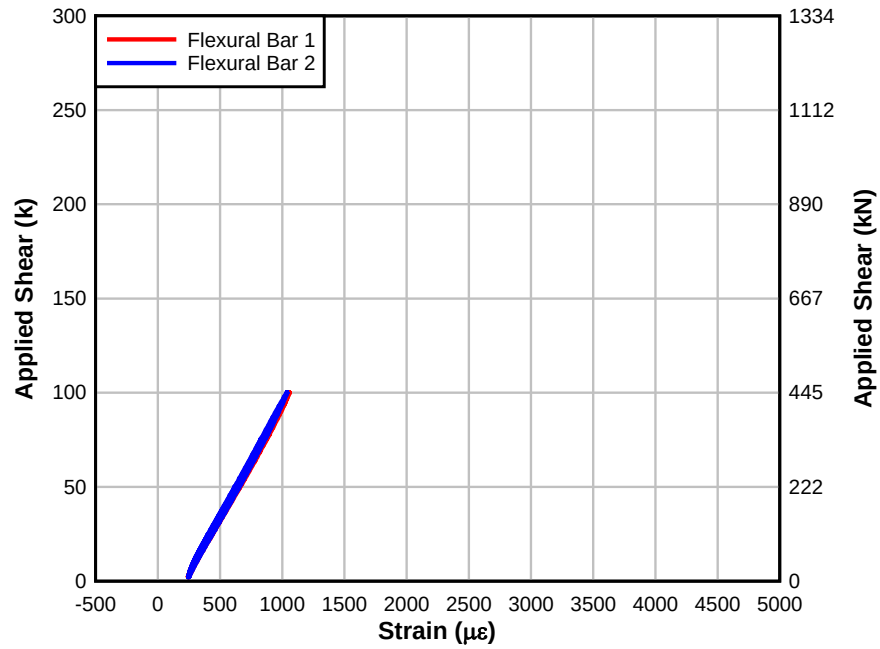


Figure B-44: Specimen IT.7.18.12.S applied shear – flexural strain (precrack test)

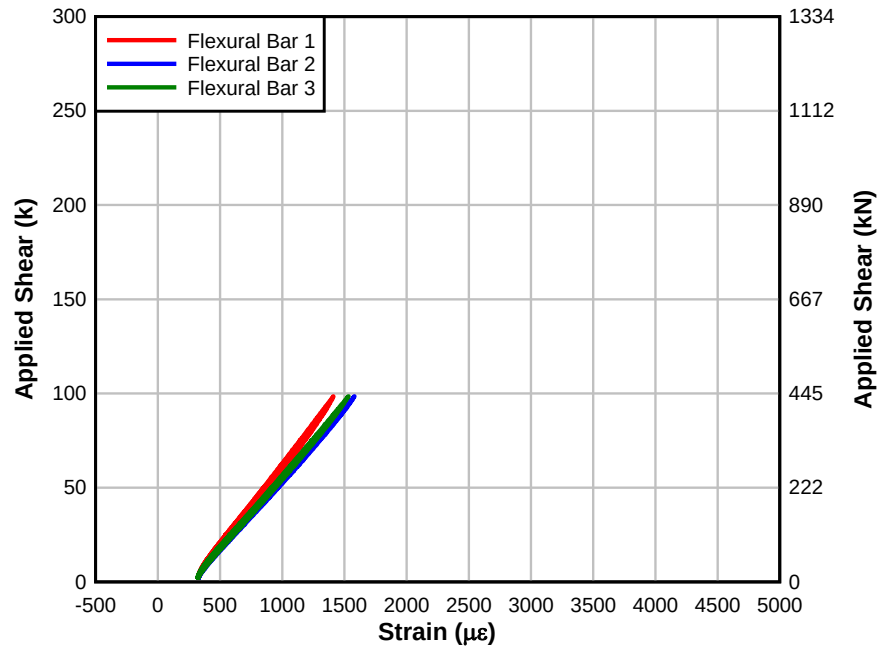


Figure B-45: Specimen IT.5.22.12*.S applied shear – flexural strain (precrack test)

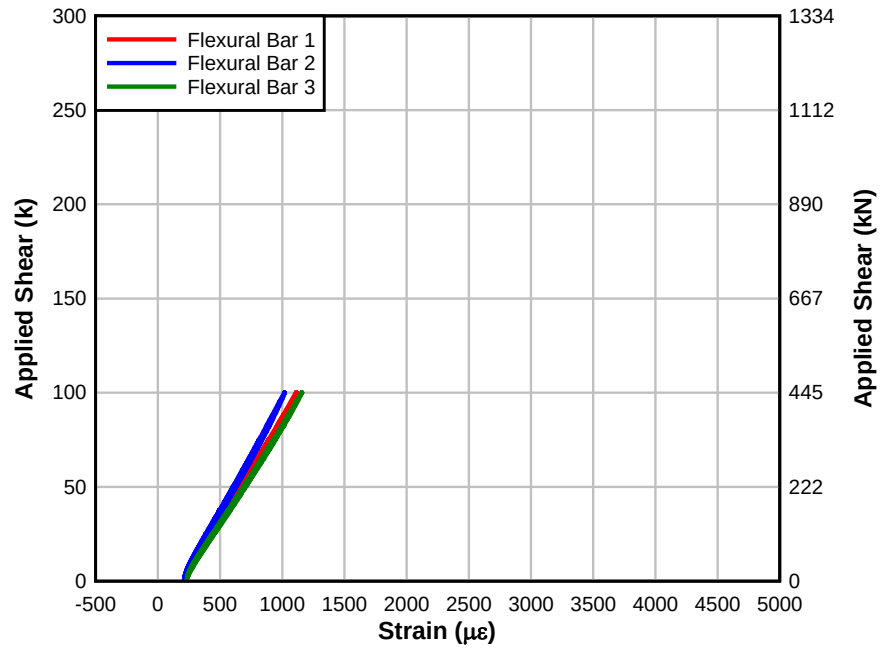


Figure B-46: Specimen IT.7.22.6.S applied shear – flexural strain (precrack test)

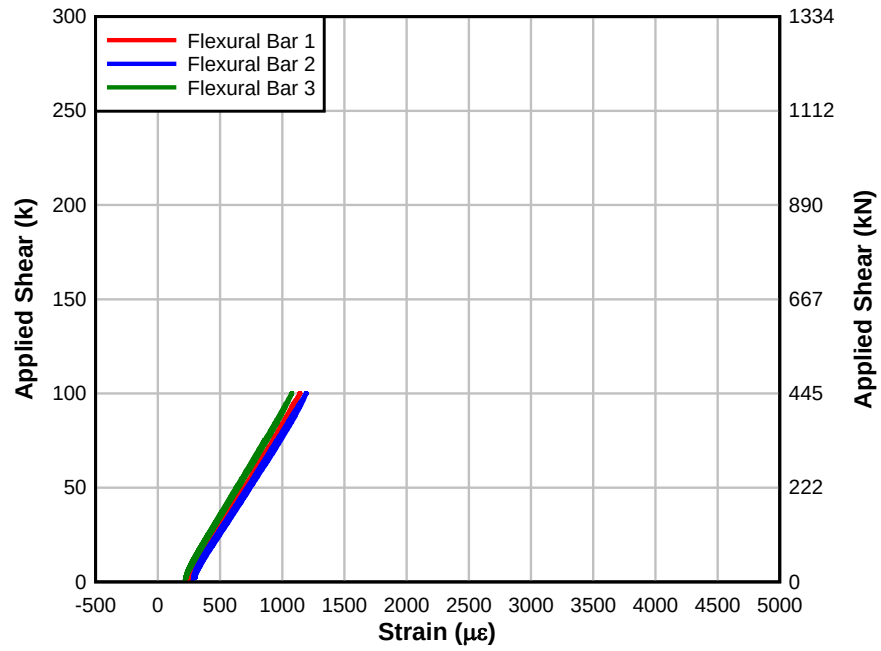


Figure B-47: Specimen IT.7.22.6.FTG applied shear – flexural strain (precrack test)

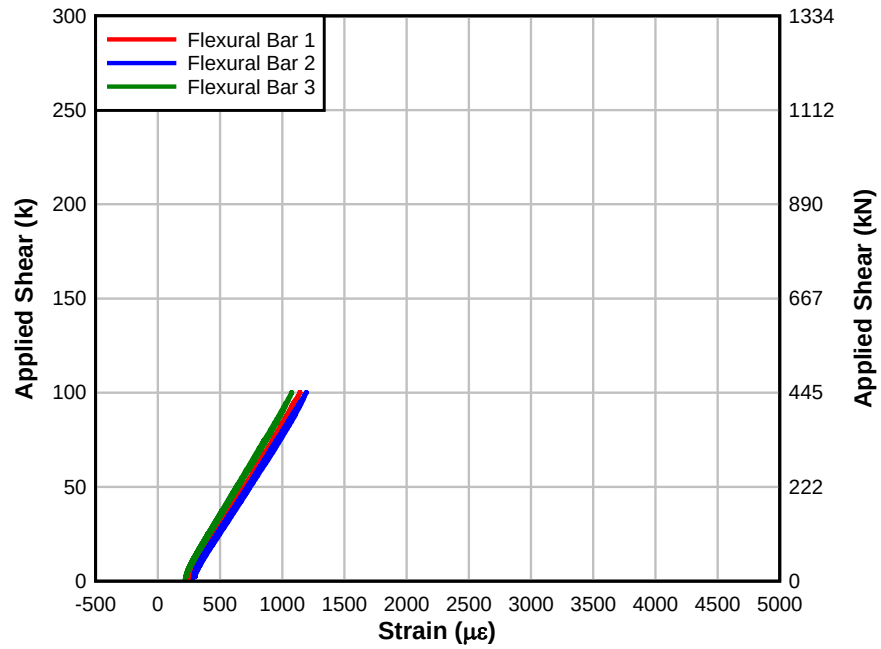


Figure B-48: Specimen IT.7.22.6.FT/FTG applied shear – flexural strain (precrack test)

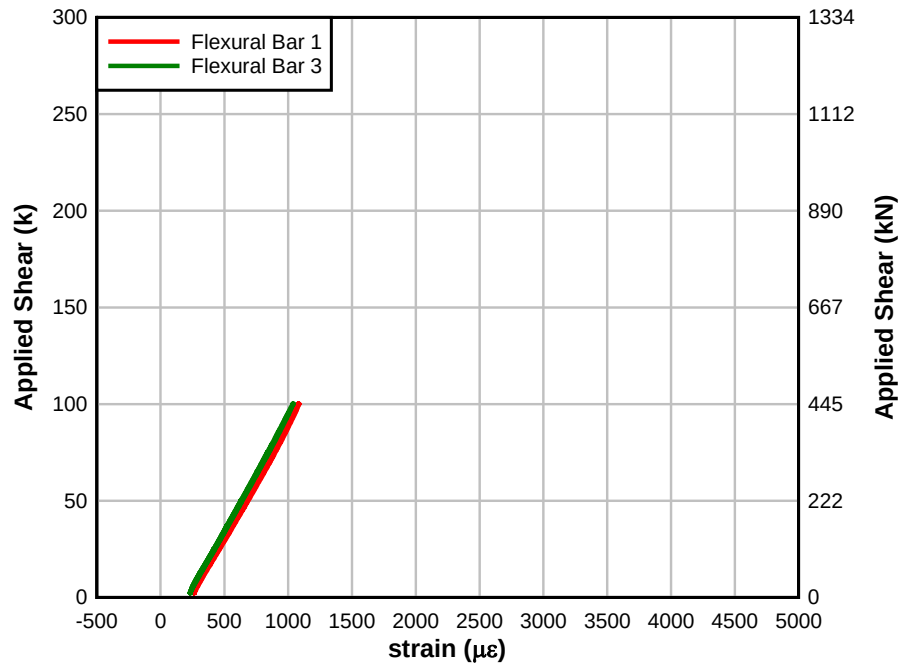


Figure B-49: Specimen IT.7.18.6.M applied shear vs. flexural bar strain (precrack test)

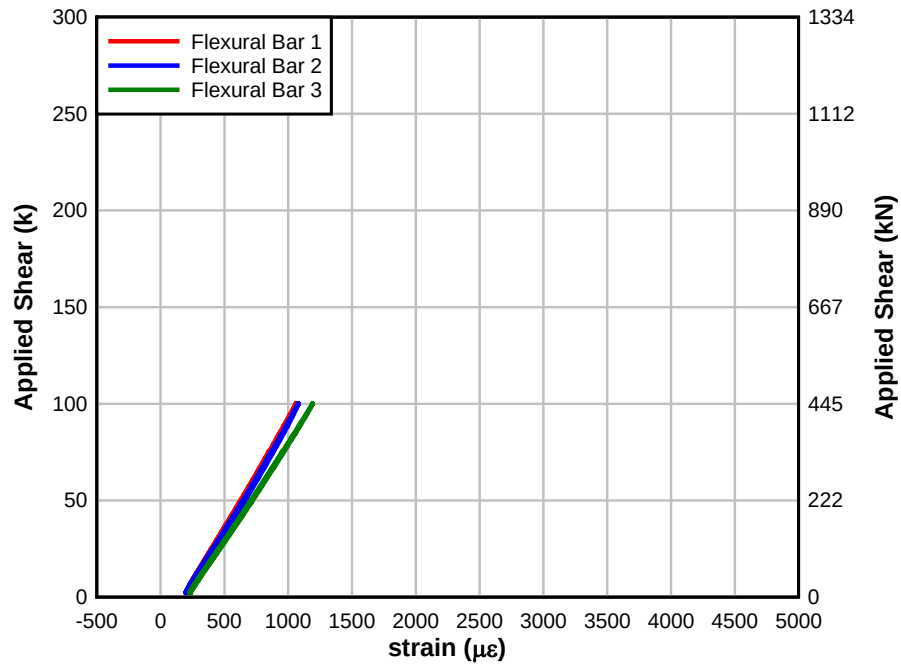


Figure B-50: Specimen IT.7.22.6.FT applied shear vs. flexural bar strain (precrack test)

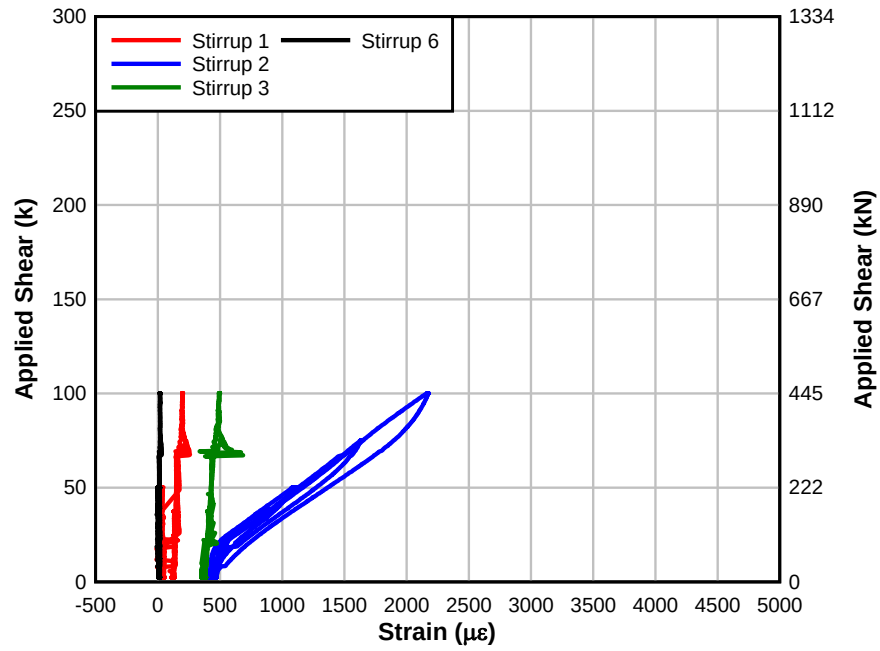


Figure B-51: Specimen T.6.18.6.S applied shear – stirrup strain (precrack test)

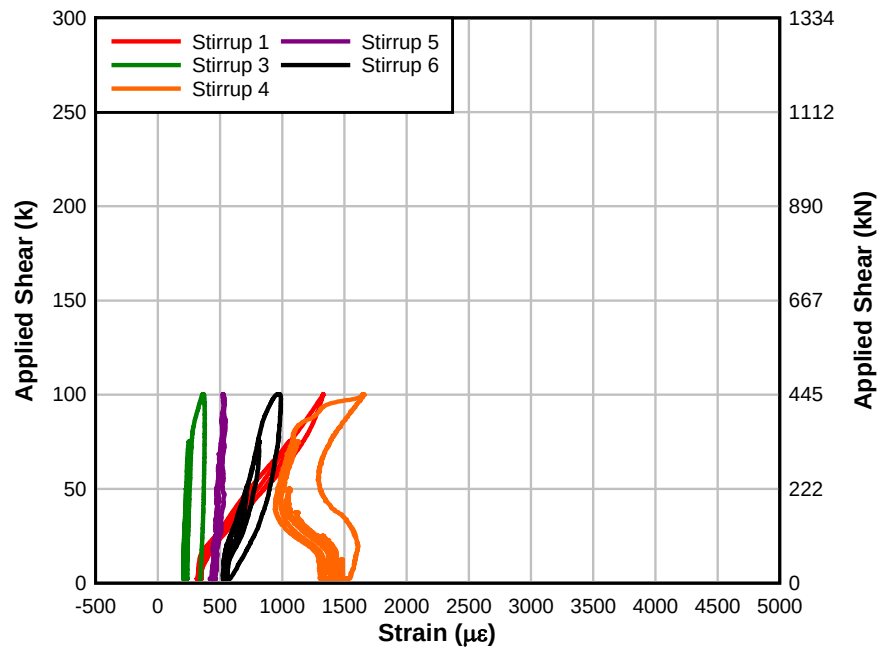


Figure B-52: Specimen T.6.18.12.S applied shear – stirrup strain (precrack test)

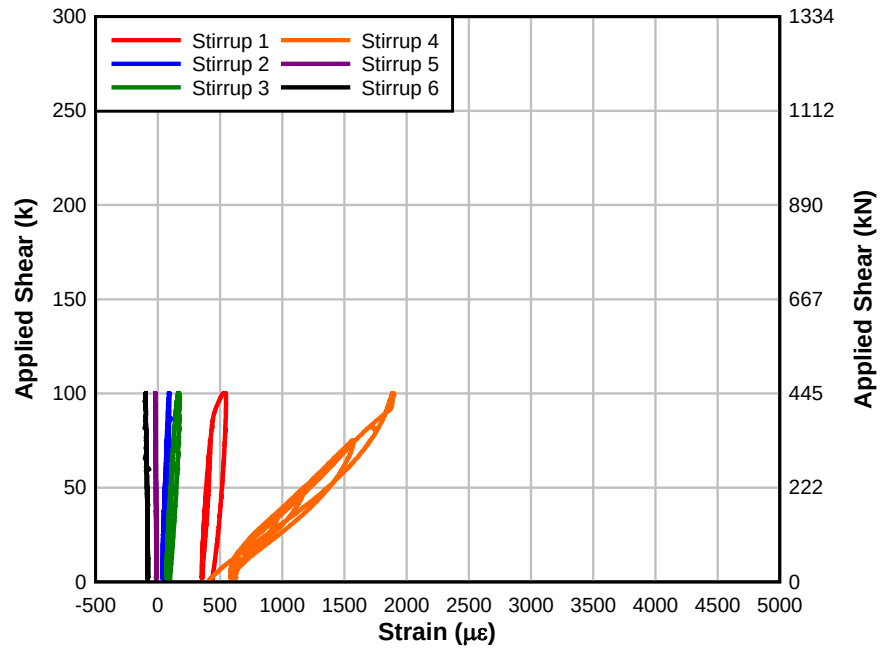


Figure B-53 Specimen IT.7.18.6.S applied shear – stirrup strain (precrack test)

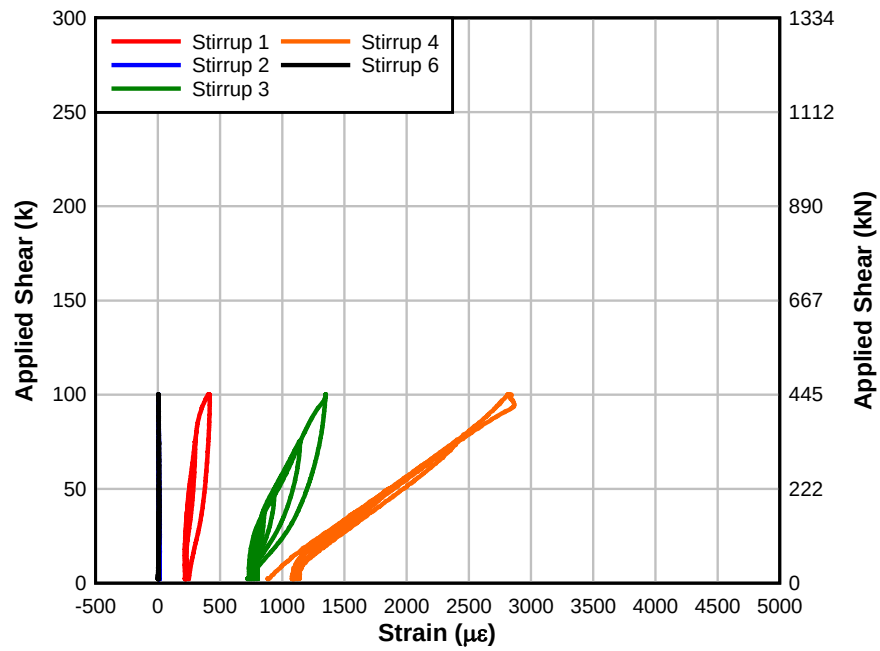


Figure B-54: Specimen IT.7.18.12.S applied shear – stirrup strain (precrack test)

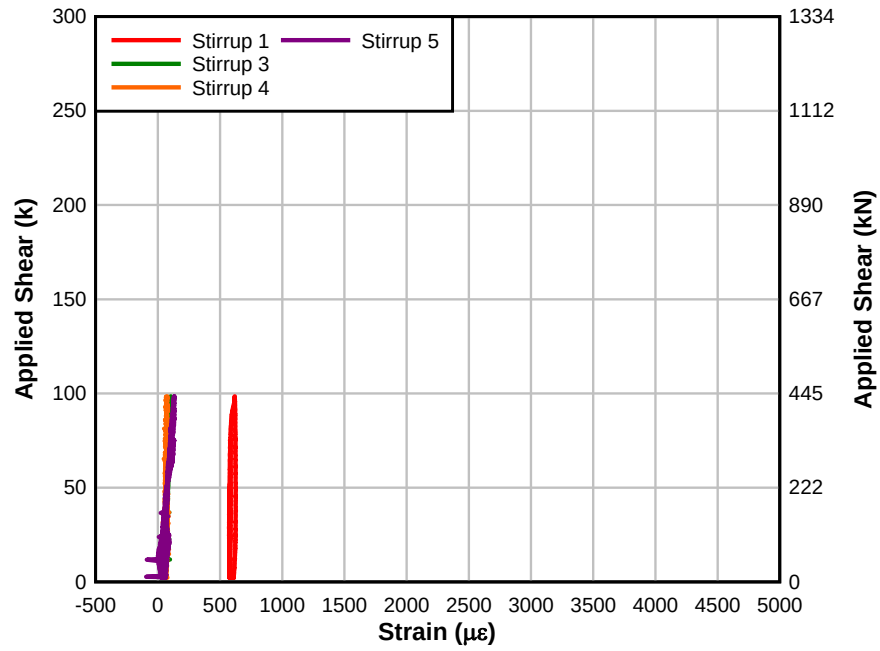


Figure B-55: Specimen IT.5.22.12*.S applied shear – stirrup strain (precrack test)

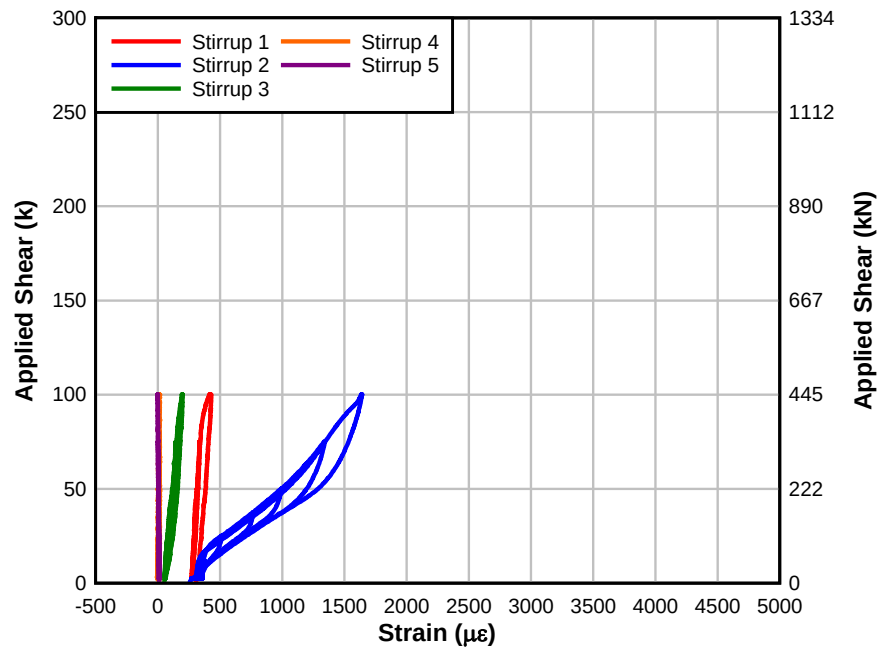


Figure B-56: Specimen IT.7.22.6.S applied shear – stirrup strain (precrack test)

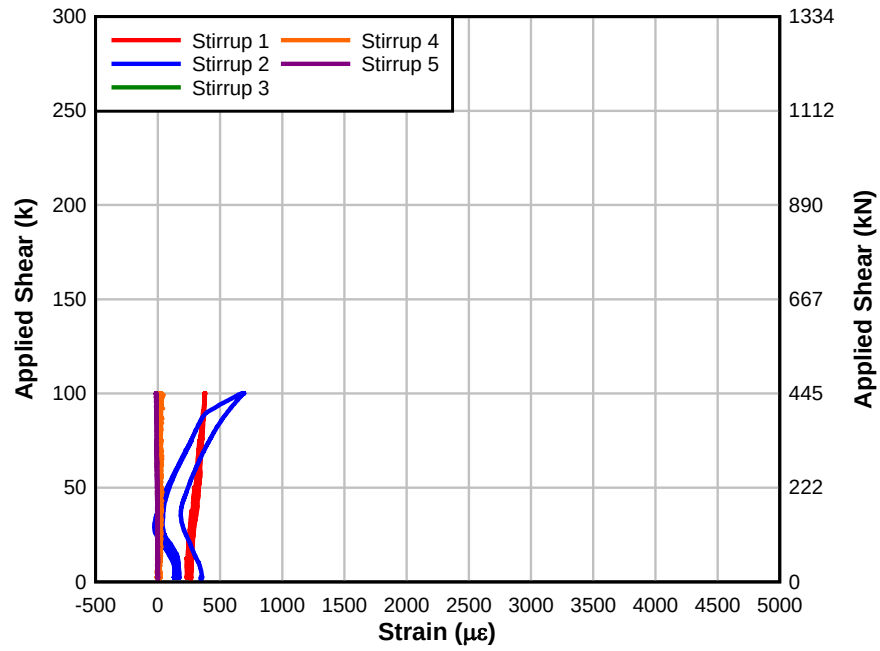


Figure B-57: Specimen IT.7.22.6.FTG applied shear – stirrup strain (precrack test)

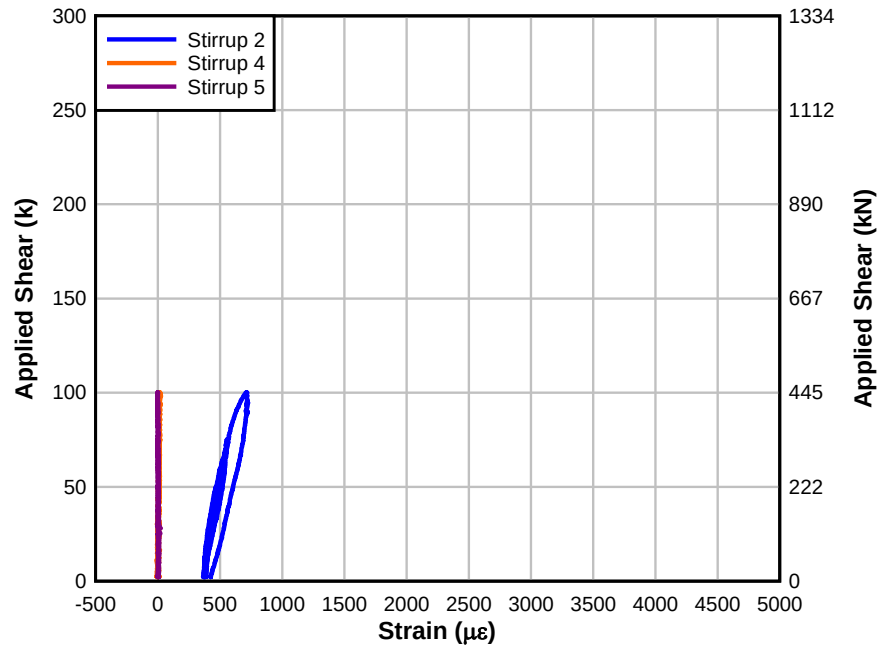


Figure B-58: Specimen IT.7.22.6.FT/FTG applied shear – stirrup strain (precrack test)

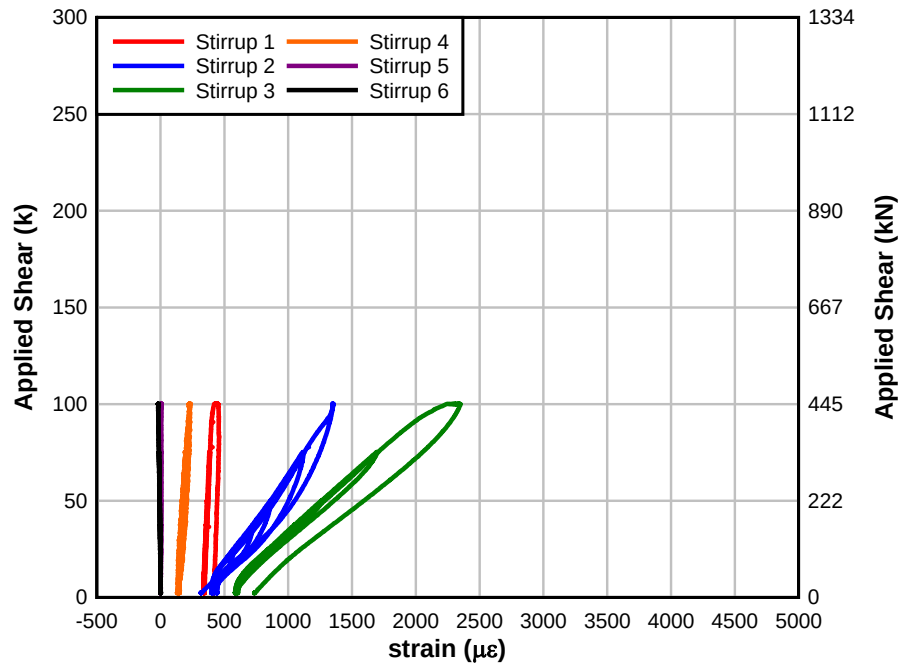


Figure B-59: Specimen IT.7.18.6.M applied shear vs. stirrup strain (precrack test)

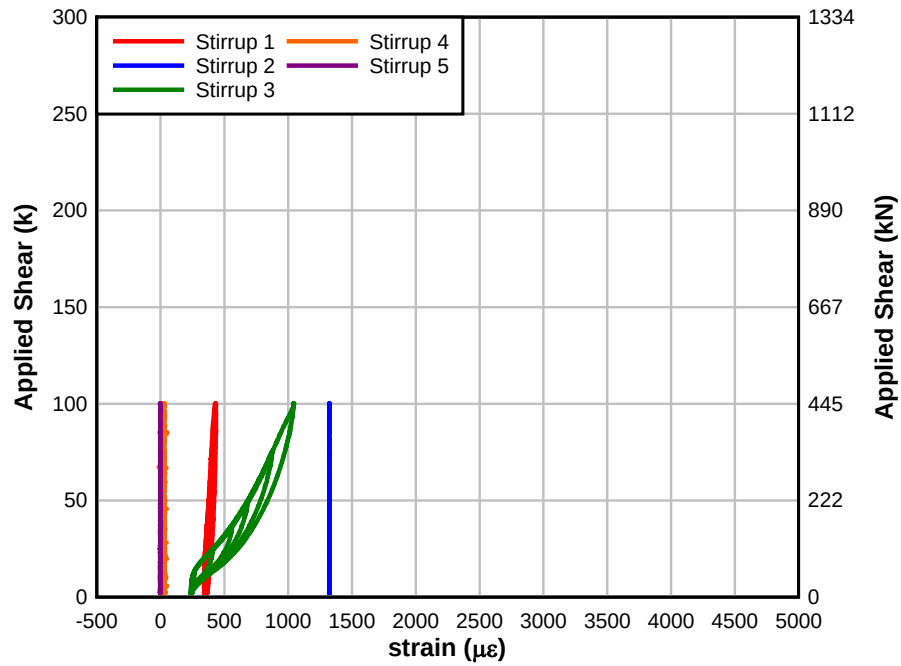


Figure B-60: Specimen IT.7.18.6.FT applied shear vs. stirrup strain (precrack test)

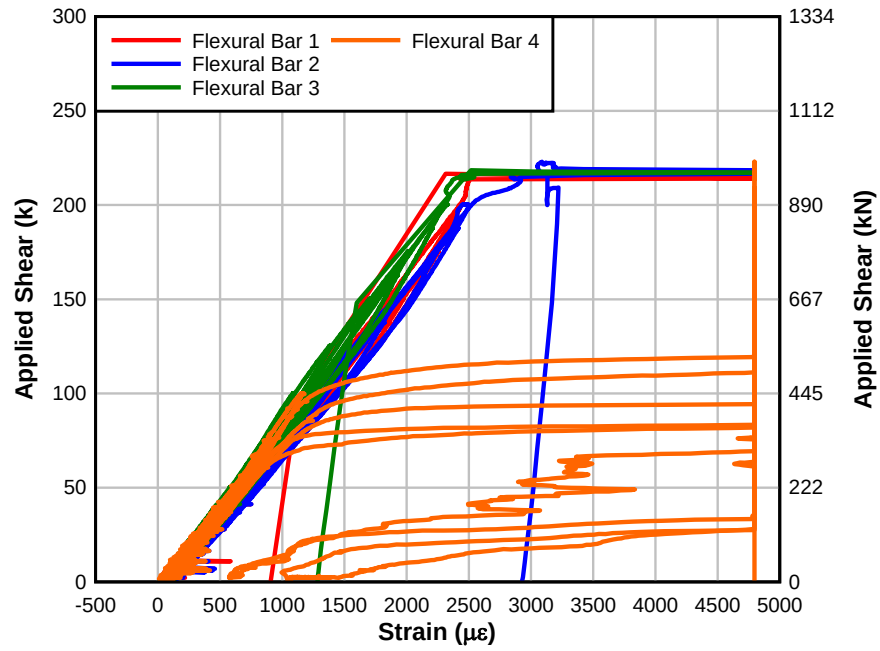


Figure B-61: Specimen T.6.18.6.S applied shear – flexural strain (failure test)

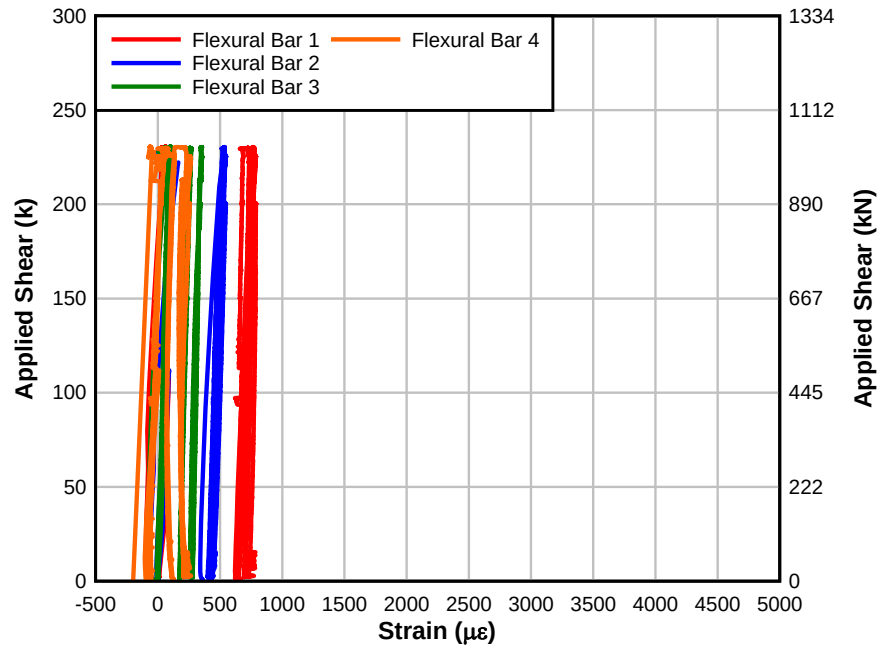


Figure B-62: Specimen T.6.18.12.S applied shear – flexural strain (failure test)

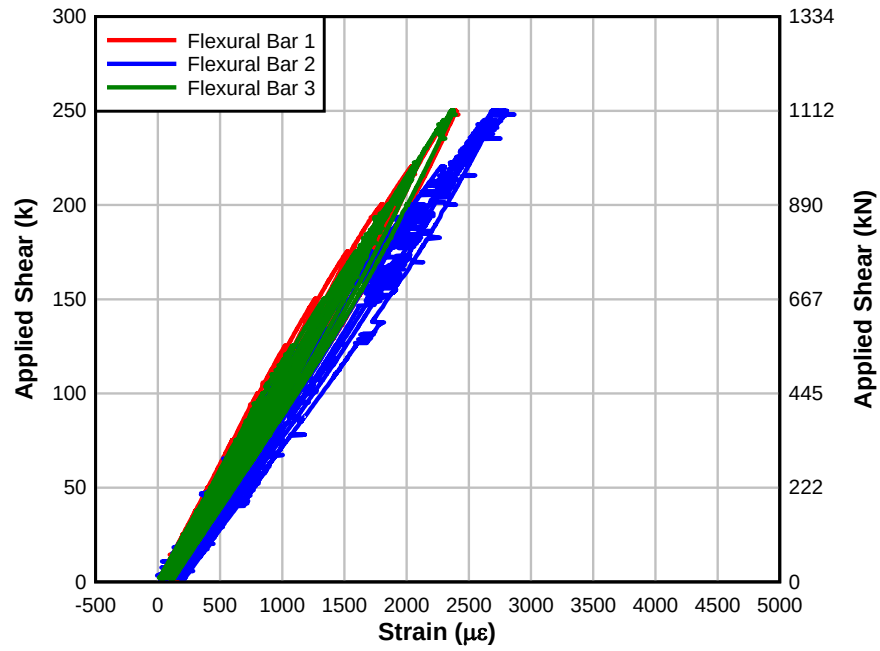


Figure B-63: Specimen IT.7.18.6.S applied shear – flexural strain (failure test to 500k)

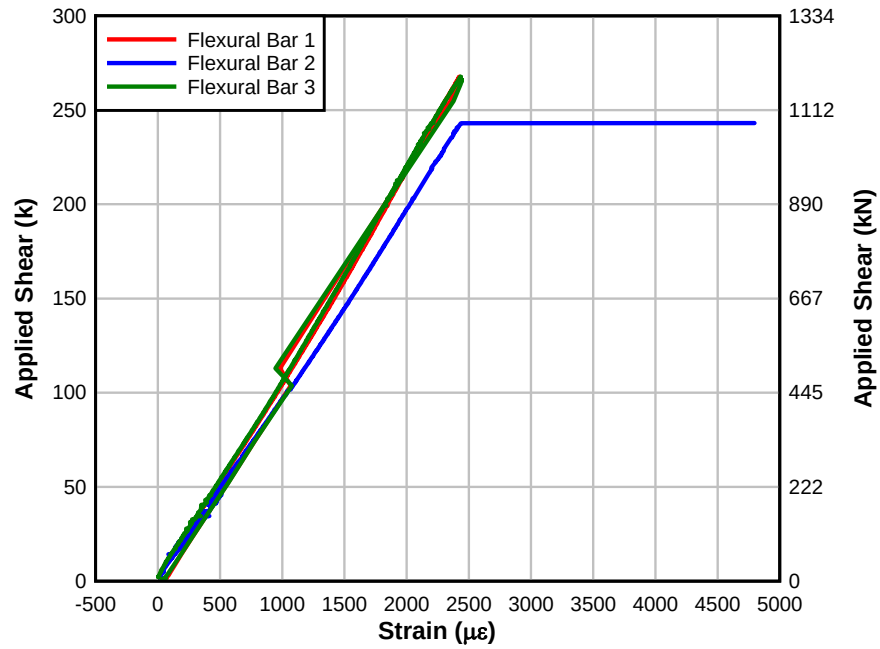


Figure B-64: Specimen IT.7.18.6.S applied shear – flexural strain (failure test to failure)

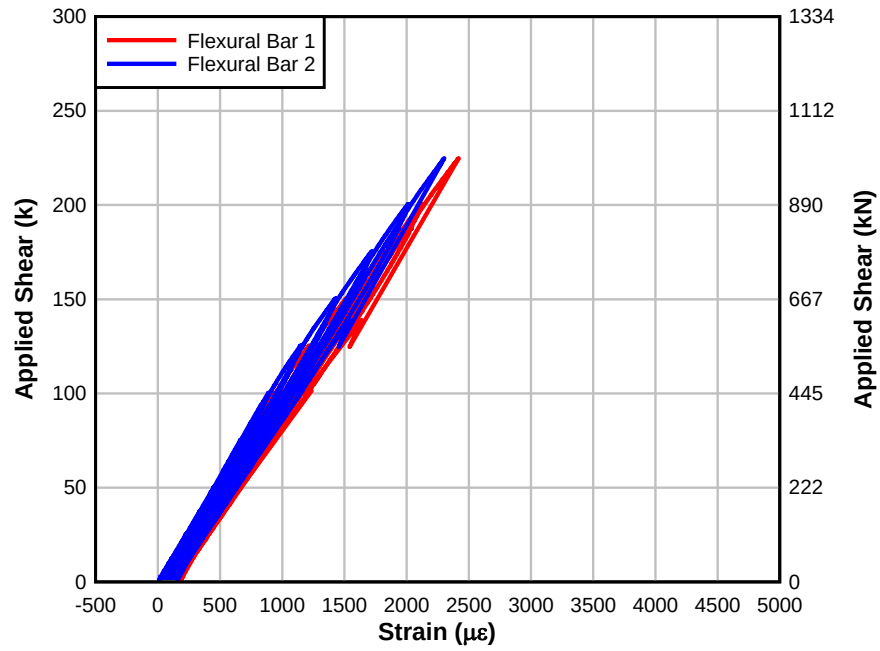


Figure B-65: Specimen IT.7.18.12.S applied shear – flexural strain (failure test)

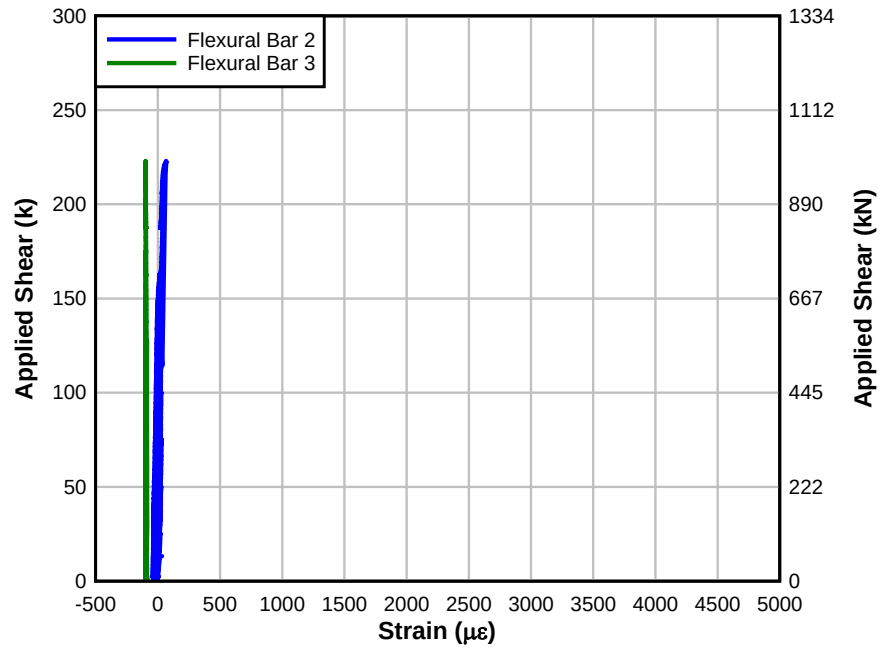


Figure B-66: Specimen IT.5.22.12*.S applied shear – flexural strain (failure test)

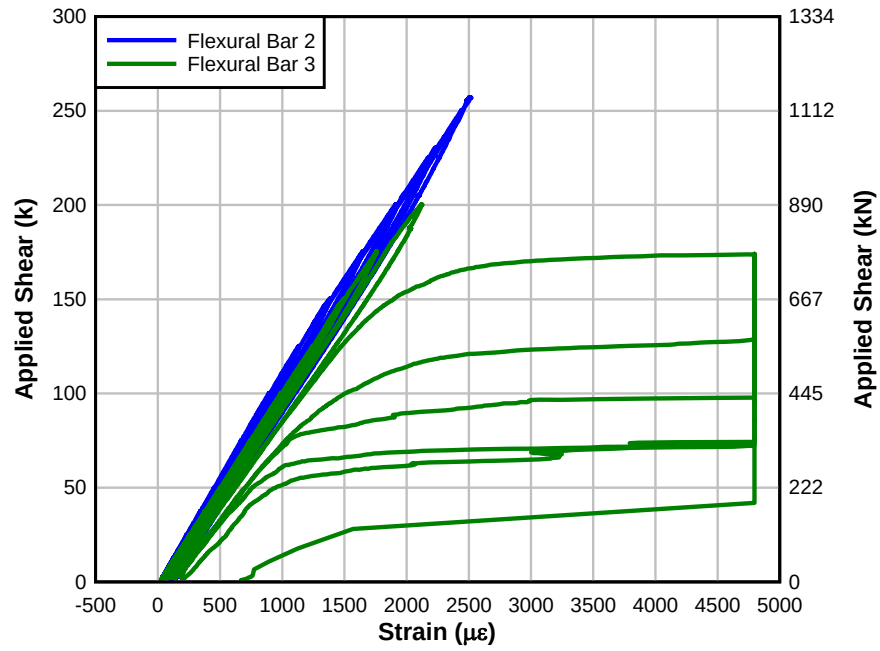


Figure B-67: Specimen IT.7.22.6.S applied shear – flexural strain (failure test)

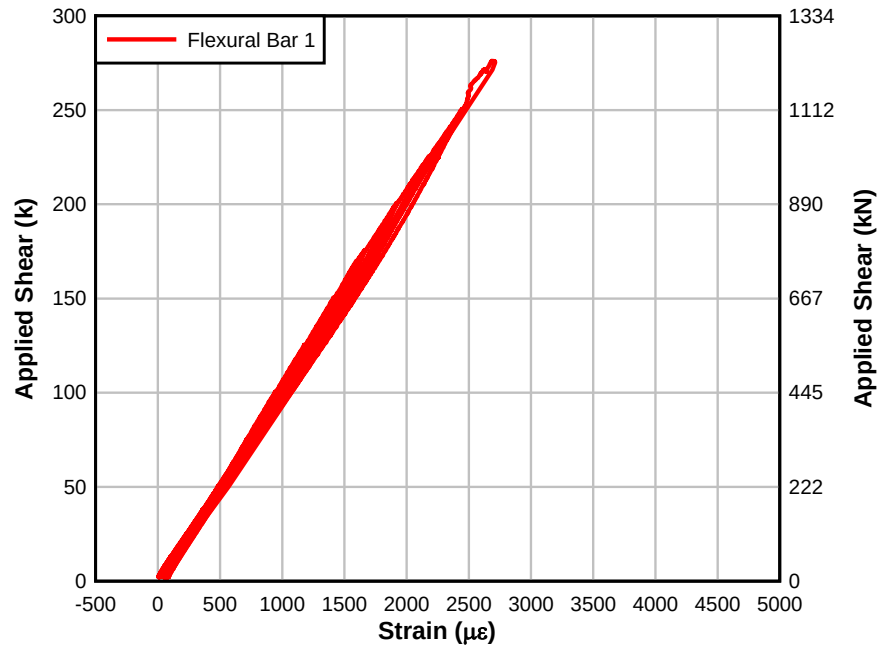


Figure B-68: Specimen IT.7.22.6.FTG applied shear – flexural strain (failure test)

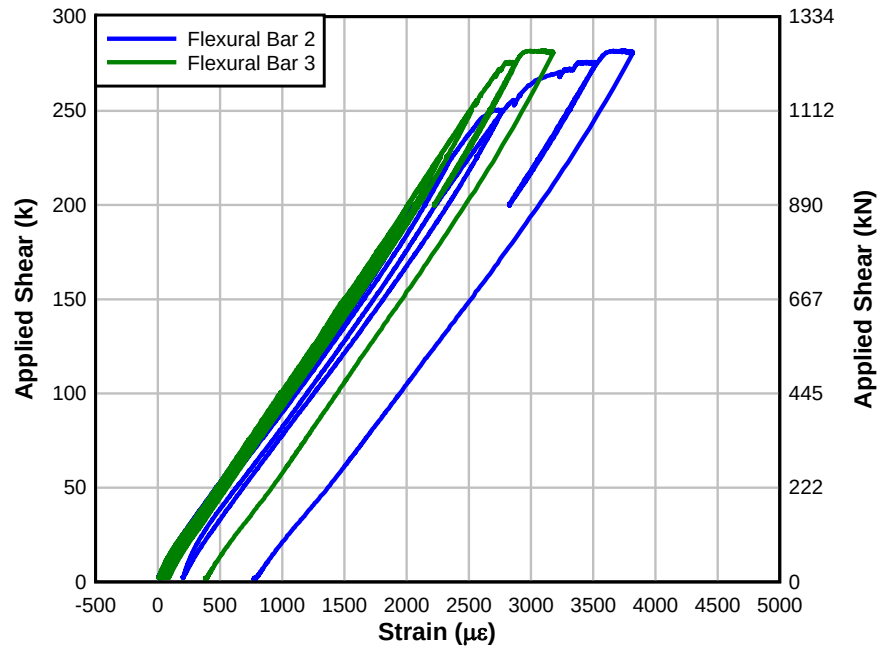


Figure B-69: Specimen IT.7.22.6.FT/FTG applied shear - flexural strain (failure test to 562k)

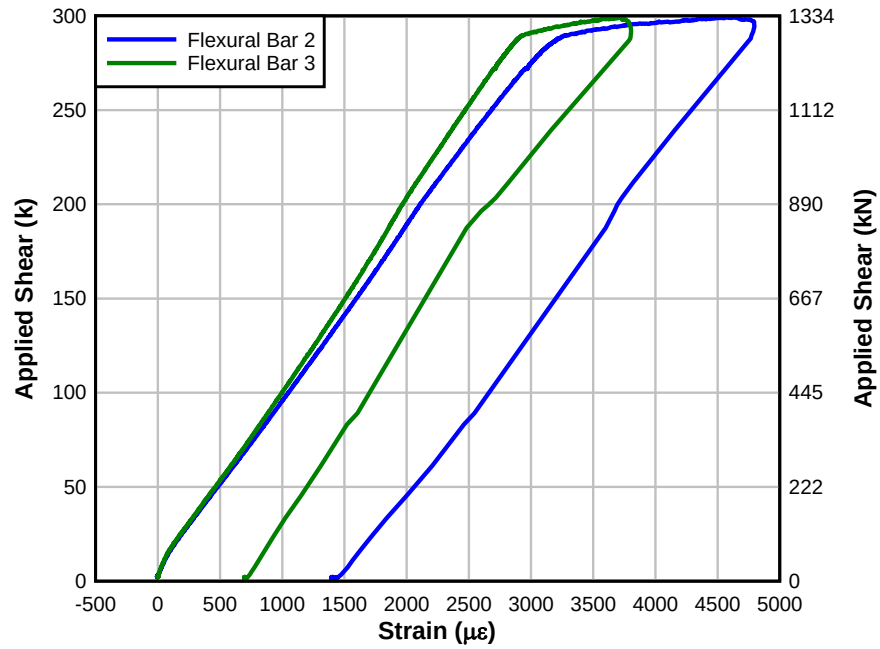


Figure B-70: Specimen IT.7.22.6.FT/FTG applied shear – flexural strain (failure test with second load)

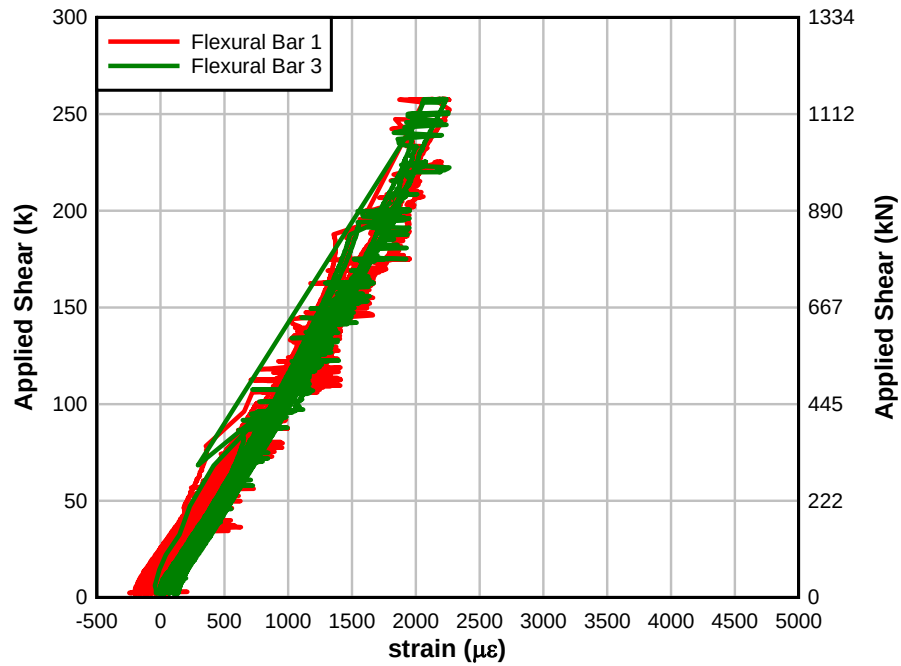


Figure B-71: Specimen IT.7.18.6.M applied shear vs. flexural bar strain (failure test)

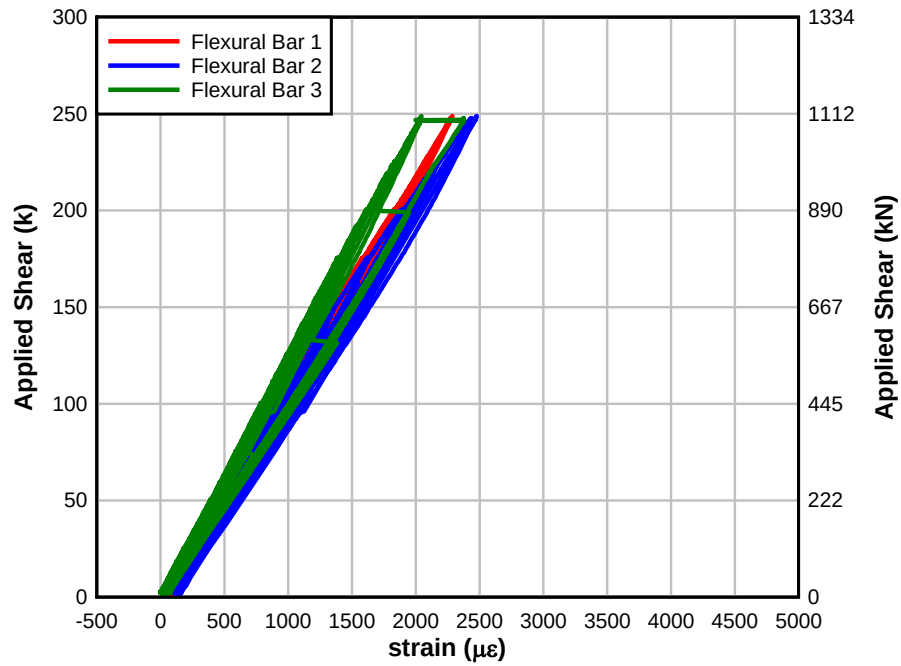


Figure B-72: Specimen IT.7.22.6.FT applied shear vs. flexural bar strain (failure test)

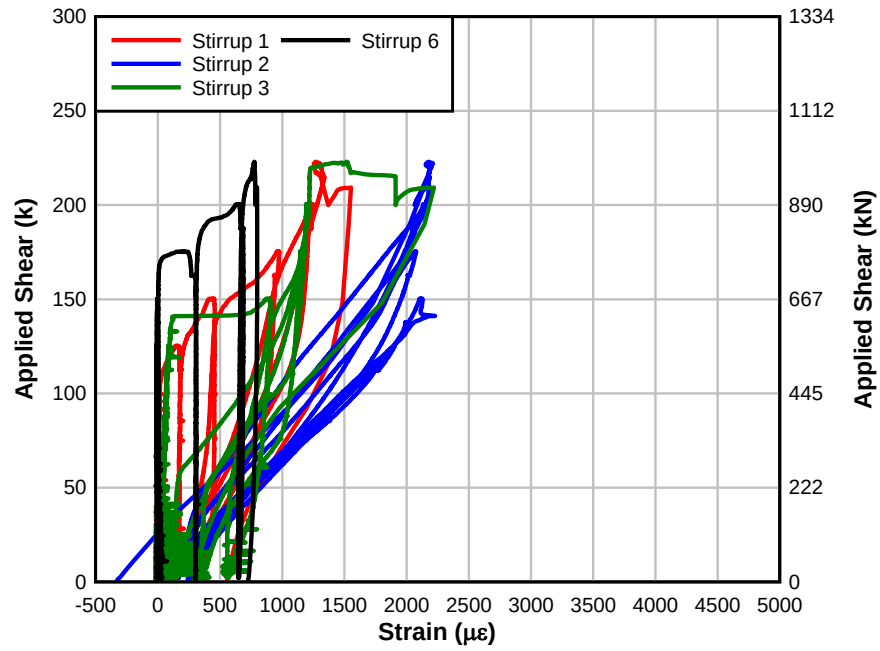


Figure B-73: Specimen T.6.18.6.S applied shear – stirrup strain (failure test)

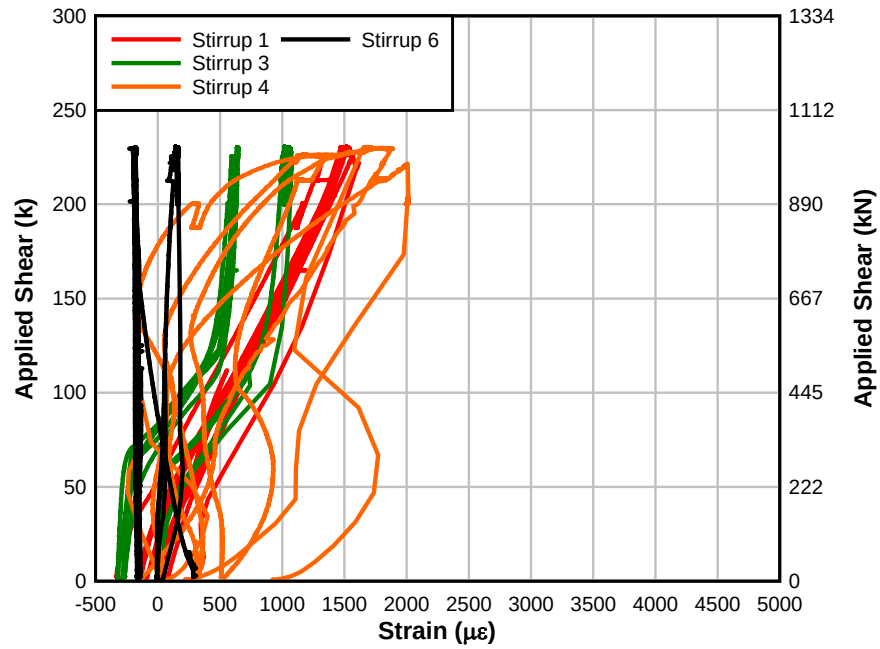


Figure B-74: Specimen T.6.18.12.S applied shear – stirrup strain (failure test)

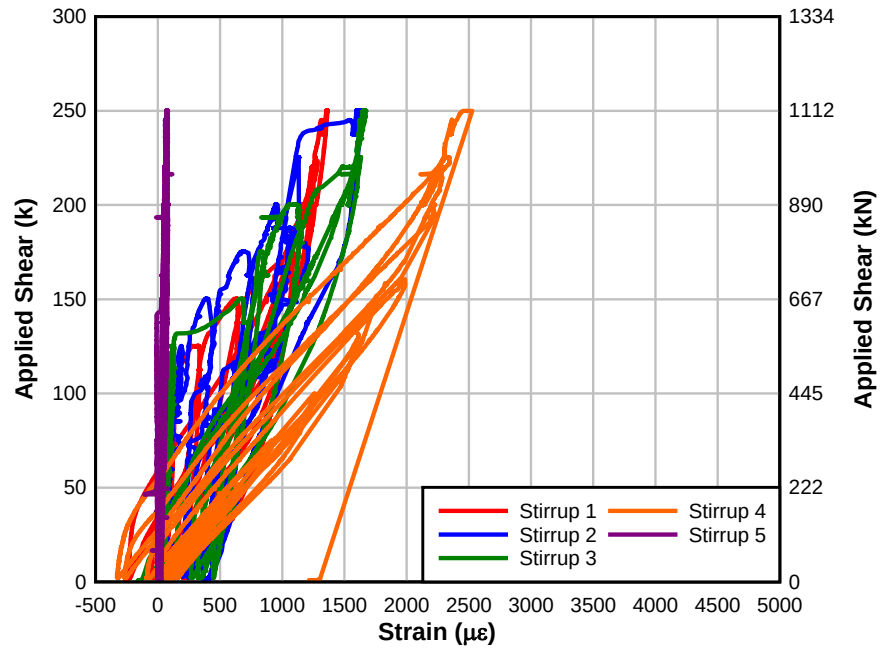


Figure B-75: Specimen IT.7.18.6.S applied shear – stirrup strain (failure test to 500k)

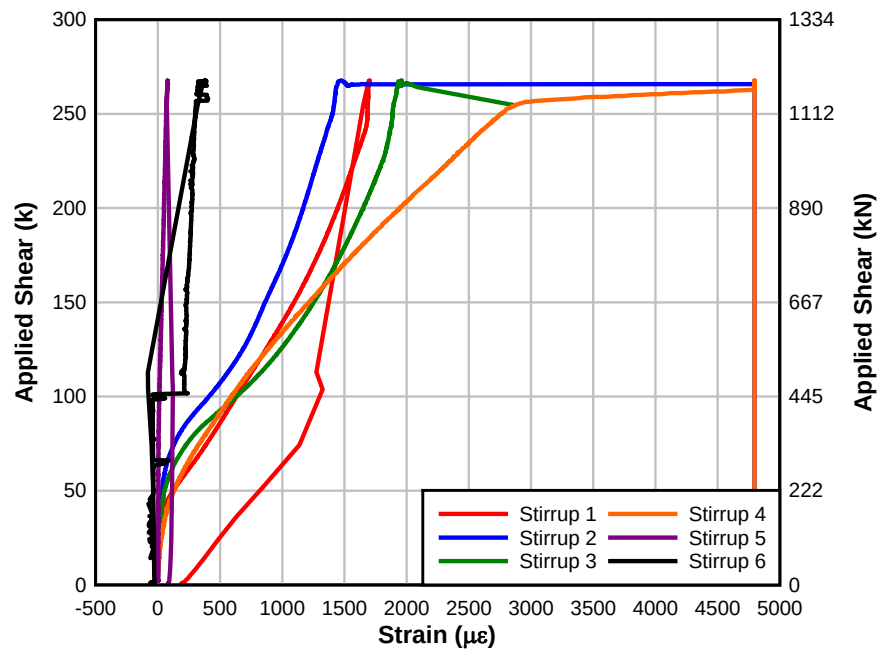


Figure B-76: Specimen IT.7.18.6.S applied shear – stirrup strain (failure test to failure)

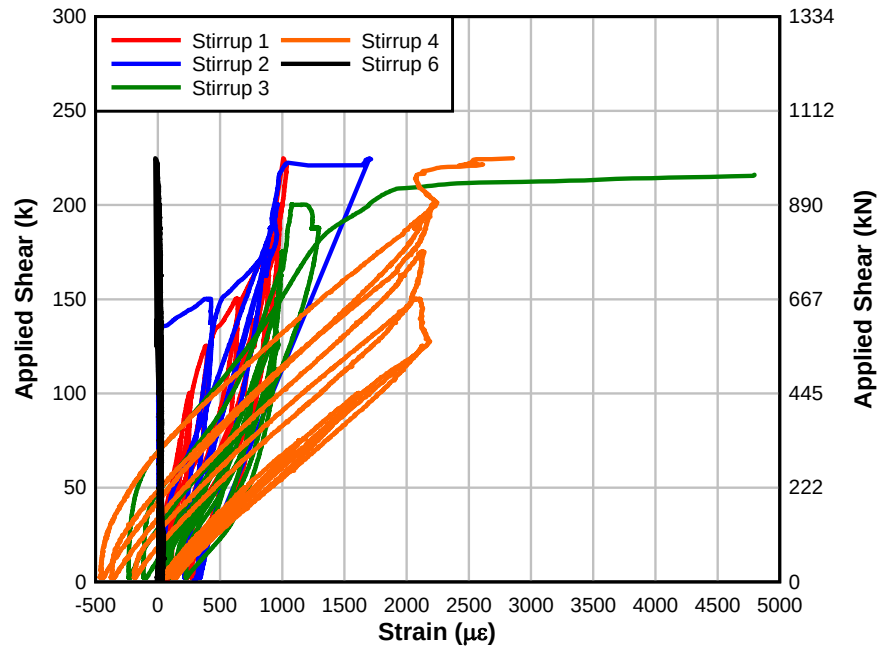


Figure B-77: Specimen IT.7.18.12.S applied shear – stirrup strain (failure test)

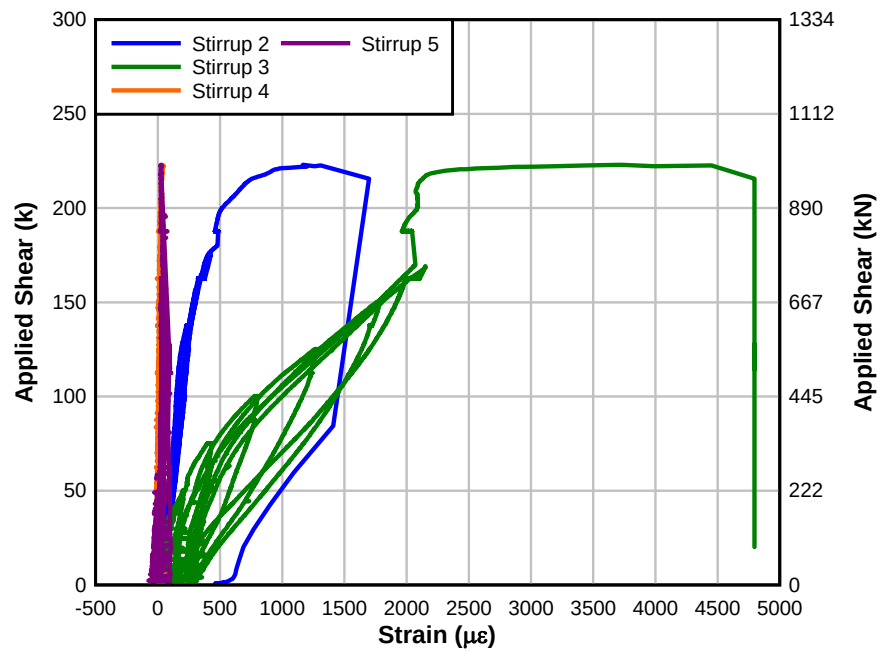


Figure B-78: Specimen IT.5.22.12*.S applied shear – stirrup strain (failure test)

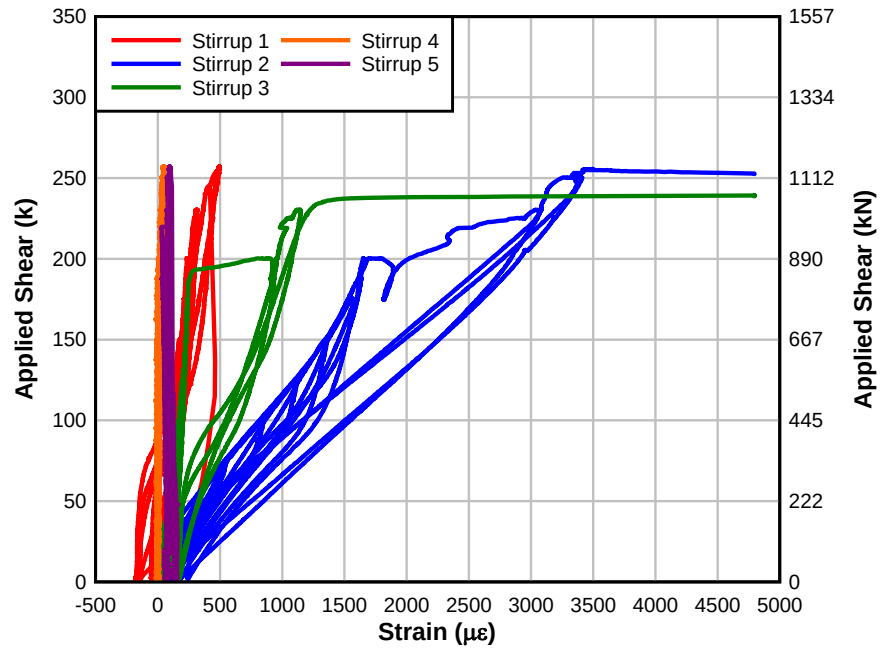


Figure B-79: Specimen IT.7.22.6.S applied shear – stirrup strain (failure test)

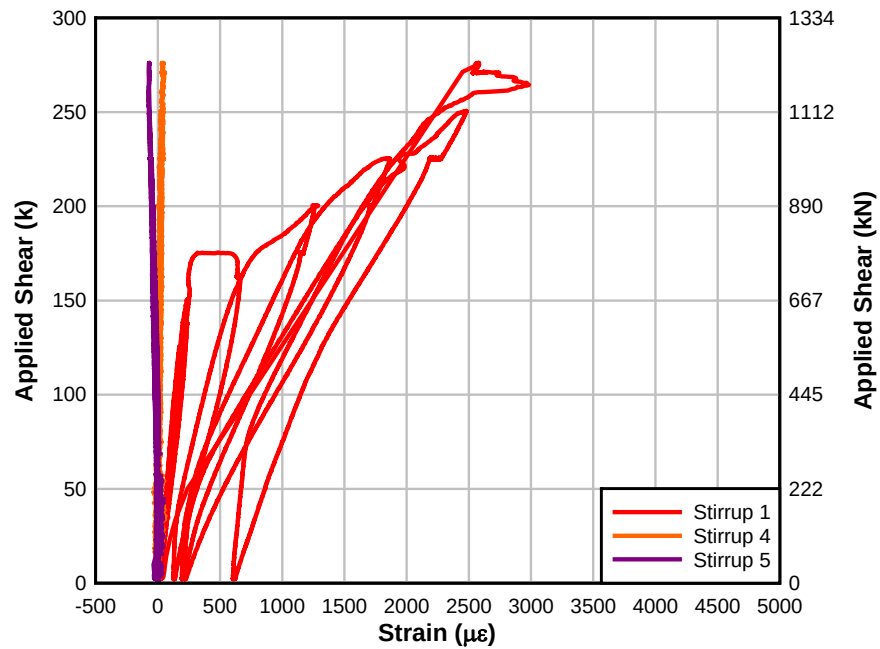


Figure B-80: Specimen IT.7.22.6.FTG applied shear – stirrup strain (failure test)

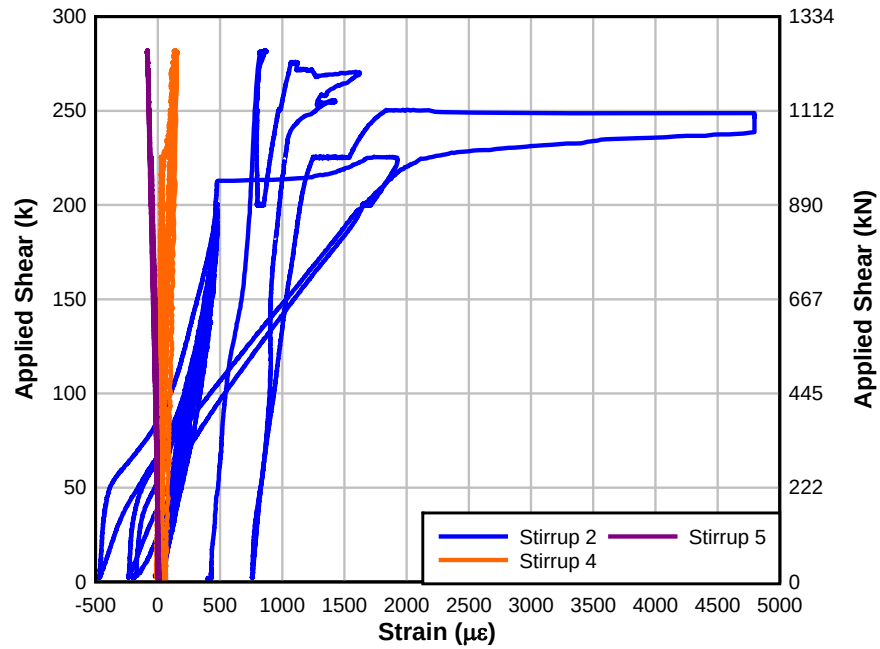


Figure B-81: Specimen IT.7.22.6.FT/FTG applied shear – stirrup strain (failure test to 562k)

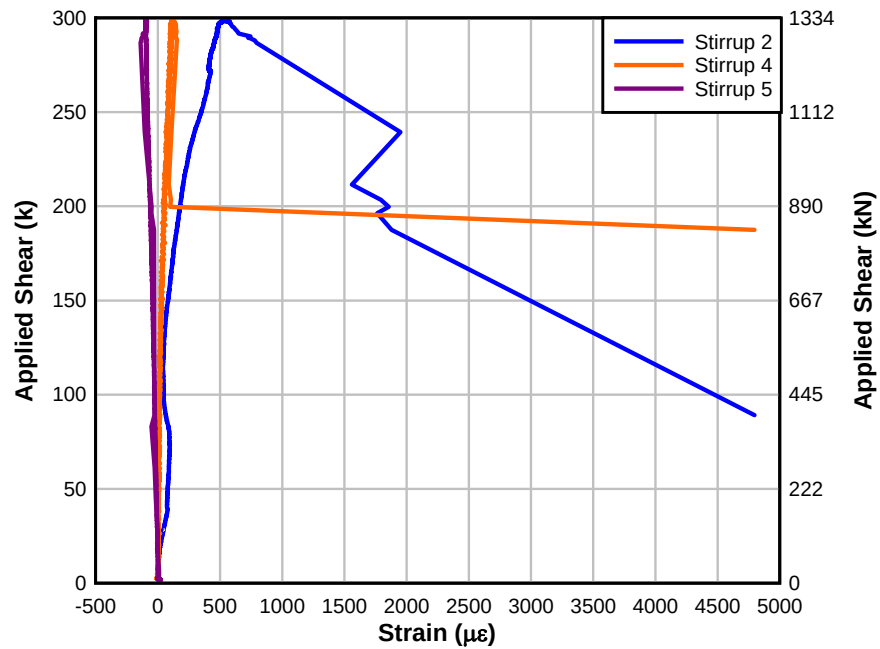


Figure B-82: Specimen IT.7.22.6.FT/FTG applied shear – stirrup strain (failure test with second load)

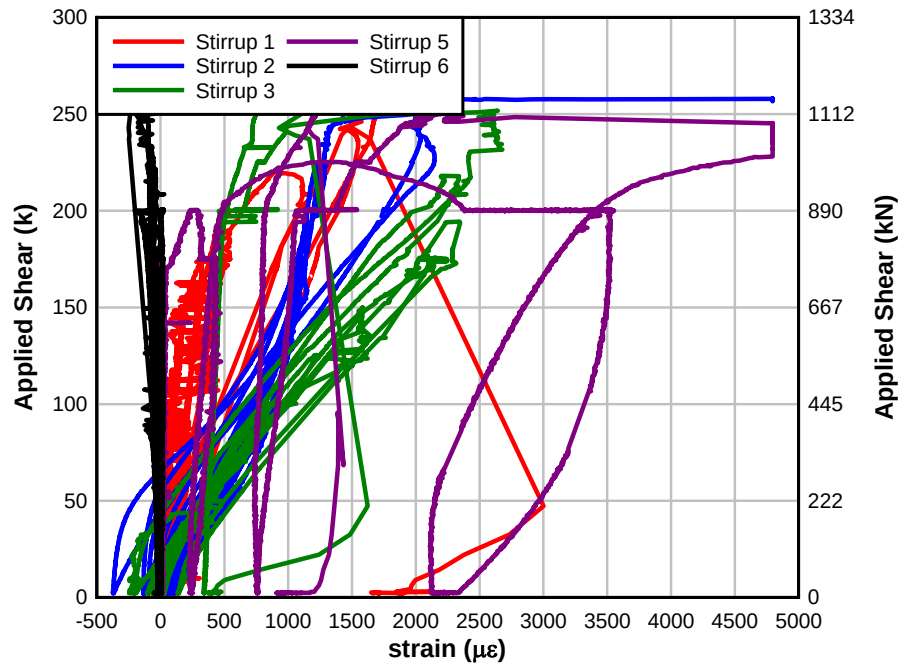


Figure B-83: Specimen IT.7.18.6.M applied shear vs. stirrup strain (failure test)

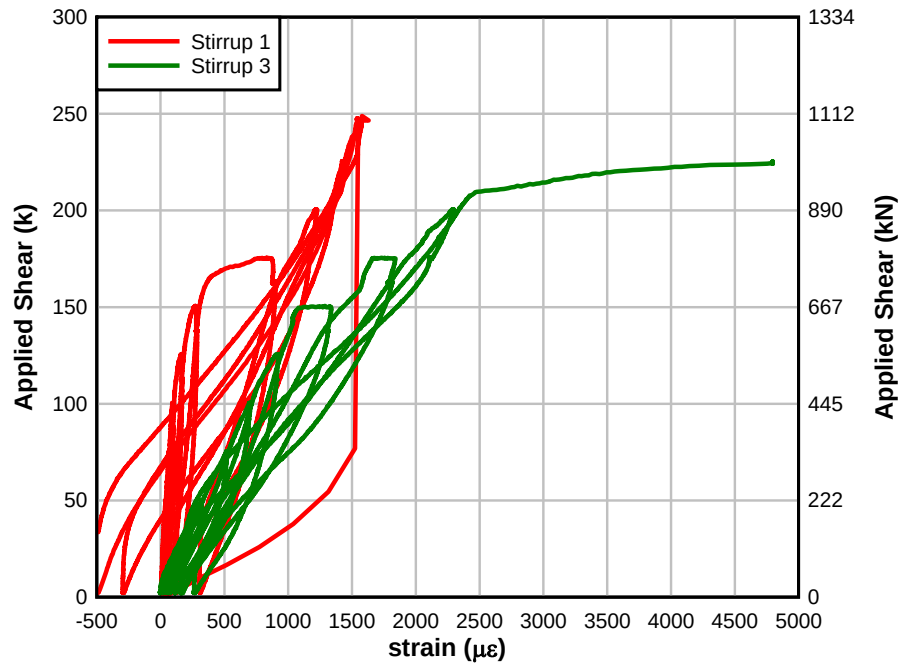


Figure B-84: Specimen IT.7.22.6.FT applied shear vs. stirrup strain (failure test)

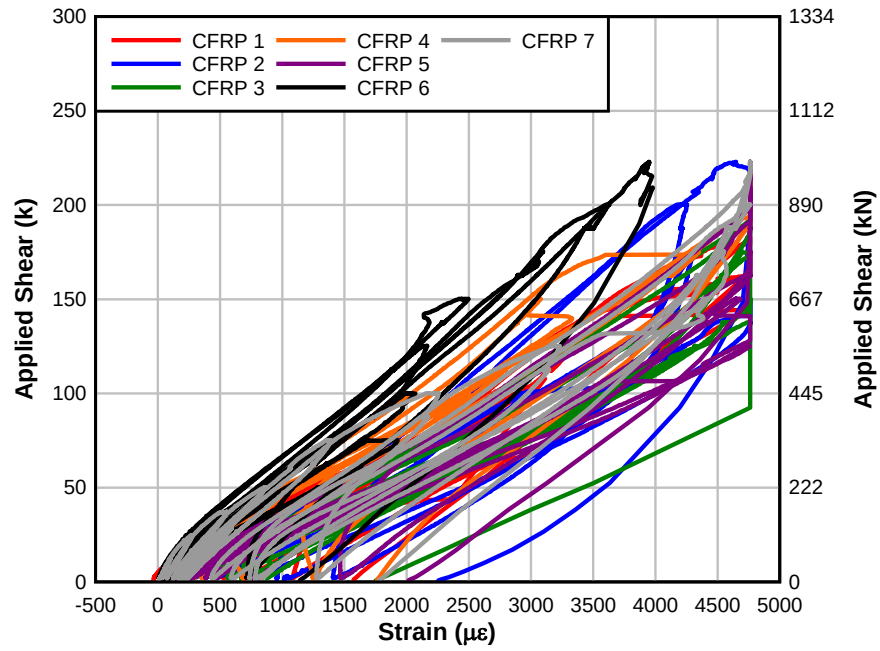


Figure B-85: Specimen T.6.18.6.S applied shear – CFRP strain (failure test)

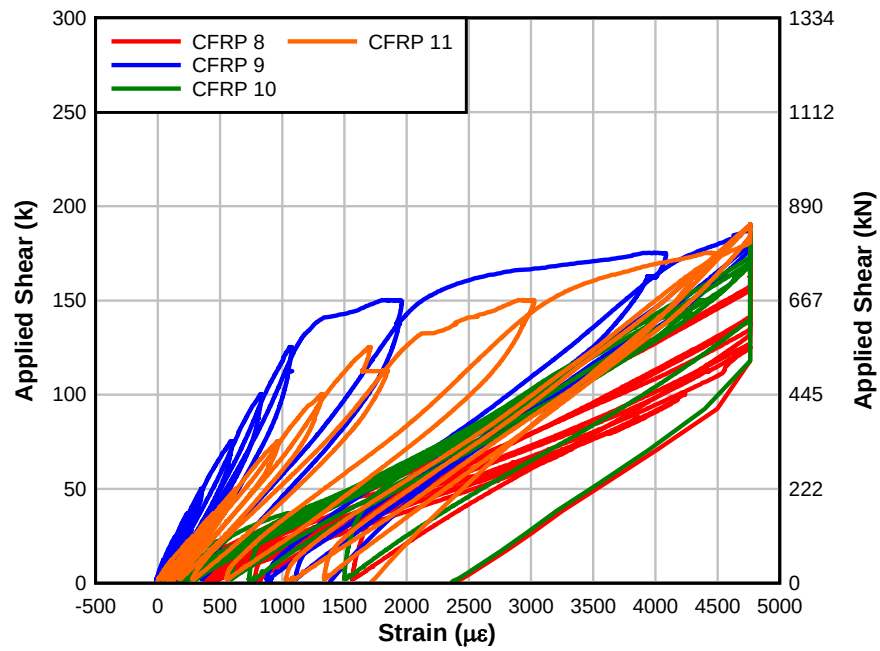


Figure B-86: Specimen T.6.18.6.S applied shear – CFRP strain (failure test)

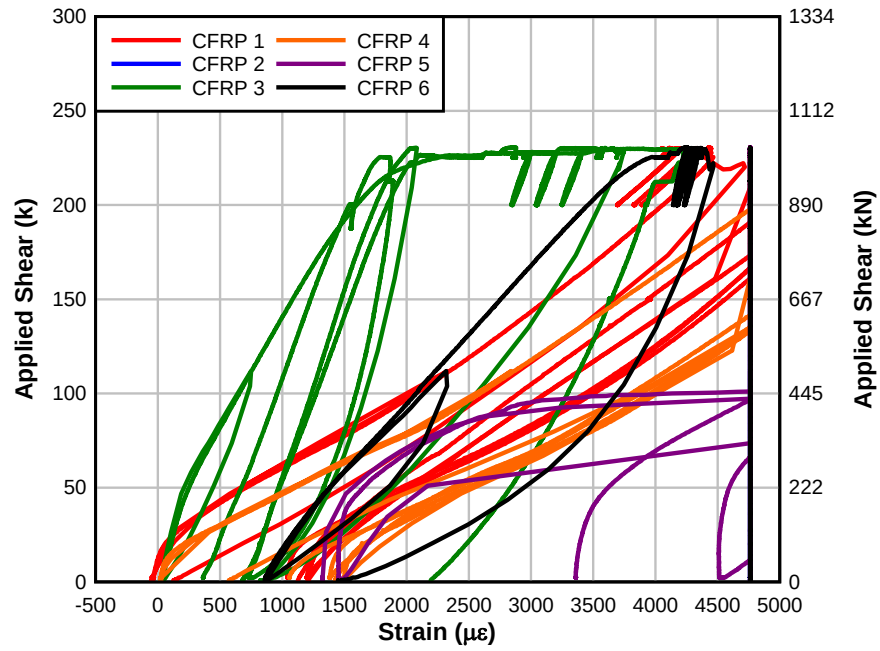


Figure B-87: Specimen T.6.18.12.S applied shear – CFRP strain (failure test)

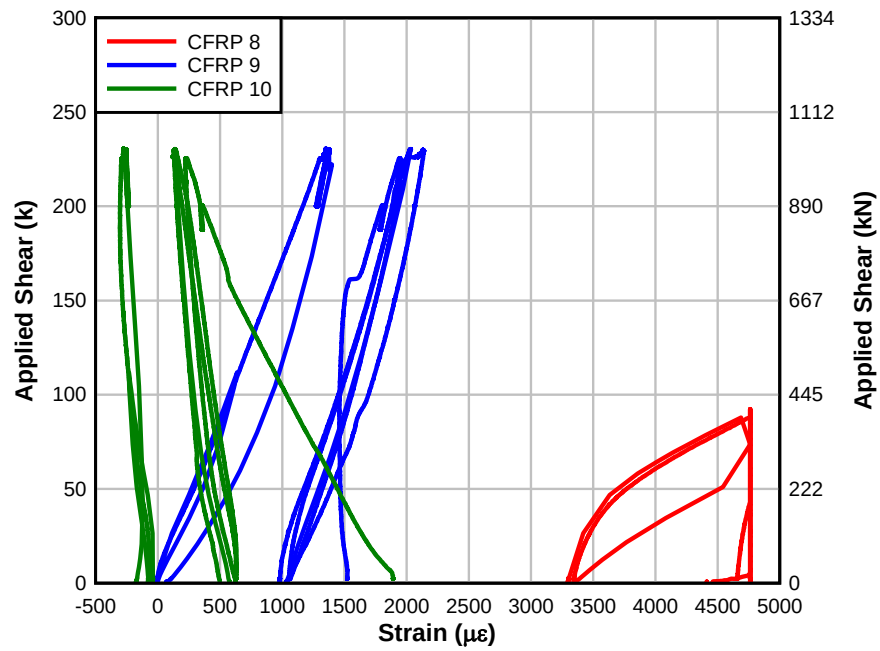


Figure B-88: Specimen T.6.18.12.S applied shear – CFRP strain (failure test)

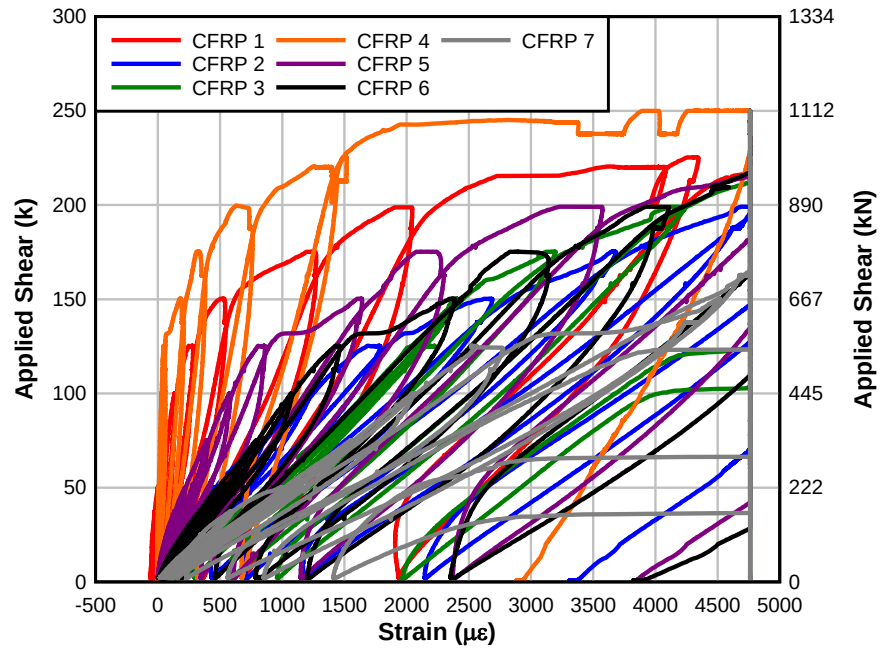


Figure B-89: Specimen IT.7.18.6.S applied shear – CFRP strain (failure test to 500k)

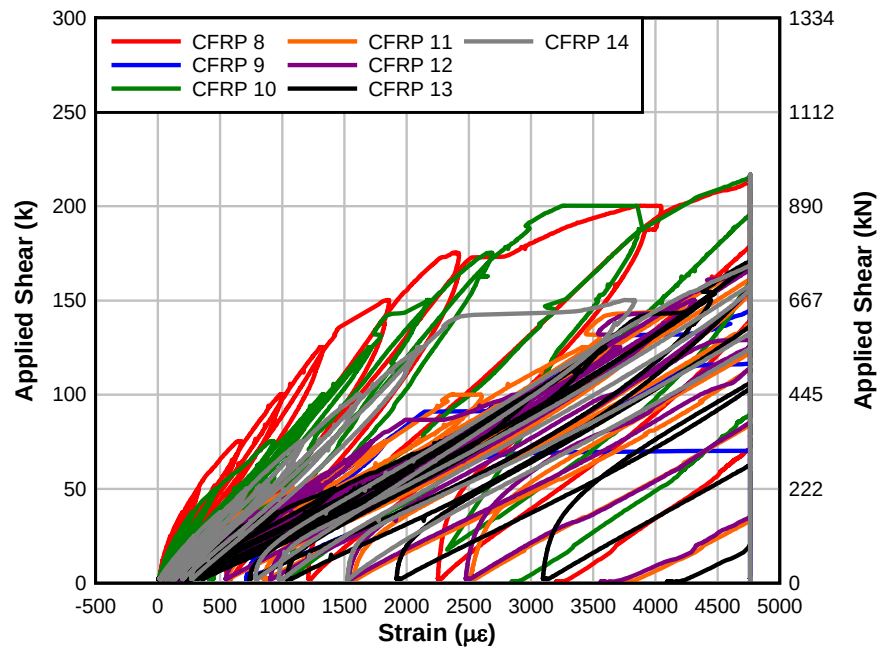


Figure B-90: Specimen IT.7.18.6.S applied shear – CFRP strain (failure test to 500k)

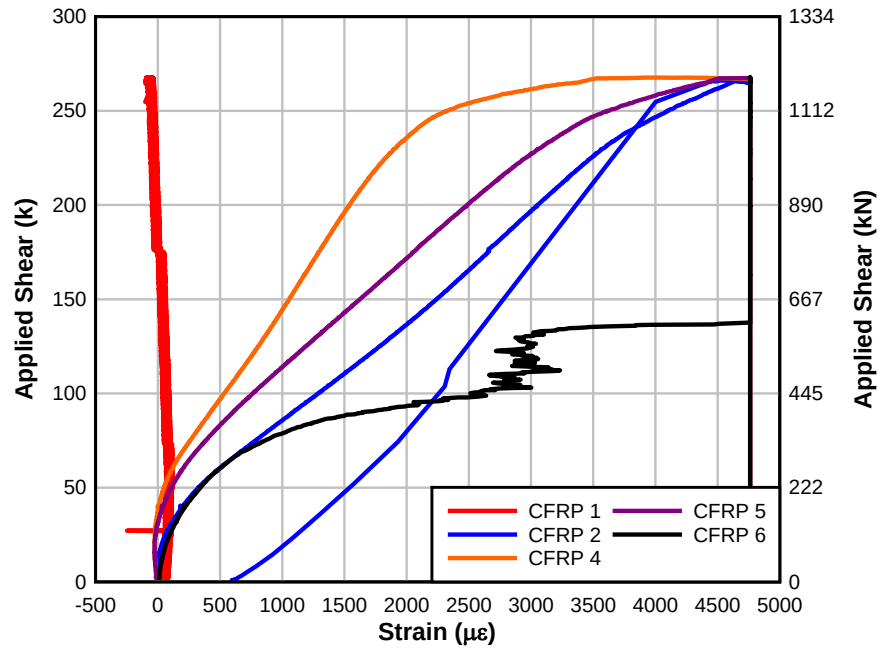


Figure B-91: Specimen IT.7.18.6.S applied shear – CFRP strain (failure test to failure)

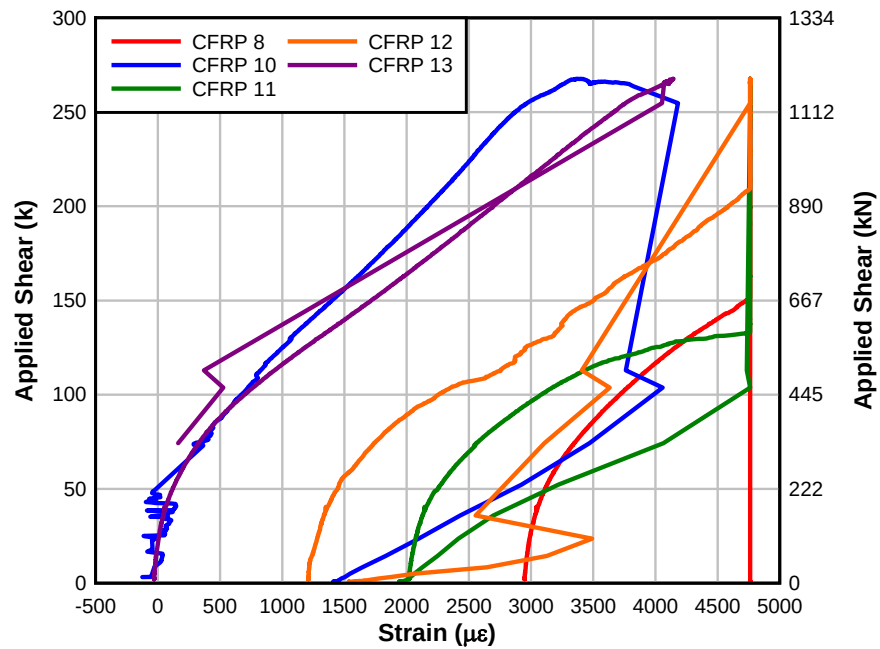


Figure B-92: Specimen IT.7.18.6.S applied shear – CFRP strain (failure test to failure)

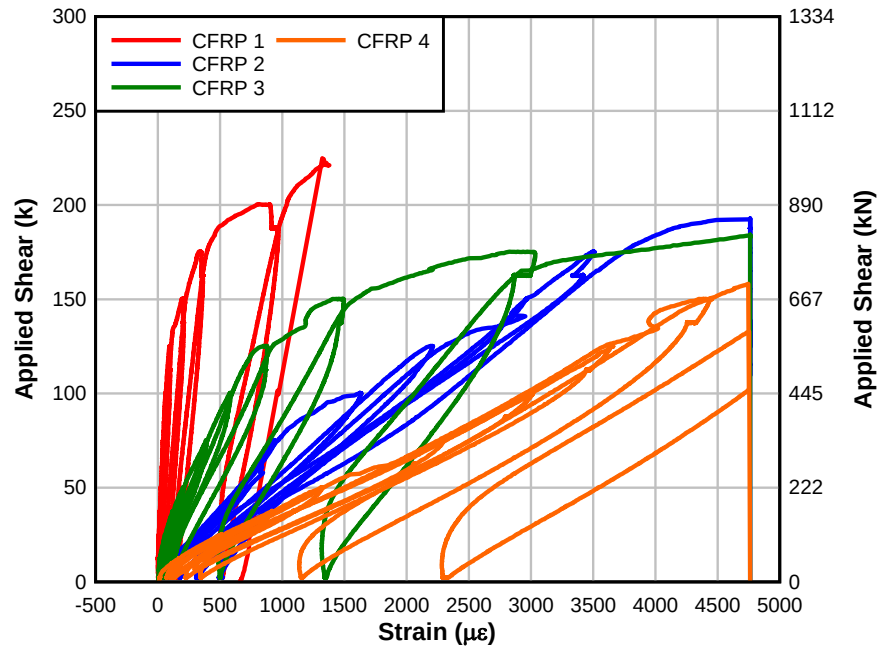


Figure B-93: Specimen IT.7.18.12.S applied shear – CFRP strain (failure test)

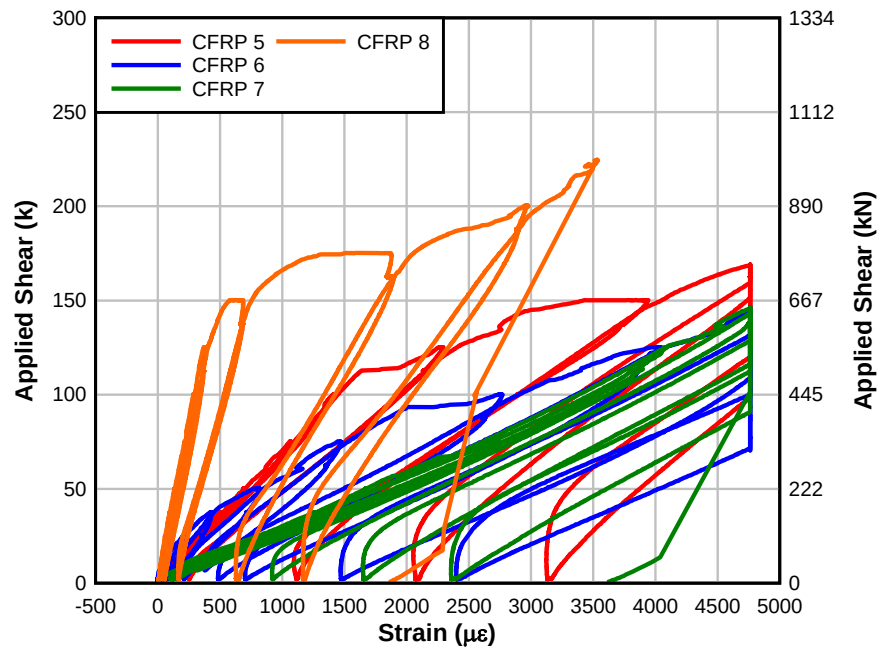


Figure B-94: Specimen IT.7.18.12.S applied shear – CFRP strain (failure test)

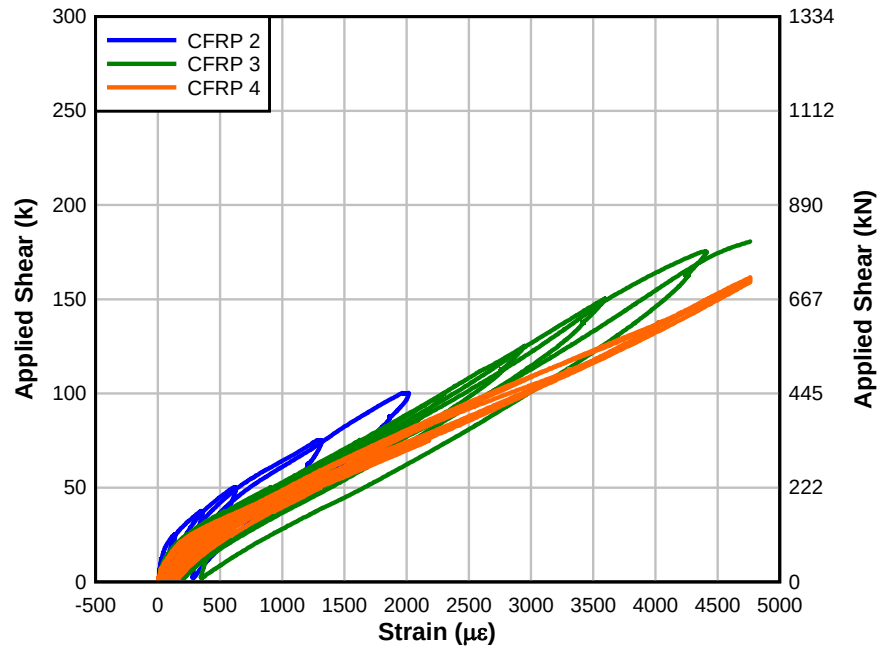


Figure B-95: Specimen IT.5.22.12*.S applied shear – CFRP strain (failure test)

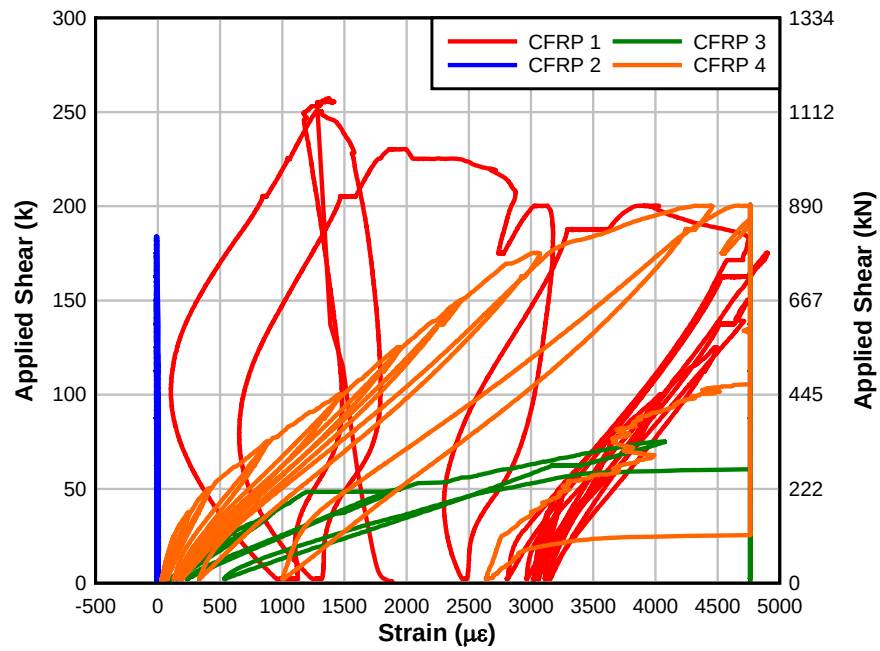


Figure B-96: Specimen IT.7.22.6.S applied shear – CFRP strain (failure test)

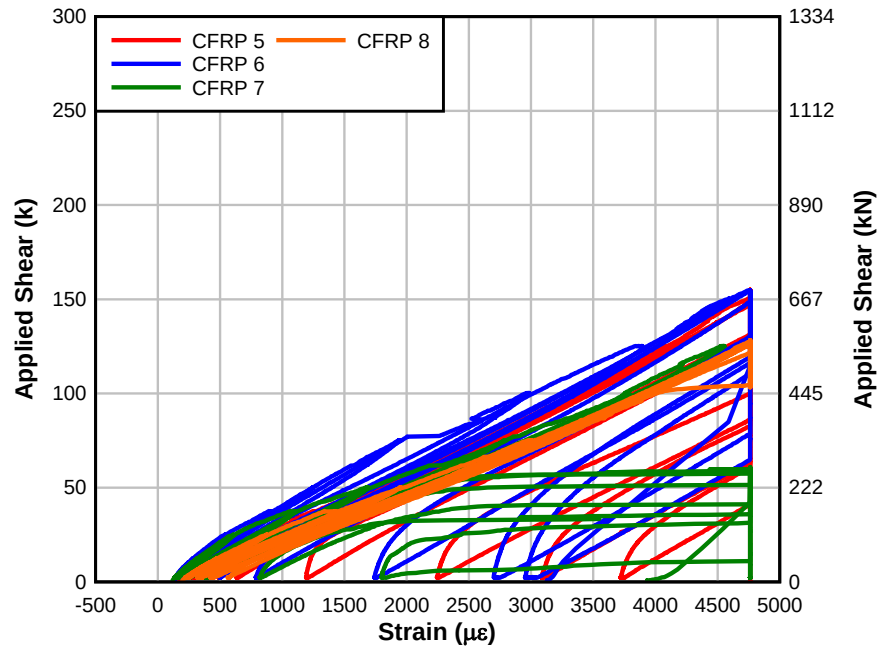


Figure B-97: Specimen IT.7.22.6.S applied shear – CFRP strain (failure test)

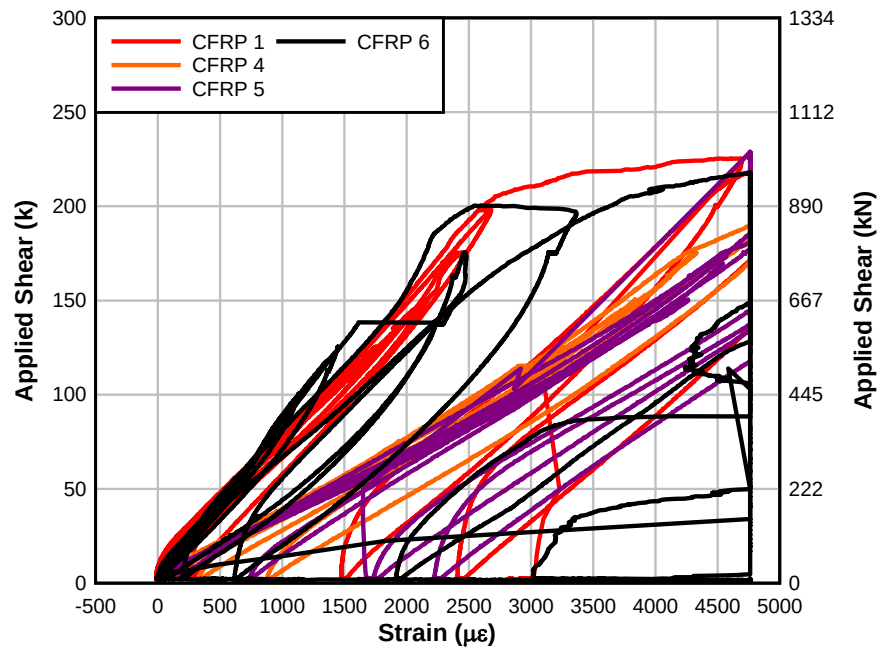


Figure B-98: Specimen IT.7.22.6.FTG applied shear – CFRP strain (failure test)

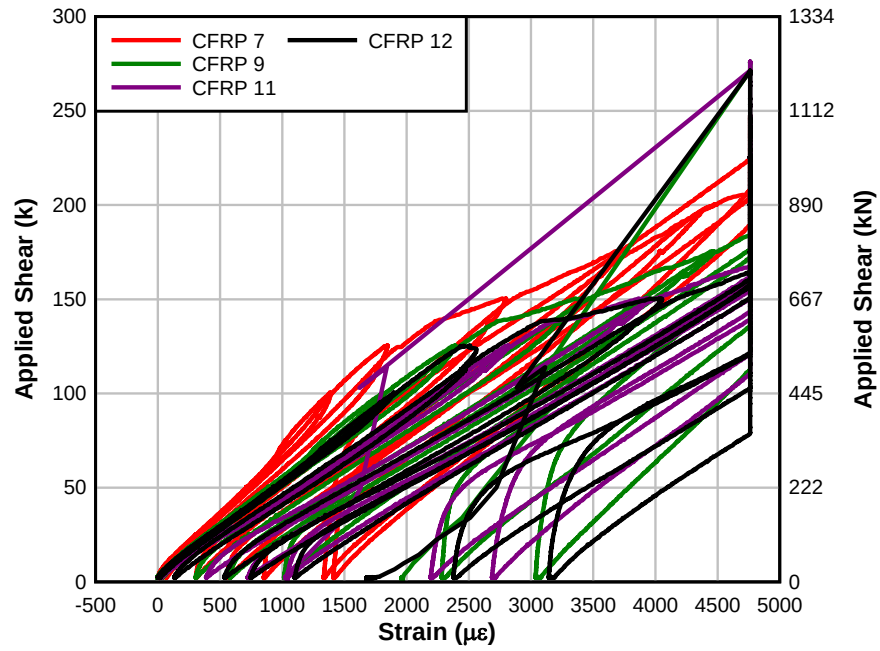


Figure B-99: Specimen IT.7.22.6.S applied shear – CFRP strain (failure test)

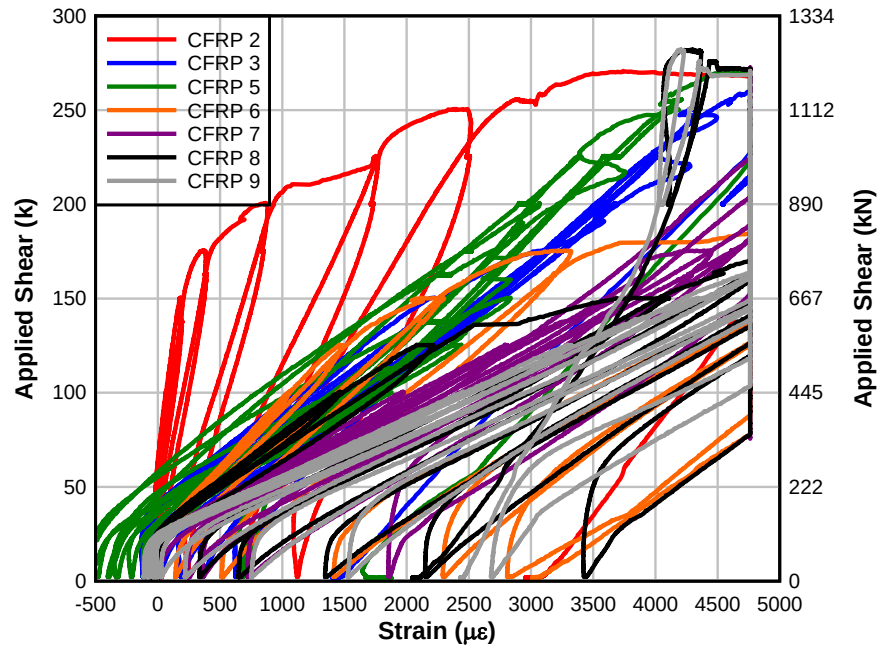


Figure B-100: Specimen IT.7.22.6.FT/FTG applied shear – CFRP strain (failure test to 562k)

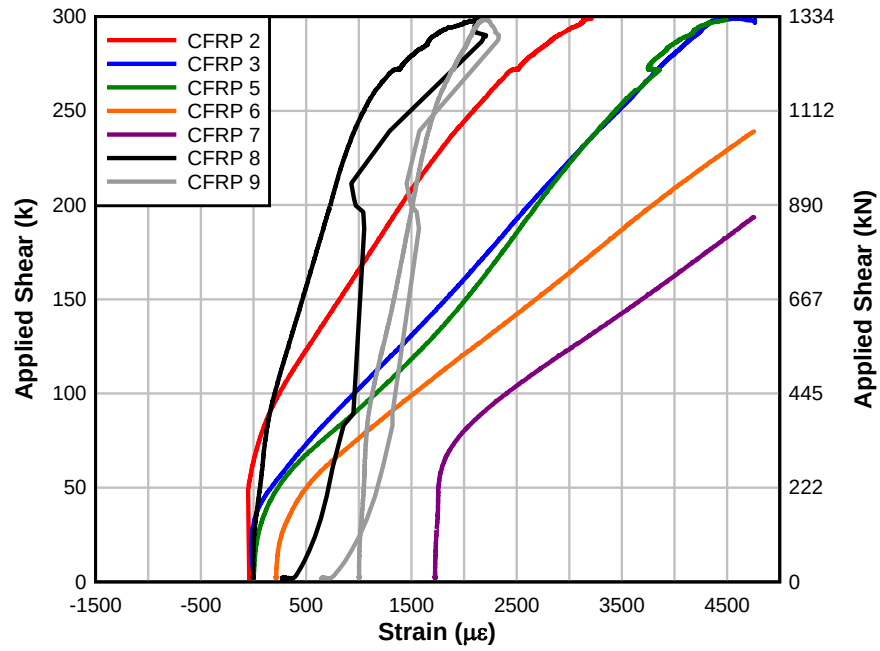


Figure B-101: Specimen IT.7.22.6.FT/FTG applied shear – CFRP strain (failure test to failure)

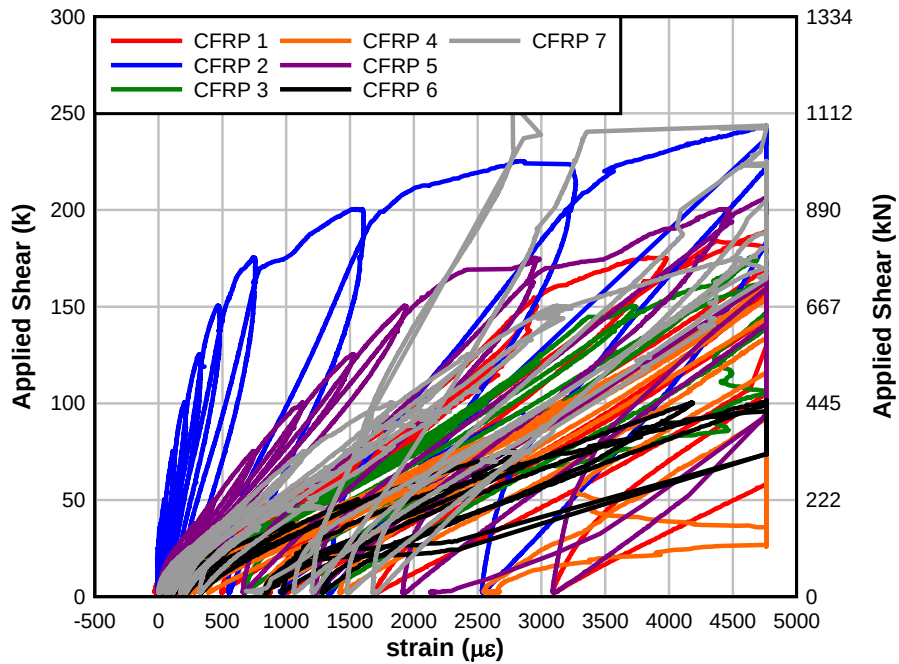


Figure B-102: Specimen IT.7.18.6.M applied shear vs. CFRP strain (failure test)

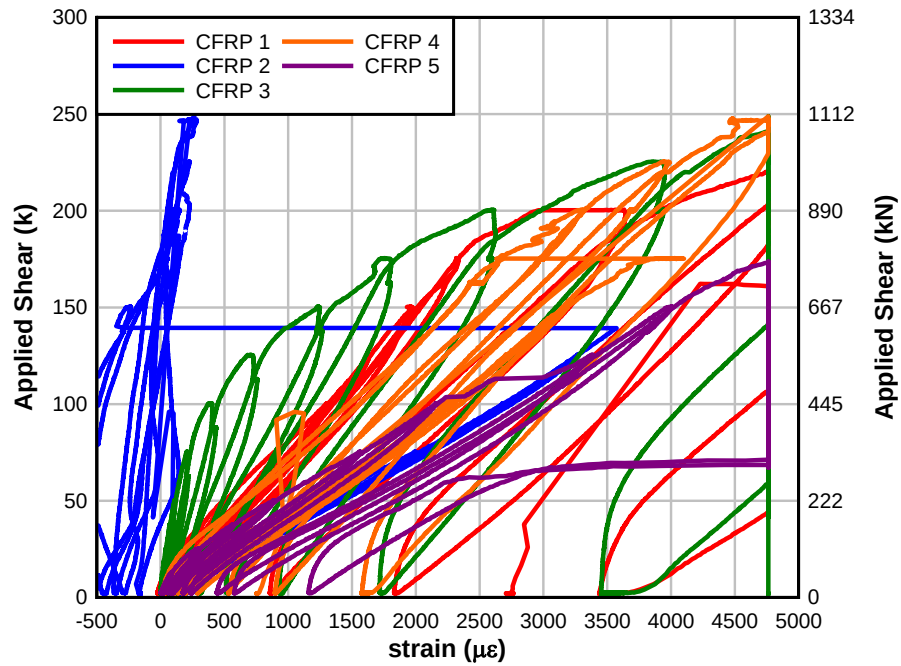


Figure B-103: Specimen IT.7.22.6.FT applied shear vs. CFRP strain (failure test)

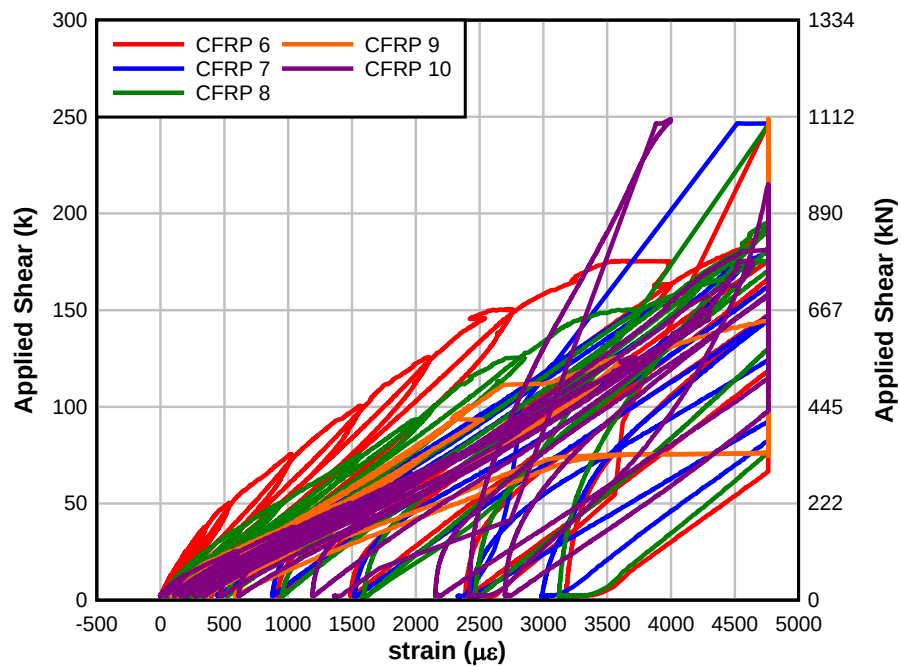


Figure B-104: Specimen IT.7.22.6.FT applied shear vs. CFRP strain (failure test)

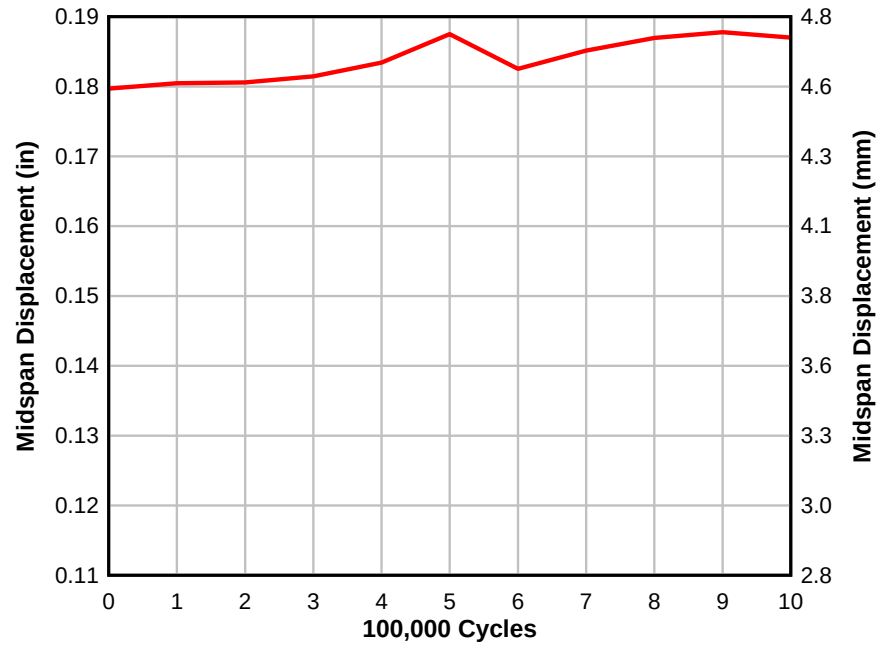


Figure B-105: Specimen IT.7.22.6.FTG fatigue midspan displacement

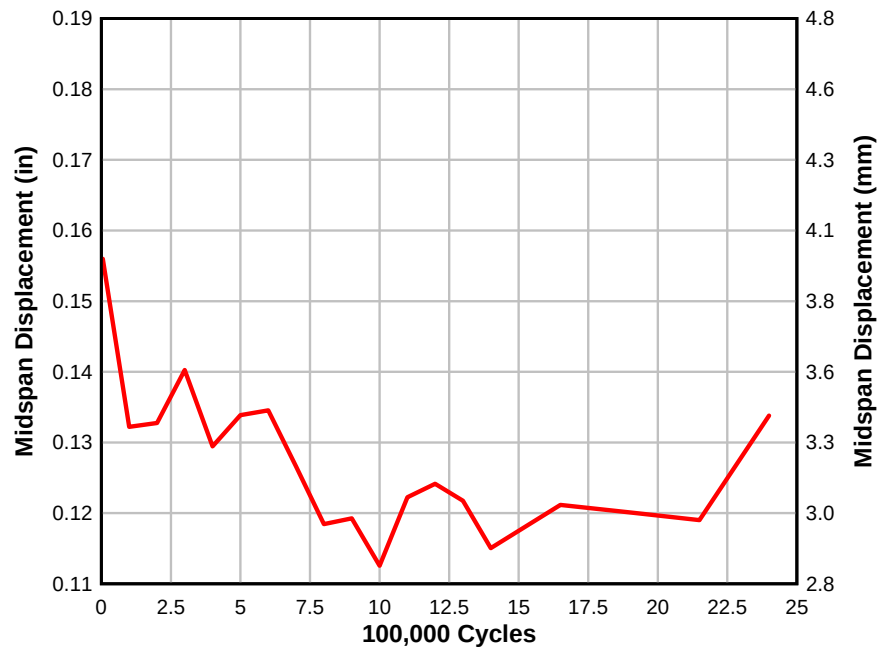


Figure B-106: Specimen IT.7.22.6.FT/FTG fatigue midspan displacement

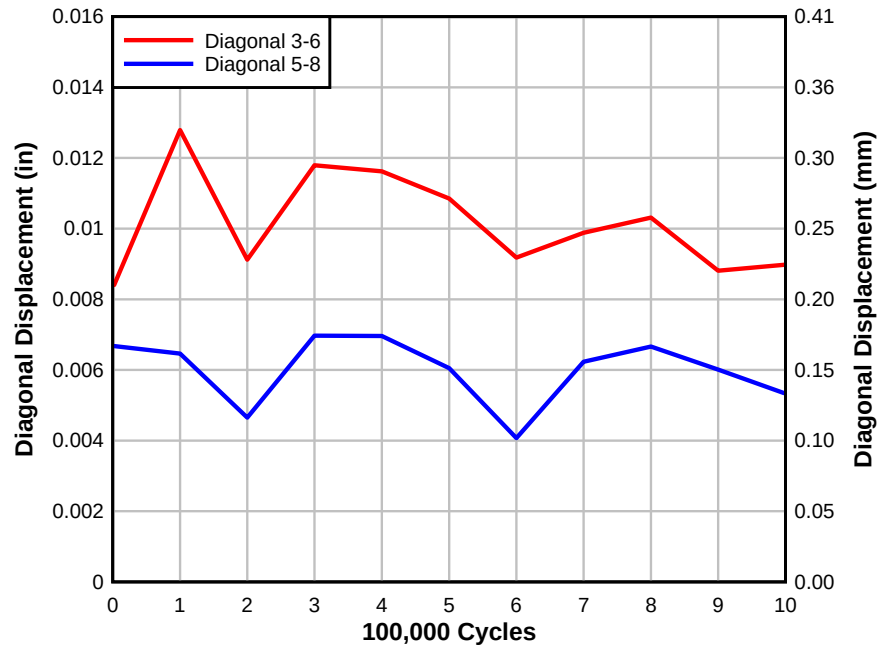


Figure B-107: Specimen IT.7.22.6.FTG fatigue diagonal displacement

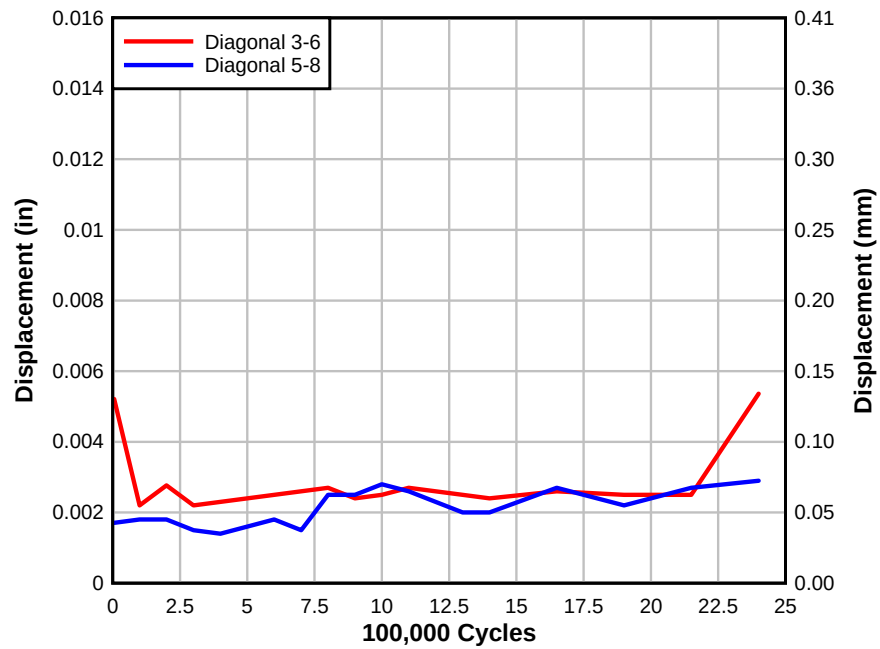


Figure B-108: Specimen IT.7.22.6.FT/FTG fatigue diagonal displacement

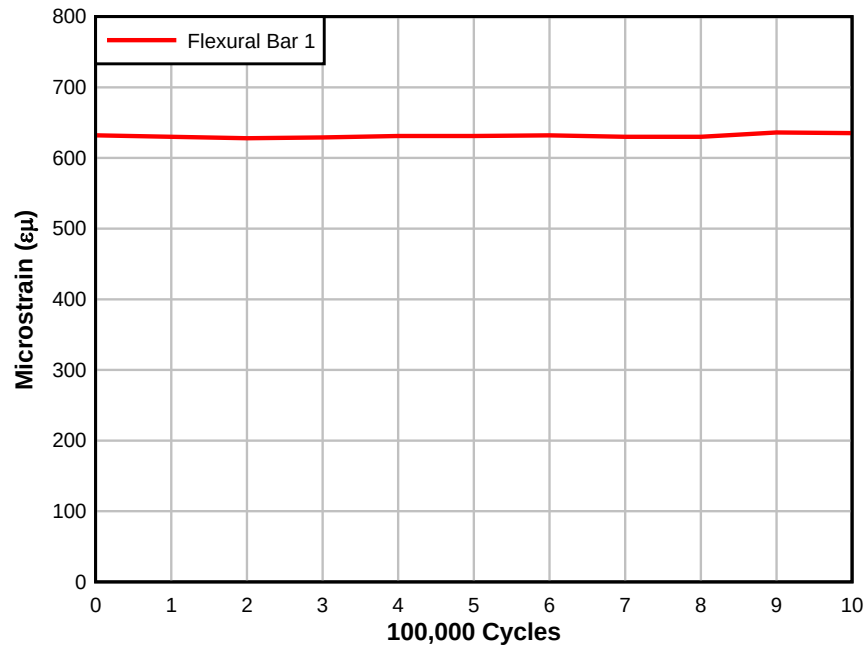


Figure B-109: Specimen IT.7.22.6.FTG fatigue flexural bar strains

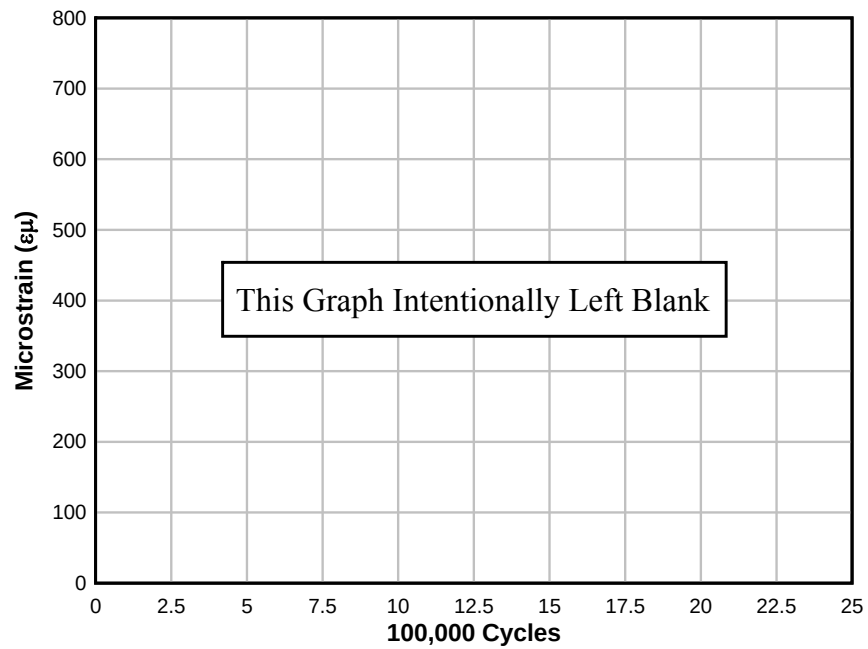


Figure B-110: Specimen IT.7.22.6.FT/FTG fatigue flexural bar strains

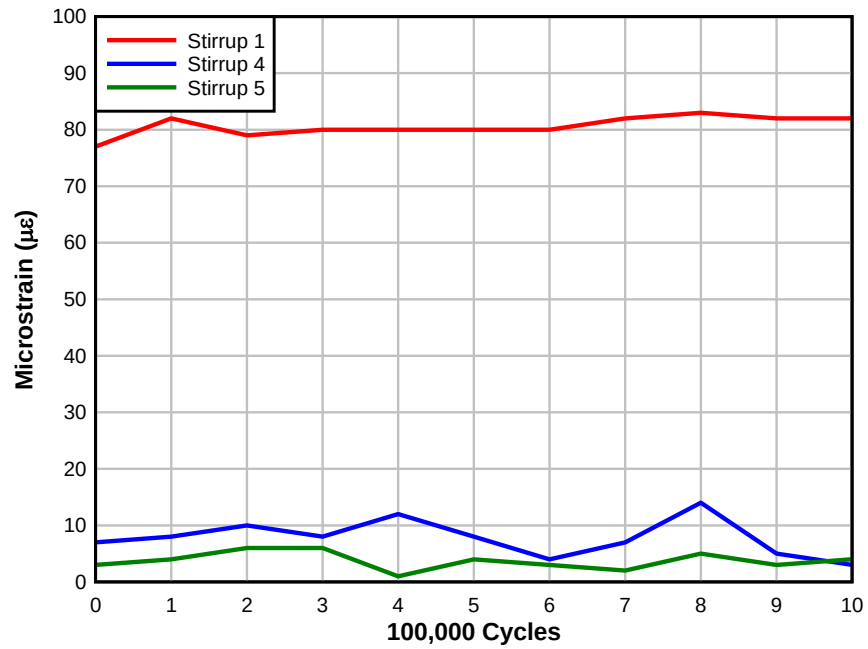


Figure B-111: Specimen IT.7.22.6.FTG fatigue stirrup strains

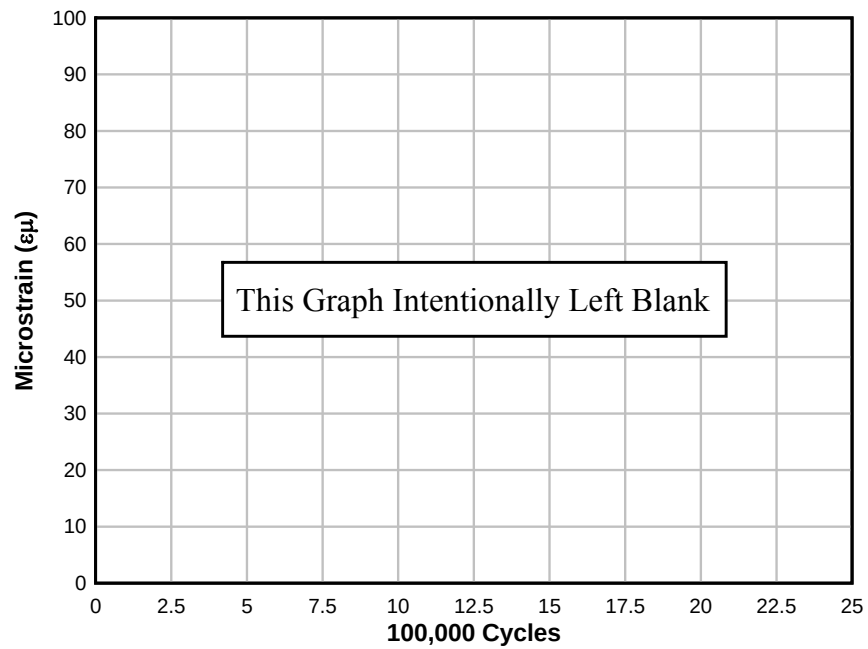


Figure B-112: Specimen IT.7.22.6.FT/FTG fatigue stirrup strains

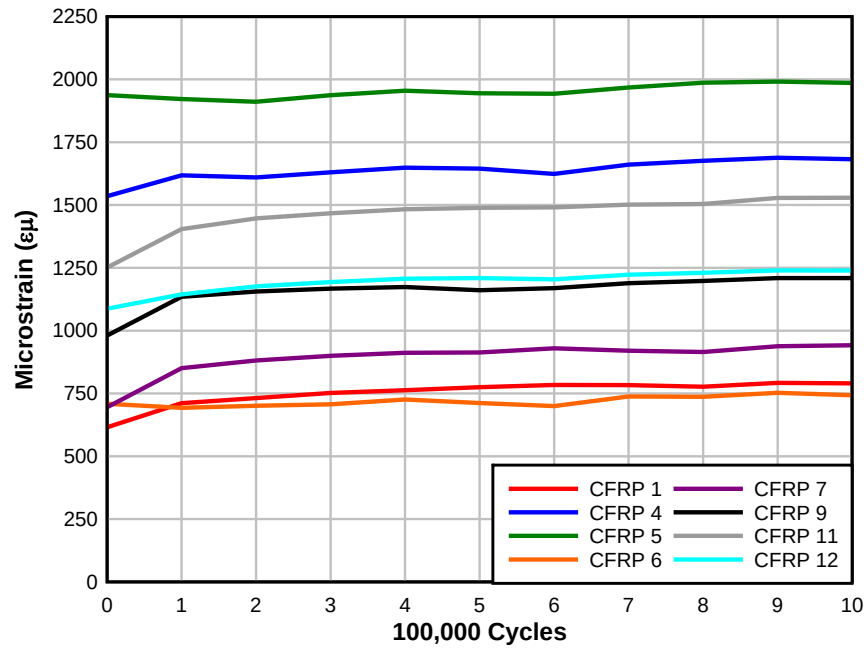


Figure B-113: Specimen IT.7.22.6.FTG fatigue CFRP strains

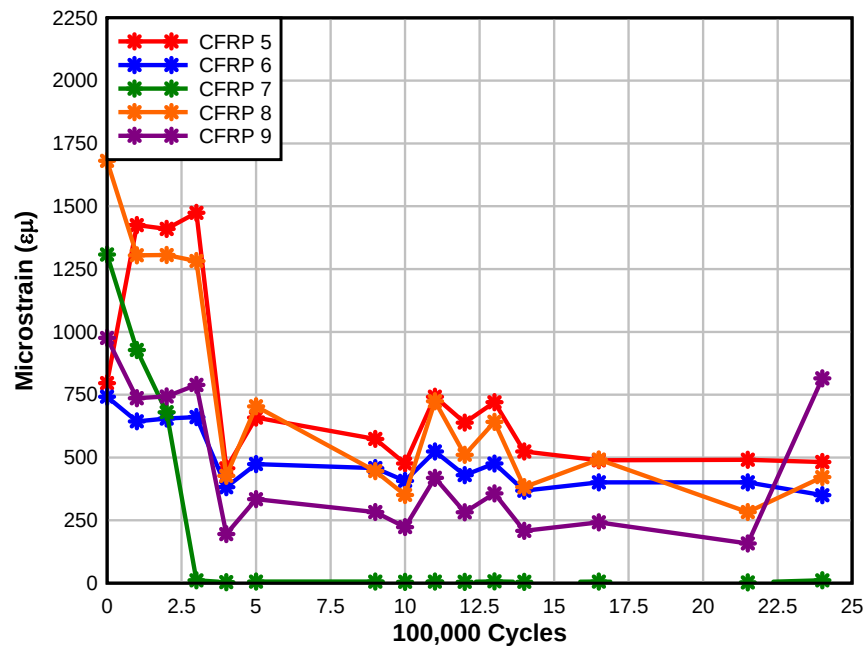


Figure B-114: Specimen IT.7.22.6.FT/FTG fatigue CFRP strains

APPENDIX C:

CRACK MAPS

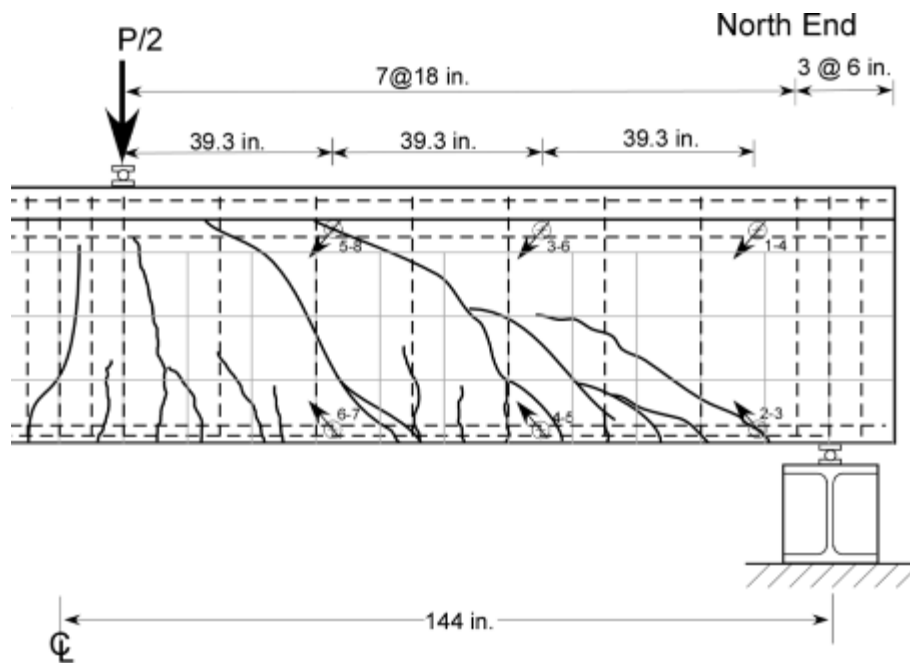


Figure C-1: Specimen T.6.18.6.S crack map (baseline test)

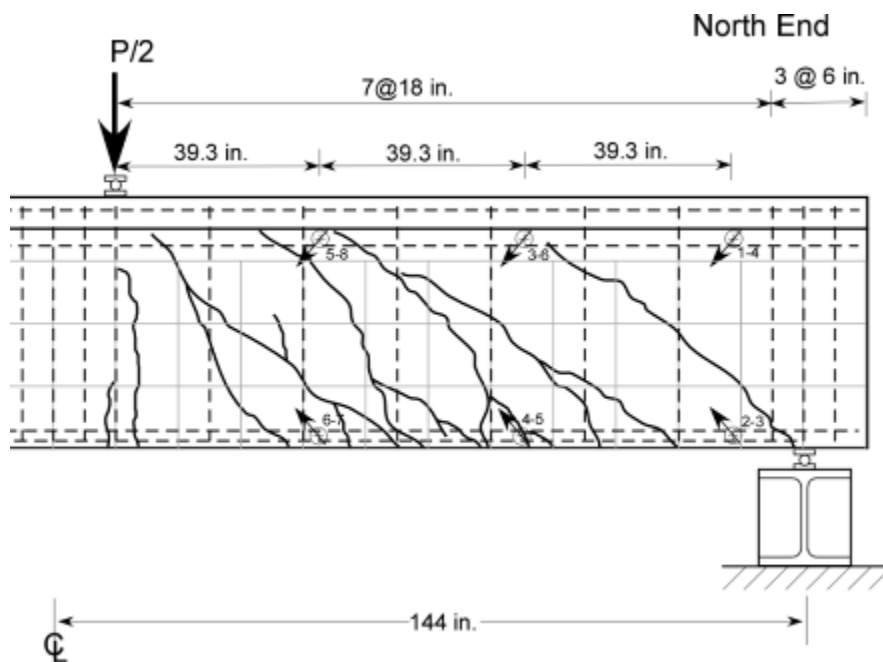


Figure C-2: Specimen T.6.18.12.S crack map (baseline test)

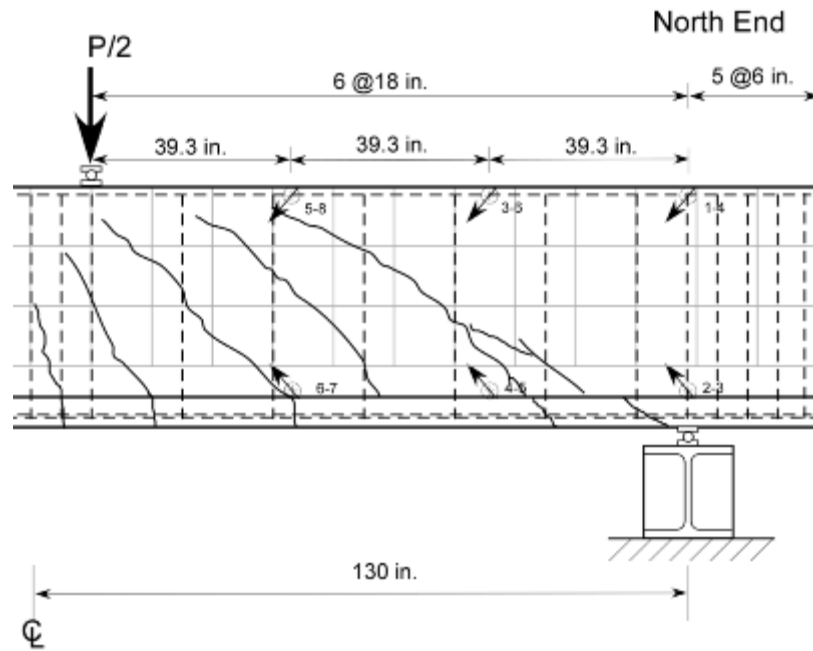


Figure C-3: Specimen IT.7.18.6.S crack map (baseline test)

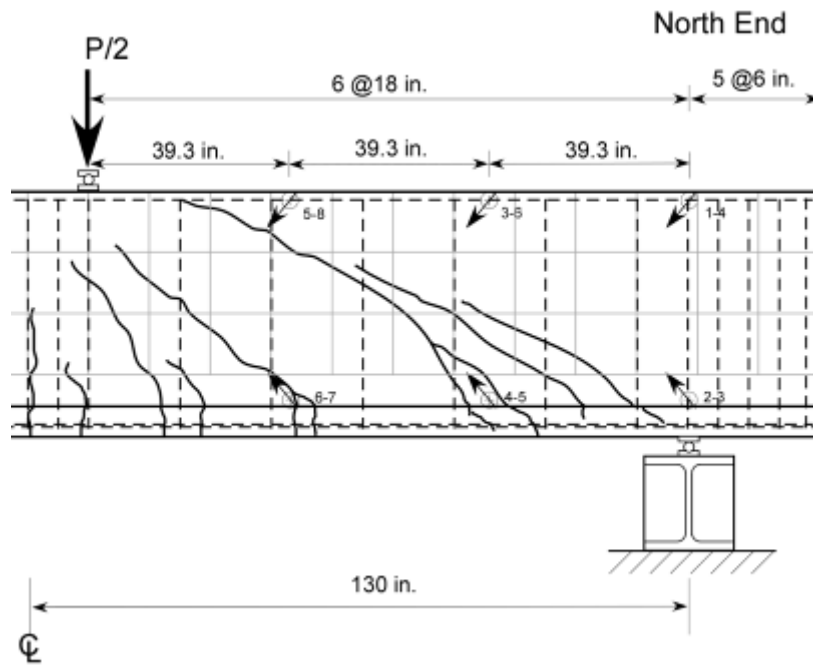


Figure C-4: Specimen IT.7.18.12.S crack map (baseline test)

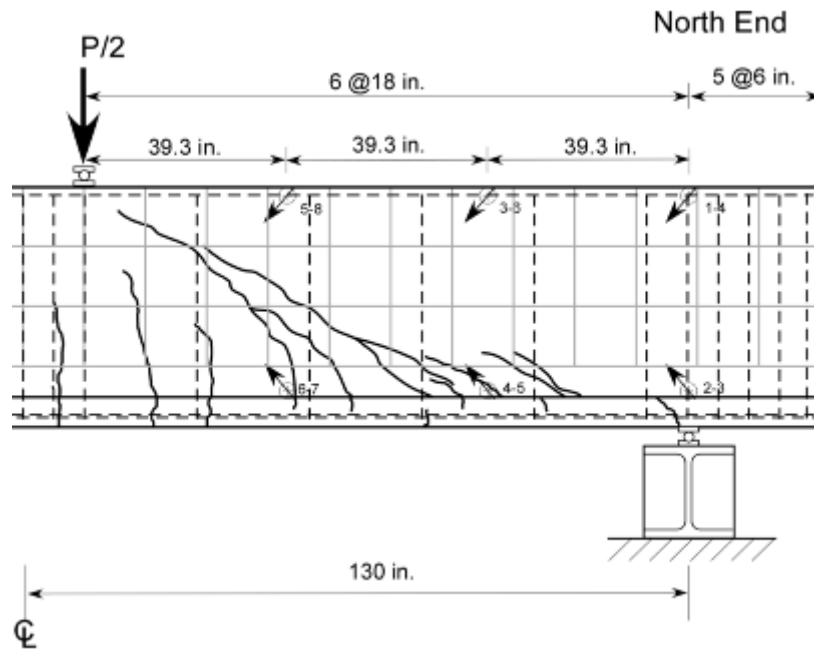


Figure C-5: Specimen IT.5.22.12*.S crack map (baseline test)

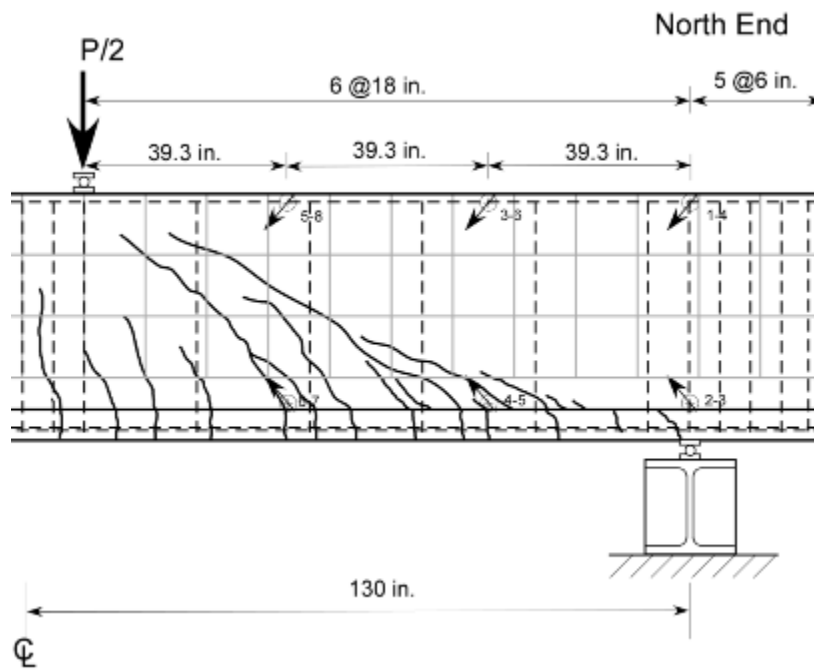


Figure C-6: Specimen IT.7.22.6.S crack map (baseline test)

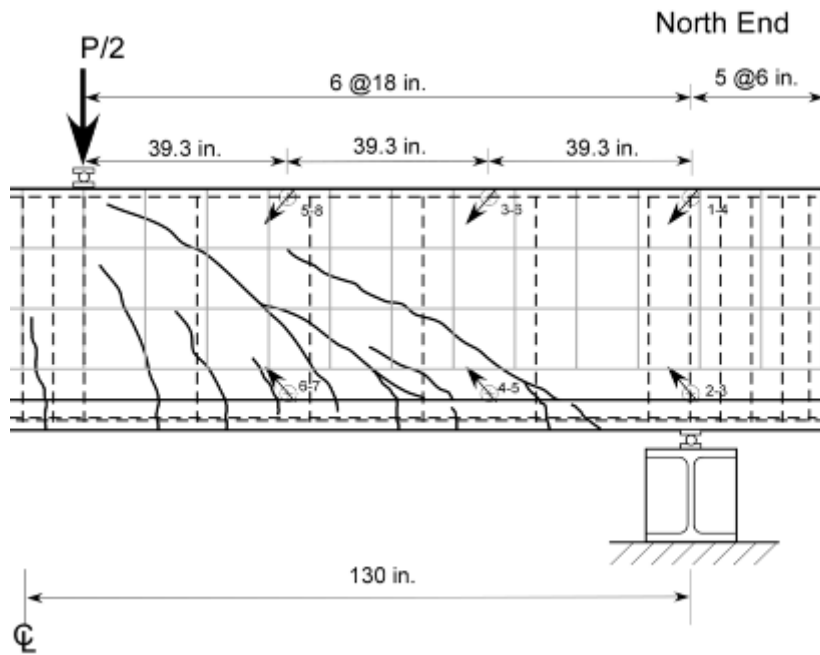


Figure C-7: Specimen IT.7.22.6.FTG crack map (baseline test)

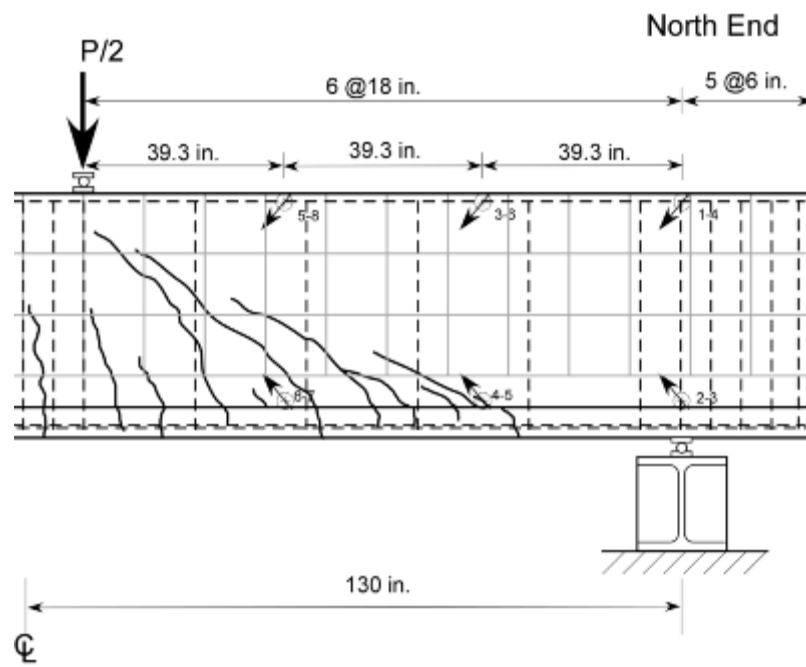


Figure C-8: Specimen IT.7.22.6.FT/FTG crack map (baseline test)

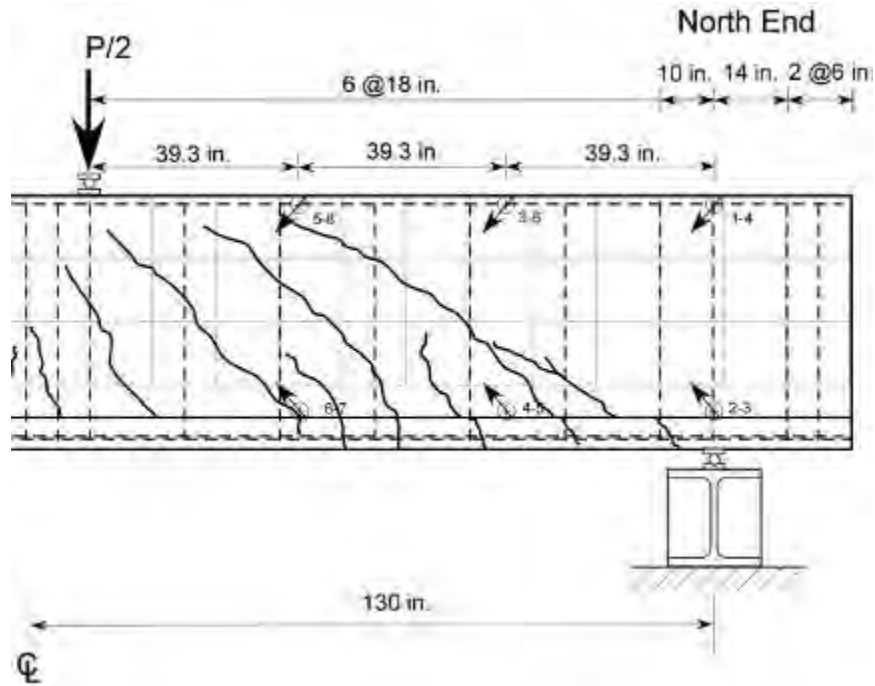


Figure C-9 – Specimen IT.7.18.6.M crack map (baseline test)

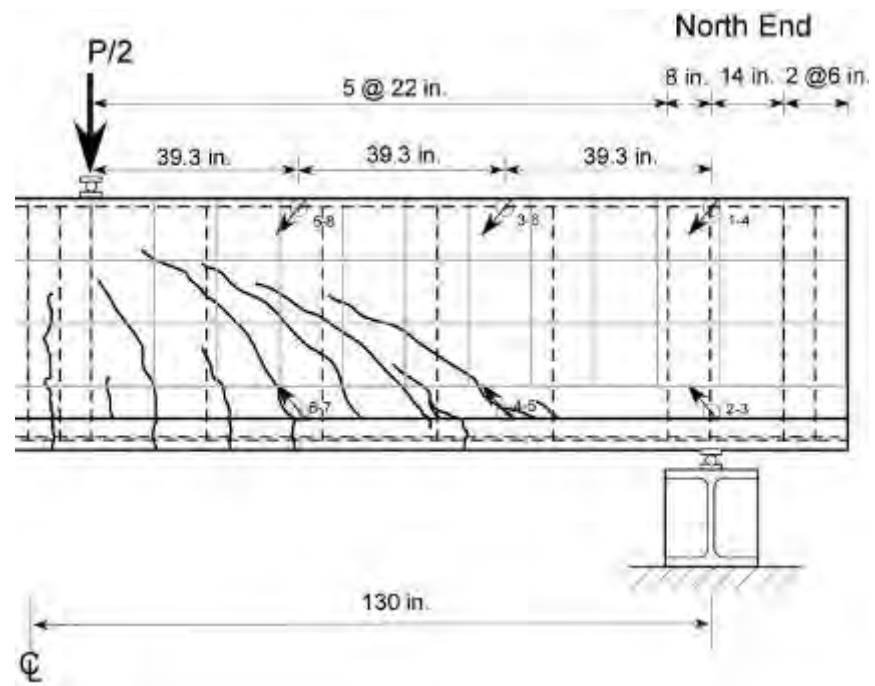


Figure C-10: Specimen IT.7.22.6.FT crack map (baseline test)

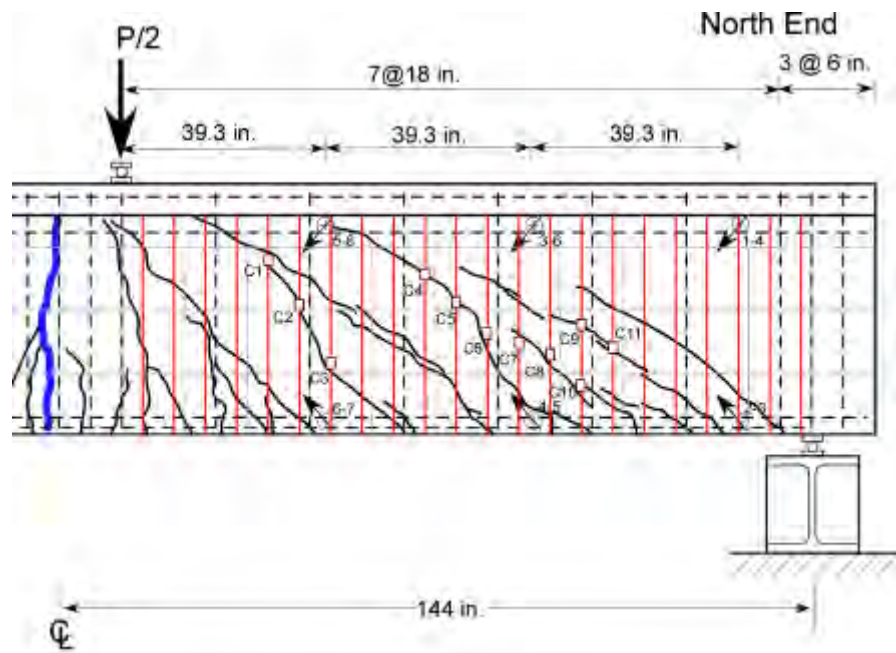


Figure C-11: Specimen T.6.18.6.S crack map (failure test)

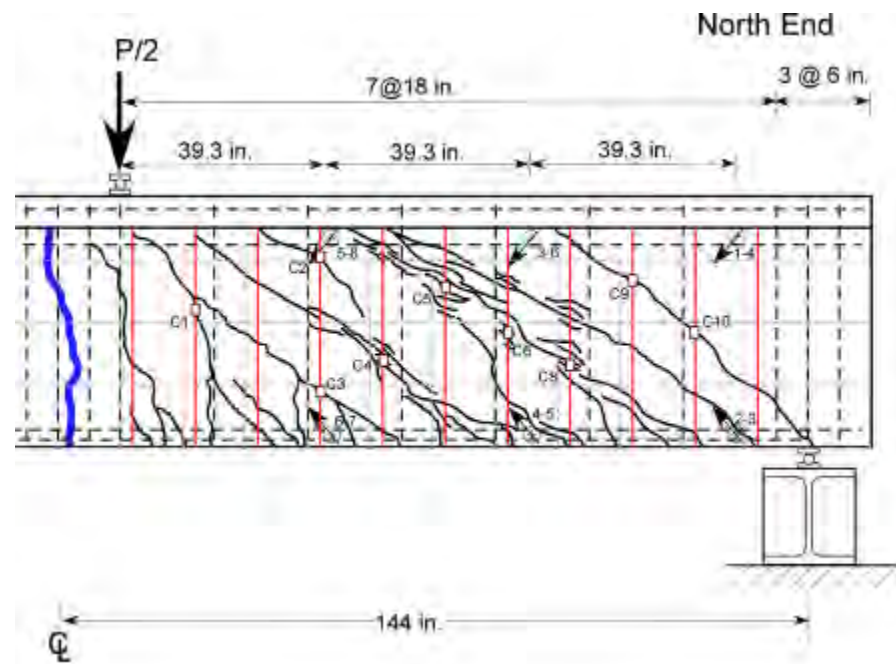


Figure C-12: Specimen T.6.18.12.S crack map (failure test)

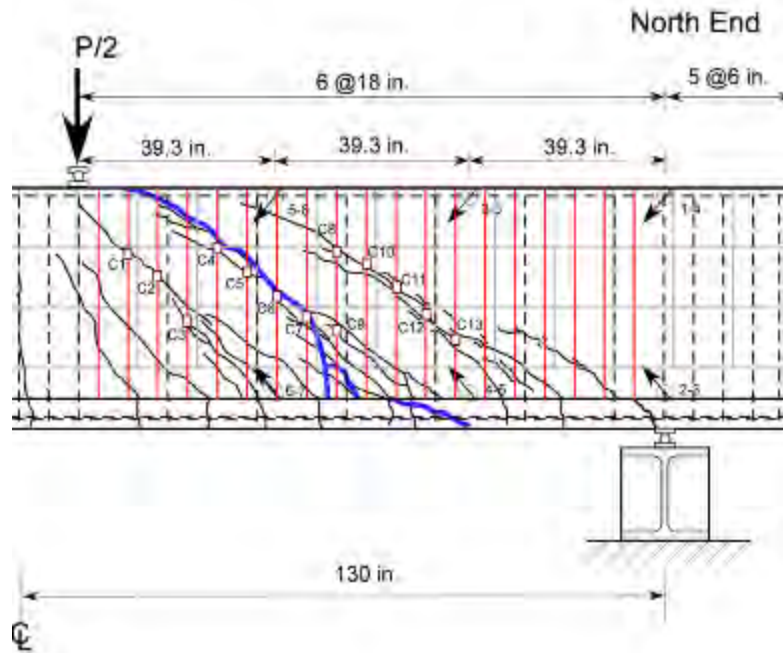


Figure C-13: Specimen IT.7.18.6.S crack map (failure test)

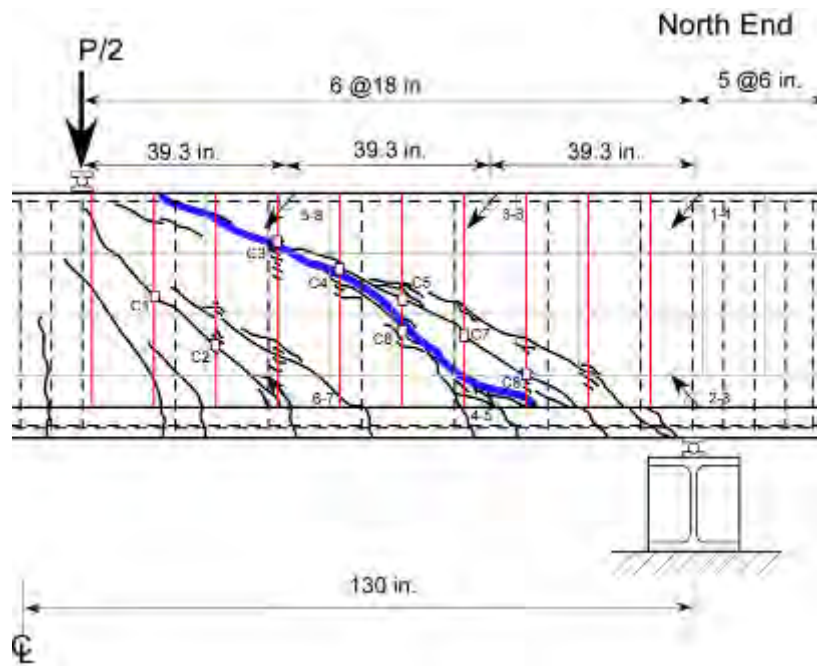


Figure C-14: Specimen IT.7.18.12.S crack map (failure test)

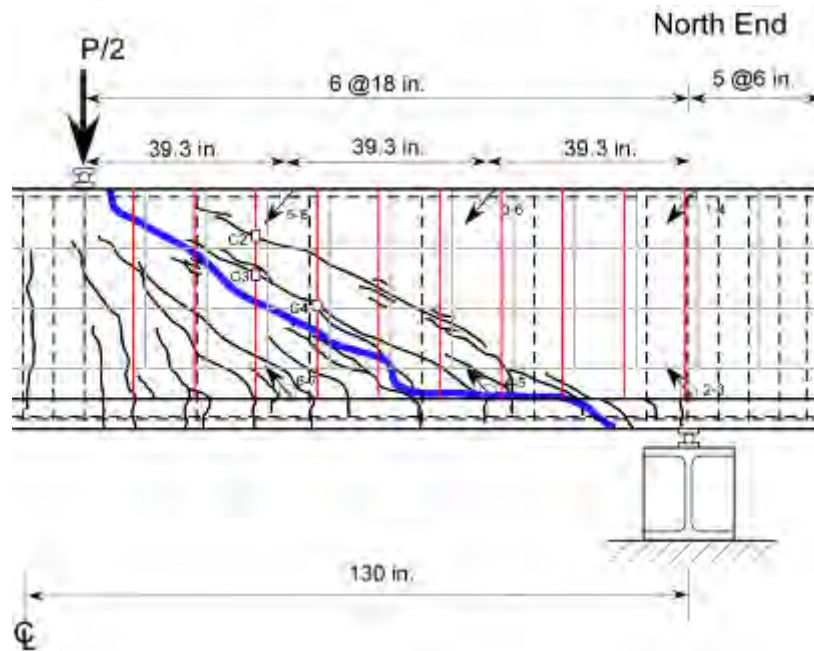


Figure C-15: Specimen IT.5.22.12*.S crack map (failure test)

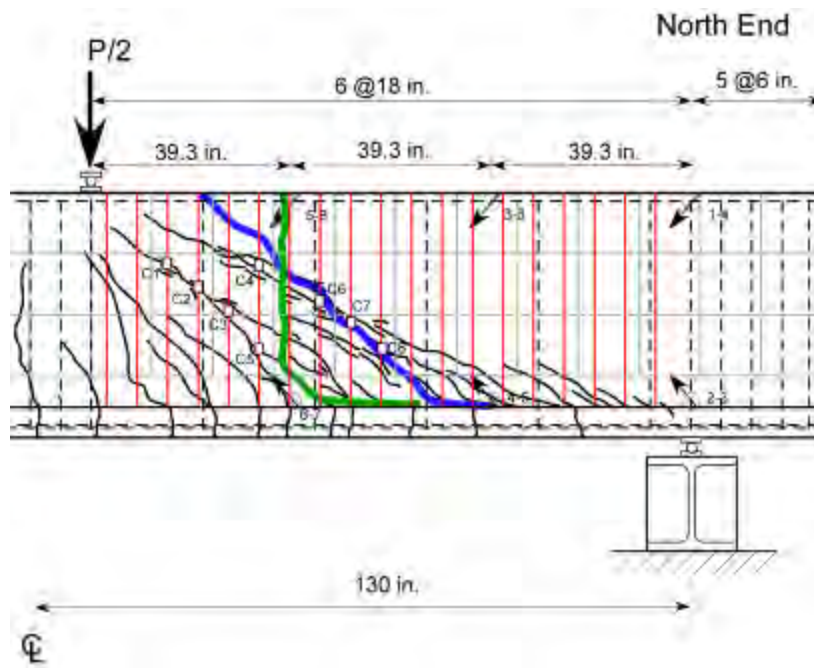


Figure C-16: Specimen IT.7.22.6.S crack map (failure test)

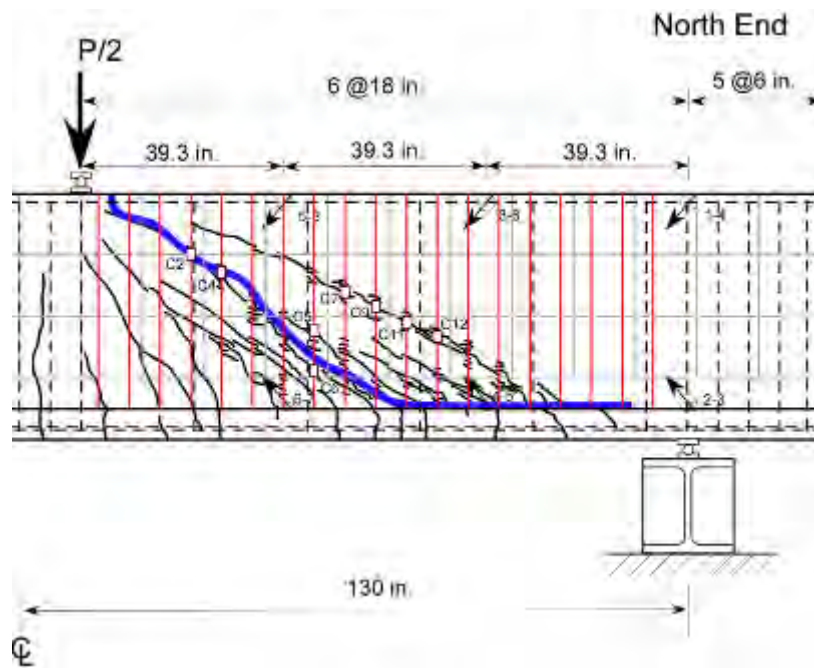


Figure C-17: Specimen IT.7.22.6.FTG crack map (failure test)

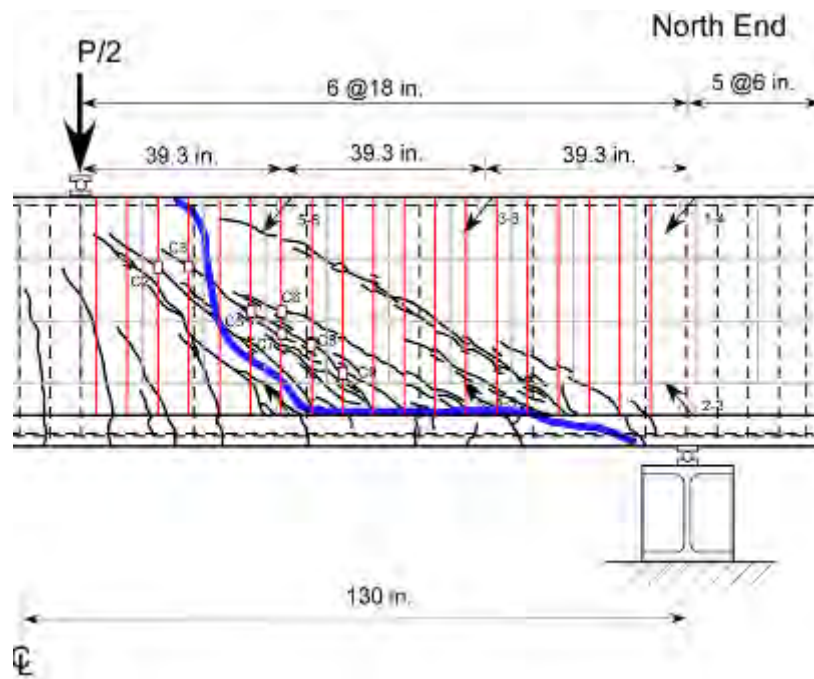


Figure C-18: Specimen IT.7.22.6.FT/FTG crack map (failure test)

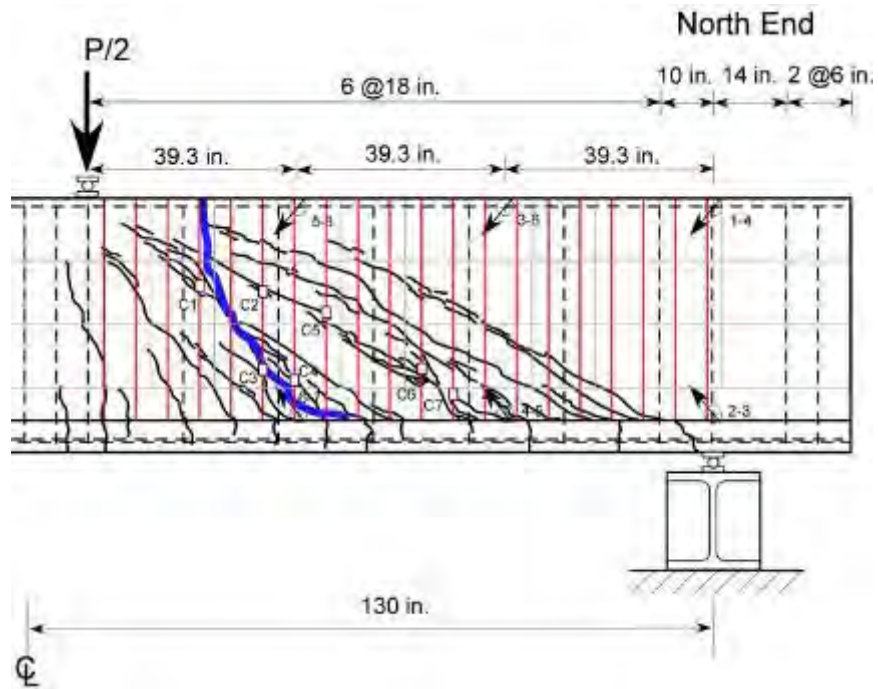


Figure C-19 – Specimen IT.7.18.6.M crack map (failure test)

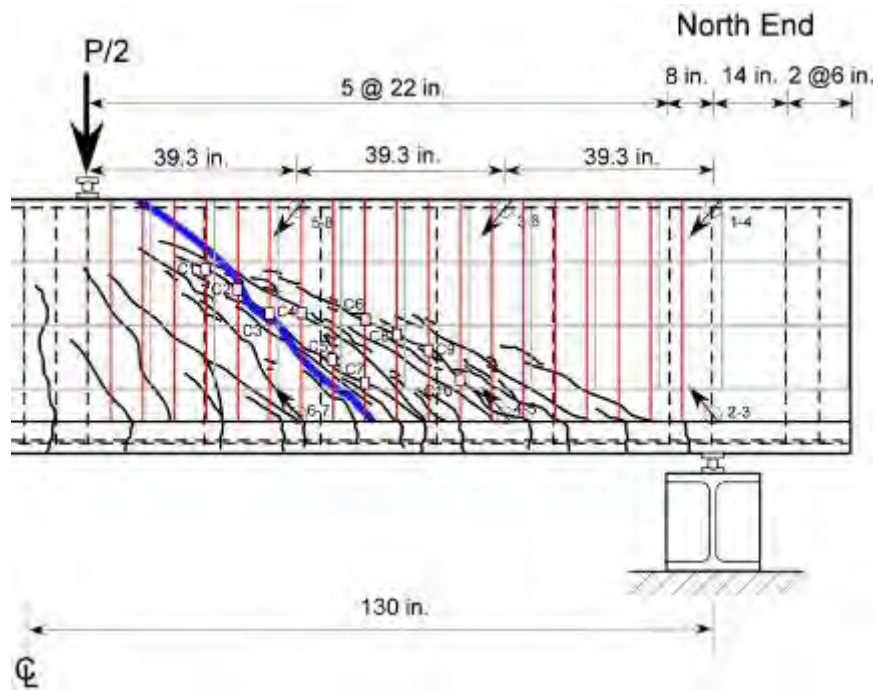


Figure C-20 – Specimen IT.7.18.6.FT crack map (failure test)

APPENDIX D:

BOND TESTS

D-1 INTRODUCTION

One of the goals of this research was to make generalized observations about NSM-CFRP performance regardless of the type of CFRP strip or adhesive used for the NSM repair. To do this, one must test combinations of different CFRP strips and adhesives. However, the full-scale girder specimens are very expensive to construct and time consuming to test. Due to this, the idea of a small bond specimen was developed in order to evaluate the relative bond strength of different CFRP materials with epoxies and subjected to different environmental exposures. This appendix reports this aspect of the research and the results of this study.

D-2 EXPERIMENTAL DESIGN

D-2.1 SPECIMEN TYPE

A conventional pull-out test could be used to examine the bond specimen variables, but it is difficult to grip the CFRP for a pull-out test without damaging the strip. For that reason it was desired to have a bond specimen made from two pieces of concrete joined together with NSM CFRP strips bonded into grooves in a concrete substrate. Then the concrete could be pushed apart (creating direct tension in the NSM-CFRP strips) until failure. One objective of the bond specimens was to make the construction easy and reproducible. To incorporate this, it was decided to construct the bond specimens from standard 305 mm (12 in.) tall concrete cylinders with a 152 mm (6 in.) diameter. These cylinders are inexpensive, easy to cast, and create a convenient sized specimen to handle. The idea of the specimens was to cut grooves in each cylinder (assuring alignment of the grooves) then cut the cylinders in half and install two 152 mm (6 in.) long NSM-CFRP strips to attach the halves together. A space was provided between the two concrete ends to allow for a hydraulic jack, load cell, and confinement plates to be placed between the concrete. An example bond specimen can be seen below in Figure D-1. All-thread with nuts at the ends is finger-tightened within the gap between the concrete halves to provide stability for handling until testing.



Figure D-1 – Example bond specimen

The bond specimens have two strips of CFRP with both ends epoxied in 152 mm (6 in.) long grooves. This leaves four possible failure locations when the concrete is pushed apart. To eliminate this, one of the CFRP strips for each bond specimen was cut shorter so one of the ends would not extend the full 152 mm (6 in.) groove length. This allowed the failure location to be known *a priori*. It was determined that 127 mm (5 in.) was a convenient bond length (L) to test. Solving for the bond strength according to equation (13-4) from ACI 440.2R-08 gives a bond stress of 14.5 MPa (2106 psi) which is in the suggested range of 3.5 to 21 MPa (500 to 3000 psi). The calculation is determined as:

$$L_{db} = \frac{a_b b_b}{2(a_b + b_b)(\tau_b)} f_{fd} \quad [D-1 - \text{ACI 440 (13.4)}]$$

$$\tau_b = \frac{a_b b_b}{2(a_b + b_b)(L_{db})} f_{fd} \quad [D-2]$$

$$\tau_b = \frac{0.63in \times 0.079in}{2(0.63in + 0.079in)(5in)} \times 300ksi = 2106psi \quad [D-3]$$

Where a and b are the CFRP strip dimensions, f_{fd} is the CFRP design stress, τ_b is the average bond strength, and L_{db} is the development length. After some initial trial tests, it was observed that L was long enough that sometimes the 152 mm (6 in.) side failed. To prevent this from occurring, a bond length of $L/2$, 64 mm (2.5 in.) was used for all the epoxy and environmental tests. Other tests in the series investigated different bond lengths of L , $L/2$ and $L/4$. There are four primary failure mechanisms expected for the bond specimens. These include 1) failure of the concrete around the NSM groove, 2) failure of the epoxy to concrete bond, 3) failure of the epoxy to CFRP bond, or 4) rupture

of the CFRP strip. To see if the bond specimen concept worked some initial trial specimens were constructed and tested. These trial bond specimens all failed by the concrete splitting in a triangular shape around the NSM CFRP strip. An example can be seen below in Figure D-2.



Figure D-2 – Failure of concrete around the NSM repair

These trials showed that the bond specimen idea was feasible, but the only failure mode observed was controlled by the concrete. Therefore, the specimen capacity was primarily controlled by the concrete strength and not on the type of epoxy or CFRP materials. It was decided to use steel plates that were notched to fit around the NSM groove to confine the concrete and force failures associated with the epoxy. With these plates placed between the hydraulic jack and concrete surfaces additional trials were performed and it was observed that the plates prevented the concrete from cracking and forced a failure to occur in the epoxy or CFRP. Thus, using the confinement plates, the strength contribution from different epoxy types and any environmental degradation experienced by the epoxy could be compared. Care was taken to make sure smooth bearing surfaces were located between the confinement plates and concrete to prevent bending of the CFRP strips. The best way to do this was to use a large concrete saw blade to make one smooth cut and then cover the surface with duct tape during placement of the NSM-CFRP to keep it clean of epoxy. Once the concept was developed, specimens could be constructed and tested as described subsequently.

D-2.2 SPECIMEN CONSTRUCTION

All the concrete cylinders used for the specimens in this research were cast from a single batch of concrete to assure the concrete properties were consistent for all specimens. The concrete came from the same truck as the full-scale girder specimen T.6.18.12.S. The concrete was placed in the cylinder molds in a single lift and consolidated with a small mechanical vibrator. Cylinders were field cured for 28 days and then stripped. The 28 day compressive strength was 28.2 MPa (4095 psi). The first step in construction was to cut two NSM grooves lengthwise on opposite sides of the cylinders. The groove dimensions were 25.4 x 7.87 mm (1 x 0.31 in.) for material C1, 25.4 x 7.37 mm (1 x 0.29 in.) for material C2, and 25.4 x 9.14 mm (1 x 0.36 in.) for material C3. After the grooves were cut, the cylinders were cut in half to make two 152 mm (6 in.) tall cylinders. These were

joined back together with CFRP strips bonded into the grooves with epoxy leaving a 165 mm (6.5 in.) space between the concrete ends. The same techniques were used to clean the grooves, clean the CFRP, epoxy the grooves, and cure the epoxy the as those used with the full-scale specimens described in the main body of the report.

D-2.3 TEST SETUP AND INSTRUMENTATION

In the bond specimen test setup the cylindrical specimens were placed on an aluminum plate. This plate supported displacement sensors which measured the displacement of the top of the specimen during loading. An average displacement was taken from the two sensors. Between the concrete ends was a bottom steel confinement plate, a 178 kN (40 kip) hydraulic jack, a 222 kN (50 kip) load cell, and a second confinement plate. A hand operated hydraulic pump provided pressure to the hydraulic jack to induce tension in the CFRP strips. The setup is shown schematically in Figure D-3.

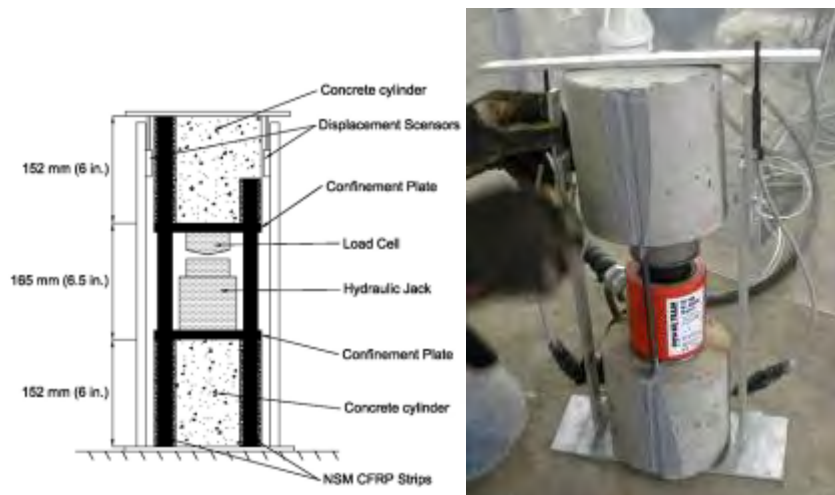


Figure D-3 – Bond specimen test setup (confinement plate not present in the photograph)

D-2.4 EXPERIMENTAL VARIABLES

The bond specimens were used to look at several variables including carbon fiber material, epoxy type, and environmental exposures. Several carbon fiber materials and epoxies were investigated during the material selection process. Availability, economic efficiency, and structural properties were taken into consideration. Three carbon-fiber materials and three epoxies were chosen for bond tests. Bond lengths were varied based on a chosen initial bond length, L , and then fractions of the bond length of $L/2$, and $L/4$ were tested for strength using each epoxy type and CFRP type. Finally different environmental exposures were considered including freeze-thaw (dry as well as alternating with wet and dry conditions), continuous moisture exposure, and repeated wetting and drying. A total of 117 bond specimens were tested in this research program.

Three different epoxies were tested including: BASF Concreative 1420 (E1), Hilti Hit-Re 500-SD (E2), and Unitex Pro-Poxy 400 (E3). These are all readily available adhesives

and were suggested from the Hughes Brothers' list for NSM repair. Properties for the epoxies are shown in Table D1.

Table D-1 – Adhesive manufacturer material Properties

Manufacturer Reported Property	E1		E2		E3	
	[MPa]	[ksi]	[MPa]	[ksi]	[MPa]	[ksi]
Tensile Strength	34.5	5.03	Not reported		43.5	6.31
Compressive Modulus	2900	420	1830	265	1493	220
Compressive strength	67.6	9.8	72.7	10.5	82.7	12.0
Bond Strength	20.7	3.0	19.9	2.89	12.4	1.80
Ensured Full Cure Time	7 days @ 77 DF		3 days		3 days	

Effort was made to select carbon fiber bars that had similar tensile strength. This was done by balancing the material strength and cross-sectional area of the strips. The three carbon fiber materials chosen were Hughes Brothers Aslan 500 10 mm #3 (C1), S&P Laminates CFK 150/2000 (C2), and a generic carbon fiber material (C3). The properties of the CFRP materials are shown in Table D2a and D2b. Material C1 was chosen for use in the full-scale girder tests as it is the only CFRP manufactured in the United States specifically for NSM applications.

CFRP tensile strengths were established from coupon tests. In an effort to prevent damage to the CFRP coupons during testing, the CFRP strips were not directly gripped. Coupons were tested after bonding fiberglass computer board to the ends of the specimens in the grip region. Only coupons that failed by rupturing or brooming of the CFRP fibers were used to calculate the CFRP tensile strength. The elastic modulus for material C1 was taken from previous tests performed by Howell [2009]. The elastic modulus for C2 and C3 are those reported by the manufacturer. The elastic modulus was not collected during coupon testing because strains were estimated from the displacement of the testing machine (so-called head travel) rather than from an extensometer.

Table D-2a: CFRP geometric properties

Manufacturer	Designation	Width		Thickness		Area		Perimeter#	
		(mm)	(in)	(mm)	(in)	(mm ²)	(in ²)	(mm)	(in)
Hughs Bros.	Aslan 500 Tape: 6 mm #2	16	0.630	2	0.079	31.2	0.048	36.1	1.42
S&P	150/2000: 10/1.4	10	0.394	1.4	0.055	14.0	0.022	21.4	0.84
Generic	GRAPHLITE	12.7	0.5	3.175	0.125	40.3	0.063	28.6	1.13

#Considering only two (2) widths and one thickness.

Table D-2b: CFRP material properties

CFRP Type	Tensile Stress at Failure# (MPa) [ksi]	Elastic Modulus (MPa) [ksi]
C1	118 [17.2]	138,458# [20081]
C2	53 [7.7]	165,000* [23931]
C3	92 [13.3]	134,000* [19435]

Measured (*Howell 2009*). * Manufacturer reported.

The effects of embedment length were established for all the CFRP materials using epoxy material type E1. The influence of the epoxy without environmental exposure was determined for the embedment length $L/2$ (64 mm = 2.5 in.) with all three material types.

Bond specimens with each of the three adhesives were subjected to environmental exposures. It was expected that the CFRP strips would not be as susceptible to environmental degradation because they are encapsulated within the epoxy used to bond them to the concrete; therefore, Hughes Brothers Aslan 500 laminate strips (C1) were used as the reinforcing for all of the environmental exposure specimens. Specimens were subjected to moisture exposure (M) by being submerged in water for six months; exposed to 400 freeze-thaw cycles where some of these specimens were dry while they were frozen and thawed (FTD) while others experienced a combination of wet and dry freeze-thaw exposure (FTWD). The wet and dry condition was created by placing the cylinder specimens in a trough inside the environmental chamber. Once a day (every eight freeze-thaw cycles) the trough was filled with tap water on a warm cycle. The water was allowed to soak the cylinders for 30 minutes and was then pumped out. A similar trough outside the environmental chamber exposed specimens to the same wet and dry conditions without the freezing and thawing (WD). A picture of one of these troughs with the specimens is shown in Figure D-4. The moisture specimens (6 month exposure) were tested wet before allowing them to dry, but the wet-dry specimens were tested in the dry condition.



Figure D-4 – Bond specimens subjected to freeze-thaw effects with wet and dry conditions

For each type of bond specimen, at least three replicates were constructed and tested. This was to account for variations and provide average strength results. Due to the long duration of the environmental exposure tests, six specimens for these categories were built and tested to provide a larger sample size considering inherent variability. The naming convention for the bond specimens is shown in Figure D-5, and the test matrix is shown in Table D-3a and Table D-3b.

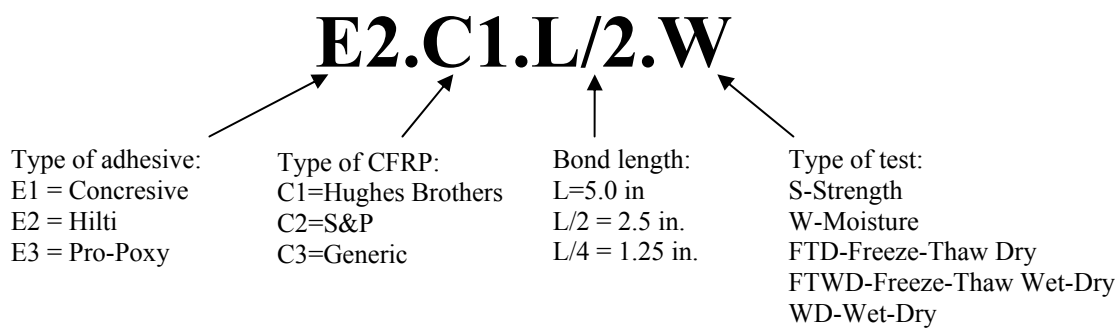


Figure D-5 –Bond specimen identification

Table D-3a - CFRP material, epoxy, and bond length test matrix (each entry = 3 tests)

CFRP Material	Epoxy E1	Epoxy E2	Epoxy E3
C1	L, L/2#, L/4	L/2	L/2
C2	L, L/2, L/4	L/2	L/2
C3	L, L/2, L/4	L/2	L/2

4 specimens

Table D-3b - Environmental exposure test matrix (each entry = 6 tests)

Epoxy Material	W	FTD	FTWD	WD
E1	C1@ L/2	C1@ L/2	C1@ L/2	C1@ L/2
E2	C1@ L/2	C1@ L/2	C1@ L/2	C1@ L/2
E3	C1@ L/2	C1@ L/2	C1@ L/2	C1@ L/2

D-2.5 TEST PROTOCOL

For safety purposes an acrylic box was built to surround the bond specimens while they were tested. The steel confinement plates, hydraulic jack, and load cell were placed in the specimen. Then the jack was pressurized to take the slack out of the system. At this point, the displacement sensors were set in place and zeroed on top of the specimens. The specimens were then loaded pseudo-statically with increasing applied force until failure.

D3 EXPERIMENTAL RESULTS

The bond specimens exhibited a variety of failure modes. The concrete around the NSM reinforcement commonly failed in a conical shape. Sometimes only the concrete on one side of the NSM groove failed thereby forming half of a cone. The confinement plates held this concrete in place and forced a failure by either the CFRP pulling out of the epoxy or a column of epoxy pulling out because the interface between the epoxy and concrete failed. Sometimes a combination of epoxy slip and CFRP slip occurred with one side of the CFRP strip clean and the other side still attached to the epoxy. All of the failures fell into eight general failure modes. These modes are listed and described below with pictures in Figure D-6 to demonstrate them.

Failure Modes:

1. Concrete cone failure and CFRP slip
2. Half concrete cone failure and CFRP slip
3. No concrete cone failure and CFRP slip
4. Concrete cone failure and epoxy concrete interface failed
5. Half concrete cone failure and epoxy concrete interface failed
6. No concrete cone failure and epoxy concrete interface failed
7. Concrete cone failure and CFRP slip/concrete interface combined failure
8. Half concrete cone failure and CFRP slip/concrete interface combined failure



Failure Mode (1)



Failure Mode (2)



Failure Mode (3)



Failure Mode (4)



Failure Mode (5)



Failure Mode (6)

Figure D-6 – Example failure modes for bonds specimens



Failure Mode (7)

Failure Mode (8)

Figure D-6 (continued) – Example failure modes for bonds specimens

D-3.1 CONTROL BOND SPECIMENS

The test results for different CFRP materials with different bond lengths embedded in different epoxy types are shown in Table D4. The load-deformation results are shown at the end of this appendix. The maximum average bond stress, $\bar{\mu}$, was estimated for each of the specimens. The active bond length, L_e , of the shorter length of NSM reinforcing in the test setup was used because this is the length that failed. Bond stresses are assumed to increase linearly along the bonded length of the CFRP strip and an average bond stress was determined as the force in the strip divided by the bonded surface area. The bonded surface area was calculated as the active bond length, L_e , multiplied by the CFRP strip perimeter, p_o . The measured maximum force was divided by two because the applied load to the specimen was carried by two NSM-CFRP strips in the test configuration. The average bond stress was determined as:

$$\bar{\mu} = \frac{F / 2}{L_e * p_o} \quad [D-4]$$

where F is the maximum applied load to the specimen (kN or kip), L_e is the bond length ($L = 127$ mm, $L/2 = 64$ mm, and $L/4 = 32$ mm; $L = 5$ in., $L/2 = 2.5$ in. and $L/4 = 1.25$ in.) and p_o is the perimeter of the strip (mm or in.) as shown previously in Table D2a. The computed maximum average bond stresses are also shown in Table D4. The calculated CFRP bond stresses ranged widely depending on the CFRP material as seen in Figure D-7. The values for C1 (the material used in the full-size girder tests) compare reasonably well to the lower end of the suggested range of 3.5 to 20.7 MPa (500 to 3000 psi) in ACI 440.2R-08 section 13.3. It is important to note that the computed maximum average bond stress is for the given setup, and not necessarily representative of the maximum average bond stress in full-scale girders because the confinement plate does not allow failure of the concrete to occur and the stress conditions in the cylinder are not representative of an actual girder.

Results from bond length tests indicated that increased bond length produced higher specimen *pullout capacity* for the C-1 specimens in epoxy E-1. Thus, the maximum

average bond stress for C1 in epoxy E1 was fairly consistent, and the bond stress did not reduce significantly from the L/2 to L bond lengths. This indicates that C-1 in epoxy E-1 at the 63.5 mm (2.5 in.) embedment length is near the active bond length.

The C-2 and C-3 specimens showed no significant increase in *pullout capacity* as the embedment length increased as seen in Table D-4. In other words, as the strips were embedded over a longer distance, the bond strength was observed to decrease because the bonded area increased but the pullout force did not. This indicates that the embedment lengths considered for materials C-2 and C-3 in epoxy E-1 were not near the active bond length. Both these materials exhibited slipping of the CFRP along the epoxy interface. This can be attributed to the surface conditions of the CFRP strips shown in Figure D-8. The surface of C-1 was textured by the manufacturer with a cross-hatch pattern (Figure D-8a), while C-2 and C-3 had smooth surfaces as shown in Figures D-8b and D-8c, respectively. The textured surface of C-1 allows mechanical interlock with the epoxy. In previous experiments using C-2, researchers have roughened the surface of the CFRP strip using sand paper or sandblasting in an effort to improve mechanical bond. However, this procedure is not prescribed by the manufacturer and this was not considered in the present research, as the degree of surface roughness would be highly variable and difficult to quantify and repeat. As a result, CFRP types C-2 or C-3 were used as permitted by the manufacturer without alteration.

Table D-4: Bond specimen test results for various embedment lengths with different CFRP and epoxy materials

Test ID	Max. Force in strip (kN) [kips]			Avg. (kN) [kips]	STD (kN) [kips]	COV %	Max. Average Bond Stress (MPa) [psi]			Avg. (MPa) [psi]	STD (MPa) [psi]	COV %
	Trial 1	Trial 2	Trial 3				Trial 1	Trial 2	Trial 3			
E1.C1.L.S	23.8 [5.35]	36.9 [8.30]	27.6 [6.20]	29.4 [6.62]	6.7 [1.52]	22.9%	5.2 [755]	8.1 [1171]	6.0 [874]	6.4 [933]	1.5 [214]	22.9%
E1.C1.L/2.S#	16.2 [3.64] 11.0 [2.48]	17.5 [3.93]	19.0 [4.27]	15.9 [3.58]	3.5 [0.78]	21.7%	7.1 [1025] 4.8 [698]	7.6 [1107]	8.3 [1203]	7.0 [1008]	1.5 [219]	21.7%
E1.C1.L/4.S	11.3 [2.54]	10.5 [2.37]	7.1 [1.61]	9.7 [2.17]	2.2 [0.50]	22.9%	9.9 [1430]	9.2 [1337]	6.2 [906]	8.4 [1224]	1.9 [280]	22.9%
E1.C2.L.S	8.3 [1.87]	4.4 [0.99]	5.4 [1.23]	6.0 [1.36]	2.0 [0.45]	33.5%	3.1 [444]	1.6 [235]	2.0 [292]	2.2 [323]	0.7 [108]	33.5%
E1.C2.L/2.S	7.6 [1.71]	7.7 [1.73]	5.2 [1.17]	6.8 [1.54]	1.4 [0.32]	20.6%	5.6 [814]	5.7 [821]	3.8 [557]	5.0 [731]	1.0 [151]	20.6%
E1.C2.L/4.S	6.4 [1.45]	6.5 [1.47]	5.4 [1.21]	6.1 [1.37]	0.6 [0.14]	10.5%	9.5 [1376]	9.6 [1395]	7.9 [1148]	9.0 [1306]	0.9 [138]	10.5%
E1.C3.L.S	6.6 [1.50]	6.6 [1.48]	7.5 [1.70]	6.9 [1.56]	0.5 [0.12]	7.8%	1.8 [265]	1.8 [261]	2.1 [300]	1.9 [275]	0.1 [22]	7.8%
E1.C3.L/2.S	6.8 [1.54]	4.7 [1.07]	4.6 [1.05]	5.4 [1.22]	1.2 [0.28]	23.0%	3.8 [545]	2.6 [377]	2.6 [370]	3.0 [431]	0.7 [99]	23.0%
E1.C3.L/4.S	5.9 [1.34]	4.6 [1.03]	4.6 [1.04]	5.0 [1.13]	0.8 [0.18]	15.6%	6.5 [945]	5.0 [726]	5.1 [733]	5.5 [801]	0.9 [125]	15.6%
E2.C1.L/2.S	20.8 [4.68]	19.3 [4.35]	16.7 [3.77]	19.0 [4.26]	2.0 [0.46]	10.8%	9.1 [1319]	8.4 [1226]	7.3 [1062]	8.3 [1202]	0.9 [130]	10.8%
E3.C1.L/2.S	11.4 [2.56]	9.8 [2.21]	14.7 [3.31]	12.0 [2.69]	2.5 [0.56]	20.8%	5.0 [722]	4.3 [623]	6.4 [932]	5.2 [759]	1.1 [158]	20.8%

four tests were performed for this case

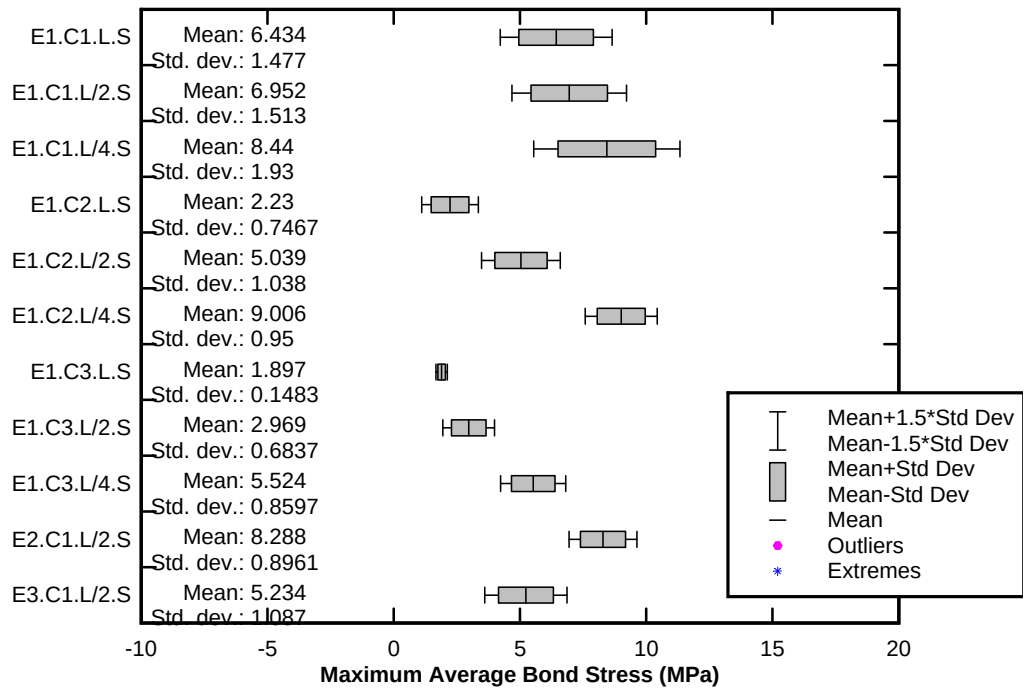


Figure D-7 –Average bond strength for control bond specimens

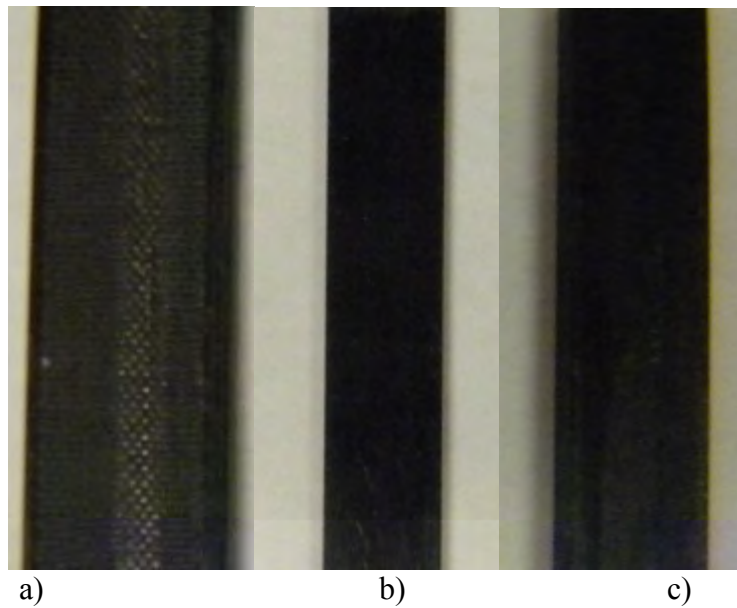


Figure D-8: CFRP surface conditions: a) C1, b) C2, and c) C3

The effect of CFRP type was also shown through the difference in failure modes. C1 specimen failure modes depended on the bond length as shown in Figure D-9. All C2 and C3 specimens failed by slipping of the CFRP through the epoxy with no apparent damage in the epoxy or concrete substrate regardless of the bond length. Figures D-10a and D-10b show typical failures for C2 and C3 specimens, respectively. The failure modes of C1 specimens changed as the bond length decreased. E1.C1.L.S specimens

failed after a crack developed longitudinally along the epoxy over the strip that allowed slipping of the CFRP shown in Figure D-11a. One of these specimens failed after a crack developed longitudinally along the epoxy/concrete interface as shown in Figure D-11b. E1.C1.L/4.S specimens failed via a conical break in the concrete substrate accompanied with failure in the epoxy concrete interface as shown in Figure D-12a. One of these specimens failed through slipping of the CFRP strip shown in Figure D-12b. Two of the E1.C1.L/2 specimens failed similarly to E1.C1.L.S specimens while the other two were more representative of E1.C1.L/4.S specimens.

Comparisons were made between the different epoxy types for constant CFRP material (C-1) and bond length (L/2). These showed that epoxy type E3 exhibited the lowest bond strength and highest variability compared to the other two epoxy materials for the conditions considered in this test series. It also showed that on average epoxy E2 was slightly stronger than E1. The average bond stress values were in the lower end of the suggested range of 3.5 to 20.7 MPa (500 to 3000 psi) in ACI 440.2R-08 section 13.3.



Figure D-9 - Failures of typical C1 specimens



Figure D-10 - Failures of typical C2 and C3 specimens



Figure D-11 - Failure of E1.C1.L.S specimens



Figure D-12 - Failure of E1.C1.L/4.S specimens

D-3.2 ENVIRONMENTAL EXPOSURE SPECIMENS

The bond test results considering a constant CFRP material (C1) and bond length of $L/2$ (63.5 mm (2.5 in.)) but with different epoxy types and environmental exposures are shown in Table D-5. The bond stresses for the specimens were computed as described previously and are reported in Table D-5 and shown in Figure D-13. The load-deformation results are shown in Figures D-14 to D-26.

Based on the observed experimental performance, no environmental degradation was evident for E1 specimens. E1 specimens showed average 0.3% to 14.3% increases to maximum average bond strength when subjected to environmental exposures, which is attributed to the experimental variability. Similarly, E2 showed no degradation. E2 specimens varied from an average 7.2% loss to a 16.4% increase in maximum average bond strength. These were also attributed to experimental variability.

Compared to the controls, both the wet and wet-dry E3 specimens showed small increases in average maximum bond strength. However, Epoxy E3 exhibited reduced strength after freeze-thaw exposures. The E3 FTD average was 18.1% less and the FTWD average was 35.4% less for the maximum average bond strength compared to the

average of the control specimens. This was the largest change observed for the specimen groups. Based on the mean strength values and the average COV, the mean value for E3 FTWD specimens is 1.7 standard deviations away from the control specimens and would be considered an outlier relative to the controls.

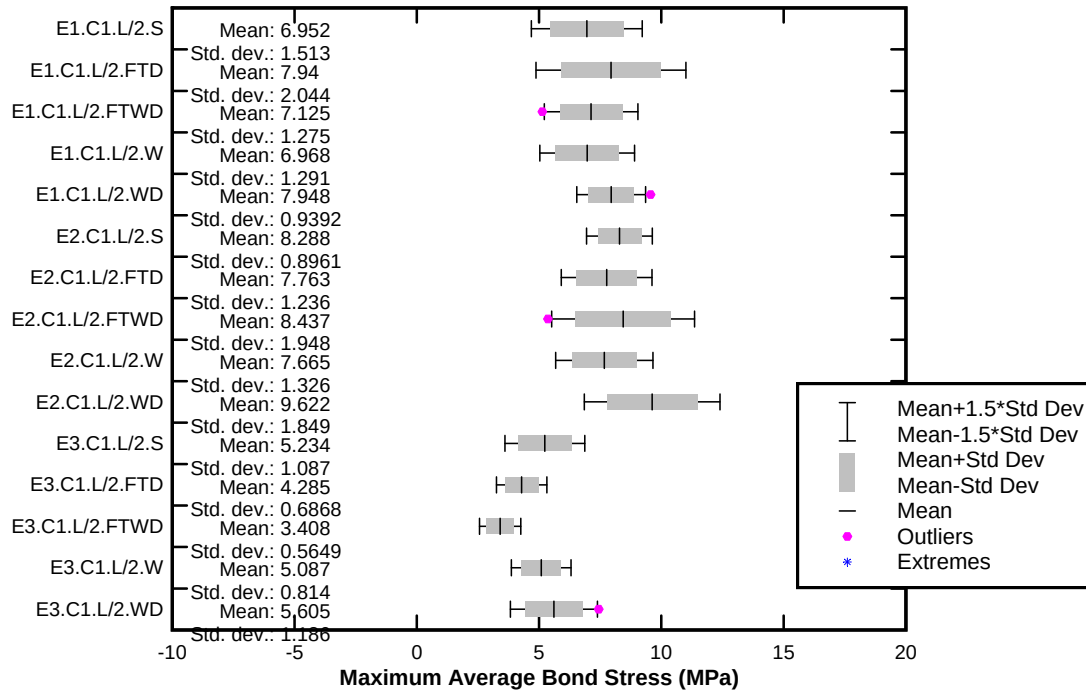


Figure D-13 –Average bond strength for bond specimens with different epoxy types and subjected to different environmental exposures

Table D-5: Bond specimen results for CFRP C1 with L/2 embedment combined with different epoxy materials and subjected to different environmental exposure conditions

Test ID	Maximum Force per strip (kN) [kips]						Avg. (kN) [kips]	STD (kN) [kips]	Maximum Average Bond Stress (MPa) [psi]						Avg. (MPa) [psi]	STD (MPa) [psi]	COV %
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6			Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6			
E1.C1.L/2.FTD	11.2 [2.52]	18.4 [4.14]	22.2 [5.00]	15.2 [3.42]	24.1 [5.42]	17.8 [4.01]	18.2 [4.08]	4.7 [1.05]	4.9 [711]	8.0 [1167]	9.7 [1410]	6.6 [964]	10.5 [1529]	7.8 [1132]	7.9 [1151.9]	2.0 [296]	25.7%
E2.C1.L/2.FTD	20.2 [4.55]	18.1 [4.07]	14.4 [3.24]	21.7 [4.88]	16.7 [3.76]	15.4 [3.45]	17.8 [3.99]	2.8 [0.64]	8.9 [1284]	7.9 [1149]	6.3 [914]	9.5 [1376]	7.3 [1061]	6.7 [974]	7.8 [1126.3]	1.2 [179]	15.9%
E3.C1.L/2.FTD	10.9 [2.45]	11.6 [2.62]	8.0 [1.79]	8.7 [1.96]	8.5 [1.91]	11.1 [2.49]	9.8 [2.20]	1.6 [0.35]	4.8 [691]	5.1 [738]	3.5 [506]	3.8 [552]	3.7 [540]	4.8 [702]	4.3 [621.5]	0.7 [100]	16.1%
E1.C1.L/2.FTWD	15.1 [3.40]	17.2 [3.86]	15.1 [3.40]	19.4 [4.37]	19.2 [4.32]	11.7 [2.64]	16.3 [3.66]	2.9 [0.66]	6.6 [958]	7.5 [1088]	6.6 [960]	8.5 [1232]	8.4 [1218]	5.1 [744]	7.1 [1033.5]	1.3 [185]	17.9%
E2.C1.L/2.FTWD	16.8 [3.79]	21.4 [4.82]	18.2 [4.09]	24.5 [5.51]	22.5 [5.07]	12.3 [2.76]	19.3 [4.34]	4.5 [1.00]	7.4 [1068]	9.4 [1359]	7.9 [1153]	10.7 [1555]	9.9 [1430]	5.4 [777]	8.4 [1223.6]	1.9 [282]	23.1%
E3.C1.L/2.FTWD	8.8 [1.97]	6.4 [1.43]	7.5 [1.68]	8.7 [1.95]	6.3 [1.41]	9.2 [2.08]	7.8 [1.75]	1.3 [0.29]	3.8 [556]	2.8 [404]	3.3 [473]	3.8 [550]	2.7 [396]	4.0 [586]	3.4 [494.2]	0.6 [82]	16.5%
E1.C1.L/2.W	12.7 [2.86]	20.1 [4.52]	13.2 [2.96]	15.2 [3.43]	18.7 [4.20]	15.7 [3.54]	15.9 [3.58]	2.9 [0.66]	5.6 [806]	8.8 [1275]	5.8 [836]	6.7 [967]	8.2 [1186]	6.9 [999]	7.0 [1011.2]	1.3 [187]	18.5%
E2.C1.L/2.W	13.4 [3.01]	16.9 [3.80]	21.9 [4.92]	16.2 [3.64]	16.7 [3.76]	20.1 [4.53]	17.5 [3.94]	3.0 [0.68]	5.9 [849]	7.4 [1072]	9.6 [1388]	7.1 [1026]	7.3 [1060]	8.8 [1278]	7.7 [1112.2]	1.3 [192]	17.3%
E3.C1.L/2.W	12.1 [2.71]	9.8 [2.20]	13.6 [3.06]	14.0 [3.14]	10.6 [2.37]	9.8 [2.20]	11.6 [2.61]	1.9 [0.42]	5.3 [766]	4.3 [622]	5.9 [862]	6.1 [885]	4.6 [670]	4.3 [620]	5.1 [737]	0.8 [118]	16.0%
E1.C1.L/2.WD	21.9 [4.92]	15.8 [3.56]	19.4 [4.36]	16.9 [3.79]	17.6 [3.95]	17.5 [3.94]	18.2 [4.09]	2.1 [0.48]	9.6 [1387]	6.9 [1004]	8.5 [1230]	7.4 [1070]	7.7 [1115]	7.7 [1111]	7.9 [1153]	0.9 [136]	11.8%
E2.C1.L/2.WD	23.3 [5.24]	18.7 [4.21]	16.7 [3.75]	20.0 [4.49]	26.0 [5.85]	27.3 [6.14]	22.0 [4.95]	4.2 [0.95]	10.2 [1479]	8.2 [1187]	7.3 [1057]	8.7 [1268]	11.4 [1651]	11.9 [1731]	9.6 [1395]	1.8 [268]	19.2%
E3.C1.L/2.WD	12.1 [2.73]	8.8 [1.97]	17.0 [3.82]	14.2 [3.18]	12.7 [2.85]	12.2 [2.74]	12.8 [2.88]	2.7 [0.61]	5.3 [770]	3.8 [556]	7.4 [1079]	6.2 [898]	5.5 [803]	5.3 [772]	5.6 [813]	1.2 [172]	21.1%

TEST DATA FOR ALL SPECIMENS

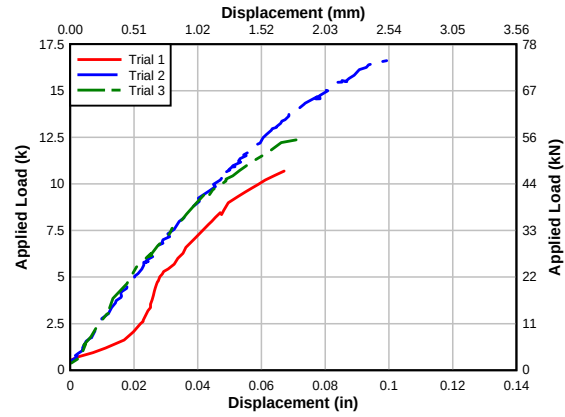


Figure D-14 - E1.C1.L.S applied load - displacement

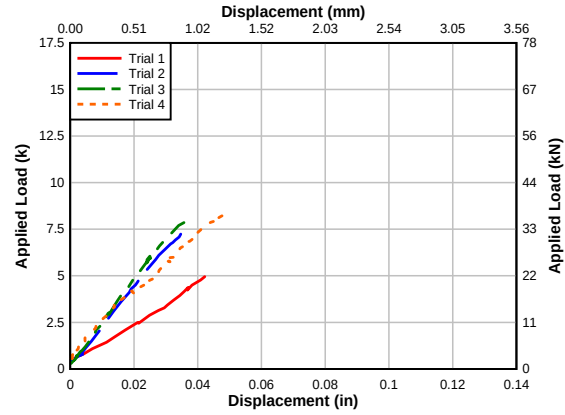


Figure D-15 - E1.C1.L/2.S applied load – displacement

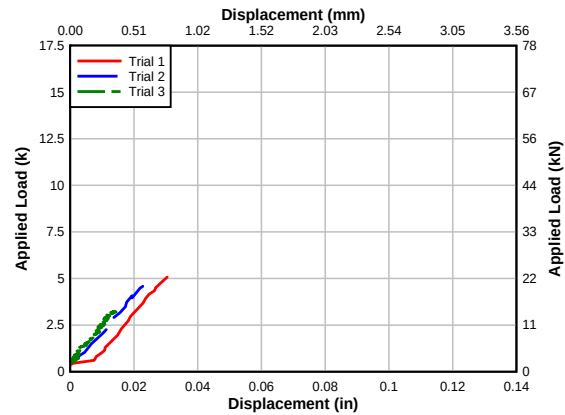


Figure D-16 - E1.C1.L/4.S applied load - displacement

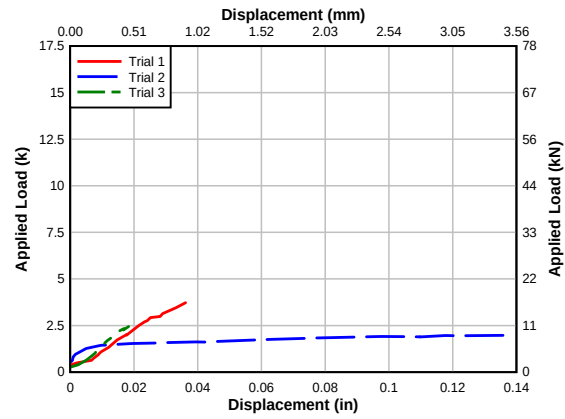


Figure D-17 - E1.C2.L.S applied load – displacement

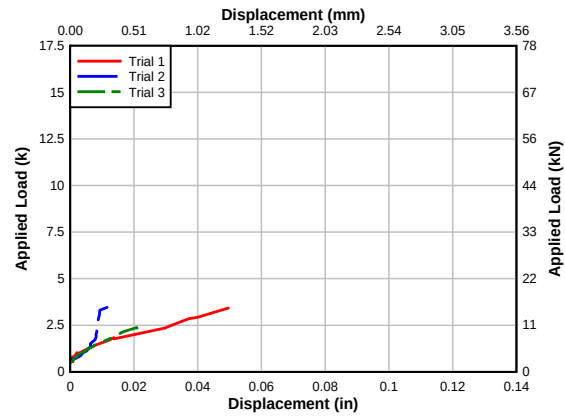


Figure D-18 - E1.C2.L/2.S applied load - displacement

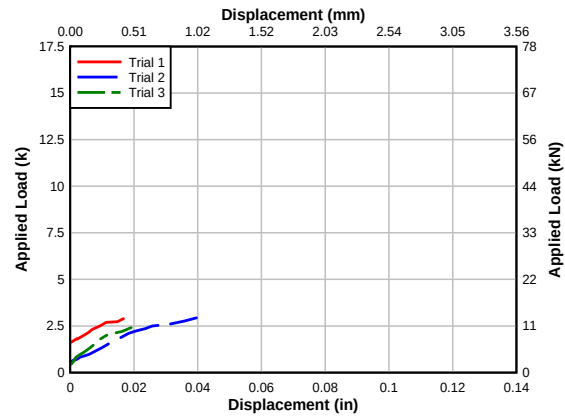


Figure D-19 - E1.C2.L/4.S applied load - displacement

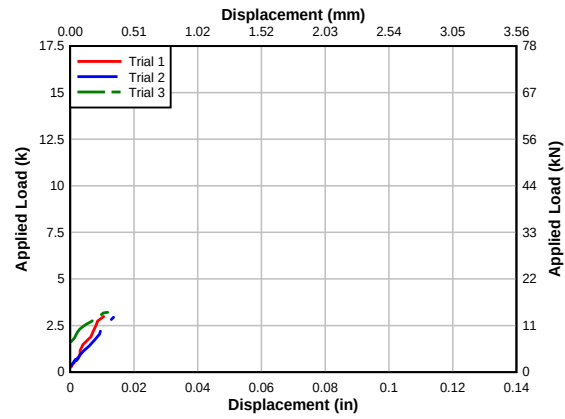


Figure D-20 - E1.C3.L.S applied load – displacement

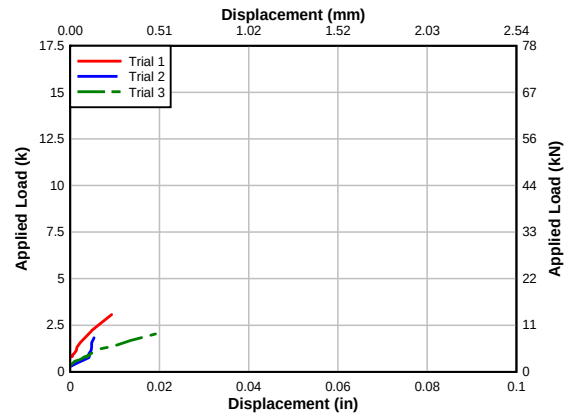


Figure D-21 - E1.C3.L/2.S applied load – displacement

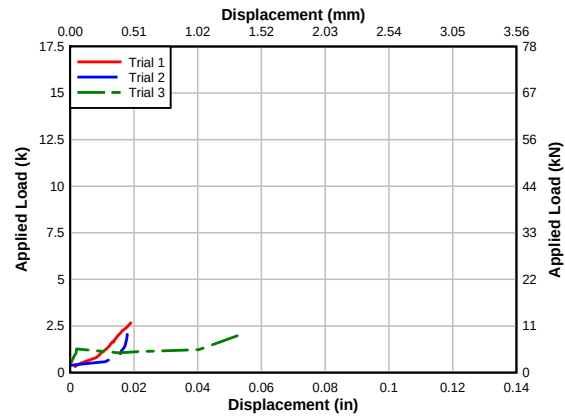


Figure D-22 - E1.C3.L/4.S applied load - displacement

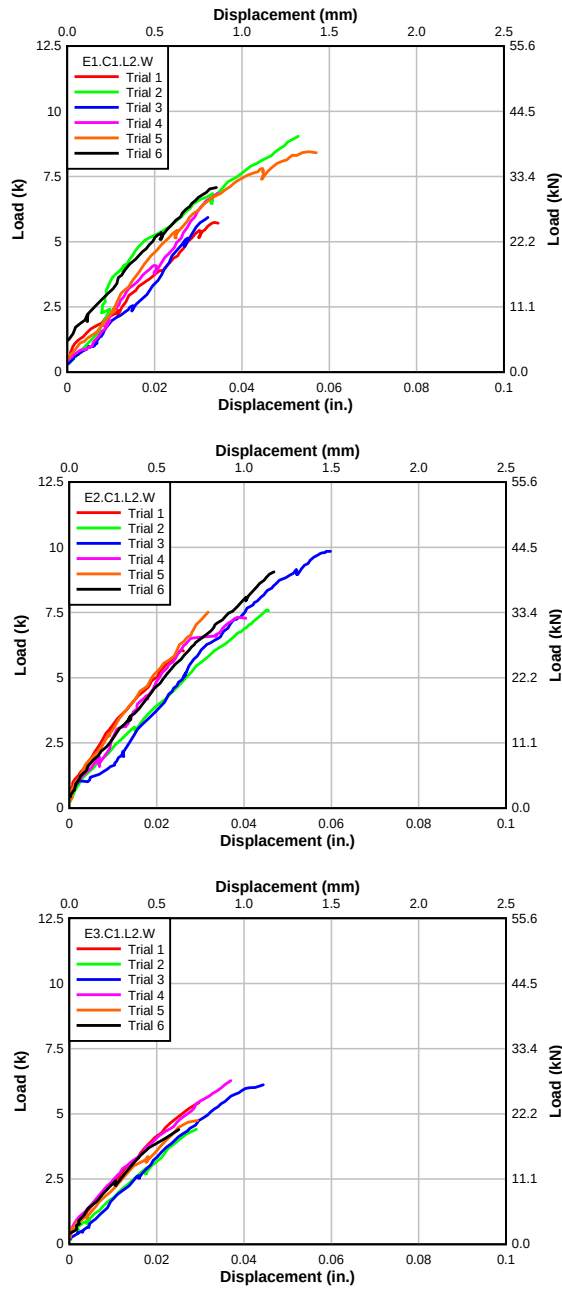


Figure D-23 – Load vs. displacement for bond specimens subjected moisture exposure

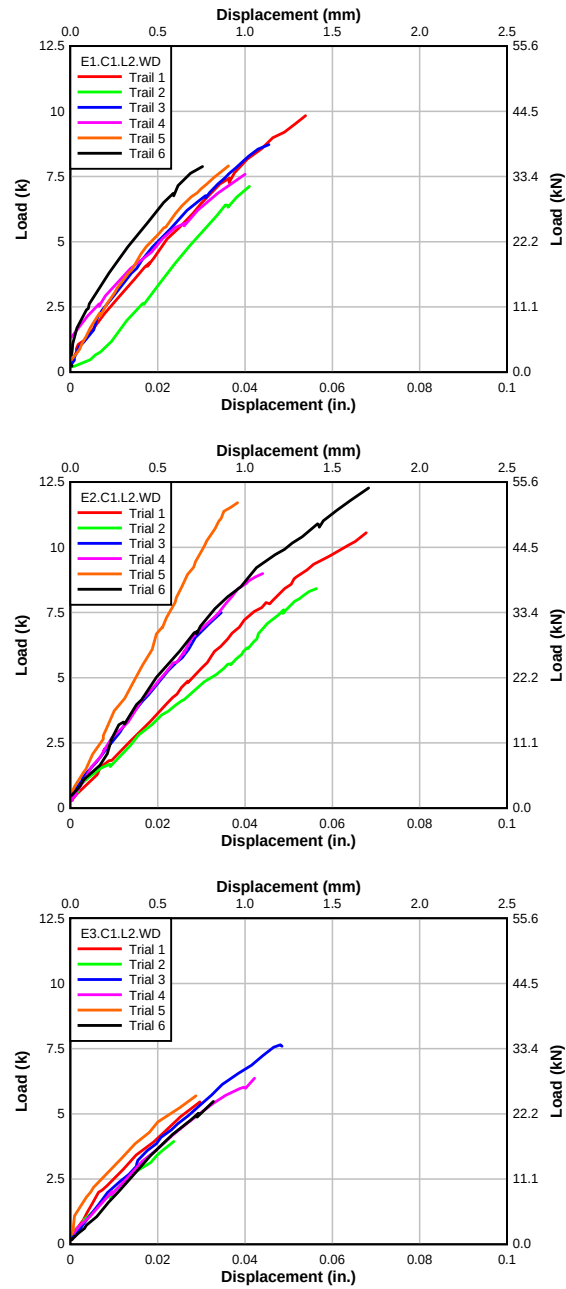


Figure D-24 – Load vs. displacement for bond specimens subjected wet-dry exposure

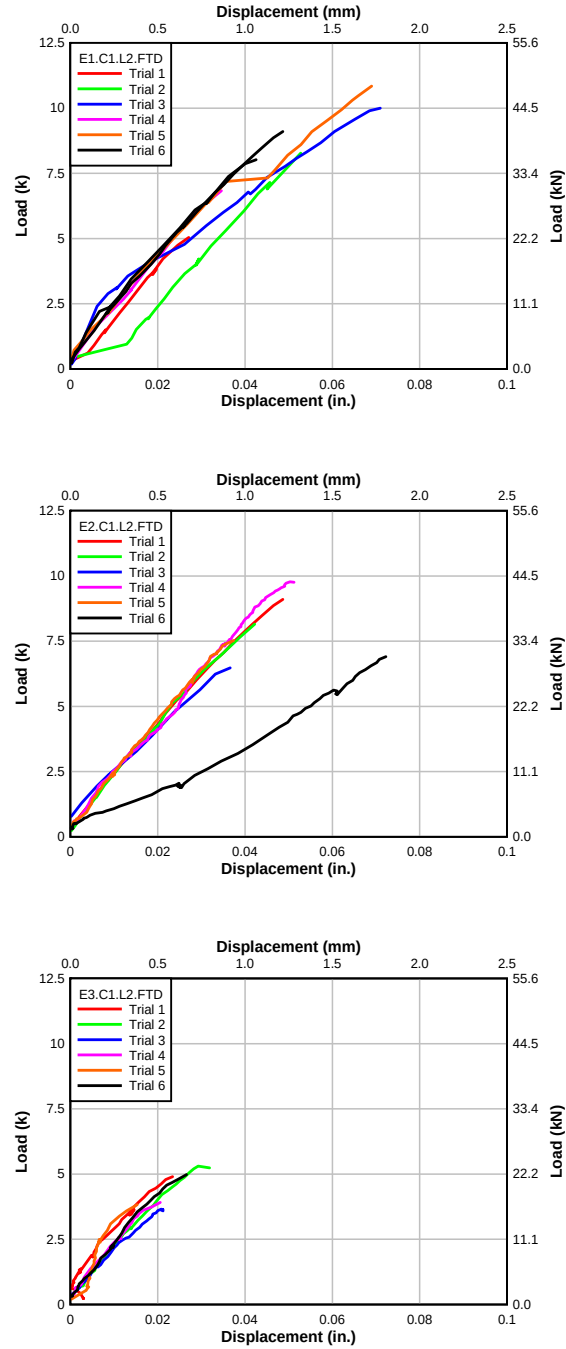


Figure D-25 – Load vs. displacement for bond specimens subjected dry freeze-thaw exposure

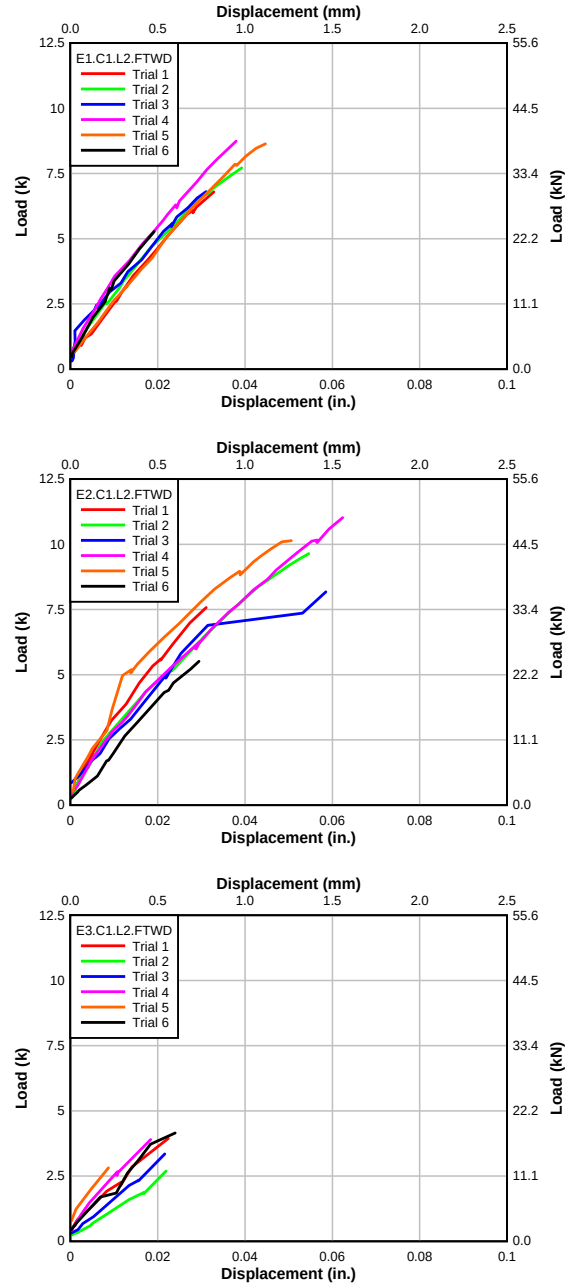


Figure D-26 – Load vs. displacement for bond specimens subjected to wet-dry with freeze-thaw exposure