TPF-5(433) Behavior of Reinforced and Unreinforced Lightweight Cellular Concrete (LCC) For Retaining Walls

Interim Report on Pull-out Testing and Friction Coefficient, F*

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March 2022

Background

The pull-out testing on metallic reinforcements was performed in connection with the lightweight cellular concrete (LCC) test box during the 6th and 7th tests with the mechanically stabilized earth (MSE) wall panels. These tests were conducted on both ribbed-strip reinforcement and welded-wire reinforcements as part of the TPF-5(433). In addition, supplemental pull-out testing was performed on ribbed-strip reinforcements in smaller test boxes at two vertical stresses to fill in gaps in the data. Finally, data from unpublished pull-out tests on ribbed-strip and welded-wire reinforcements were collected to provide additional information on the variation of the friction coefficient, F* with vertical stress level. Additional details regarding these tests and the interpreted friction coefficients are discussed subsequently in this interim report.

Test Set-up

Ribbed-Strip Reinforcement Testing

Testing in Large LCC test box

The test box was 10 feet tall by 10 feet long and 12 feet deep. The MSE wall panels were nominally 5 feet tall by 10 feet wide and 0.5 feet thick and were positioned on two sides of the LCC backfill. The west side of the LCC backfill was reinforced by 0.2-inch-thick by 2-inch-wide ribbed-strips as shown in Figure 1. Each of the four 30-inch thick LCC lifts were reinforced by four ribbed-strip reinforcements tied into the west MSE wall panel, and four shorter ribbed-strip reinforcements tied into the east wall. Lifts one and three were also supported by three short welded-wire reinforcements tied into the east wall.

Initial pull-out tests were performed using the 0.2-inch-thick x 2-inch-wide ribbed-strip reinforcements placed in the large-scale test box. A total of 12 ribbed-strip reinforcements were tested in the large-scale test box. Two ribbed-strip reinforcements were tested within the first and fourth lifts (shown in red in Figure 2(a) and 2(d)), and four ribbed-strip reinforcements were tested within the second and third lifts (shown in red in Figure 2(b) and 2(c)). The reinforcements were centered in each LCC lift. See Figure 2 for ribbed-strip horizontal spacing. The length that each reinforcement extended into the LCC is shown in Figure 2. The reinforcements extended through a hole in the facing panel so that the strips could be pulled horizontally from the wall face. Figure 3 shows the inside of the test box before placement of the first LCC lift. The Class II LCC fill had an average cast unit weight of 28.1 pcf. The average compressive strengths for the first, second, third, and fourth lift were 99.0, 69.8, 102.8, and 97.0 psi at the time of pull-out testing, respectively.

The surcharge weight varied for the four LCC lifts. For the pull-out tests performed on the first and second lift, the surcharge weight consisted of LCC with an average self-weight from lifts one, two, and three of 28.3, 27.4, and 28.0 pcf; creating a vertical surcharge pressure of 173.9 psf for lift one and 57.6 psf for lift two. The surcharge pressure for pull-out tests performed in lifts three and four consisted of LCC self-weight, gravity loads from concrete blocks, and loads from hydraulic jacks. The average self-weights of lifts three and four were 28 and 28.7 pcf, applying a pressure of 106.8 psf for lift 3 and 35.9 psf for lift 4. The concrete blocks applied a surcharge pressure of 240 psf and the hydraulic jacks applied 10 psi. The resulting vertical pressure was 1787 psf for lift 3 and 1716 psf for lift 4.

The pull-out test setup is shown in Figure 4 for the LCC backfill in Test 6. A center-pull jack was used to apply a progressively higher tensile force to each reinforcement. A frame was used to provide a reaction against the concrete wall panel at a distance of about six inches from the reinforcement. The horizontal displacement of the reinforcement was measured by a string potentiometer attached to an independent reference beam.

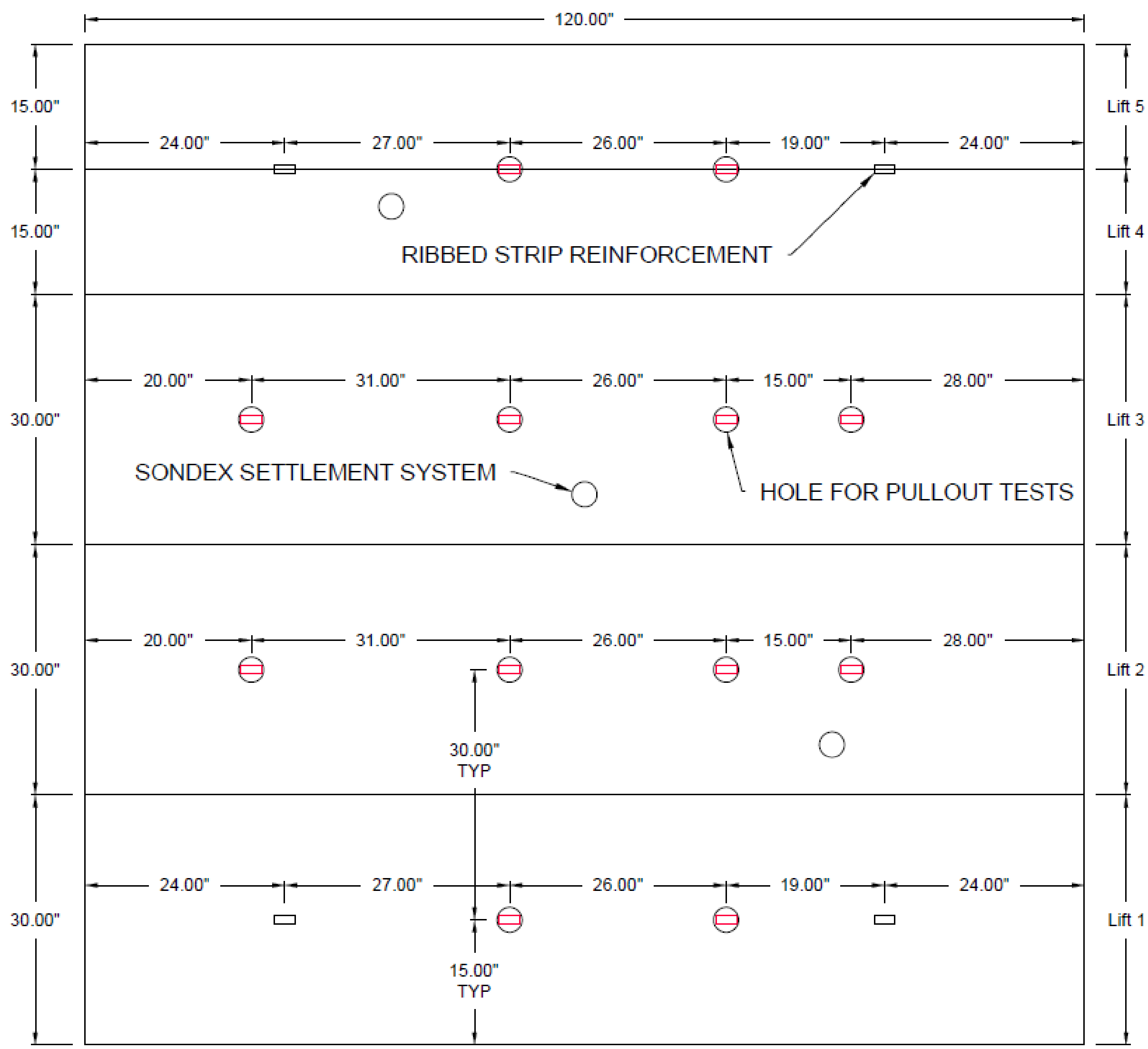


Figure 1. Elevation view showing the arrangement of pull-out reinforcements (shown in red) located in the west wall of LCC for Test 6.

(a)

(b)

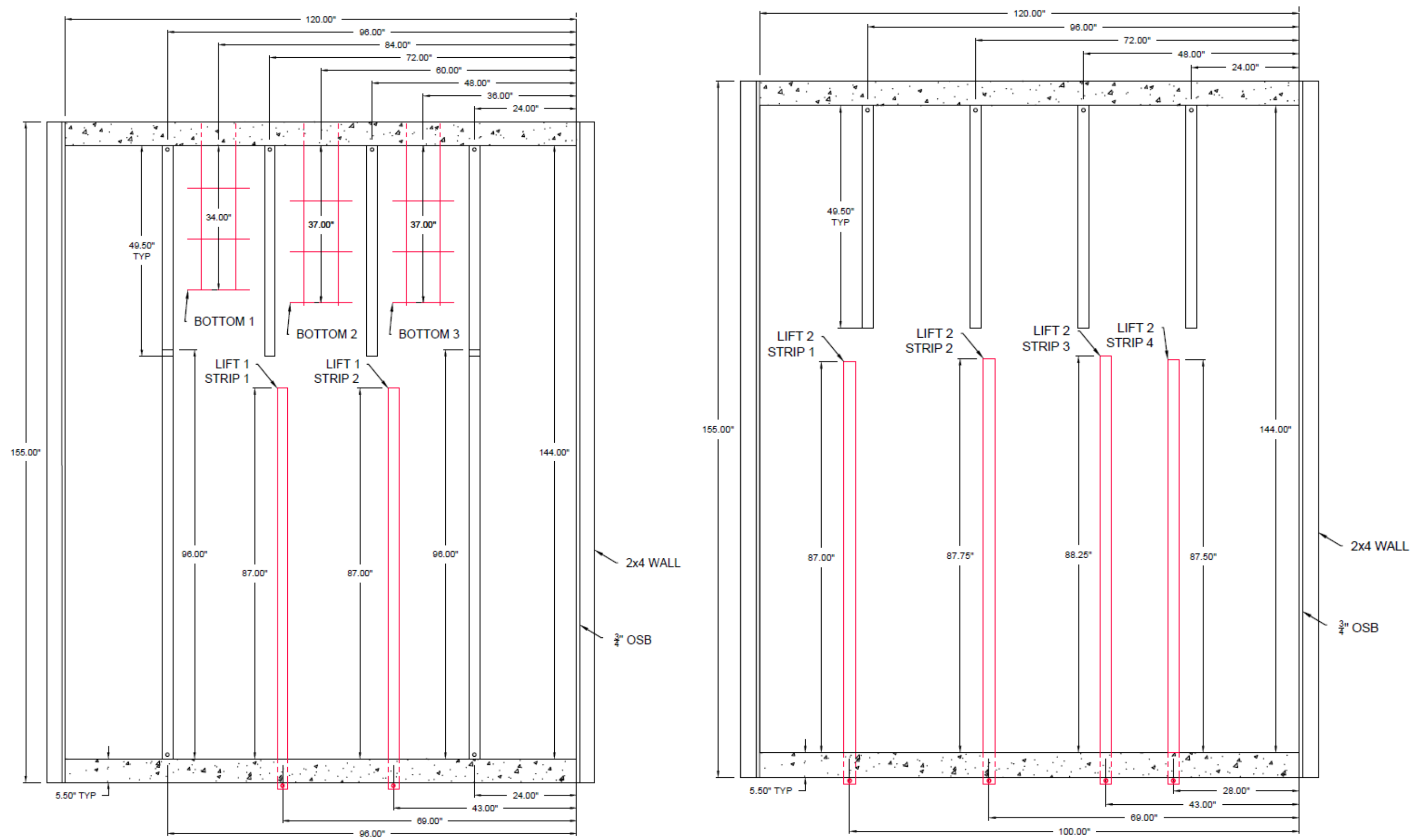
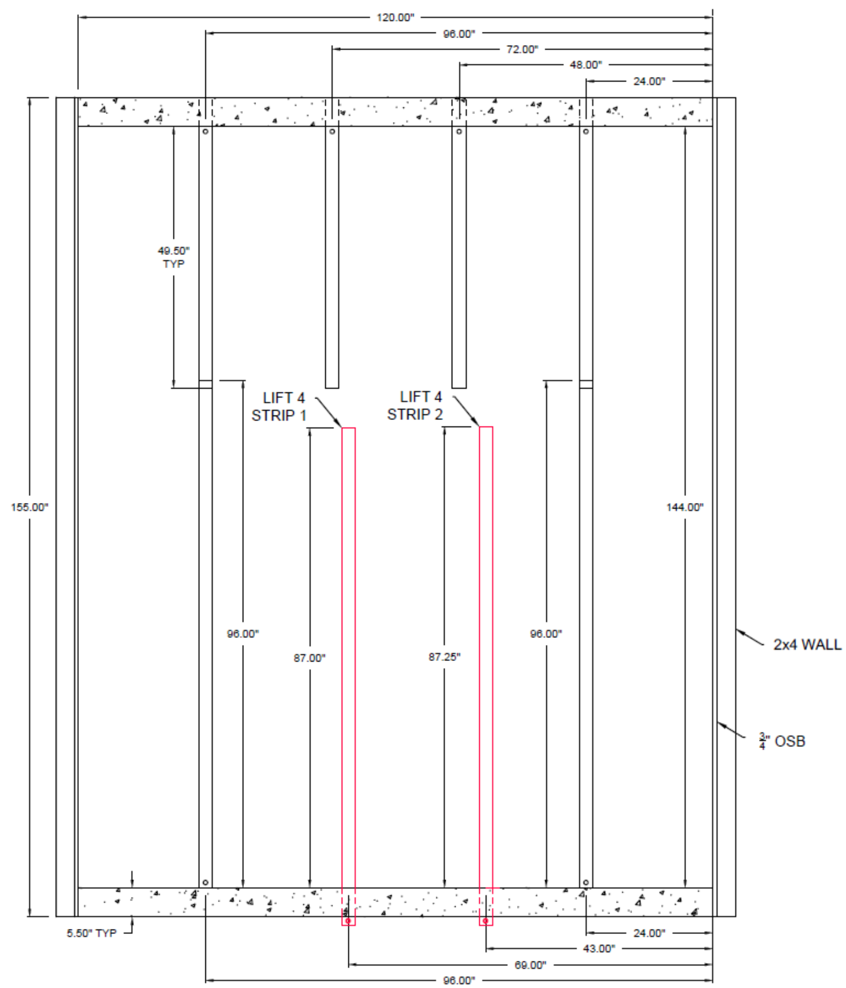


Figure 2. Plan view showing the arrangement of pull-out reinforcements (shown in red) in: (a) lift 1, (b) lift 2, (c) lift 3, (d) lift 4 of LCC for Test 6

(c)



(d)

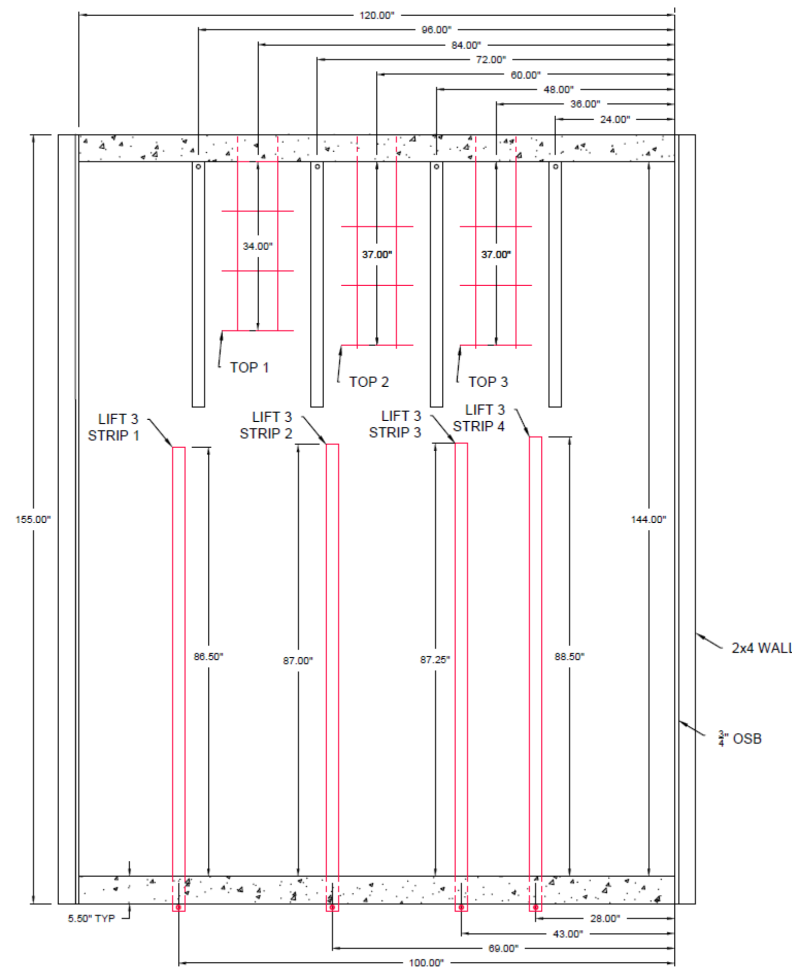


Figure 2.Continued   Plan view showing the arrangement of pull-out reinforcements (shown in red) in: (a) lift 1, (b) lift 2, (c) lift 3, (d) lift 4 of LCC for Test 6

Figure 3. Reinforcements in concrete test box 6 prior to pouring the first lift.

Figure 4. Photograph of the center-pull hydraulic jack used to apply the pull-out force to the ribbed-strip reinforcement along with string potentiometer attached to an independent reference point to monitor horizontal displacement of the reinforcement.

Testing in small LCC test boxes

Supplemental pull-out tests were performed using the 0.2 inch thick x 2 inch wide ribbed-strip reinforcements in smaller test boxes. Four reinforcements were tested within two LCC blocks that were 30 inches tall x 10 ft long and 6 ft deep as shown in Figure 5. The reinforcements were located 1.5 feet below the surface of the LCC and centered at 2.5 feet horizontally. The reinforcements extended 5.5 feet into the LCC behind a 0.5-foot concrete facing panel. The reinforcements extended through a hole in the facing panel so that they could be pulled horizontally from the wall face. The Class II LCC fill had an average unit weight of 30 pcf. Pull-out tests were performed after 7 and 28 days of curing; compressive strengths were between 76.5 and 90.9 psi after 7 days of curing, and between 127 and 216 psi after 28 days of curing.

Prior to the pull-out tests, a surcharge weight consisting of concrete blocks were placed on top of the LCC backfill shown in Figure 5(b). This surcharge consisted of 30 pcf LCC self-weight, and due to concrete blocks, resulting in vertical surcharge of 486.3 psf or 901.7 psf. The pull-out test setup is shown in Figure 6 for the tests the in small LCC test boxes.

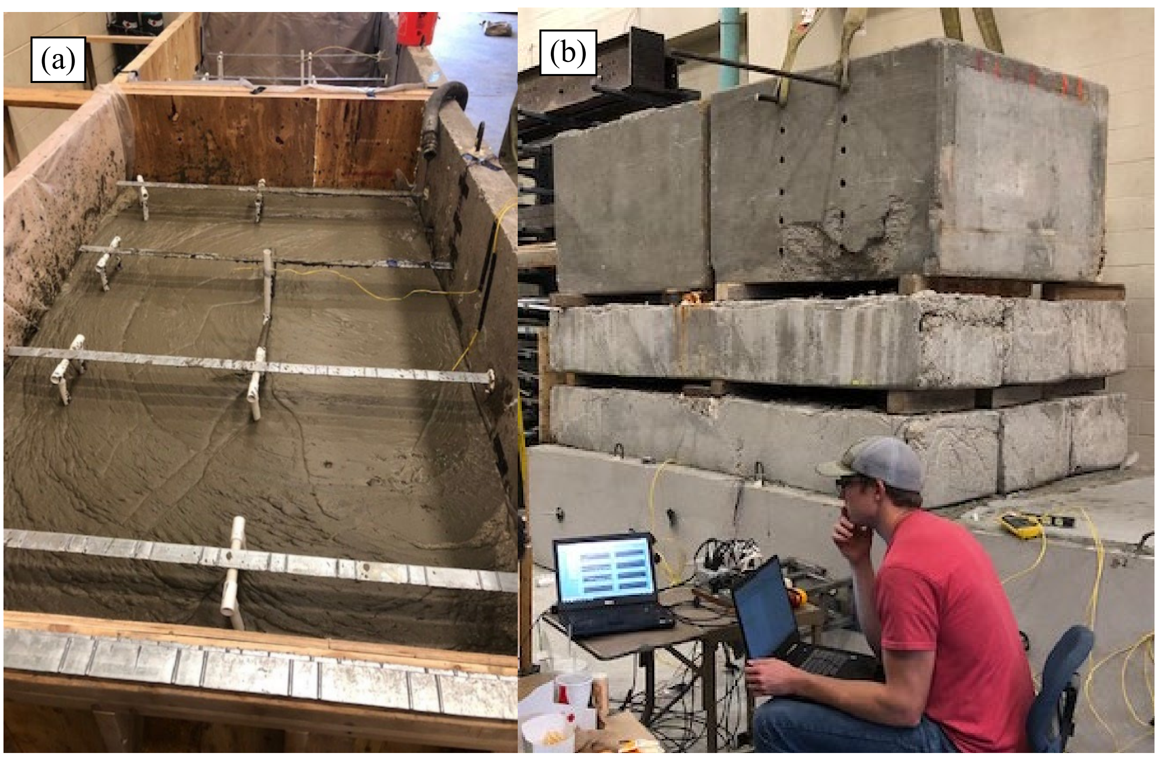


Figure 5. Photographs of (a) four ribbed-strip reinforcements with LCC being filled and (b) surcharge loading of LCC prior to pull-out testing.

Figure 6. Photograph of the center-pull hydraulic jack used to apply the pull-out force to the ribbed-strip reinforcement along with string potentiometer attached to an independent reference point to monitor lateral displacement of the reinforcement.

Welded-wire reinforcement testing

Test 6

The test box used in Test 6 is the same described above, where both the east and west wall contained MSE wall panels. The east side of lifts 1 and 3 were reinforced by three welded-wire reinforcements, one of which was shorter than the other two, as shown in Figure 2(a) and 2(c). The welded-wire reinforcements were 3/8-inch-thick consisting of W11 bars, provided by SSL, LLC. All 6 reinforcements had 2 longitudinal W11 bars spaced 8 inches transversely center to center and cross bars spaced 12 inches longitudinally center on center. All cross bars were 14 inches long. Dimensions of the welded-wire reinforcements used in Test 6 are shown in Figure 8.

The reinforcements were located 27 inches above the ground and the top of lift 2, as shown in Figure 7. The welded-wire horizontal spacing is also given in Figure 7. The reinforcement extended through drilled holes in the facing panel so that the welded-wire could be pulled horizontally from the wall face. The distance that each reinforcement protruded into the backfill is shown in Figure 2(a) and 2(c). Steel plates were welded to the reinforcement at various distances after the MSE wall was backfilled with LCC; this allowed the jack to hook to the reinforcements, as shown in Figure 9. The Class II LCC fill had an average cast unit weight of 28.1 pcf. The average compressive strengths for the first and third lifts at time of pull-out testing was 83 and 89 psi, respectively.

The surcharge weight at the time of pull-out varied for lifts one and three. For the north reinforcement from the first lift, the surcharge weight consisted of the LCC average self-weight from lift one, two, and three, creating a vertical surcharge weight of 145.6 psf. For the middle and south reinforcement from the first lift, the surcharge weight consisted of the LCC average self-weight from lifts one, two, three, and half of four, creating a vertical surcharge weight of 193.4 psf. For lift three, the surcharge weight consisted of the LCC self-weight for lifts three and four, and surcharge loads from concrete blocks and hydraulic jacks. The average self-weight of lift three and four applied 78.8 psf of pressure. Six, 10 feet x 2 feet x 1.5 feet precast concrete blocks were placed on the LCC, applying a pressure of 240 psf. The vertical surcharge applied by the hydraulic jacks was 5 psi resulting in a total surcharge pressure for lift three of 1038.8 psf. Figure 9 shows the jack setup for the Test 6 pullout tests.

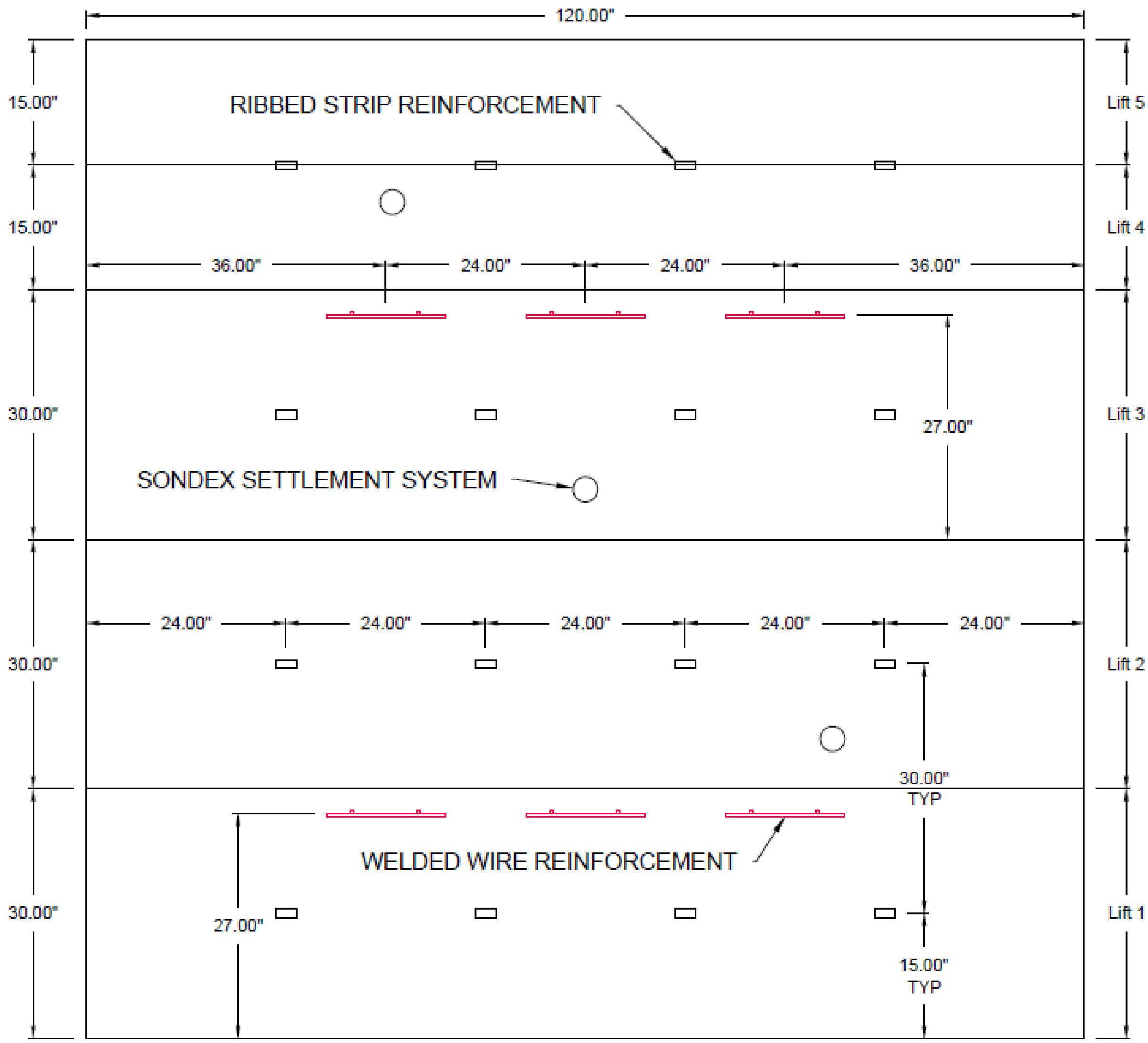


Figure 7. Test 6 east wall elevation view with welded-wire pull-out reinforcements in red.

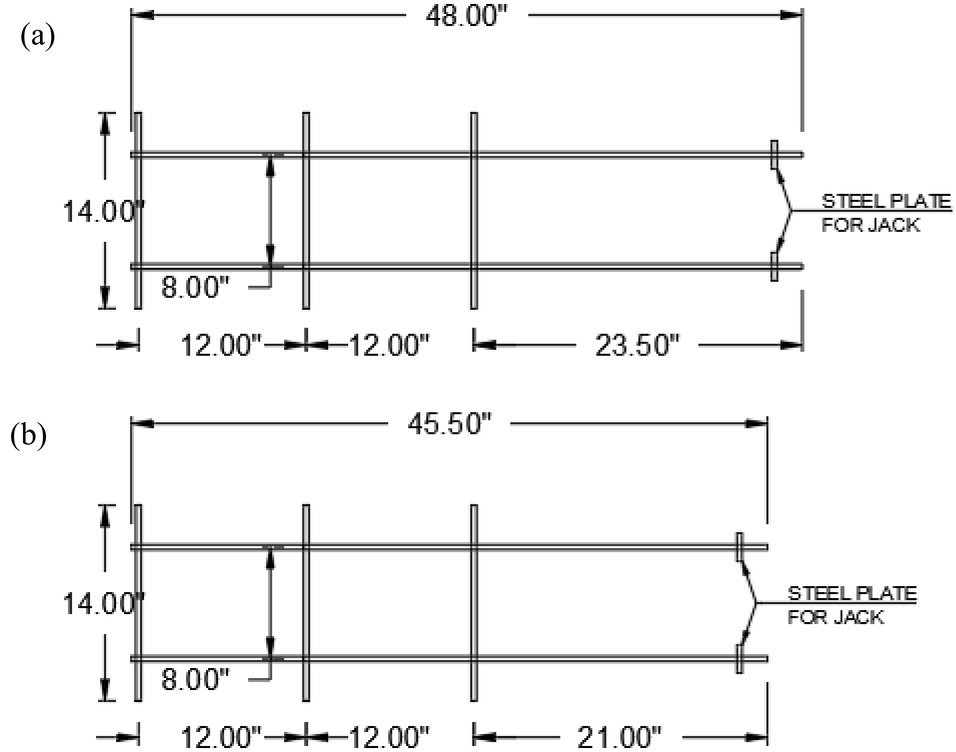


Figure 8. Dimensions of (a) longer welded-wire reinforcement, and (b) shorter welded-wire reinforcement used in Test 6.

Figure 9. Photograph of the center-pull hydraulic jack used to apply the pull-out force to the welded-wire reinforcement.

Pull-out Tests for LCC Test 7

Schematic plan and elevation drawings for the reinforced LCC backfill in Test 7 are shown in Figure 10 and Figure 11. The test box used in Test 7 was the same as in Test 6, however, only one side contained MSE wall panels rather than both sides. Therefore, the east side of the LCC backfill was tested as a free face. The free face of the LCC backfill was supported by two different welded-wire reinforcement sizes. Each of the top three 30-inch thick LCC lifts were supported by four welded-wire reinforcements. Reinforcements consisted of welded-W11 wire reinforcements that were 3/8 of an inch in diameter provided by SSL, LLC. For Test 7, 12 welded-wire reinforcements were placed in 3 layers with 4 reinforcements spaced at 2.5 feet vertically. All 12 reinforcements had 2 W11 longitudinal bars spaced 8 inches transversely center to center and cross bars spaced 12 inches longitudinally center to center. Six reinforcements were 4.5 feet long with 3 W11 cross bars and six were 5.5 feet long with 4 W11 cross-bars. All cross bars were 14 inches long. Dimensions of the reinforcements are detailed in Figures 12 and 13. Figure 14 provides a photograph of the top lift with the pull-out reinforcements shown on the left side.

The reinforcements were centered in each LCC lift. See Figure 10 for welded-wire horizontal spacing. The 13-inch mark in Figure 13 displays how far back the first cross bar was from the east side of the wall, while the steel plates were attached at various distances along each reinforcement to allow the pull-out jack to be hooked to the reinforcements. The length that each reinforcement extended into the LCC is shown in Figure 10. The reinforcement extended through drilled holes in the facing panel so that the welded-wire could be pulled horizontally from the wall face. The Class II LCC fill had an average cast unit weight of 27.7 pcf. The average compressive strengths for the second, third, and fourth lifts were 124 psi, 113 psi, and 78.4 psi at the time of testing, respectively.

The surcharge weight varied for the three LCC lifts. For the second lift pull-out tests, the surcharge weight consisted of the LCC average self-weight from lift one, two, three, and four creating a vertical surcharge weight of 168.4 psf. The surcharge weight for pull-out tests performed in lift three and four consisted of LCC self-weight, gravity loads, and loads from hydraulic jacks. The average self-weight of lifts three and four was 99.2 psf and 36.9 psf, respectively. The gravity loads composed of six, 10 feet x 1.5 feet x 2 feet precast concrete blocks applied to the surface of the LCC, applied a pressure of 240 psf. The vertical surcharge applied by the hydraulic jacks was 552 psf and 1240 psf respectively for lifts 3 and 4. In summary, the total pressures that were applied to lift two, three, and four were 408.4 psf, 891.2 psf, and 1516.9 psf, respectively.

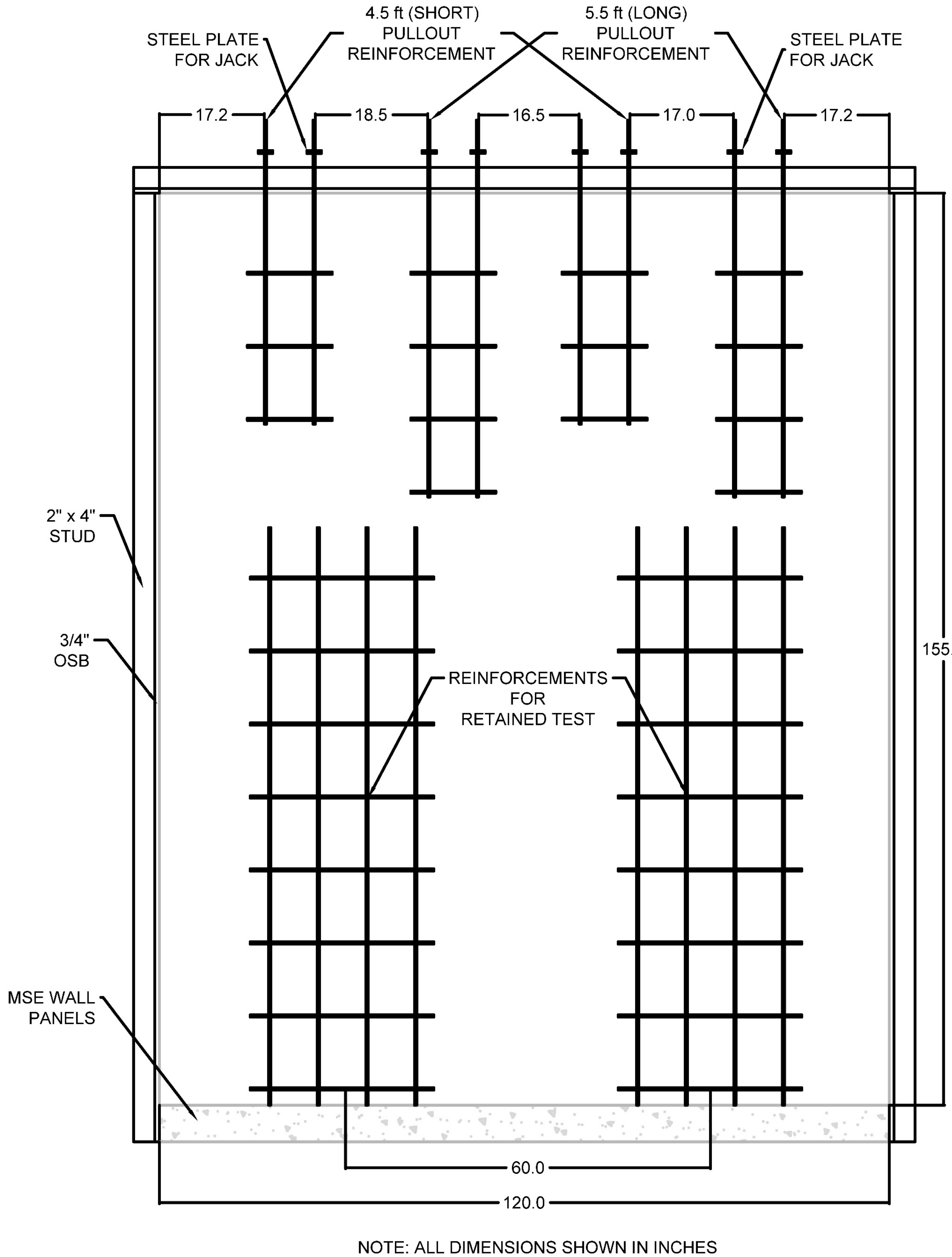


Figure 10. CAD drawing showing plan view of Test 7 set up with pull-out test reinforcements being on the right-hand side.

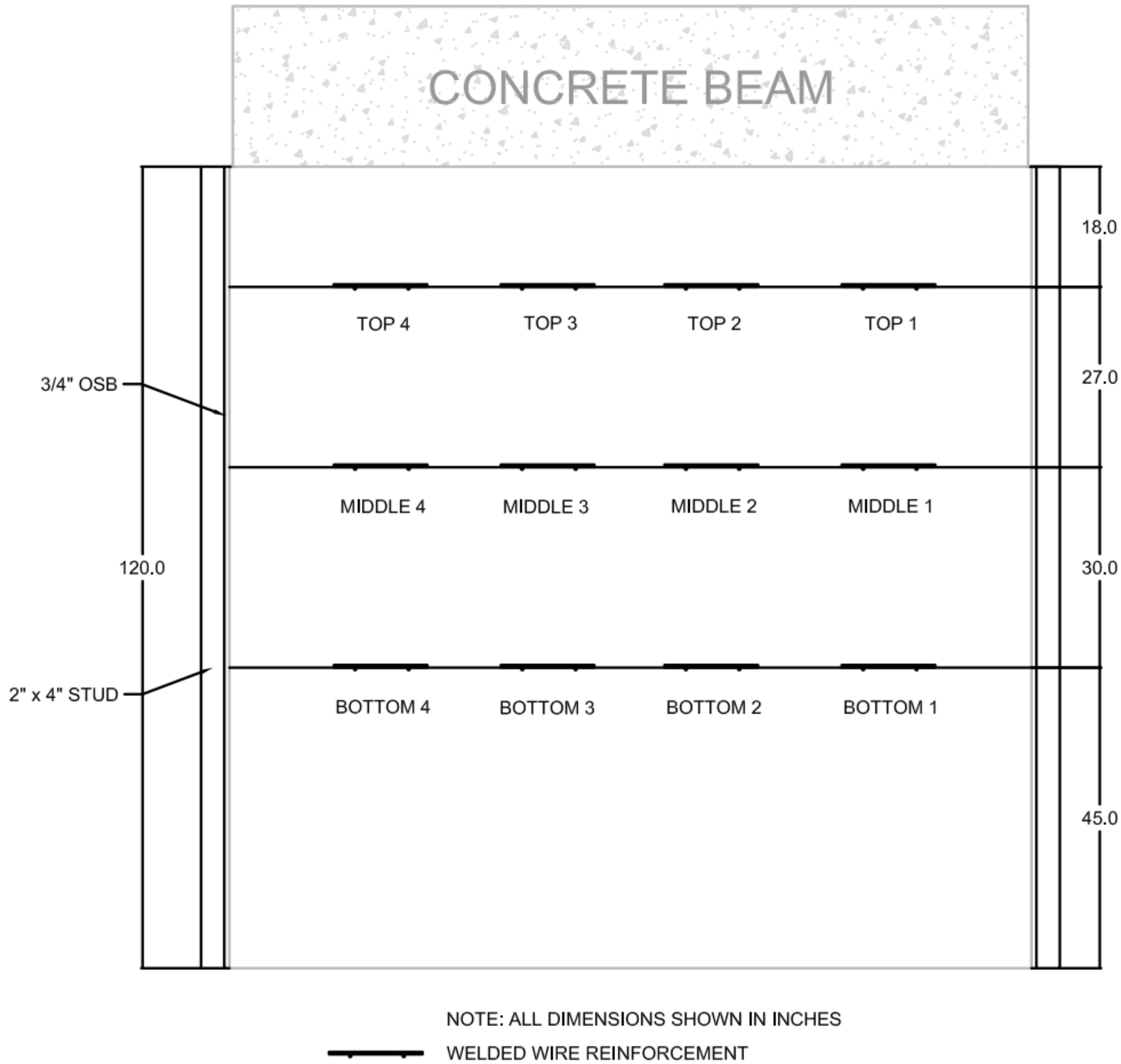


Figure 11 CAD drawing showing elevation view of pull-out reinforcement locations for Test 7.

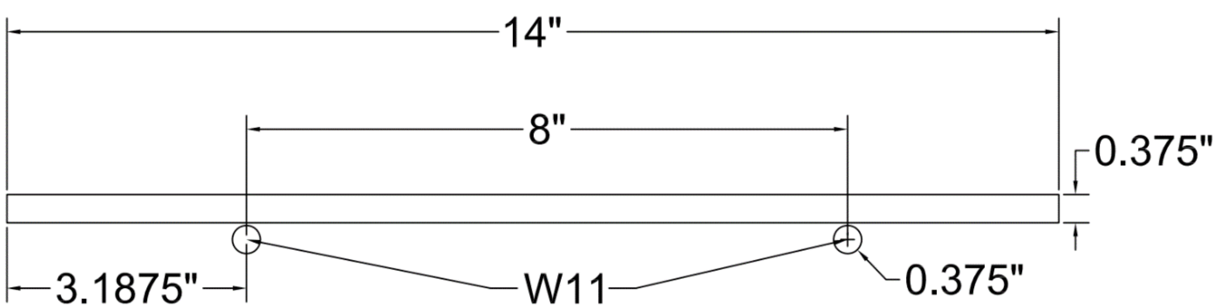


Figure 12. CAD drawing showing dimensions of reinforcements for Test 7.

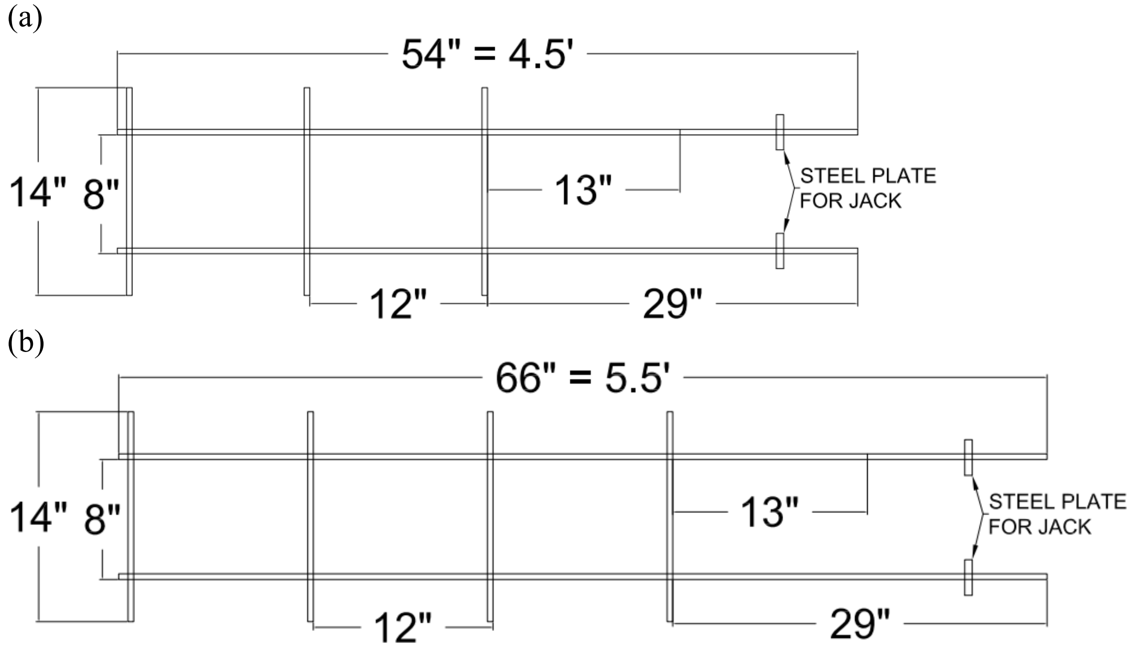


Figure 13. Auto CAD drawings showing (a) plan view of 4.5-foot reinforcements and (b) plan view of 5.5-foot reinforcements for pull-out testing.

Figure 14. Photograph showing the welded-wire reinforcement layout for Test 7, with the left-hand side containing the reinforcements used for pull-out testing.

Pull-out Testing Procedure
During the pull-out tests, horizontal load was applied with a center-pull jack with force measured by a load cell while lateral displacement of the reinforcement was monitored by a string potentiometer attached to an independent reference frame as shown in Figure 9. A load frame was used to distribute the reaction force to the facing panel as load was applied. The pull-out tests were performed by applying load incrementally and holding for one-minute prior to applying the next load increment. The lateral displacement and peak pull-out force were recorded using a data acquisition system. Although load was applied until displacements of about 4 to 11 inches to determine the full load-displacement curve, the pull-out resistance was taken as the maximum force measured within the first 0.75 inch of displacement.

Pull-out Test Results

<u>Test 6 Load vs. Displacement Curves</u>

Load versus displacement curves were produced for each of the pull-out tests. Figure 15 through Figure 18 show the load versus displacement curves for the ribbed-strip pull-out tests from lifts 1, 2, 3, and 4, respectively. Figures 19 and 20 show the load versus displacement curves for the welded-wire pull-out tests in lifts 1 and 3. The sudden drops in pull-out force coincided with an audible pop while pull-out tests were performed. We believe that this pop was a result of the reinforcements overcoming the initial cementation of LCC to the reinforcements.

The shape of the ribbed-strip reinforcement load versus displacement curves follow a general shape within each backfill lift, but the shapes vary slightly between lifts. In general, the maximum load occurred before 0.75 inches of displacement was reached. The load versus displacement curves for the welded-wire reinforcements follow a more consistent shape than the ribbed-strip reinforcements. In contrast to the ribbed-strip reinforcements, the welded-wire load versus displacement curves show that the maximum load is reached at a displacement of 2 to 4 inches, which is well beyond 0.75 inches of displacement. The pull-out resistance remains relatively constant beyond the peak load until the maximum displacement.

Figures 21 and 22 display normalized pull-out force-displacement curves for the welded-wire reinforcements. The load is normalized to the reinforcement's maximum pullout force within 0.75-inch of displacement. Figure 21, which includes 5 inches of displacement, illustrates that the maximum pull-out force ultimately ranges between 1.2 and 1.7 times that reached within 0.75-inches of displacement. Figure 22 focuses on the normalized curves for the welded-wire reinforcement up to 0.75 inches of displacement. About 60% of the maximum force is developed with only about 0.1 inch of displacement, which the remaining 40% of the resistance develops in a relatively linear fashion in the remaining 0.65 inches of displacement. The minor changes in the load shown in Figures 21 and 22 are due to hand pumping the hydraulic jack whereas the major changes in the load are due to the 1-minute holding prior to applying the next load, illustrating creep of the reinforcement between each load increment.

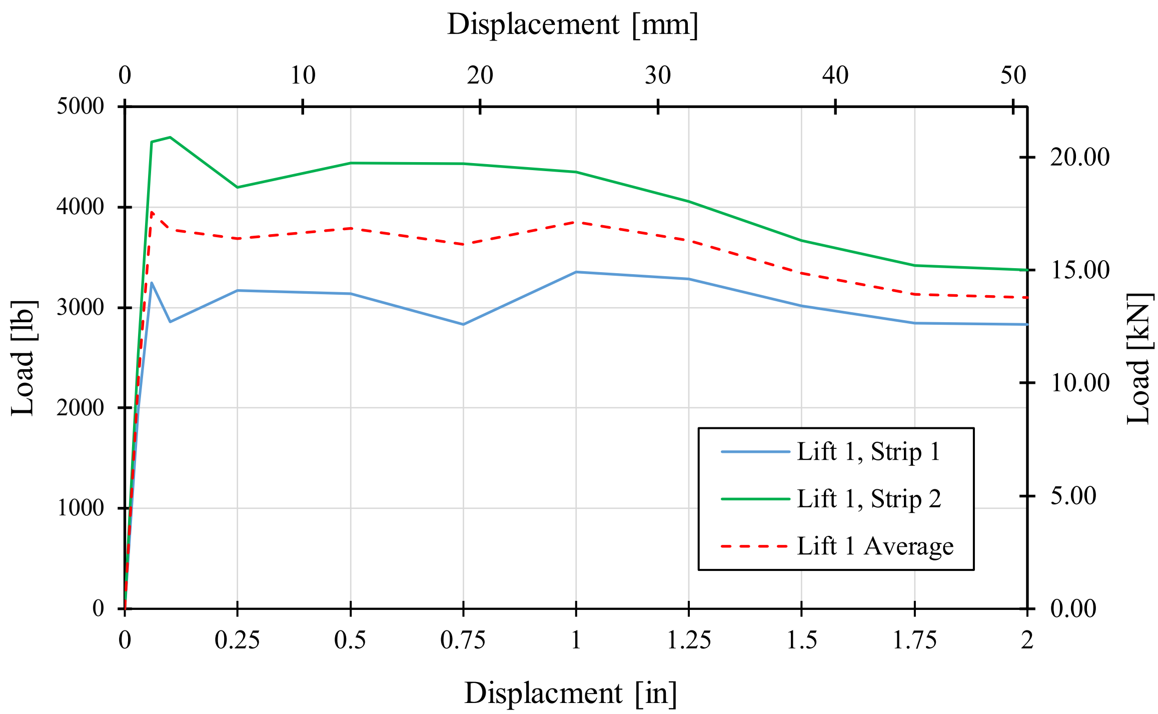


Figure 15. Load vs. displacement for lift one ribbed-strip pull-out tests.

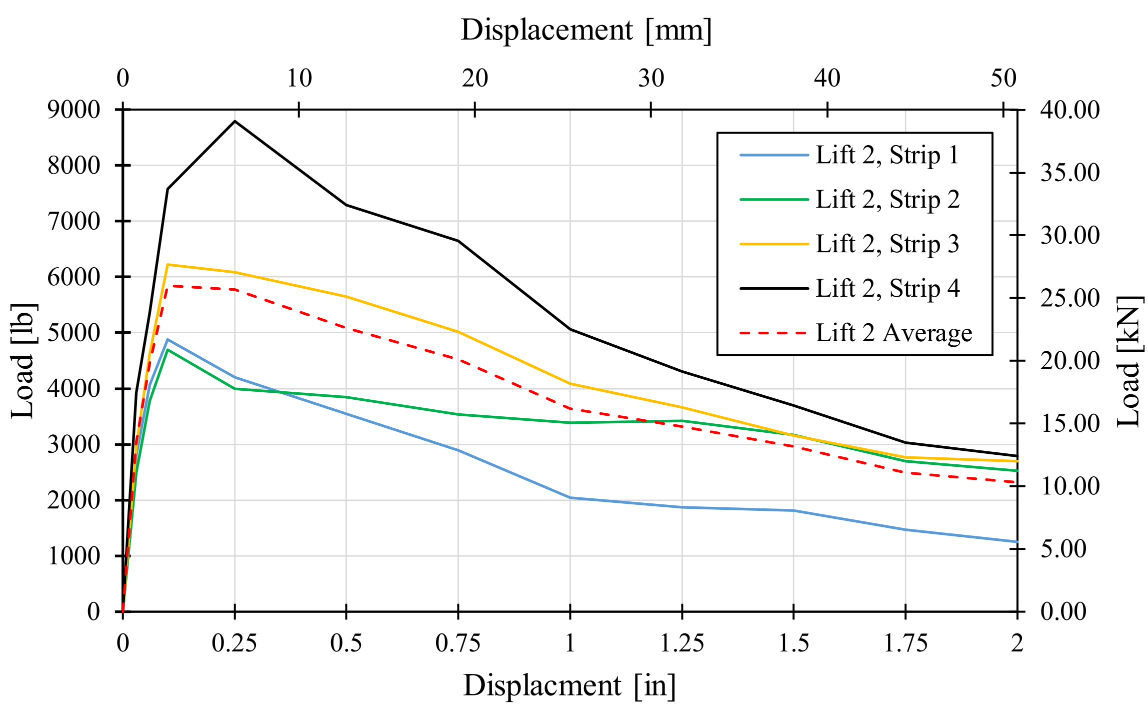


Figure 16. Load vs. displacement for lift two ribbed-strip pull-out tests.

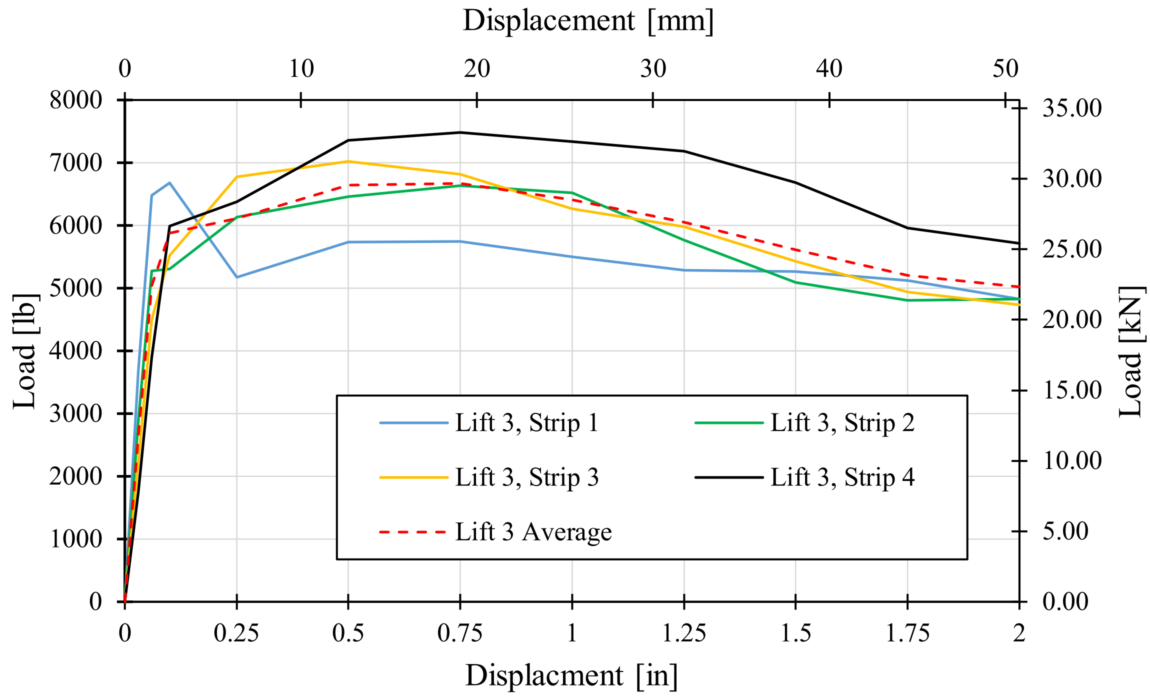


Figure 17. Load vs. displacement for lift three ribbed-strip pull-out tests.

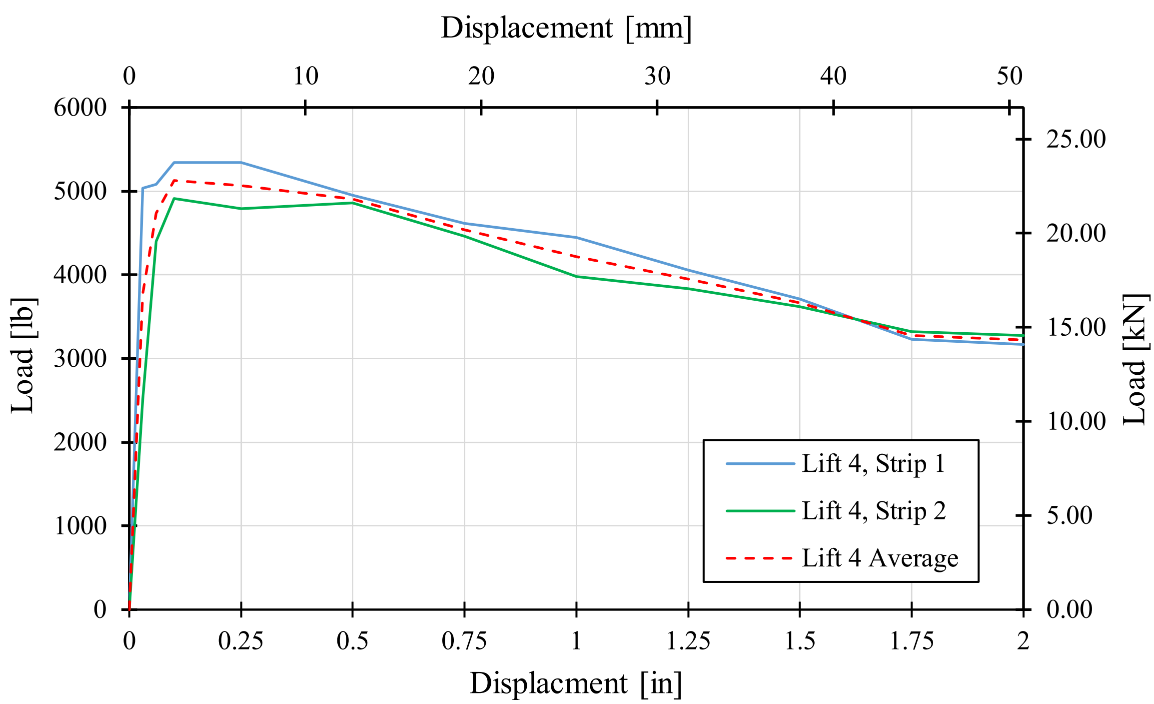


Figure 18. Load vs. displacement for lift four ribbed-strip pull-out tests.

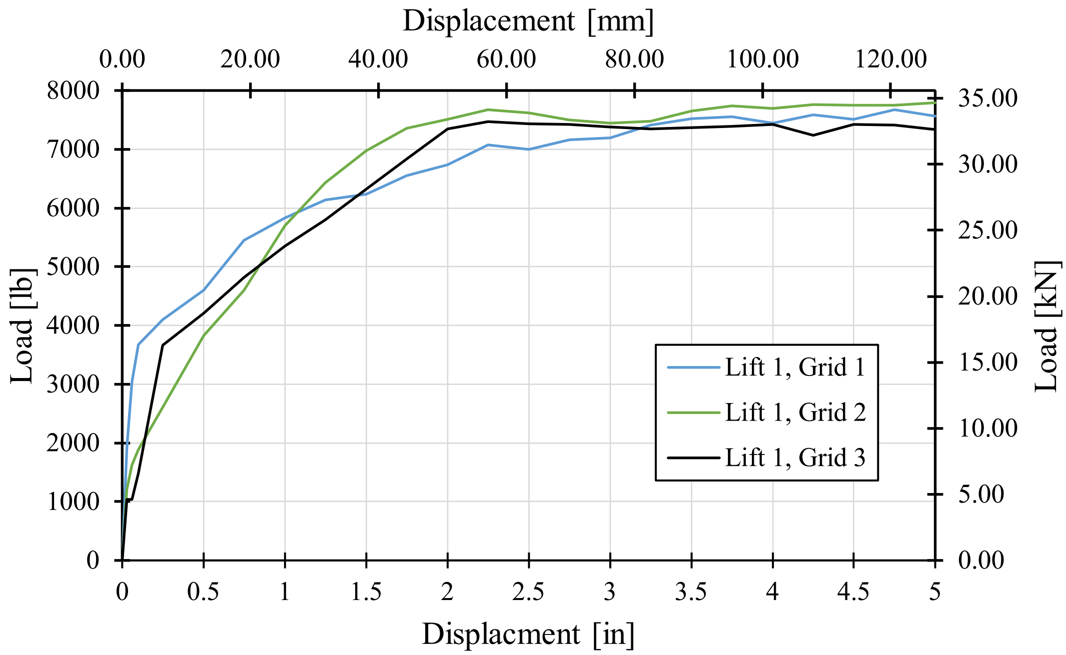


Figure 19. Load vs. displacement for lift one welded-wire pull-out tests.

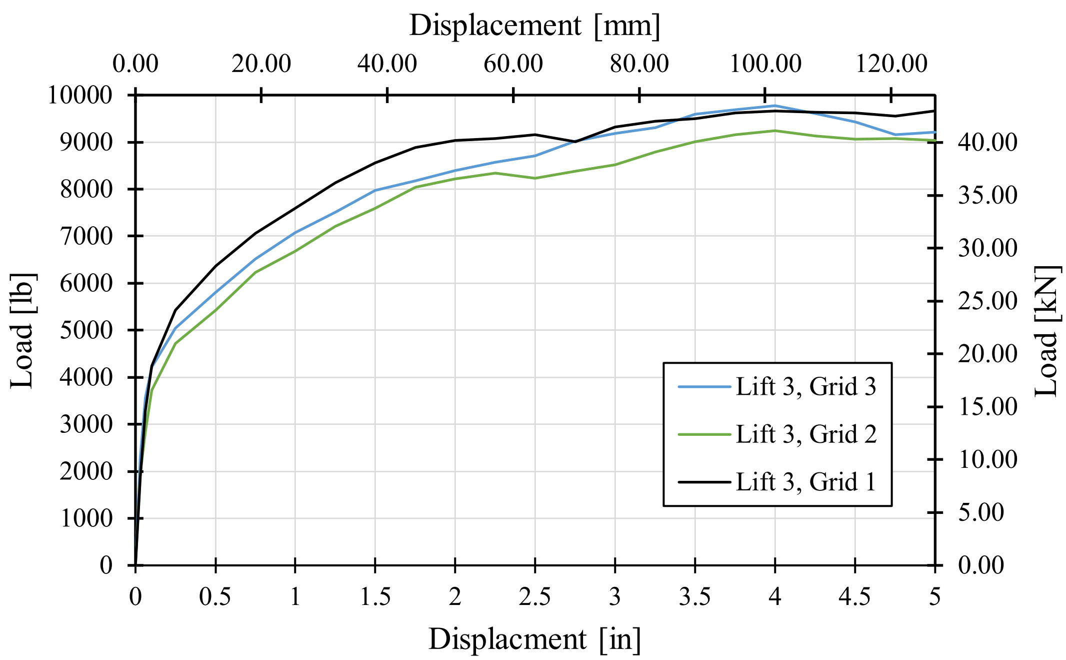


Figure 20. Load vs. displacement for lift three welded-wire pull-out tests.

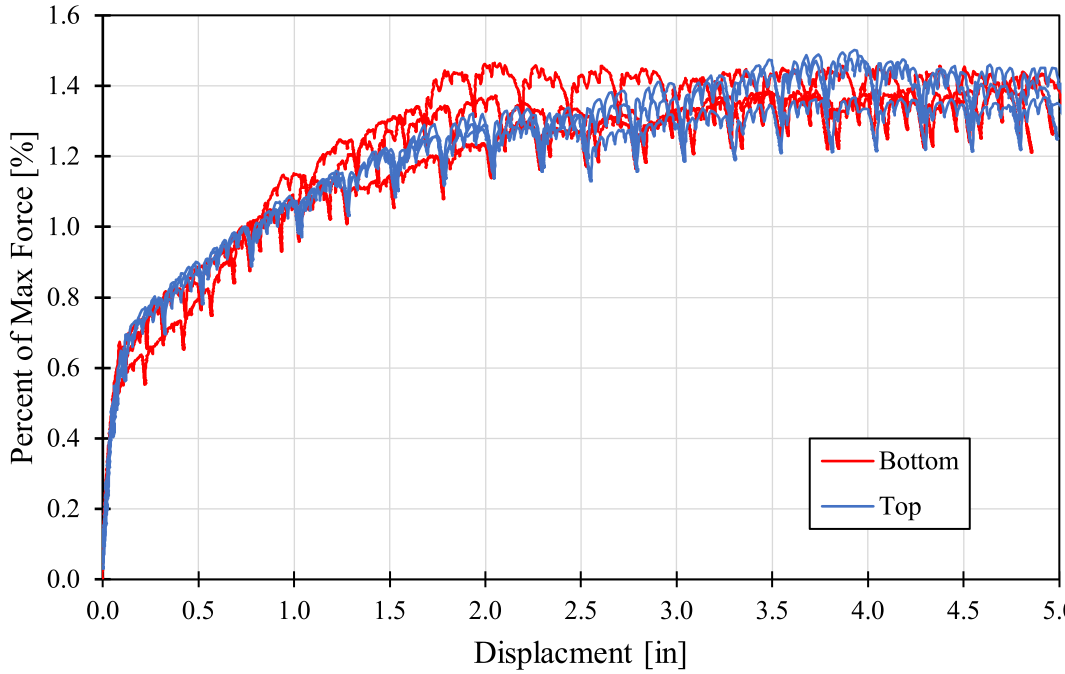


Figure 21. Graph showing normalized displacement versus pull-out force of the maximum force for welded-wire reinforcement pull-out tests from Test 6.

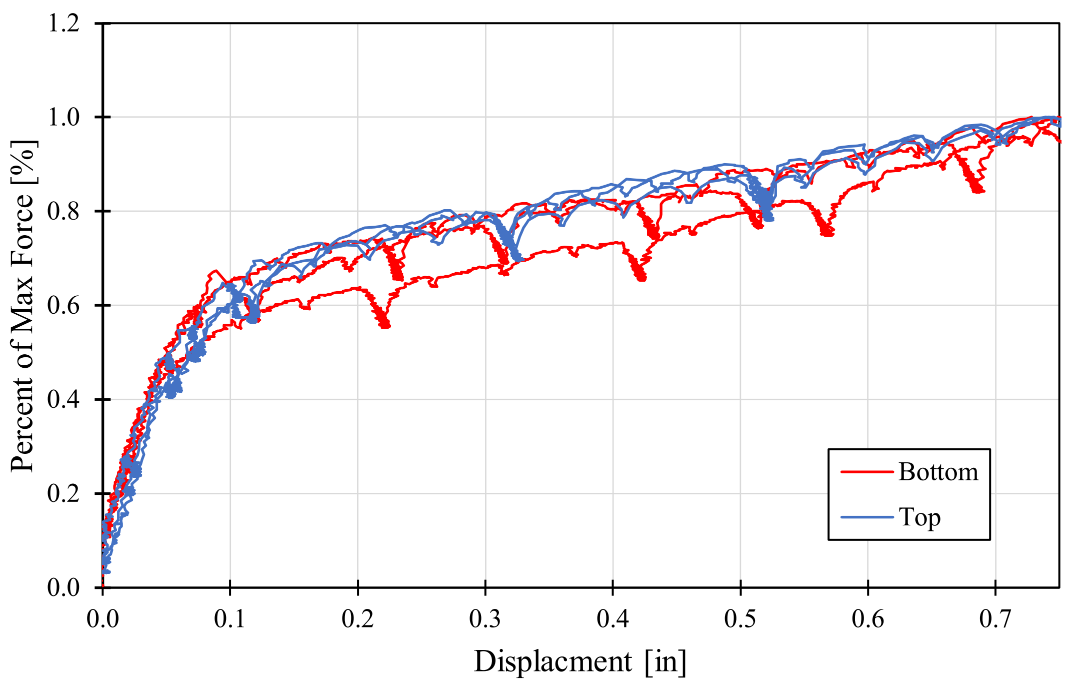


Figure 22. Graph showing normalized displacement versus pull-out force of the maximum force within 0.75-inch displacement for welded-wire reinforcement pull-out tests from Test 6.

Small LCC test boxes load vs. displacement curves

Load versus displacement curves are plotted for each of the ribbed-strip pull-out tests performed in the small LCC test boxes. Figure 23 shows the pull-out tests performed 7-days after LCC placement and Figure 24 shows the pull-out tests performed 28-days after LCC placement. The two different vertical surcharge loads are also noted in these figures. The sudden drops in pull-out forces coincided with an audible pop while pull-out tests were performed. The pop appears to be a result of the reinforcements overcoming initial cementation of the LCC to the reinforcements. First, these figures indicate a slight gain in pullout resistance over an additional 21 days of curing. Second, these figures illustrate that surcharge loading does not greatly impact the maximum pullout force. Finally, these figures illustrate that the max pullout force is typically reached within 0.75-inches of displacement, which is consistent with the ribbed strip pull-out tests performed in for the LCC backfill in Test 6. At displacements of 2 inches, pull-out resistance decreased by 6 to 33%.

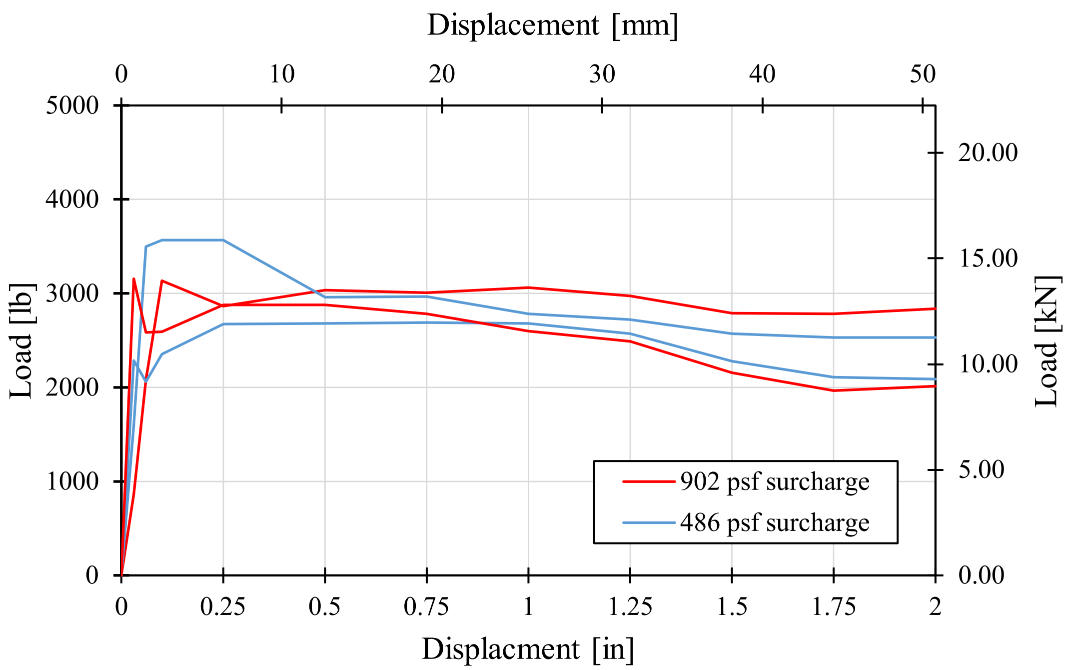


Figure 23. Pull-out load vs. displacement curves for additional ribbed strip tests performed 7-days after placement.

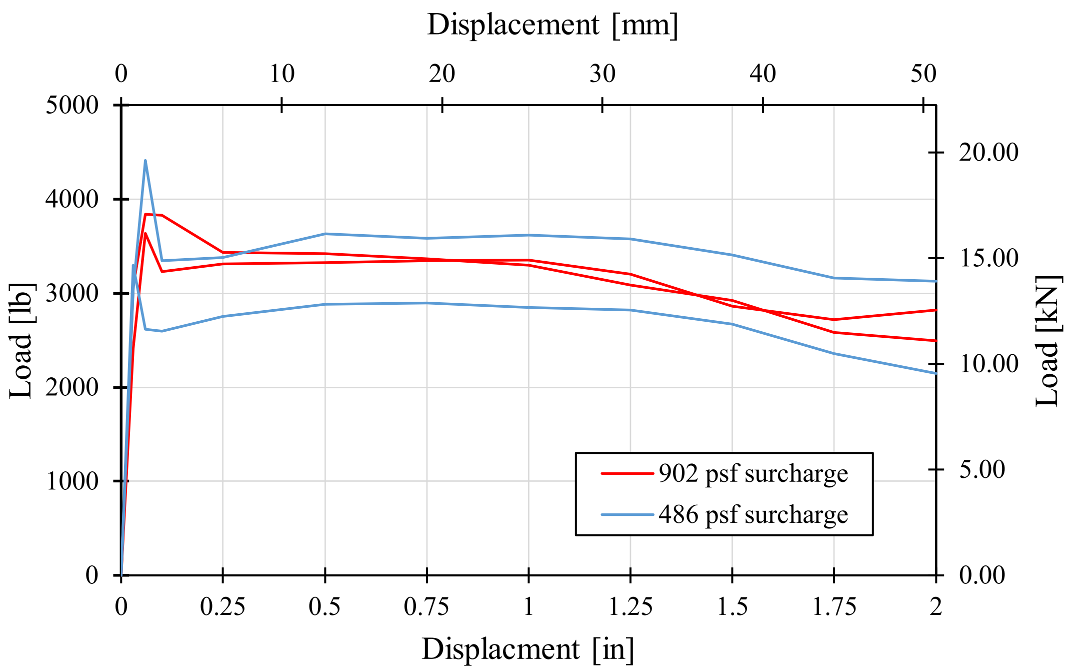


Figure 24. Load vs. displacement for additional ribbed strip pull-out tests performed 28-days after placement.

Test 7 Load vs. Displacement Curves

Load versus displacement curves were plotted for each of the pull-out tests. Figure 25 shows the load versus displacement curves for the short welded-wire reinforcements, while Figure 26 shows the curves for long welded wire reinforcements in Test 7. Both figures show displacements up until 0.75 inches, as in previous plots. The sudden drops in pull-out force were associated with an audible pop while pull-out tests were in process. The pop was a likely a result of the reinforcements overcoming initial cementation of the LCC to the reinforcements and typically occurred at displacements less than about 0.1 inch. Despite the drops in load, the pull-out resistance regained strength with further displacement. The longer reinforcement generally had more consistent load-displacement curve shapes in comparison to the shorter reinforcements.

Figure 27 and Figure 28 show the load versus displacement for short and long reinforcements, respectively, for the full range of displacements in the tests which reached 6 to 10 inches. pull-out test. The associated surcharge pressures are given as well. Figure 29 and Figure 30 show the full displacement range of each test. The load-displacement curves generally flattened considerably after displacement of about two inches. The minor changes in the load are due to the hand pumped hydraulic jack whereas the major changes in the load is due to the 1-minute holding increment, illustrating reinforcement creep during holding. Figure 31 and Figure 32 display the normalized pull-out data based on each reinforcement's maximum pullout force. Figure 33 and Figure 34 display the normalized pull-out data based on each reinforcement's maximum pullout force up to 0.75-inch of displacement.

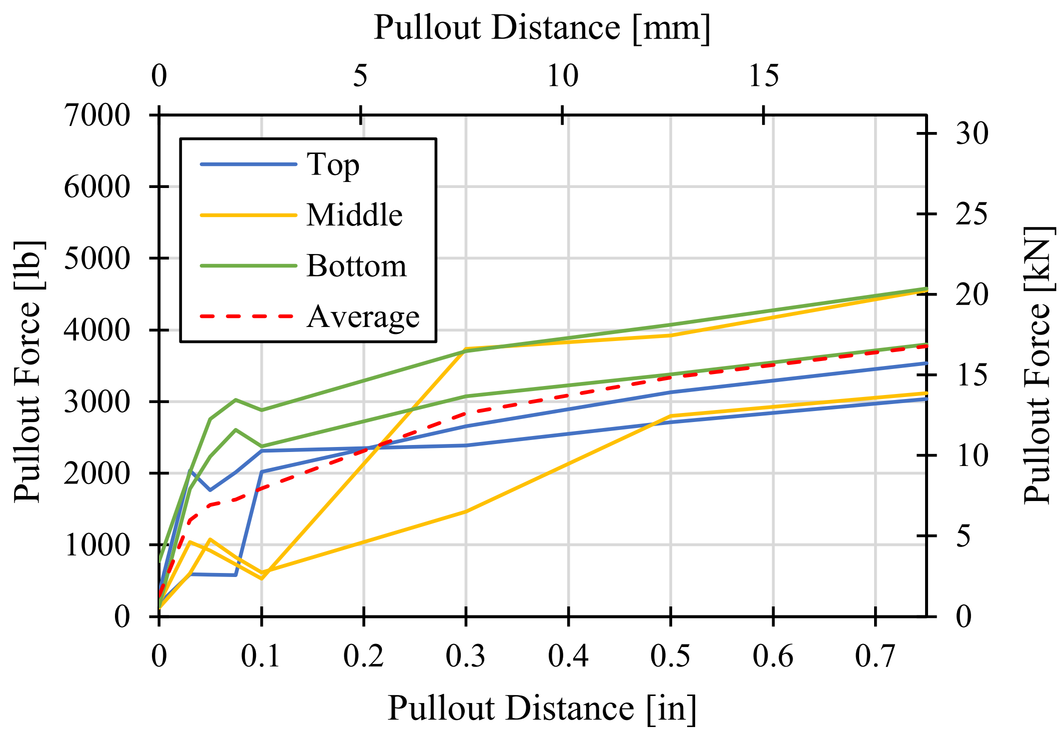


Figure 25. Load versus displacement curves for short welded-wire reinforcements up to 0.75 inch deflection for LCC Test 7.

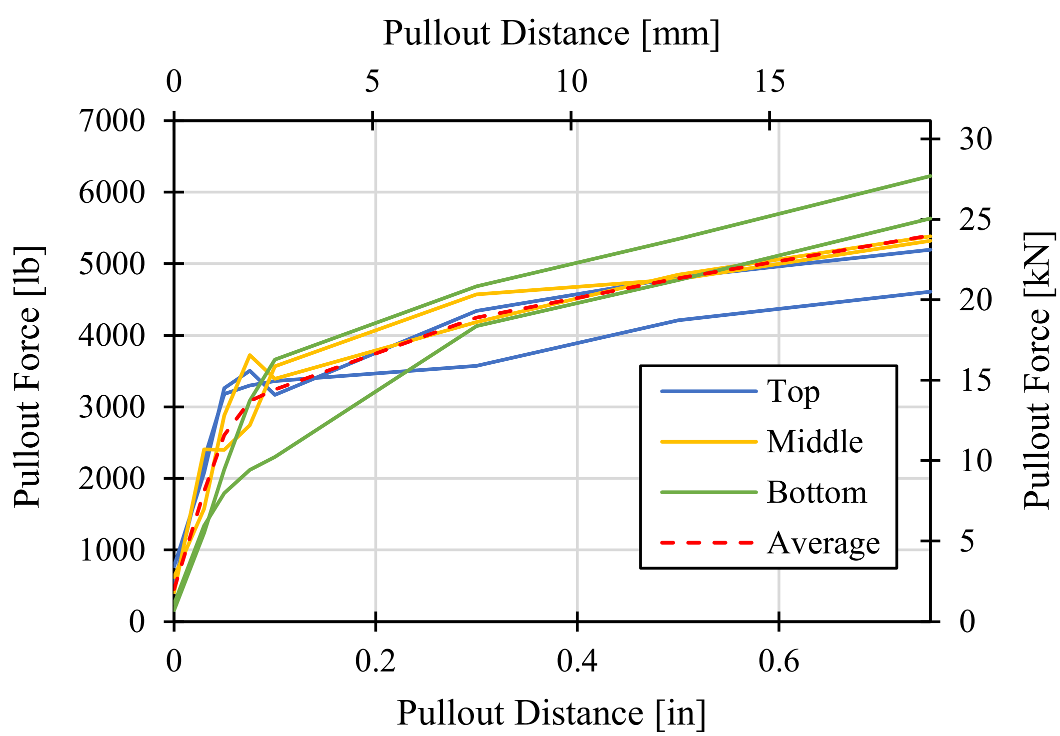


Figure 26. Load versus displacement curves for long welded-wire reinforcements up to 0.75 inches for LCC test 7

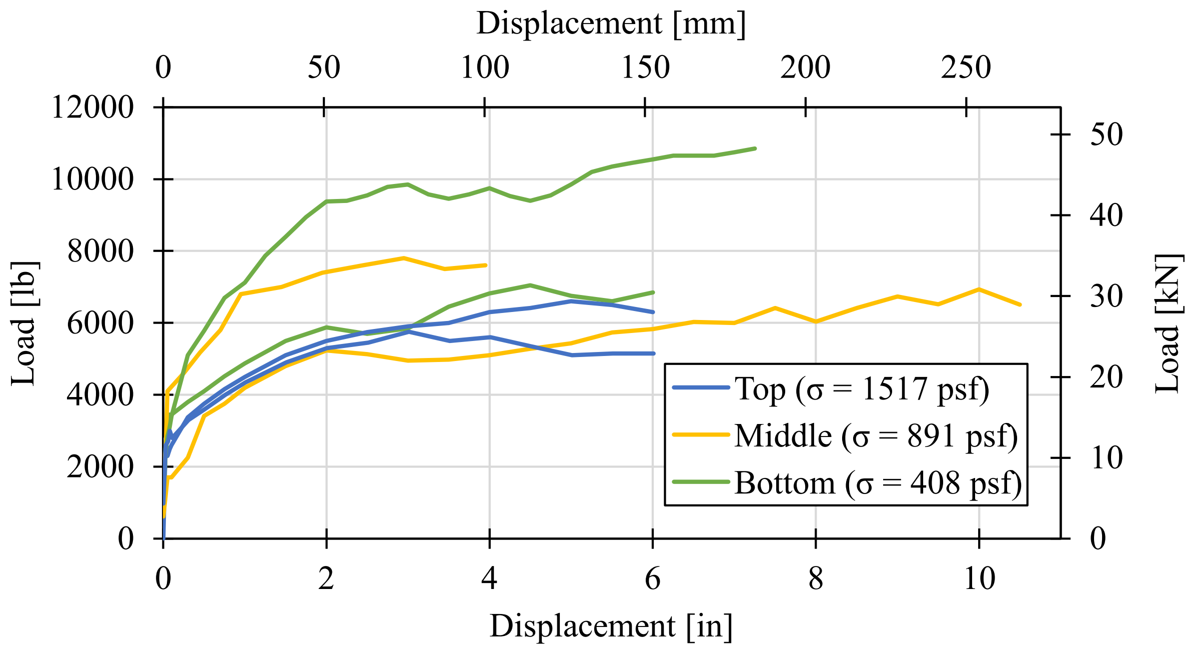


Figure 27. Load versus displacement curves for each of the short welded-wire reinforcements for each pull-out test during LLC Test 7.

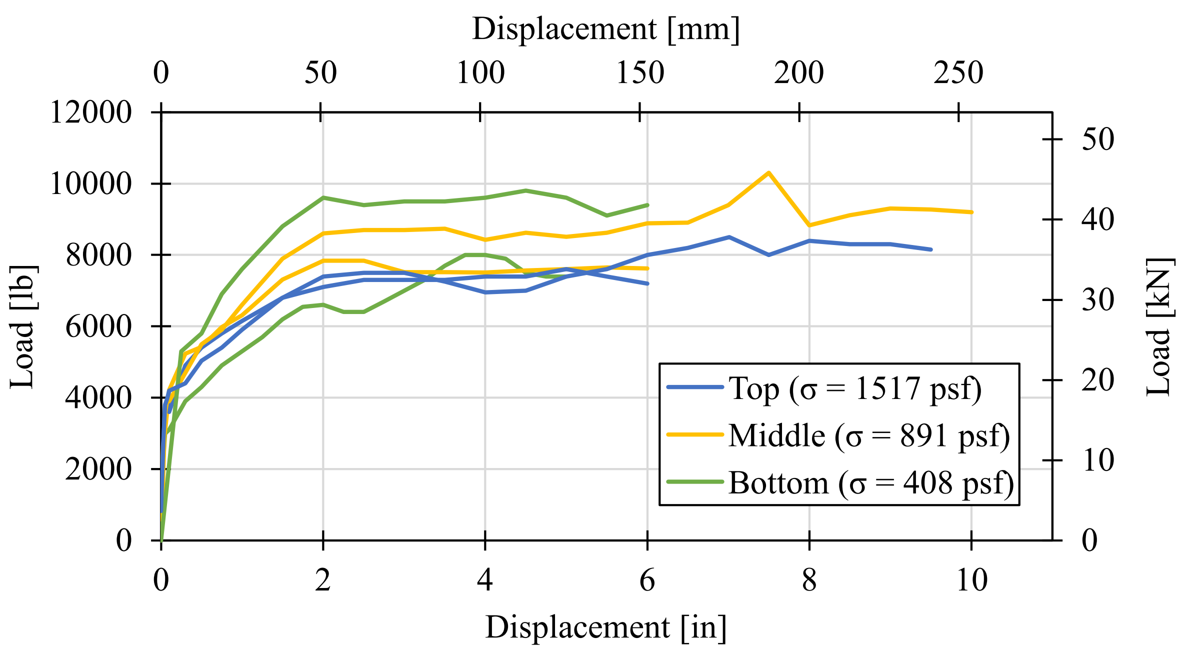


Figure 28. Graph showing complete load versus displacement curves for each of the long welded-wire reinforcements during each pull-out test during LCC Test 7.

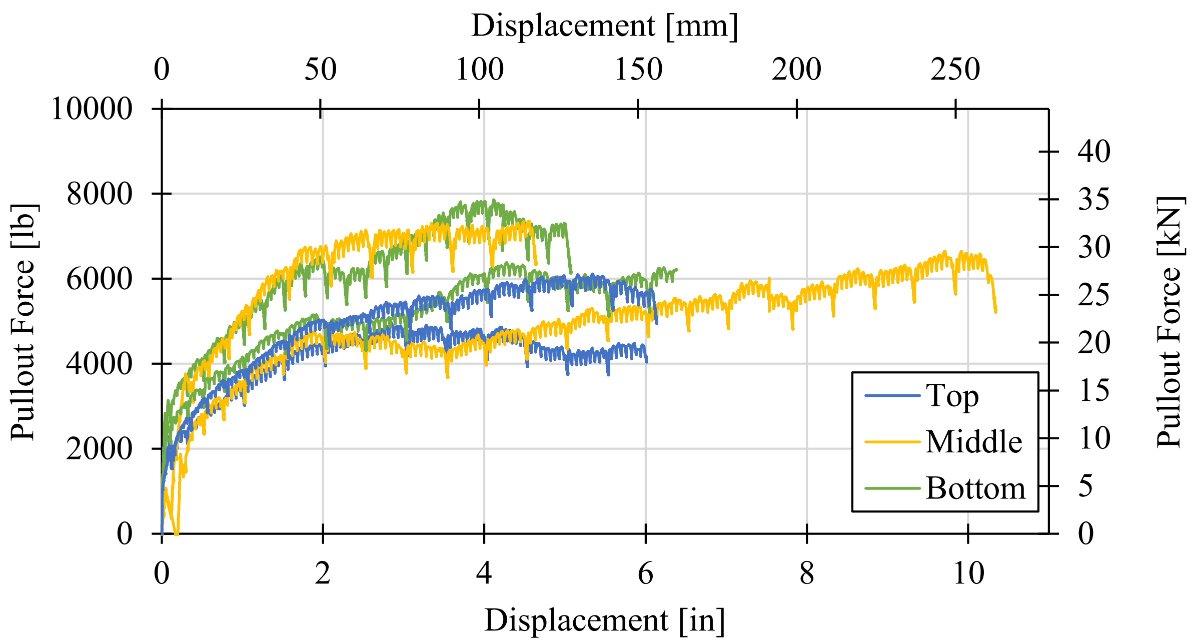


Figure 29. Graph showing complete measured load versus displacement curves for the short welded-wire reinforcement tests from Test 7.

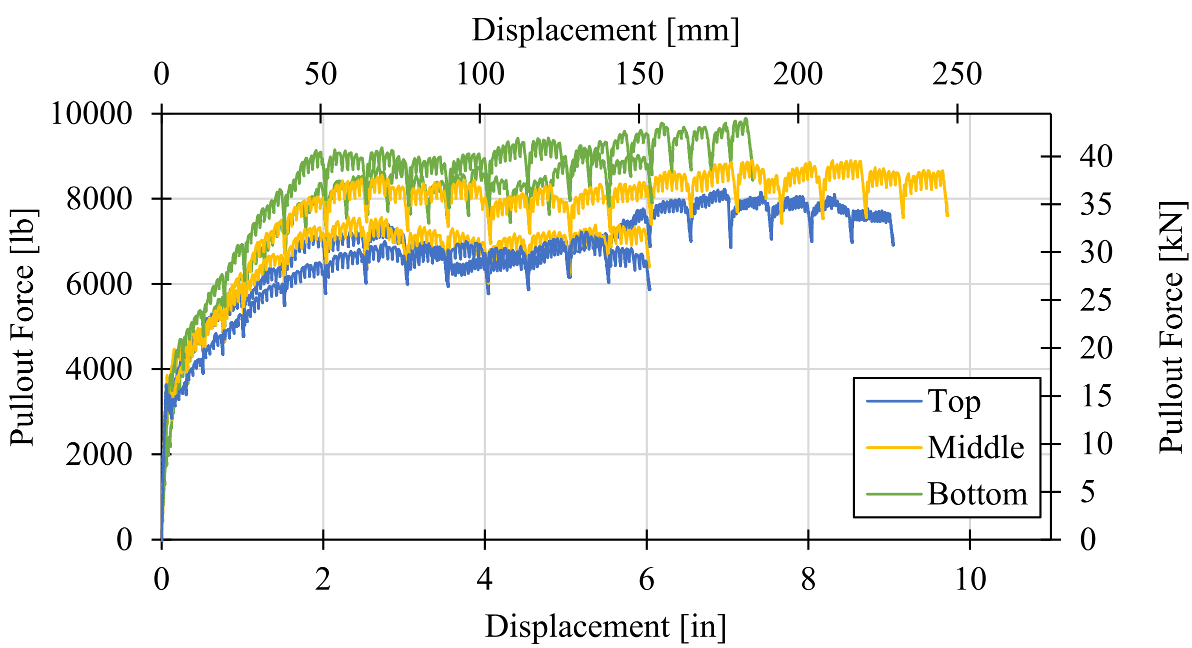


Figure 30. Graph showing complete measured displacement versus pull-out force for the long welded-wire reinforcement tests from Test 7.

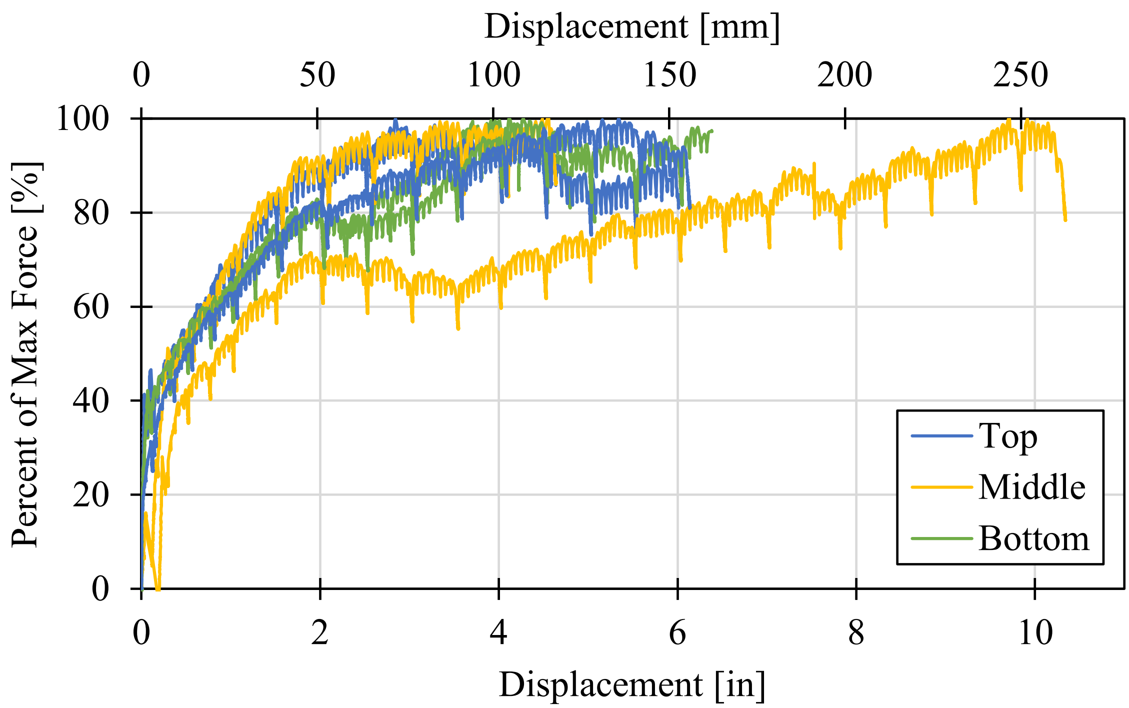


Figure 31. Graph showing normalized displacement versus pull-out force of the maximum force for short reinforcement tests from Test 7.

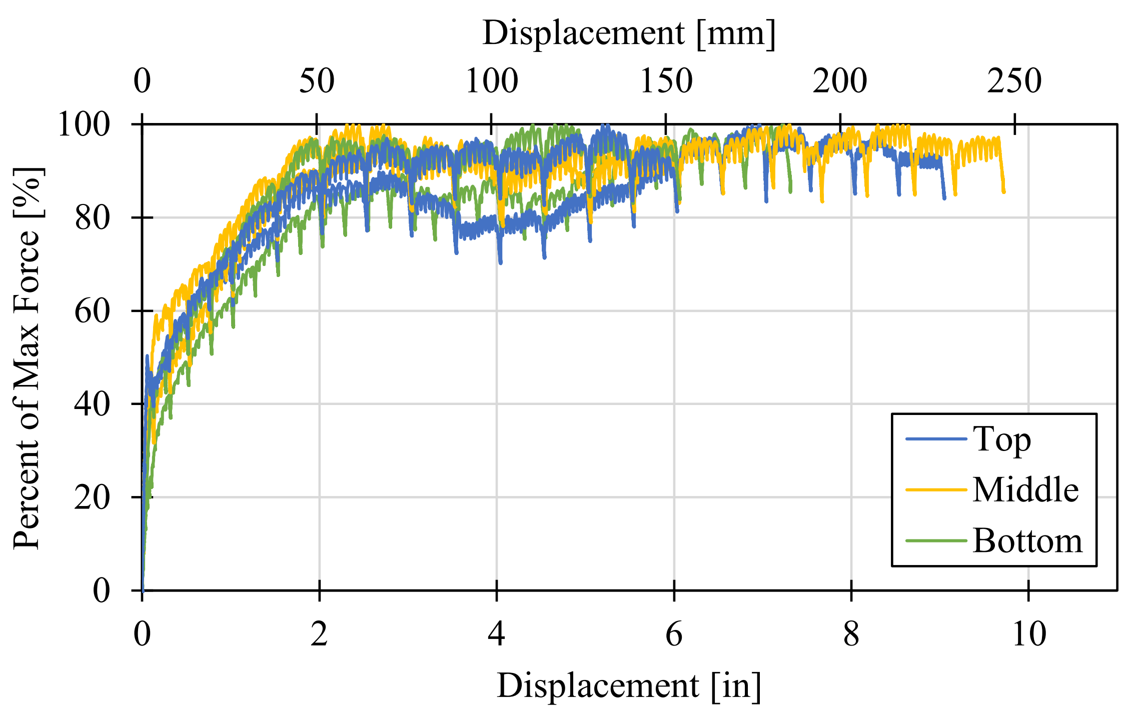


Figure 32. Graph showing normalized displacement versus pull-out force of the maximum force for long reinforcement tests from Test 7.

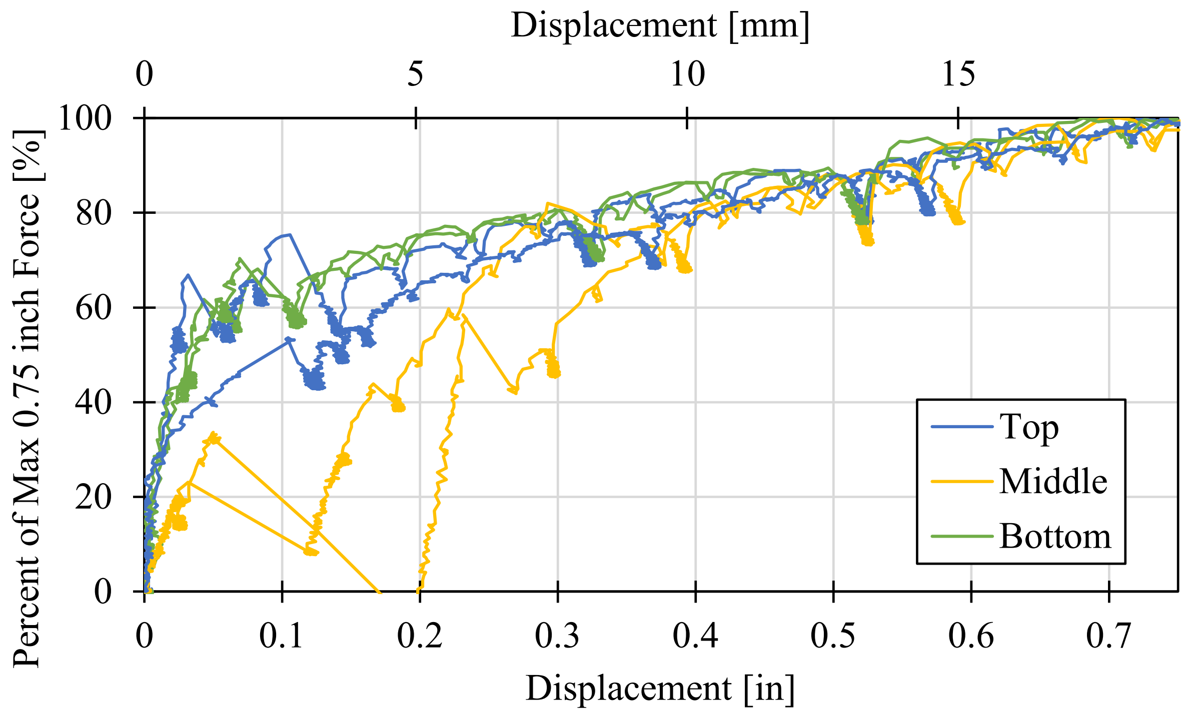


Figure 33. Graph showing normalized displacement versus pull-out force of the maximum force within 0.75-inch displacement for short reinforcement tests from Test 7.

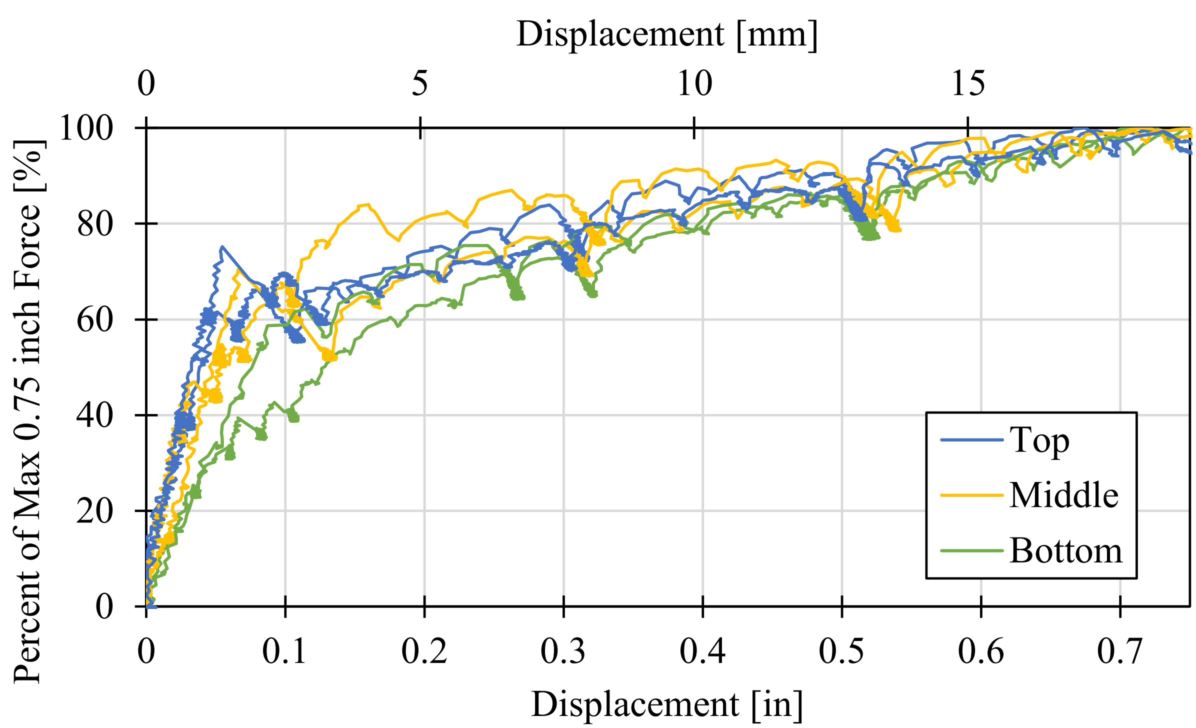


Figure 34. Graph showing normalized displacement versus pull-out force of the maximum force within 0.75-inch displacement for long reinforcement tests from Test 7.

Comparison between ribbed-strip and welded-wire load versus displacement data.

The shape of the ribbed-strip reinforcement load versus displacement curves follow a general shape within each backfill lift, but the shapes vary slightly between lifts. Typically, the maximum load occurs before 0.75 inches of displacement is reached. The load versus displacement curves for the welded-wire reinforcements follow a more consistent shape than the ribbed-strip reinforcements. The welded-wire load versus displacement curves show that the maximum load is reached well beyond 0.75 inches of displacement, reaching a general peak around 2 to 4 inches of displacement, and generally maintain that load as displacement continues to increase.

A summary of the characteristics of the various pull-out tests performed for the ribbed-strip reinforcement in each test is summarized in Table 1. Table 1 indicates the maximum pull-out force developed within a horizontal displacement of 0.75 inches and the corresponding friction coefficient. Table 2 provides similar information for welded wire reinforcements, but also includes the absolute maximum pullout force and corresponding friction coefficient, F*. A total of 12 pull-out tests were conducted on ribbed-strip reinforcements and 18 pull-out tests (12 from Test 7) were performed on the welded-wire grids during this study.

Pull-out Failure Mechanism for Steel Reinforcements

To observe the pull-out failure mechanism, the LCC was carefully excavated adjacent to several of the reinforcements after the completion of the pull-out tests. Figure 35 illustrates the observed failure mechanisms during pull-out of the welded wire reinforcement using a schematic drawing. Initially, the longitudinal bars and cross-bars are fully surrounded by LCC backfill (see Figure 35(a)). As the pull-out load is applied, the black arrows show both passive resistances, or a bearing force on the cross-bar against the LCC, and frictional resistances along the length of the longitudinal reinforcement from the LCC (see Figure 35(b). Failure may occur once the pull-out force overcomes the pull-out resistance of the reinforcement. Figure 35 (c) shows the LCC behind the cross-bar after it has been pulled outward. The lighter sections within the dotted line show the gaps behind the cross-bars where the LCC was displaced by pull-out. These gaps are maintained because of the compressive strength of ths surrounding LCC. The LCC crushes into a fine powder behind the sections of reinforcements that were in contact with the bearing or passive forces. Figure 36 shows a photo of the gap or void space, illustrated in Figure 35(c) behind the cross-bar. A similar gap is shown behind the two ribs on a strip reinforcement in Fig. 37.

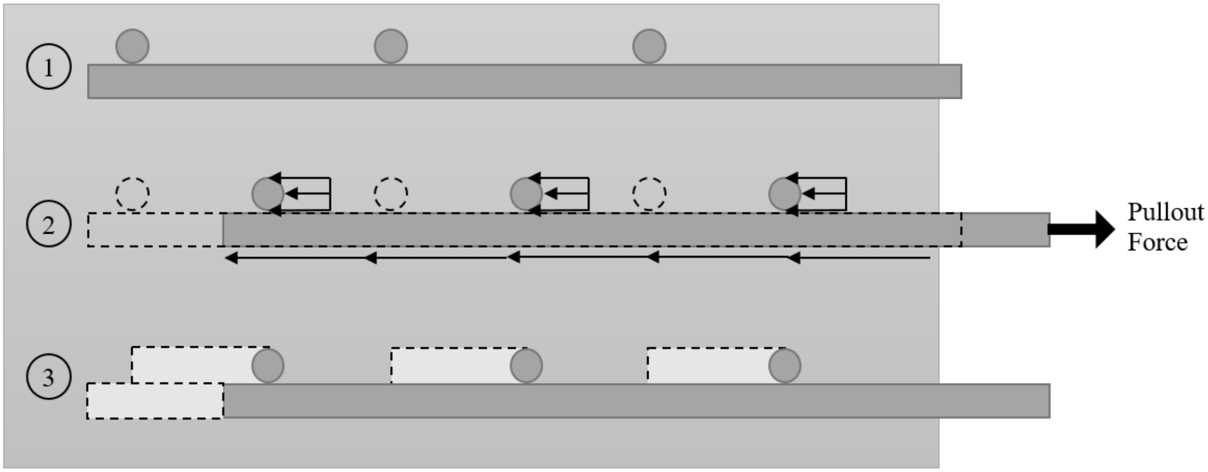


Figure 35. Drawing showing the failure mechanism of welded-wire reinforcement.

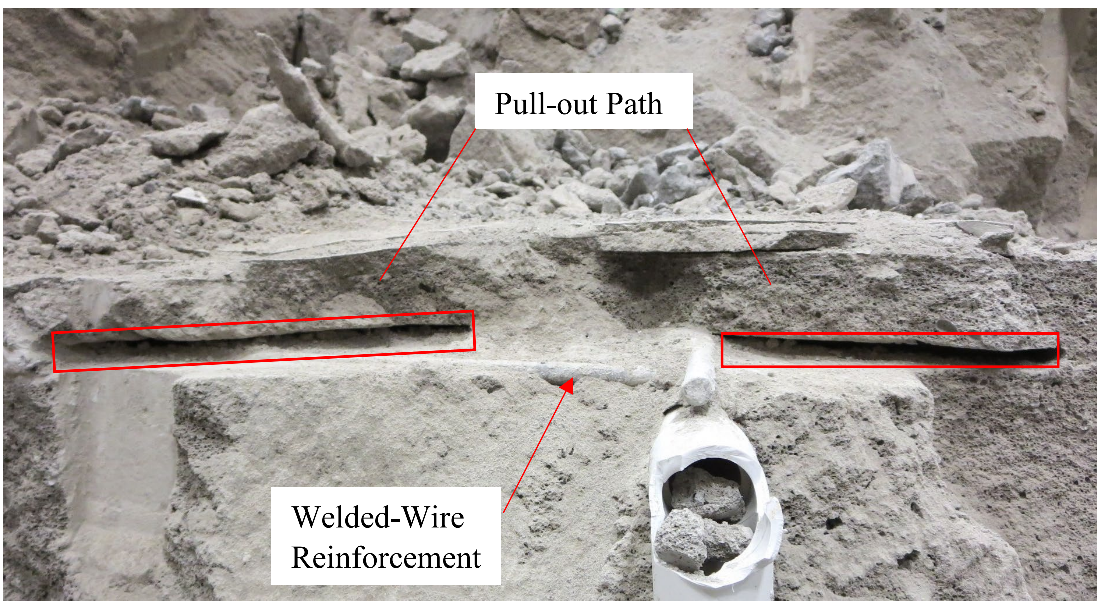


Figure 36. Photograph showing welded-wire reinforcement path after pull-out test.

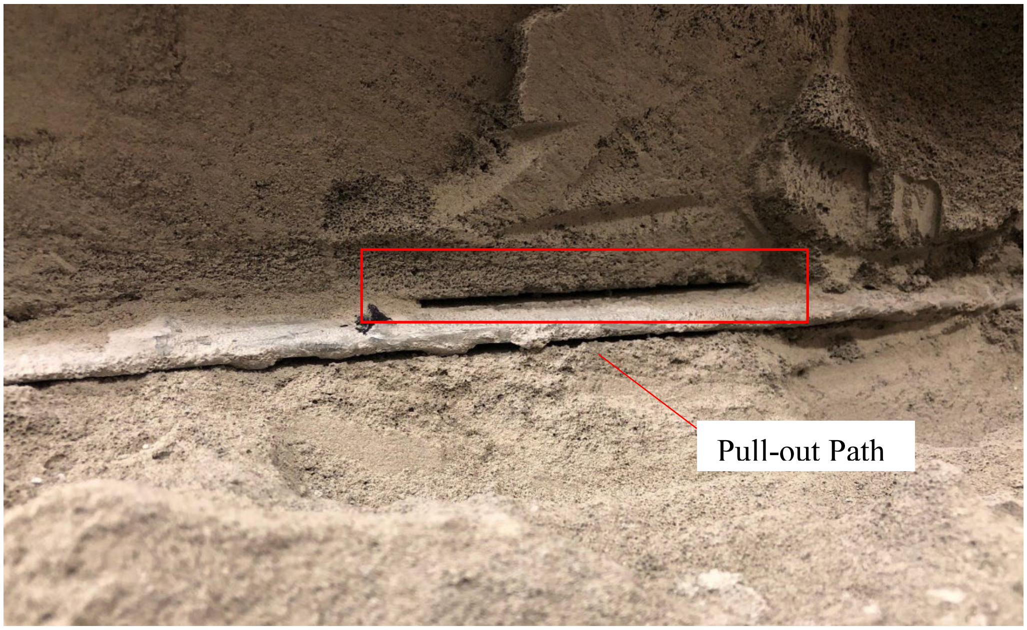


Figure 37. Photograph showing gaps in LCC behind ribs on strip reinforcements after pullout test.

Determination of F* Values from Pull-Out Tests

The friction Coefficient, F*, is based on the pull-out force, P_r, the width of the reinforcement, the length of reinforcement in LCC and the vertical stress. F* was calculated based on the maximum force developed within a 0.75-inch displacement. However, F* values were also calculated based on the ultimate pull-out resistance at any displacement for comparison purposes. The friction coefficient, F* for pull-out was computed using the equation,

$$F^* = P_r/(2bL\sigma'_v) \tag{1}$$

where P_r is the pull-out force, b is the width of the reinforcement, L is the length of the reinforcement within the LCC, and σ'_v is the vertical effective stress at the center of the reinforcement.

Dimensions of reinforcements were shown previously as well as surcharge pressures. Table 1 summarizes the test data for the ribbed-strip tests with location of the reinforcement, surcharge, pullout force, and F*. values. Table 2 summarizes the welded-wire pull-out data with location of the reinforcement, surcharge, pullout force, F*, and the normalized F* value that takes into consideration the spacing of cross bars (S_t) and thickness of cross bars (t).

Table 1. Ribbed-Strip Friction Coefficient Data

	Reinforcement	Vertical Stress		Max Pullout Force, Fp within 0.75 inch		Friction Coefficient, F*
		[psf]	[kPa]	[lb]	[kN]	
January 2021 Tests	Lift 4, Strip 1	1716	82.16	5342	23.76	1.27
	Lift 4, Strip 2	1716	82.16	4912	21.85	1.17
	Lift 3, Strip 1	1787	85.55	7482	33.28	1.70
	Lift 3, Strip 2	1787	85.55	7021	31.23	1.62
	Lift 3, Strip 3	1787	85.55	6634	29.51	1.53
	Lift 3, Strip 4	1787	85.55	6679	29.71	1.56
	Lift 2, Strip 1	58	2.76	8791	39.10	62.81
	Lift 2, Strip 2	58	2.76	6222	27.68	43.95
	Lift 2, Strip 3	58	2.76	4695	20.88	33.45
	Lift 2, Strip 4	58	2.76	4879	21.70	35.06
	Lift 1, Strip 1	174	8.33	3354	14.92	7.47
	Lift 1, Strip 2	174	8.33	4695	20.88	10.45
October 2021 Tests	Strip 1	486	23.28	3567	15.87	3.80
	Strip 2	486	23.28	2690	11.97	2.87
	Strip 3	486	23.28	3297	14.67	3.52
	Strip 4	486	23.28	4412	19.63	4.70
	Strip 5	902	43.17	3135	13.95	1.81
	Strip 6	902	43.17	3156	14.04	1.81
	Strip 7	902	43.17	3636	16.17	2.09
	Strip 8	902	43.17	3839	17.08	2.22

Table 2. Welded-Wire Friction Coefficient Data

	Reinforcement	Vertical Stress		Pullout Force, Fp				Friction Coefficient			
	[Layer, #]	[psf]	[kPa]	[lb]		[kN]		F*		F* (S_t/t)	
				0.75 inch	Max	0.75 inch	Max	0.75 inch	Max	0.75 inch	Max
Test 6	Top 1	145.6	6.97	5446	7812	24.22	34.75	5.58	8.00	178.45	255.98
	Top 2	193.4	9.26	4603	7792	20.48	34.66	3.26	5.53	104.45	176.81
	Top 3	193.4	9.26	4823	7470	21.45	33.23	3.42	5.30	109.44	169.50
	Bottom 1	1038.8	49.74	7065	9665	31.43	42.99	1.01	1.39	32.44	44.38
	Bottom 2	1038.8	49.74	6224	9243	27.69	41.11	0.82	1.22	26.30	39.05
	Bottom 3	1038.8	49.74	6511	9775	28.96	43.48	0.86	1.29	27.51	41.30
Test 7	Top 1	1516.9	72.63	3575	6117	15.90	27.21	0.32	0.55	10.21	17.46
	Top 2	1516.9	72.63	4840	7221	21.53	32.12	0.33	0.49	10.50	15.67
	Top 3	1516.9	72.63	3083	4984	13.71	22.17	0.28	0.44	8.80	14.23
	Top 4	1516.9	72.63	5361	8224	23.85	36.58	0.36	0.56	11.63	17.84
	Middle 1	891.2	42.67	4591	7358	20.42	32.73	0.70	1.12	22.31	35.76
	Middle 2	891.2	42.67	5320	7562	23.66	33.64	0.61	0.87	19.65	27.93
	Middle 3	891.2	42.67	3200	6654	14.23	29.60	0.49	1.01	15.55	32.34
	Middle 4	891.2	42.67	5474	8908	24.35	39.62	0.63	1.03	20.22	32.90
	Bottom 1	408.4	19.55	4604	7859	20.48	34.96	1.53	0.38	48.82	12.29
	Bottom 2	408.4	19.55	5646	9884	25.11	43.97	1.42	0.40	45.50	12.85
	Bottom 3	408.4	19.55	3824	6383	17.01	28.39	1.27	0.47	40.55	15.13
	Bottom 4	408.4	19.55	6225	9423	27.69	41.92	1.57	0.42	50.17	13.48

Friction Coefficient, F*, versus Vertical Pressure, σ'_v for Ribbed-Strip Reinforcements

A plot of the friction ratio, F*, from pull-out load tests on the ribbed-strip reinforcements that were conducted as part of Task 4 are shown in Figure 38. All these tests were performed in Class II LCC with unconfined compressive strengths of between 70 and 215 psi. Six of these tests were performed at very low vertical stress values (58 to 174 psf) representing LCC depths of 2 to 3 ft while an additional six tests were performed at higher pressures (1500 to 1600 psf) applied by a uniform surcharge over the surface of the LCC block. These higher pressures represent the equivalent of 50 ft of LCC backfill with a unit weight of about 30 pcf. Multiple tests were performed in each pressure range to consider the potential variability in the compressive strength. To provide F* values for intermediate pressures (486 and 902 psf) additional pull-out tests were subsequently conducted on four separate LCC blocks using 5.5-ft long ribbed-strip reinforcements with vertical load applied by dead load consisting of concrete blocks, as noted previously.

Figure 38 provides a plot of the F* values as a function of vertical stress at the level of the reinforcement from the BYU tests with blue round markers. The F* values decrease with vertical stress and the variability in the F* values also decrease substantially with vertical stress. To provide additional context for the results of the BYU pull-out tests, F* values obtained from pull-out tests on ribbed-strip reinforcements reported by Reinforced Earth Company (RECo) are also shown with green triangular markers in Figure 38. In addition, results from pull-out tests conducted on ribbed-strip reinforcements by Univ. of Kansas (U of K) researchers in recent webinars are also shown with open square markers in Figure 38. The agreement between the BYU tests and those from RECo and U of K is very good throughout the range of vertical pressures involved. Since each of the test series were conducted independently using different test arrangements and details, the agreement between the various tests adds confidence in the reliability of the overall results.

The F* versus vertical pressure design curve recommended by AASHTO for ribbed-strip reinforcements with granular backfill are also plotted in Figure 38 for comparison. This design curve has been computed assuming a unit weight of 120 lbs/ft^3 for a sand backfill. The measured F* values for LCC all plot considerably beyond the AASHTO design curve particularly at low pressure but are just to the right of the curve at greater pressures. The tentative design curve suggested by RECo based on their limited set of pull-out test results is also shown in Figure 38. Although the RECo curve is higher than the AASHTO curve near the ground surface it is becomes lower than the AASHTO curve at greater pressures.

It should be recognized that F* design curves have typically been based on a conservative lower-bound envelope of the measured F* values rather than averages of the F* values because of the significant variation in the measured values. Based on this practice, we have proposed a tentative F* versus vertical pressure design curve, that allows for higher F* values in comparison with both the RECo design curve for LCC and AASHTO design curve for granular backfill. This tentative design curve for LCC could be useful in design until additional testing provides further guidance. It should be noted, however, that the difference between our tentative F* design curve and the AASHTO curve insignificant as vertical pressure increases above 600 psf.

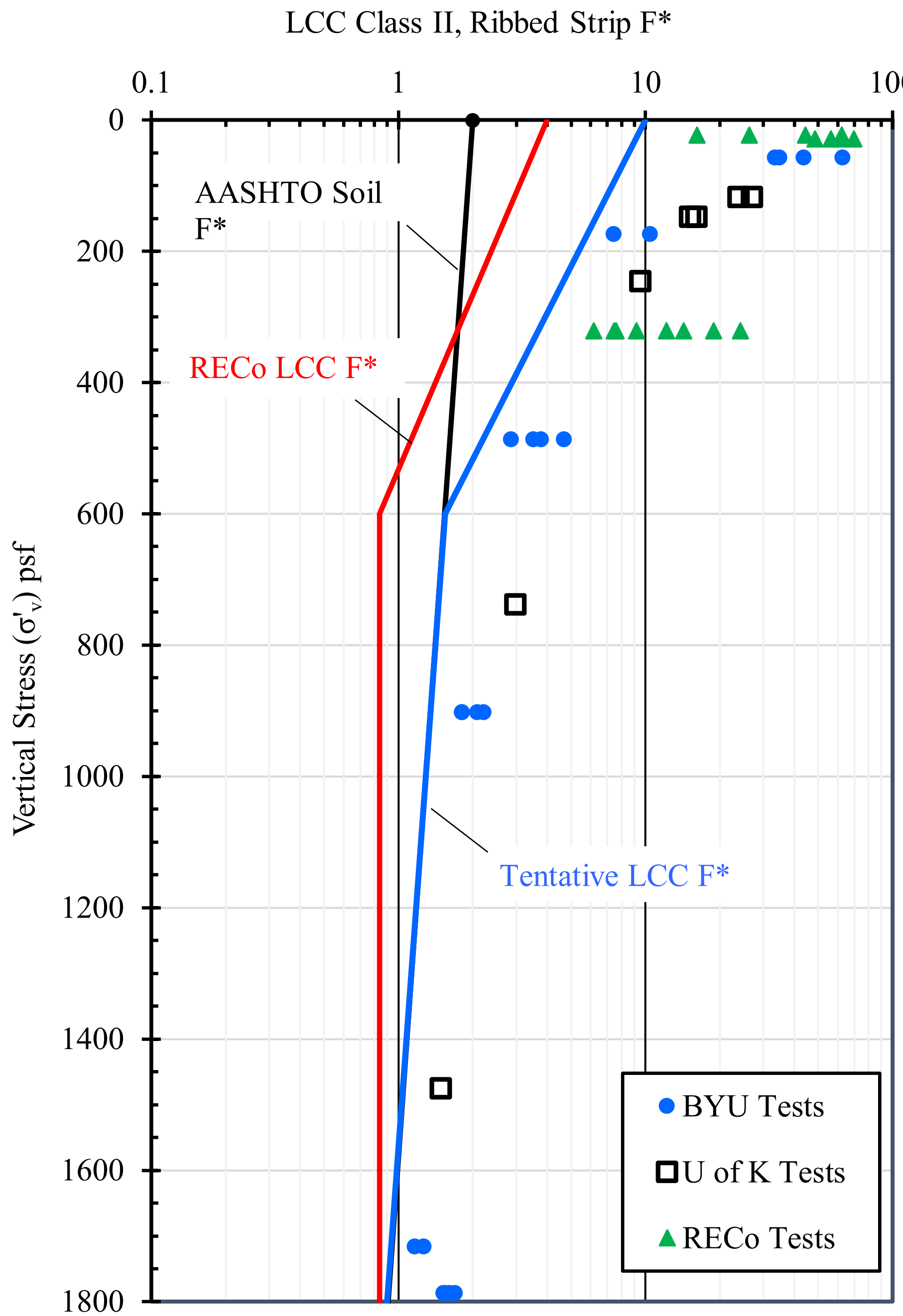


Figure 38. F* vs. vertical stress data points from pull-out tests on ribbed-strip reinforcements in LCC conducted at BYU along with data points obtained from pull-out tests conducted by Reinforced Earth Co. and University of Kansas (both Unpublished). Design curves for ribbed-strip reinforcements in soil (AASHTO) and in LCC (RECo) are also shown along with a tentative design curve based on all available data.

Friction Coefficient, F*, versus Vertical Pressure, σ'_v for Welded-Wire Reinforcements

A plot of the friction ratio, F*(S_t/t), vs. vertical stress, σ'_v, for welded-wire reinforcement based on pull-out tests conducted within two of the LCC test boxes at a variety of vertical pressures is provided in Figure 39. In this plot, S_t is the spacing between crossbars while t is the diameter of the crossbar. The welded-wire reinforcements consisted of a ladder of two W11 longitudinal bars with two, three, or four crossbars consisting of a W11 (0.375 inch) diameter bar (t) that was 14 inches long with a longitudinal spacing (S_t) of 12 inches between crossbars. These tests were performed in Class II LCC with unconfined compressive strengths of about 75 psi to 125 psi.

Pull-out resistance was selected as the highest value at a displacement less than or equal to a reinforcement deflection of 0.75 inch, although the pull-out resistance typically continued to increase significantly beyond this displacement level as described previously. F* values from previous testing on welded-wire reinforcements in Class II LCC reported by SSL at a vertical stress of 30 psf are also shown in Figure 39. The F*(S_t/t) values from the BYU and SSL tests show a consistent trend with depth. The F*(S_t/t) values decrease with increasing pressure but are consistently higher than those recommended AASHTO (20t/S_t at the surface decreasing to 20t/S_t at a pressure associated with 20 ft) for granular soil with vertical pressures above 1000 psf. However, at vertical pressures greater than about 1000 psf, the F*(S_t/t) values were about the same as those for granular soils. This result is consistent with the results from the ribbed-strip reinforcements. A tentative design curve, is also provided in Figure 39, that becomes coincident with the AASHTO curve for granular soil at vertical stresses greater than 1000 psf. A somewhat less conservative design curve might be appropriate as additional pull-out data are accumulated.

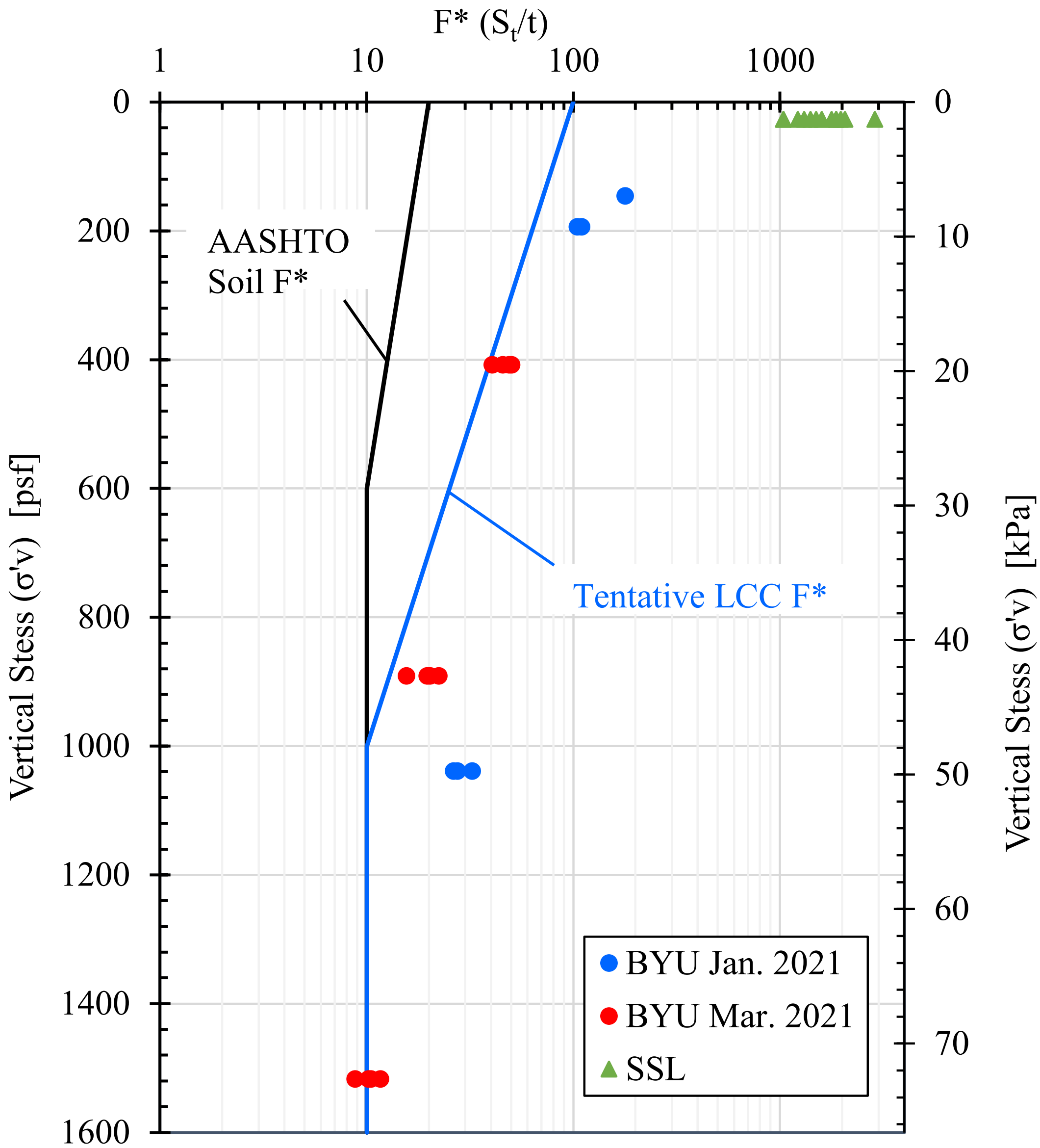


Figure 39. F*(S_t/t) vs. vertical stress, σ'_v data points from pull-out tests on welded-wire reinforcements in LCC conducted at BYU along with data points obtained from pull-out tests conducted by SSL, LLC (Unpublished). Design curves for welded-wire reinforcements in granular soil (AASHTO) are also shown along with a tentative design curve for LLC based on all available data.

Preliminary Conclusions

1. The pull-out resistance of ribbed-strip reinforcements in Class II LCC backfill typically peaked at displacements less than 0.75 inch and then slowly reduced (6 to 30%) with further displacement. In contrast, the pull-out resistance of welded-wire reinforcements continued to increase by 20 to 40% for displacements beyond 0.75 inch, peaked at 2 to 4 inches of displacement, and maintained resistance once ultimate resistance was reached. Typically, the ribbed-strip reinforcements developed about 60% of their resistance with displacement of about 0.1 inch and increased linearly to a displacement of 0.75 inch.

2. Observations of the failure zone in the LCC adjacent to the reinforcements indicate that pull-out of the welded-wire reinforcements left a gap behind the crossbar that remained open, although the LCC appeared to be pulverized and granular in nature immediately adjacent to the failure zone. Similar gaps were observed behind the ribbing for the ribbed-strip reinforcements.

3. For both the welded-wire and ribbed-strip reinforcements, the F* values in Class II LCC backfill decreased as vertical pressure increased as has been observed for reinforcements in granular soil backfills. In addition, the variability in the measured F* values decreased as the vertical stress level increased.

4. The F* values for the reinforcements in Class II LCC backfill were considerably higher than F* values predicted using AASHTO design equations for granular backfill at lower vertical pressures (less than 600 to 1000 psf), but the discrepancy decreased with depth. At vertical stresses greater than 600 to 1000 psf, the F* values for reinforcements in LCC backfill were very similar to those for granular soil.

5. The F* values obtained from the large-scale pull-out testing conducted by BYU are consistent with F* values from pull-out test conducted by other researchers on Class II LCC. The general consistency from these tests makes it possible to develop conservative tentative design curves based on a lower-bound envelope of available test results that should be useful for design MSE walls with LCC backfill to depths of about 50 ft. Additional pull-out tests were be useful in while additional pull-out test results are being accumulated.