ANCHORING TO LIGHTWEIGHT CONCRETE: CONCRETE BREAKOUT STRENGTH OF CAST-IN, EXPANSION, AND SCREW ANCHORS IN TENSION

by

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To my family and JT

Thank you for your love and support.

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ABSTRACT

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The use of lightweight concrete in the concrete industry provides economical and practical advantages. Structural anchors are commonly used in the industry for various structural applications. In *ACI 318-19: Building Code Requirements for Structural Concrete and Commentary*, a modification factor, λ_a, is specified for the calculated design strengths of anchors installed in lightweight concrete that experience concrete or bond failure. The modification factor consists of the general lightweight concrete modification factor, λ, specified in the code multiplied by an additional reduction factor dependent on the anchor and failure type. For the concrete breakout strength of expansion and screw anchors in lightweight concrete, the value of λ_a is specified as 0.8λ. For the concrete breakout strength of cast-in anchors in lightweight concrete, the value of λ_a is 1.0λ. In both cases, however, the specified value of λ_a is based on limited test data. A research program was therefore conducted to provide the data needed for more appropriate lightweight modification factors. A primary objective of the research was to evaluate the concrete breakout strengths of cast-in, expansion, and screw anchors installed in lightweight concrete by conducting a systematic experimental program that included various types of lightweight concrete. More specifically, the experimental program included tension tests on torque-controlled expansion anchors, displacement-controlled expansion anchors, and screw anchors from four manufacturers in addition to tension tests on cast-in headed stud anchors. A total of seven concrete types were included in the research: one normalweight concrete mixture and six lightweight concrete mixtures.

The lightweight concrete included sand-lightweight and all-lightweight mixtures composed of expanded shale, clay, and slate aggregates. The results of the experimental program are compared to limited data available from previous tension tests on anchors in lightweight concrete. Based on the results of the research, revised lightweight concrete modification factors for the concrete breakout design strengths of the anchor types included in the test program are provided.

CHAPTER 1. INTRODUCTION

1.1 Background

The use of lightweight concrete in structural applications provides economic and other practical advantages resulting from reduced weights of structural members, lower transportation costs, better fire resistance, and enhanced durability compared to normalweight concrete. In the precast concrete industry in the United States, lightweight concrete is widely used due to these advantages. Furthermore, because of their many uses, structural anchors are commonly used in precast components, including those made of lightweight concrete. For example, torque-controlled anchors may be used to support precast tilt walls to concrete floor slabs, and cast-in anchors may be used as connectors between precast partial depth deck panels and steel beams. Several types of anchors are readily available, providing additional versatility. Anchors can be post-installed into hardened concrete or cast into the concrete (i.e., cast-in anchors). Common types of anchors include expansion anchors, concrete screw anchors, and cast-in headed studs, examples of which are shown in Figure 1.1.

Figure 1.1: Examples of common anchor types (from left to right: torque-controlled, displacement-controlled, screw, and cast-in anchors)

Expansion anchors are designed with an expanding element that compresses against the concrete. Expansion anchors can be either displacement-controlled or torque-controlled. Displacement-controlled anchors develop load carrying capacity through a tapered plug that is driven through the anchor sleeve using a setting tool to expand the base of the anchor, creating friction against the concrete. Alternatively, displacement-controlled expansion anchors may develop capacity by the movement of a sleeve over a plug (ACI 355.2-07). Drop-in anchors are a common type of displacement-controlled anchor. Torque-controlled anchors carry loads by creating friction against the concrete through a sleeve or other element that expands when torque is applied (ACI 355.2-07). Wedge anchors are a popular type of torque-controlled anchor. Concrete screw anchors utilize threads to provide a mechanical interlock by cutting into the concrete during installation. Cast-in headed studs consists of a steel shaft with a round head that provides resistance to applied loads.

The use of anchors in lightweight concrete, however, is impacted by the strength reduction factors that are included in design equations. Strength reduction factors are necessary when designing structures composed of lightweight structural concrete due to the lower tensile strength of lightweight concrete compared to normalweight concrete with the same compressive strength. However, the strength reduction factors specified in the *Building Code Requirements for Structural Concrete* (ACI 318-19) for anchors are based on a limited number of tests from the literature and anchor manufacturers (see Section R17.2.4.1 of ACI 318-19). Because of the limited test data, values believed to be conservative were selected as the specified reduction factors in the code. The values may not be representative of the variety of lightweight concrete commonly used in the United States and may be overly-conservative in some cases. Therefore, a systematic test program is needed to determine the strengths of various post-installed anchors and cast-in anchors in concrete composed of the common lightweight aggregates currently used in structural concrete. The Precast/Prestressed Concrete Institute (PCI) sponsored a research program to fulfill this need with specific focus on the precast concrete industry. The research program is the subject of this thesis.

1.2 Strength Reduction in Lightweight Concrete

Accounting for the lower tensile strength of lightweight concrete, a modification factor λ is included in relevant provisions of ACI 318-19. The values of the modification factor as presented in Table 19.2.4.1(b) of ACI 318-19 are provided in Table 1.1 and are based on the composition of aggregates in the mixture design. The values of λ given in the table are 0.85 and 0.75 for sand-lightweight concrete and all-lightweight concrete, respectively. As indicated in Table 1.1, the standard specification for normalweight aggregate is ASTM C33, and the standard specification for lightweight aggregate in structural concrete is ASTM C330.

Table 1.1: Values of modification factor λ for lightweight concrete based on composition of aggregates (from Table 19.2.4.1(b) of ACI 318-19)

Concrete	Composition of Aggregates	λ
All-lightweight	Fine: ASTM C330 Coarse: ASTM C330	0.75
Lightweight, fine blend	Fine: Combination of ASTM C330 and C33 Coarse: ASTM C330	0.75 to 0.85[1]
Sand-lightweight	Fine: ASTM C33 Coarse: ASTM C330	0.85
Sand-lightweight, coarse blend	Fine: ASTM C33 Coarse: Combination of ASTM C330 and C33	0.85 to 1[2]

[1] Linear interpolation from 0.75 to 0.85 is permitted based on the absolute volume of normalweight fine aggregate as a fraction of the total absolute volume of fine aggregate.
[2] Linear interpolation from 0.85 to 1 is permitted based on the absolute volume of normalweight coarse aggregate as a fraction of the total absolute volume of aggregate.

In 2019, another table was added within ACI 318 that gives an alternative method for determining the modification factor λ. These values of λ are given in Table 19.2.4.1(a) of ACI

318-19 and duplicated in Table 1.2. As indicated in the table, the value of λ is based on the equilibrium density, w_c, determined in accordance with ASTM C567 for lightweight concrete.

Table 1.2: Values of λ for modification factor lightweight concrete based on equilibrium density (from Table 19.2.4.1(a) of ACI 318-19)

w_c, lb/ft^3	λ
≤100	0.75
100 < w_c ≤ 135	0.0075w_c ≤ 1.0
> 135	1.0

1.3 Anchorage to Lightweight Concrete

For the design of anchors in lightweight concrete governed by concrete failure, a modification factor λ_a is applied to the calculated design strengths per Section 17.2.4.1 of ACI 318-19. The modification factor λ_a represents an additional strength reduction factor applied to anchors and is equal to a constant multiplied by the appropriate modification factor λ for lightweight concrete given in Table 1.1 or Table 1.2. The modification factor λ_a as specified in Section 17.2.4.1 of ACI 318-19 for concrete failure is given in Table 1.3. Anchors in tension governed by concrete breakout strength are subject to the modification factor λ_a. A concrete breakout failure is illustrated in Figure 1.2.

Table 1.3: Modification factor λ_a for lightweight concrete (from Section 17.2.4.1 of ACI 318-19)

Case	λ_a
Cast-in and undercut anchor concrete failure	1.0λ
Expansion, screw, and adhesive anchor concrete failure	0.8λ

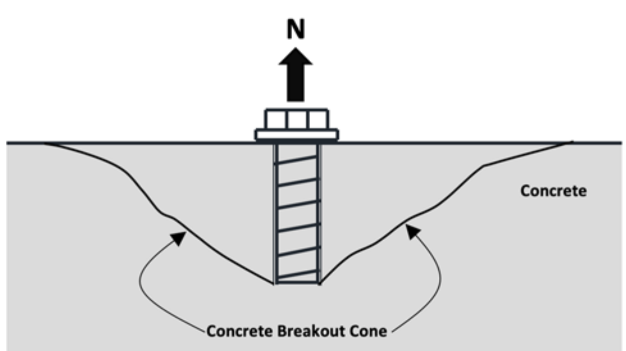


Figure 1.2: Concrete breakout failure

When applied to the calculated concrete breakout strength, the lightweight modification factor λ_a specified in Section 17.2.4.1 of ACI 318-19 can have a significant impact on design capacities. Specifically, compared to anchors in normalweight concrete, the design strength (excluding the ϕ-factor) of expansion and screw anchors in lightweight concrete governed by concrete breakout failure is reduced by a factor of (0.8)(0.85) = 0.68 in sand-lightweight concrete and by (0.8)(0.75) = 0.66 in all-lightweight concrete. The current reduction factors for cast-in anchors in lightweight concrete governed by concrete failure are less severe. The design strength of cast-in anchors in lightweight concrete governed by concrete breakout failure is reduced by a factor of (1.0)(0.85) = 0.85 in sand-lightweight concrete and by (1.0)(0.75) = 0.75 in all-lightweight concrete.

In either case, however, limited data are available for tests on anchors in tension governed by concrete failure. Additional tests are needed to determine if the current strength reduction factors are warranted or if less severe factors are appropriate.

1.4 Concrete Capacity Design (CCD) Method

The Concrete Capacity Design (CCD) method was introduced by Fuchs et al. (1995) as a simple design approach for calculating the strengths of anchors in concrete. The CCD method can be used to design anchors under tension or shear loading in uncracked or cracked concrete. In the research by Fuchs et al., the concrete breakout strength, N_{no}, of a single anchor in tension in uncracked normalweight concrete is defined as follows:

$$N_{no} = k_{nc} \cdot \sqrt{f'_c} \cdot {h_{ef}}^{1.5}, \qquad lb \tag{1-2}$$

where:

k_{nc} = 35 for post-installed anchors in uncracked concrete

k_{nc} = 40 for cast-in anchors in uncracked concrete

f'_c = concrete compression strength (psi)

h_{ef} = effective embedment depth (in.)

The k_{nc} of 35 for post-installed anchors and 40 for cast-in anchors is used to determine the mean strength of anchors in tension with concrete breakout failures.

Since 2002, the CCD method has been included in ACI 318 as the basic design method for cast-in and post-installed anchors. However, in the code provisions (Section 17.6.2.2.1 of ACI 318-19), k_{nc} in Equation 1-2 is replaced by k_c, which is based on the 5% fractile of a large database (Fuchs et al. 1995; see Section R17.6.2.2.1 of ACI 318-19). The value of k_c is 24 for post-installed anchors and 30 for cast-in anchors in uncracked concrete.

1.5 Project Objectives and Scope

The objectives of the research described in this thesis are:

- Determine the concrete breakout strengths of post-installed anchors (i.e., torque- and displacement-controlled expansion anchors and screw anchors) and cast-in anchors (i.e., headed studs) in lightweight concrete.
- Recommend strength reduction factors in consideration of anchor type and concrete composition.
- Provide comparisons of the performance of post-installed and cast-in anchors from various manufacturers installed in different types of lightweight concrete.

To achieve these objectives, a series of total 200 tensile tests were conducted on expansion, screw, and cast-in anchors. While most of the tests were conducted on anchors installed in lightweight concrete, anchors in normalweight concrete were included for comparison purposes.

1.6 Organization

A summary of previous tests on post-installed and cast-in anchors in lightweight concrete is provided in Chapter 2, including test data from domestic and international sources. In Chapter 3, an overview of the experimental program conducted as part of the current research project is presented. Details of the concrete test specimens, test setup, instrumentation, and testing procedure are provided. The selection of anchor types and concrete materials included in the experimental program is also described. In Chapter 4, the test results and observations are presented. The ultimate applied load for each anchor is reported and typical load-displacement behaviors of anchors are described. Furthermore, the concrete properties, including concrete compressive strengths, tensile splitting strengths, fresh concrete densities, and approximate equilibrium densities, are presented. The analysis of experimental results is discussed in Chapter 5, and detailed comparisons with regard to different anchor types, concrete types, and manufacturers are presented. Furthermore, strength reduction factors based on the test results are provided and compared to current specification in ACI 318-19. In Chapter 6, an overall summary of the research program is provided, and the primary conclusions are summarized.

CHAPTER 2. PREVIOUS RESEARCH

2.1 Introduction

To determine strength reduction factors for post-installed and cast-in anchors in lightweight concrete, published and unpublished test data were reviewed. First, results from tests performed on cast-in anchors at Lehigh University as reported by McMackin et al. (1973) are introduced. Then, results from past tests on post-installed anchors in lightweight concrete from domestic and international sources are discussed. Past results from tests performed in concrete believed to be representative of typical lightweight concrete used in the United States are of primary interest. Such test results for which complete information was available to the author are included in further analysis and compared to the test results of the current study.

2.2 Past Tests on Cast-in Anchors in Lightweight Concrete

Currently, the only known tension tests on cast-in anchors resulting in concrete breakout failure that are reported in the literature were performed at Lehigh University (McMackin et al., 1973) approximately 50 years ago. Only two tensile tests in lightweight concrete are reported. According to Section R17.2.4.1 of ACI 318-19, the modification factor for cast-in anchors was influenced by Shaikh and Yi (1985), who considered the two tests in lightweight concrete reported by McMackin et al. (1973), and Anderson and Meinheit (2005), who focused on the pryout capacity of headed studs. The strength reduction factors for mechanical anchors are primarily based on a limited number of tests from anchors manufacturers (see Section R17.2.4.1 of ACI 318-19).

The data from the two tests performed my McMackin et al. (1973) are provided in Table 2.1. The information will be included in the analysis discussed in Chapter 5.

Table 2.1: Summary of McMackin et al. (1973) test data

Test ID	**Concrete Compressive Strength at Test, f_c (psi)**	**Concrete Splitting Tensile Strength at 28-Day, f_t (psi)**	**Average Density (pcf)**	**Anchor Type**	**Effective Embedment, h_{ef} (in.)**	**h_{ef}/ d_a**	**Load at Failure, N_{test} (lbf)**
D1-1	5300	467	121.6	½" dia. headed steel anchor stud	7.625	10.17	30,100
D1-2							31,500

2.3 Past Tests on Post-Installed Anchors in Lightweight Concrete

Tension tests on post-installed anchors in lightweight concrete have been previously performed by manufacturers and researchers in the United States and Europe. The data available for inclusion in a database for the evaluation of concrete breakout strength, however, are relatively sparse. Past tension test data on post-installed anchors in lightweight concrete available to the author consist of unpublished tests performed at Virginia Tech (2009), a relatively small database from the Concrete and Masonry Anchor Manufacturers Association (CAMA), and tests reported in Wildermuth et al. (2012). The data from the tests performed at Virginia Tech were reported in detail and made available to the author for inclusion in the analysis of the current study. The test data from CAMA, however, are largely incomplete and unorganized. Wildermuth et al. conducted tests on 96 post-installed anchors in both lightweight and normalweight concrete. The lightweight aggregate used in the lightweight concrete mixtures was expanded clay produced in Europe. Additional details of test data from the three sources are provided in the following subsections.

2.3.1 Tests Conducted at Virginia Tech

In 2009, a total of 63 tests on post-installed anchors in lightweight concrete were performed at Virginia Tech. The unpublished data include the results of 31 tests on torque-controlled expansion anchors. Two combinations of anchor diameter and embedment depth were considered: ½-in. diameter anchors with an effective embedment depth 2 in. and ⅝-in. diameter anchors with an effective embedment depth of 2.75 in. The expansion anchors were wedge anchors produced by one of the manufacturers included in the research funded by PCI (referred to as Manufacturer D in this thesis; see Section 3.6). The research also included 32 tests on screw anchors with two combinations of anchor diameter and embedment depth: ½-in. diameter anchors with an effective embedment depth of 1.65 in. and ⅝-in. diameter anchors with an effective embedment depth of 2.15 in. The screw anchors were also produced by Manufacturer D.

The wedge anchors and screw anchors were post-installed in a sand-lightweight concrete specimen. The coarse aggregate was expanded slate produced by Stalite Lightweight Aggregate. The concrete had a unit weight of 118 pcf, a compressive strength of 5960 psi and a tensile splitting strength of 550 psi at the time of the tests. The research group performed the anchor tests using a lightweight concrete deck of a bridge girder that had previously been used for another structural experiment. The appearance of the deck before and after the anchor tests is shown in Figure 2.1. All anchors failed by concrete breakout. The test setup used by the researchers is shown in Figure 2.2.

(a) Before anchor tests (b) After anchor tests

Figure 2.1: Specimen at Virginia Tech

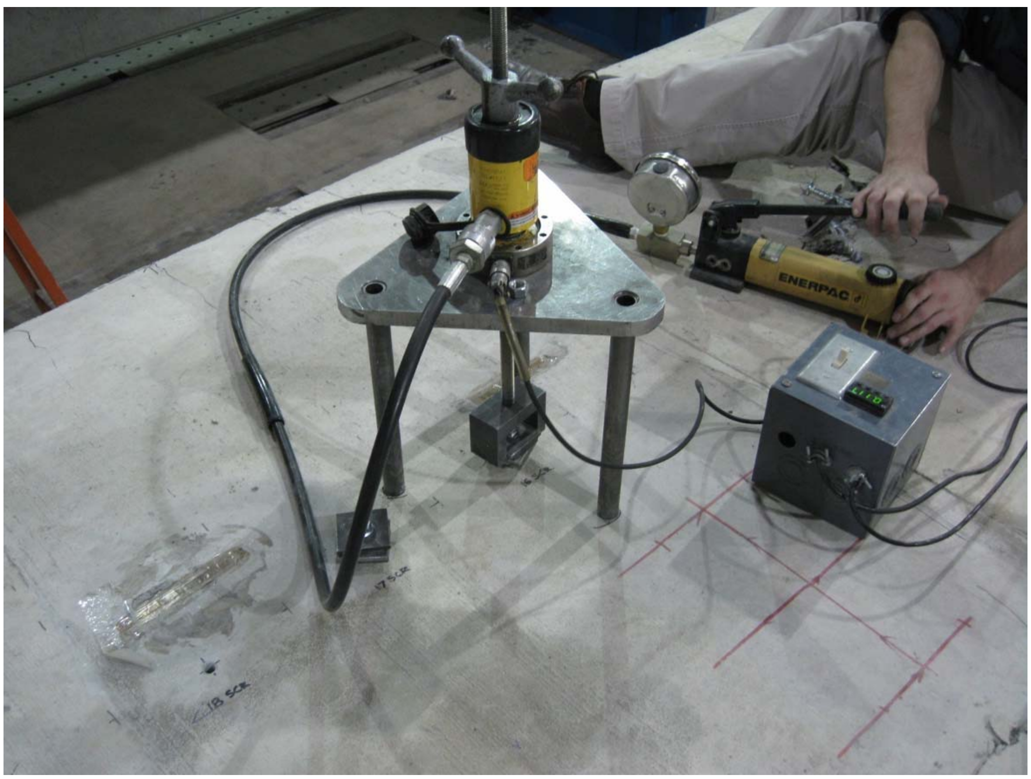


Figure 2.2: Test setup used at Virginia Tech

The test data from the 63 anchors tests are summarized in Table 2.2. The reported results show that the ½-in. diameter torque-controlled expansion anchors carried an average ultimate load of 4976 lbf and that the ⅝-in. diameter expansion anchors carried an average ultimate load of 10,373 lbf. The average ultimate loads of the ½-in. and ⅝-in. diameter screw anchors were 4919 lbf and 7525 lbf, respectively.

Table 2.2: Summary of tests performed at Virginia Tech

Torque-Controlled Expansion Anchors				Screw Anchors			
dia. = ½ in. h_{ef} = 2 in.		dia. = ⅝ in. h_{ef} = 2.75 in.		dia. = ½ in. h_{ef} = 1.65 in.		dia. = ⅝ in. h_{ef} = 2.15 in.	
Test ID	Load at Failure, N_{test} (lbf)	Test ID	Load at Failure, N_{test} (lbf)	Test ID	Load at Failure, N_{test} (lbf)	Test ID	Load at Failure, N_{test} (lbf)
1E	5048	1-5E	9295	1S	5207	2-5S	6908
3E	4685	3-5E	10,800	3S	5461	4-5S	8146
5E	5778	5-5E	10,004	5S	4217	3-5S	8451
6E	5103	7-5E	10,585	6S	5088	5-5S	6786
8E	4843	9-5E	10,777	8S	5320	7-5S	6749
9E	5378	11-5E	10,288	10S	4911	6-5S	7838
11E	4319	13-5E	10,080	7S	5131	8-5S	6417
13E	5128	14-5E	10,402	9S	5649	9-5S	8340
14E	4960	16-5E	9914	11S	4578	10-5S	8079
16E	5142	18-5E	10,961	13S	5437	11-5S	8331
18E	3989	19-5E	10,991	12S	5341	16-5S	7533
19E	4900			14S	4388	17-5S	7956
22E	4376			15S	4869	18-5S	6813
23E	4993			16S	4346	19-5S	6711
25E	4943			18S	4571	20-5S	7817
27E	4828			19S	4530		
29E	5286			20S	4574		
30E	5436						
31E	5179						
32E	5206						

2.3.2 CAMA Data

Data from the Concrete and Masonry Anchor Manufacturers Association (CAMA) for tests conducted prior to 2005 were made available to the author. The test report includes tension tests on 58 post-installed anchors in lightweight concrete, including 26 tests on wedge anchors, 5 tests on drop-in anchors, 4 tests on sleeve anchors, and 23 tests on screw anchors. Diameters, d_a, of the anchors ranged from ¼ in. to ¾ in., and the effective embedment depths, h_{ef}, ranged from 1.0 in. to 5.0 in. The resulting effective embedment depth to diameter ratios, h_{ef}/d_a, varied from 4 to 9. Three tests on screw anchors in normalweight concrete were also included in the dataset.

The data from CAMA, however, are largely incomplete and unorganized. Although a concrete failure is indicated for a majority of the tests, some anchors experienced other failure modes or the failure mode is not provided or is unclear. The concrete compression strength was not reported, and the concrete tensile strength is also unknown. The concrete unit weight was reported as 110 pcf for only three of the tests. The unit weight was not reported for the rest of the tests. Furthermore, the ultimate load is not reported for any anchor test. Although CAMA reported the ratio of the experimental capacity of the anchors to the predicted capacity, these data were deemed to be unusable for inclusion in the analyses detailed in this thesis.

2.3.3 Tests Conducted by Wildermuth et al. (2012)

Several post-installed anchors tests were performed and reported in Europe. Wildermuth et al. (2012) conducted 96 tests on post-installed mechanical anchors, including 53 anchors tested in lightweight concrete and 43 anchors tested in normalweight concrete. For both concrete types, a low-strength concrete mixture (water-cement ratio of 0.54 and density of 1.55 t/m^3) and a high-strength mixture (water-cement ratio of 0.30 and density of 2.10 t/m^3) were included. The low-strength concrete used an expanded clay called Fibo ExClay with a maximum size of 8 mm as the coarse aggregate. For the high-strength concrete, the coarse aggregate was composed of a blend of Liapor, an expanded clay aggregate, with a maximum size of 8 mm and gravel with a maximum size of 16 mm. Both types of concrete used sand as the fine aggregate. The lightweight aggregates produced in Europe, however, are not representative of typical lightweight aggregates in the United States. Therefore, the data from Wildermuth et al. (2012) will not be included in the analysis and compared to the test results of this thesis obtained during this study.

2.4 Summary

Because detailed information for the tests performed at Virginia Tech are available to the author and applicable to the current study, the data are included with the experimental results of the research supported by PCI for further analysis. However, the data from CAMA, which lacked critical information, and the data reported by Wildermuth et al. (2012), which consisted of results from tests on anchors in lightweight concrete not representative of concretes used in the United States, are not included in the analysis presented in this thesis.

CHAPTER 3. EXPERIMENTAL PROGRAM

3.1 Introduction

An experimental program was conducted to expand the current knowledge of the strength of anchors installed in lightweight concrete with various aggregate types. The program consisted of tension tests on cast-in anchors and three types of post-installed anchors (i.e., torque-controlled expansion anchors, displacement-controlled expansion anchors, and screw anchors) to determine the capacity of each anchor type under concrete breakout failure. For each type of post-installed anchor, products from four manufacturers were acquired, resulting in 12 unique types of anchors. The nominal diameter of all anchors used in the test program was 0.5 in., and the effective embedment depth of each anchor was approximately 2 in. with some variations. With the resulting ratios of the effective embedment depth to the nominal diameter, concrete breakout was the expected failure mode for the anchors. In addition to the four anchor types, seven different concrete mixtures were included in the research program. Six of the seven types of concrete mixtures were lightweight concrete containing three types of lightweight aggregates available in the United States: expanded shale, expanded clay, and expanded slate. For each lightweight aggregate material, tests both involving sand-lightweight and all-lightweight concrete were conducted. The research also included anchor tests conducted in normalweight concrete for comparison purposes.

3.2 Test Matrix

The anchor tests of the research program are represented by the test matrix presented in Table 3.1. As previously explained, tension tests on four types of anchors in seven types of concrete are included. Each row in the matrix represents a unique combination of anchor type and concrete composition. For each combination, at least five tests were performed. For the five tests performed for each combination of post-installed anchor type and concrete composition, a test was performed on an anchor from each of the four manufacturers. The fifth anchor that was selected for each set of five tests alternated among the four manufacturers. For the cast-in anchors, seven or eight tests were performed for each concrete type. In total, 200 anchors tests were performed. An explanation of the test identification labels used in the test matrix is provided in Figure 3.1.

Table 3.1: Test Matrix

Test*	Anchor				Concrete						
	Mechanical		Screw	Cast-in	Normalweight	Sand-Lightweight			All-Lightweight		
	Torque-Cntrl.	Displ.-Cntrl.				Shale†	Clay†	Slate†	Shale†	Clay†	Slate†
NW-T-#	■				■						
SL-SH-T-#	■					■					
SL-CL-T-#	■						■				
SL-SL-T-#	■							■			
AL-SH-T-#	■								■		
AL-CL-T-#	■									■	
AL-SL-T-#	■										■
NW-D-#		■			■						
SL-SH-D-#		■				■					
SL-CL-D-#		■					■				
SL-SL-D-#		■						■			
AL-SH-D-#		■							■		
AL-CL-D-#		■								■	
AL-SL-D-#		■									■
NW-S-#			■		■						
SL-SH-S-#			■			■					
SL-CL-S-#			■				■				
SL-SL-S-#			■					■			
AL-SH-S-#			■						■		
AL-CL-S-#			■							■	
AL-SL-S-#			■								■
NW-C-#				■	■						
SL-SH-C-#				■		■					
SL-CL-C-#				■			■				
SL-SL-C-#				■				■			
AL-SH-C-#				■					■		
AL-CL-C-#				■						■	
AL-SL-C-#				■							■

*The notation to identify each test is given in this column.
†Expanded aggregate

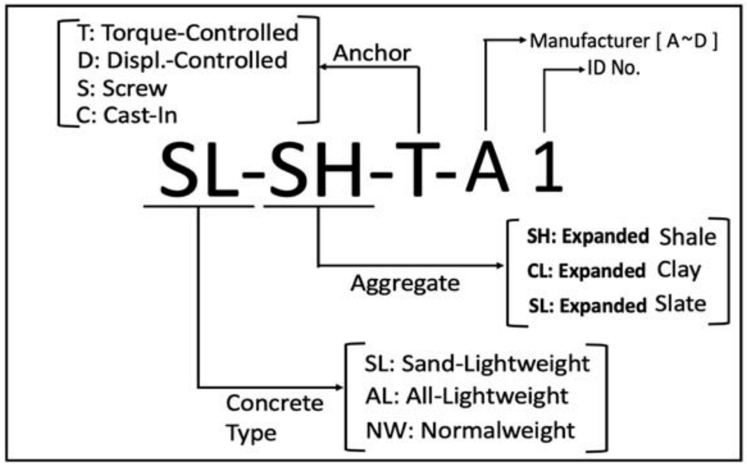
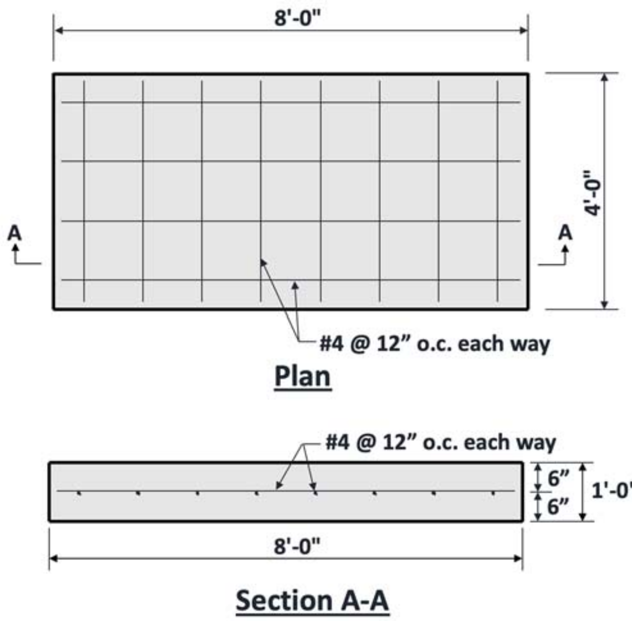


Figure 3.1: Test identification label

3.3 Slab Specimen Details and Fabrication

The anchors were tested after being installed in concrete slab specimens. The details of the specimens are presented in Figure 3.2. As indicated, the specimens measured 8 ft by 4 ft and had a thickness of 1 ft. Four slabs were fabricated for each concrete mixture. Therefore, a total of 28 slabs were used to conduct the experimental program. In consideration of temperature and shrinkage effects as well as shipping and handling, each specimen was reinforced with a mat of No. 4 Grade 60 reinforcing bars with 12-in. spacing in both directions. The reinforcing mat was located at the mid-depth of the slabs. One or two cast-in anchors were fixed with epoxy onto the bottom soffit of the formwork before casting, as explained in Section 3.6.4. The slab specimens were fabricated at a precast concrete plant in Indianapolis, Indiana. The slabs were later transported to the Robert L. and Terry L. Bowen Laboratory at Purdue University for testing.



(a) Design drawing of specimen details (b) Reinforcing bars and formwork
Figure 3.2: Specimen details

After being transported to the laboratory, the slabs were flipped to conduct the anchor tests on the formed face of the concrete. Due to space limitations on the concrete surface, 37 anchor tests were conducted on the other side of the slabs (i.e., the finished side of the slabs when cast).

3.4 Concrete Materials

The seven concrete mixtures consist of one normalweight concrete, three types of sand-lightweight concrete, and three types of all-lightweight concrete. The aggregates used in the concrete mixtures included crushed limestone, river sand, and three types of lightweight aggregates (expanded shale, expanded clay, and expanded slate). For the sand-lightweight mixtures, expanded shale, clay, or slate was used as the coarse aggregate while river sand was used as the fine aggregate. The all-lightweight mixtures included expanded shale, clay, or slate as both the coarse and fine aggregates in the concrete. Details of the aggregates and cement used in the concrete mixtures are provided in the following subsections. In addition, these sections also include description of the admixtures that were added to enhance workability and to preclude segregation.

3.4.1 Aggregates

A total of eight types of aggregate were used in the research program. The details of each aggregate type are summarized in Table 3.2. As indicated in the table, the normalweight coarse aggregate used in the normalweight concrete mixture was crushed limestone, and the normalweight fine aggregate was river sand. The coarse and fine expanded slate lightweight aggregates were produced by Stalite Lightweight Aggregate. The coarse and fine expanded shale and expanded clay aggregates were produced by Arcosa Lightweight. To comply with the general requirements of ACI 355.2-07 and ACI 355.4-11, the maximum aggregate size of the normalweight coarse aggregate and the expanded slate and shale coarse aggregates was ¾ in. The coarse expanded clay aggregate with the largest maximum aggregate size available from Arcosa Lightweight, ½ in., was used. The normalweight aggregates satisfied ASTM C33, and all lightweight aggregates satisfied ASTM C330. The coarse and fine aggregates are presented in Figure 3.3.

Table 3.2: Details of aggregates used in the study

Aggregate	Origin	Density lb/ft^3	Specific Gravity	Maximum Size
Crushed Limestone – Coarse	Martin Marietta, Indianapolis, IN	163.49	2.62	½”
River Sand – Fine	Martin Marietta, Indianapolis, IN	166.80	2.67	No. 4
Shale – Coarse	Arcosa Lightweight, Mooresville, IN	98.59	1.58	¾”
Shale – Fine		114.82	1.84	No. 4
Clay – Coarse	Arcosa Lightweight, Erwinville, LA	84.86	1.36	⅝”
Clay – Fine		98.59	1.58	No. 4
Slate – Coarse	Stalite Lightweight Aggregate, Gold Hill, NC	94.85	1.52	¾”
Slate – Fine		113.57	1.82	No. 4

Crushed Limestone – Coarse

River Sand – Fine

Expanded Shale – Coarse

Expanded Shale – Fine

Expanded Clay – Coarse

Expanded Clay – Fine

Expanded Slate – Coarse

Expanded Slate – Fine

Figure 3.3: Coarse and fine aggregates used in the study

3.4.2 Cement

To study anchoring to concrete that is representative of mixtures commonly used in the precast concrete industry, all concrete mixtures of the research program included Type III (ASTM C150) Portland cement. The cement was manufactured by Buzzi Unicem USA in Greencastle, IN.

3.4.3 Admixtures

To produce workable concrete mixtures representative of the mixtures typically used at precast concrete plants, two different water reducers were used during the project. Depending on the aggregate type and the resulting fresh properties of the concrete mixtures, a high-range water reducer (HRWR), a normal-range water reducer (NRWR), or a combination of both were added to provide the desired slump and workability of the concrete for casting. A viscosity modifying admixture (VMA) was added to each concrete mixture to increase resistance to segregation. The three types of admixtures used during the research program are summarized in Table 3.3. The admixtures were produced by BASF Corporation.

Table 3.3: Admixtures

Admixture	Name	Type
High-Range Water Reducer	MasterGlenium® 7920	ASTM C494 Types A and F
Water Reducer	MasterPozzolith® 80	ASTM C494 Types A, B, and D
Viscosity-Modifying Admixture	MasterMatrix® VMA 362	ASTM C494 Type S

3.4.4 Mixture Designs

As previously described, the lightweight concrete mixtures consisted of both sand-lightweight and all-lightweight concrete with three types of lightweight aggregate available in the United States: expanded shale, clay, and slate. The target compressive strength of each mixture design was 6500 to 8500 psi to correspond with high-strength concrete as defined in ACI 355.2-07, and the target slump was 6 to 8 in. The mixtures were based on recommendations from the aggregate manufactures. The final mixture designs for casting specimens shown in Table 3.4 were developed after performing various trial batches at Bowen Laboratory, as described in Section 3.4.5. Detailed information of final mixture design is included in Appendix III.

When mixing the concrete at the precast plant, the fresh properties of the relatively large batch varied from the properties of the concrete mixed for the small trial batches. Water and admixtures were adjusted as needed to produce a mixture with the desired fresh properties (i.e., workability). The actual concrete mixtures used to cast the slab specimens are provided in Table 3.5. While mixing the clay sand-lightweight and clay all-lightweight concrete, extra water was added during casting to increase workability, resulting in compressive strengths below the target compressive strength range. Based on these results and additional trial batches, the water-cement ratio of the shale and slate sand-lightweight concrete and the slate all-lightweight concrete was adjusted to 0.41. The resulting compressive strengths of the concrete varied (see Section 4.2.3).

Table 3.4: Concrete mixture design proportions (based on SSD condition)

Material/ Property	Description	Normal weight	Sand-Lightweight			All-Lightweight		
			Shale	Clay	Slate	Shale	Clay	Slate
Cementitious Material	Portland Type III Cement (lb/yd^3)	653	799	719	720	659	744	741
Water	Water (lb/yd^3)	258	270	278	295	270	268	304
Coarse Aggregate	#9 Limestone* (lb/yd^3)	1738	---	---	---	---	---	---
	3/4 in. Shale (lb/yd^3)	---	823	---	---	964	---	---
	1/2 in. Clay (lb/yd^3)	---	---	686	---	---	757	---
	¾ in. Slate (lb/yd^3)	---	---	---	924	---	---	921
Fine Aggregate	#23 River Sand* (lb/yd^3)	1469	1576	1783	1389	---	---	---
	Shale (lb/yd^3)	---	---	---	---	1003	---	---
	Clay (lb/yd^3)	---	---	---	---	---	973	---
	Slate (lb/yd^3)	---	---	---	---	---	---	921
Admixtures	High-Range Water Reducer (fl. oz/cwt)	3.04	2.25	4.14	---	4.10	8	---
	Viscosity-Modifying Admixture (fl. oz/cwt)	3.04	2.25	4.14	3.75	1.37	8	3.64
	Normal-Range Water Reducer (fl. oz/cwt)	---	3.38	---	1.25	0.46	3.33	1.21
Concrete Properties	Slump (in.)	7	7.5	8.25	8	8	7.5	6.5
	Average 28-day f_c' (psi)	7400	6980	7010	7040	6940	6500	7070

* Aggregate size designations in accordance with Indiana DOT Standard Specifications (2018)

Table 3.5: Actual concrete mixture design proportions (free water included in aggregate weights)

Material/ Property	Description	Normal weight	Sand-Lightweight			All-Lightweight		
			Shale	Clay	Slate	Shale	Clay	Slate
Cementitious Material	Portland Type III Cement (lb/yd^3)	671	850	732	750	705	776	741
Water	Water (lb/yd^3)	265	310	247	242	231	120	289
Coarse Aggregate	#9 Limestone* (lb/yd^3)	1770	---	---	---	---	---	---
	3/4 in. Shale (lb/yd^3)	---	820	---	---	968	---	---
	1/2 in. Clay (lb/yd^3)	---	---	688	---	---	802	---
	¾ in. Slate (lb/yd^3)	---	---	---	928	---	---	917
Fine Aggregate	#23 River Sand* (lb/yd^3)	1504	1598	1862	1452	---	---	---
	Shale (lb/yd^3)	---	---	---	---	1042	---	---
	Clay (lb/yd^3)	---	---	---	---	---	1078	---
	Slate (lb/yd^3)	---	---	---	---	---	---	922
Admixtures	High-Range Water Reducer (fl. oz/cwt)	3.87	3.14	4.98	1.67	0.47	10.3	---
	Viscosity-Modifying Admixture (fl. oz/cwt)	3.04	2.25	4.14	4.20	3.83	8	3.84
	Normal-Range Water Reducer (fl. oz/cwt)	---	3.38	---	2.80	1.28	3.33	1.42
Concrete Properties	Slump (in.)	---	8.5	8.75	8.25	5.75	8	7.75
	Average 28-day f_c' (psi)	7740	7430	5930	8120	6280	5000	5530

* Aggregate size designations in accordance with Indiana DOT Standard Specifications (2018)

3.4.5 Trial Batch Procedure

The procedure below for casting both normalweight and lightweight concrete was followed based on recommendations from concrete material experts and modified to achieve targeted strength and workability.

a. Immerse aggregate:

   To ensure the aggregates were adequately saturated, the coarse and fine shale and clay aggregates as well as the limestone and river sands were immersed in 5-gallon buckets for 24 hours. The coarse and fine slate aggregates were immersed in the buckets for 72 hours.

b. Drain water:

   The coarse and fine aggregates were spread over/piled on a sloped surface for water to drain off, with the exception of the coarse shale and clay aggregates. These two aggregate types were kept in the buckets, and the water was allowed to drain through holes in the bottom of the buckets. Both the coarse and fine aggregates were drained overnight before conducting a trial batch.

c. Determine the free moisture content of the aggregates:

   In order to adjust the amount of water added to each concrete mixture, the free moisture content (i.e., surface water) for the drained aggregates was determined. The procedure to determine the free moisture content for coarse/fine aggregates is as outlined below and presented in Table 3.6:

   c1. A sample was taken from the batch of saturated aggregate.

   c2. The sample was reduced in accordance with ASTM C702.

   c3. The sample of saturated coarse/fine aggregate were weighed using a scale with 0.01-gram precision.

c4. The sample of the coarse/fine aggregate was dried with commercial grade brown paper towels until the aggregate reached a surface-dry state.

c5. The samples of surface-dry aggregates were weighed.

c6. The weight of free water was determined.

c7. The free moisture content for the saturated aggregate was determined.

Table 3.6: Procedure for determining free moisture content of saturated aggregates

Step		Calculation
c3	Weight of wet aggregates.	A
c4	Weight of surface-dry aggregates.	B
c5	Weight of free water	C = A - B
c6	Free moisture content of wet aggregates	D (%) = C / A × 100%

d. <u>Determine the absorbed moisture content of the surface-dry aggregates:</u>

The objective of this step is to determine the moisture content of the surface-dry aggregates from Step c4 to determine if recommended values based on the aggregate manufacturers were reached (see Table 3.8). The procedure is outlined below and presented in Table 3.7:

d1. The sample of surface-dry coarse/fine aggregate was weighed.

d2. The sample of surface-dry coarse/fine aggregate was dried using a hot plate until the aggregate reached the oven-dry state in accordance with ASTM C127 and C128.

d3. The sample of oven-dry coarse/fine aggregate was weighed.

d4. The weight of absorbed water was determined.

d5. The absorbed moisture content of the surface-dry aggregate was determined.

Table 3.7: Procedure for determining absorbed moisture content of surface-dry aggregates

Step		Calculation
d1	Weight of surface-dry aggregates.	A
d2	Weight of oven-dry aggregates.	B
d3	Weight of absorbed water	C = A – B
d5	Absorbed moisture content of surface-dry aggregates	D (%) = C / A × 100%

Table 3.8: Recommended absorbed moisture content of surface-dry aggregates

Aggregate	Recommended Min. Absorbed Moisture Content
Expanded Shale – Coarse	10%
Expanded Shale – Fine	10%
Expanded Clay – Coarse	18%
Expanded Clay – Fine	15%
Expanded Slate – Coarse	6%
Expanded Slate – Fine	6%

e. Adjust the Mixture Design:

The mixture design was adjusted based on the free moisture content of the saturated coarse and fine aggregates. The adjustment is described in Table 3.9. In the table, X% represents the free moisture content of the coarse aggregate, and Y% represents the free moisture content of the fine aggregate.

Table 3.9: Calculation for adjusting mixture design

Material	Original Weight (A)	Adjusted Weight (B)
Coarse Aggregate	A1	B1 = A1 × (1+X%)
Fine Aggregate	A2	B2 = A2 × (1+Y%)
Cement	A3	B3 = A3
Water	A4	B4 = (A1+A2+A3+A4) – (B1+B2+B3)

3.4.5.1 Mixing Procedure

Generally, 3 cu. ft of concrete was mixed for a trial batch. Trial batches with volumes of 1 to 3 cu. ft. were also performed. A modified version of the mixing sequence described in ASTM C192 was used for the trial batches. A drum mixer with a capacity of 3.5 cu. ft was used for trial batches with a volume of 1 to 2 cu. ft. For the batches with a volume of 2 to 3 cu. ft, a larger drum mixer with capacity of 14.5 cu. ft. was used. Based on observations during the trial batches, the mixing sequence had a significant effect on the fresh concrete properties. Therefore, several different sequences were evaluated. The general sequence that resulted in satisfactory fresh concrete properties is as follows:

a. Wet the mixer with water.
b. "Butter" the mixer. Before mixing a trial batch, the mixer was "buttered" by mixing a batch of cement, water, and fine aggregate with similar proportions as the trial batch.
c. Add the coarse aggregate followed by the fine aggregate.
d. Add the adjusted amount of water.
e. Add normal-range water reducer (NRWR) as needed. Then, mix the concrete for one minute.
f. Add high-range water reducer (HRWR) as needed. Then, mix the concrete for one minute.
g. Add viscosity modifying admixture (VMA). Then, mix the concrete for two minutes.

For each trial batch, a slump test in accordance with ASTM C143 was performed. Then, a total of 15 cylinders were cast in accordance with ASTM C192. The cylinders were used to measure the 1-day, 7-day, 14-day, and 28-day compressive strengths of the concrete in accordance with ASTM C39.

3.5 Casting, Curing, and Storage

In the following subsections, the general procedure for casting of the slab specimens is provided, and the procedures for measuring the density of the fresh concrete and preparing concrete cylinders for compressive and splitting tensile tests are described.

3.5.1 Casting of Slab Specimens

Each cast at the precast concrete plant consisted of the fabrication of a set of four slabs of the same concrete type. Each set of slabs was cast on a different day at the plant. In general, the coarse and fine lightweight aggregates were piled and then sprinkled for approximately 24 hours before casting. For the slate coarse and fine aggregates, the aggregate piles were sprinkled for approximately 72 hours (as suggested by the manufacturer). After sprinkling, the aggregate piles were typically allowed to drain overnight in preparation for casting the next day. On the day of casting, the free moisture content of the coarse and/or fine lightweight aggregate was measured using the same procedure that was followed for the trial batches performed at Bowen Laboratory. Sensors within the aggregate bins were utilized to measure the free moisture of normalweight aggregate. Using the value of the free moisture content, water and aggregate contents were adjusted accordingly. The free moisture content and absorbed moisture content are reported in Table 3.10.

Table 3.10: Actual free water moisture and absorbed moisture

Concrete	Coarse Aggregates		Fine Aggregates	
	Free Water Moisture (%)	Absorbed Moisture (%)	Free Water Moisture (%)	Absorbed Moisture (%)
Normalweight	1.0	--	2.1	--
Shale Sand-Lightweight	1.0	10.4	2	--
Shale All-Lightweight	1.0	11.0	4.4	10.9
Clay Sand-Lightweight	15	19.3	4.7	--
Clay All-Lightweight	7.0	20.4	11.6	16.3
Slate Sand-Lightweight	1.7	6.7	5.1	--
Slate All-Lightweight	0.1	8.6	1.4	13.5

While batching the materials, the coarse and fine aggregates were first added to the drum of the commercial mixer and combined. Then, the water and cement were simultaneously added to the drum. Next, the admixtures were added. The order in which the admixtures were added varied for different concrete mixtures. The admixture quantities were adjusted as needed to achieve the desired fresh properties of the concrete. The concrete needed for one cast required two or three batches with the same proportions to be produced in the mixer. However, the batches were placed in a single truck and mixed together prior to casting.

Figure 3.4 shows the process of casting concrete and an example slump test performed during a concrete cast. During the cast, the concrete was consolidated using a high-frequency internal vibrator. The surface of the slabs was finished with a finishing trowel and left uncovered after casting. The forms were removed from the slabs the day after the cast, and the slabs were stored at the precast plant until transported. The slabs were transported to Bowen Laboratory at least 14 days after casting.

(a) Casting concrete (b) Sump test

Figure 3.4: Pouring concrete and slump test

3.5.2 Density Measurements and Concrete Cylinders

After casting two of the four slabs, the density of the fresh concrete was measured based on ASTM C138. At the same time, concrete was taken from the truck to prepare forty 4 in. x 8 in. cylinders and six 6 in. x 12 in. cylinders. The 4 in. x 8 in. cylinders were cast for future compressive strength and splitting tensile tests, and the 6 in. x 12 in. cylinders were cast for future measurement of equilibrium density of lightweight concrete. The cylinder molds were sealed with plastic lids to prevent moisture loss and to maintain the shape of the cylinders during curing. The cylinders were demolded at the same time the forms were removed from the slab specimens. As required by ACI 355.2-07, cylinders were cured in the same conditions as the slab specimens. The cylinders were cured, stored, and transported with the slabs to prevent differences in humidity and temperature.

Compressive strength tests were conducted at 28 days after casting of concrete maturity for each concrete mixture. Furthermore, compressive strength and split tensile tests were conducted in accordance with ASTM C39 and ASTM C496, respectively, at the time of the anchor tests to provide an accurate estimate of the material properties of the slab specimens.

3.6 Anchor Selection and Installation

The research consisted of tests on concrete screw anchors, torqued-controlled expansion anchors, and displacement-controlled expansion anchors provided by four different manufacturers: DEWALT, Hilti, ITW Red Head, and Simpson Strong-Tie. Throughout this document, each of these four manufactures have been assigned a consistent designation of Manufacture A through D. The designation for each company has been assigned randomly. For comparison, cast-in anchors manufactured by Nelson were also included in the research. Details of the anchors and installation procedures are described in the following sections. Installation tools included a Slotted Drive System (SDS+) rotary hammer with SDS+ hollow bits connected to a 10-gallon vacuum, a cordless impact wrench, a calibrated digital torque wrench, and manual setting tools for drop-in anchors. For the screw anchors from Manufacture A, a $^{7}/_{16}$-in. SDS hammer drill bit was used.

3.6.1 Torque-Controlled Expansion Anchors

The torque-controlled expansion anchors used in the test program from Manufacturers B, C, and D were zinc-plated carbon steel wedge anchors, and the anchors from Manufacturer A were galvanized steel wedge anchors. During this study, 37 torque-controlled anchors were tested on the formed side of the slab specimens, and 35 torque-controlled anchors were tested on the finished side. Due to improper installation of the anchors that resulted in effective embedment depths that were less than 2 in. for 29 of the anchors tested on the formed side of the slabs, an additional 35 torque-controlled anchors were tested on the finished side considering the lack of remaining testing space for the anchors on the formed side. For tests on torque-controlled anchors conducted on the finished side of the slab specimens, the torque-controlled anchor from Manufacturer C was replaced with a different torque-controlled anchor produced by the same manufacturer. This anchor was a zinc-plated carbon steel wedge anchor. The anchors provided by Manufacturers A, B, and D were ½ in. × 4 ½ in. (½-in. nominal diameter and 4 ½-in. length) wedge anchors, and the anchors from Manufacturer C were ½ in. × 4 in. wedge anchors. Installation involved drilling holes in the slab specimen using the rotary hammer drill and a drill bit with a diameter specified by the manufacturer. Concrete debris was cleaned out using a vacuum while drilling. After setting the anchor using a hammer until the washer was flush with the surface of the removable insert of the loading fixture (refer to Section 3.7.1), as shown in Figure 3.5, a calibrated torque wrench was used to install each anchor, adhering to the torque specified by each manufacturer. The installation torque applied to each torque-controlled anchor was recorded along with the number of turns (i.e., rotations) of the anchor. This information is presented in Appendix I.

Figure 3.5: Torque-controlled anchor expansion after being installed in concrete specimen

3.6.2 Displacement-Controlled Expansion Anchors

Displacement-controlled expansion anchors provided by all four manufacturers were ½ in. × 2 in. (½-in. internal diameter and 2-in. overall length) drop-in anchors. After drilling and cleaning a hole in the same manner as for the torque-controlled anchors, a displacement-controlled anchor was inserted into the hole and tapped flush with the surface of the slab specimen using a hammer. A manual setting tool provided by each manufacturer was driven into the anchor using a hammer until the shoulder of the setting tool contacted the top of the anchor, expanding the base of the anchor into the surrounding concrete. A ½ in.-13 (½-in. diameter with 13 threads per inch) Grade 8 high-strength steel threaded rod was inserted into the anchor and tightened using a wrench, and a nut with a washer was then threaded on the rod until the washer was flush with the surface of the removable insert of the loading fixture, as shown in Figure 3.6.

Figure 3.6: Displacement-controlled expansion anchor after being installed in concrete specimen

3.6.3 Screw Anchors

Concrete screw anchors provided by all four manufacturers were ½ in. × 4 in. (½-in. nominal diameter and 4-in. length) carbon steel screws with hex washer heads. The anchors from the four manufacturers were zinc-plated. For installation, holes with a depth of 3.5 in. were drilled in the slab specimen using a drill bit with a diameter specified by the manufacturer. Again, concrete debris was cleaned out using a vacuum while drilling. The screw anchors were installed using the impact wrench until flush with the washers placed between the screw head and the removable insert of the loading fixture, as shown in Figure 3.7. The removable insert and washers had a combined thickness of 1 in., resulting in the nominal embedment depth of the screw anchors to be 3 in. Lastly, the calibrated torque wrench was used to torque the screws to 1 lb-ft below the maximum value specified by each manufacturer. The installation torque applied to each screw anchor was recorded and is presented in Appendix I.

Figure 3.7: Screw anchor after being installed in concrete specimen

3.6.4 Cast-in Anchors

The cast-in anchors used in the research were ½-in. diameter low-carbon steel headed studs with a length of 2 ⅛ in. Each stud was welded to a 3 in. by 3 in. by $^{3}/_{8}$ in. low-carbon steel plate by the stud manufacturer. The anchors and attached plates were placed on the bottom soffit of the formwork for the slab specimens and fixed with epoxy before casting. A $^{7}/_{8}$ in.-9 ($^{7}/_{8}$-in. diameter with 9 threads per inch) fully threaded stud with a length of 2 ½ in. provided by the stud manufacturer was welded to the plate attached to each stud anchor using a stud welding machine before conducting the tension tests. The embedment depth of the anchors was 2.07 in., calculated by subtracting the weld burn-off (0.125 in.) and the head thickness (0.312 in.) from the stud length

(2.125 in.) and adding the plate thickness (0.375 in.). A photograph of a stud assembly that was extracted from the concrete after a tension test is shown in Figure 3.8.

Figure 3.8: Cast-in anchor after tension test

3.7 Test Setup and Instrumentation

An unconfined test setup was used to conduct all anchor tests of the experimental program. Applied load and displacement of the anchors were monitored continuously throughout each test. Details of the test equipment and instrumentation are provided in the following subsections. A drawing of the test setup and instrumentation is shown in Figure 3.9.

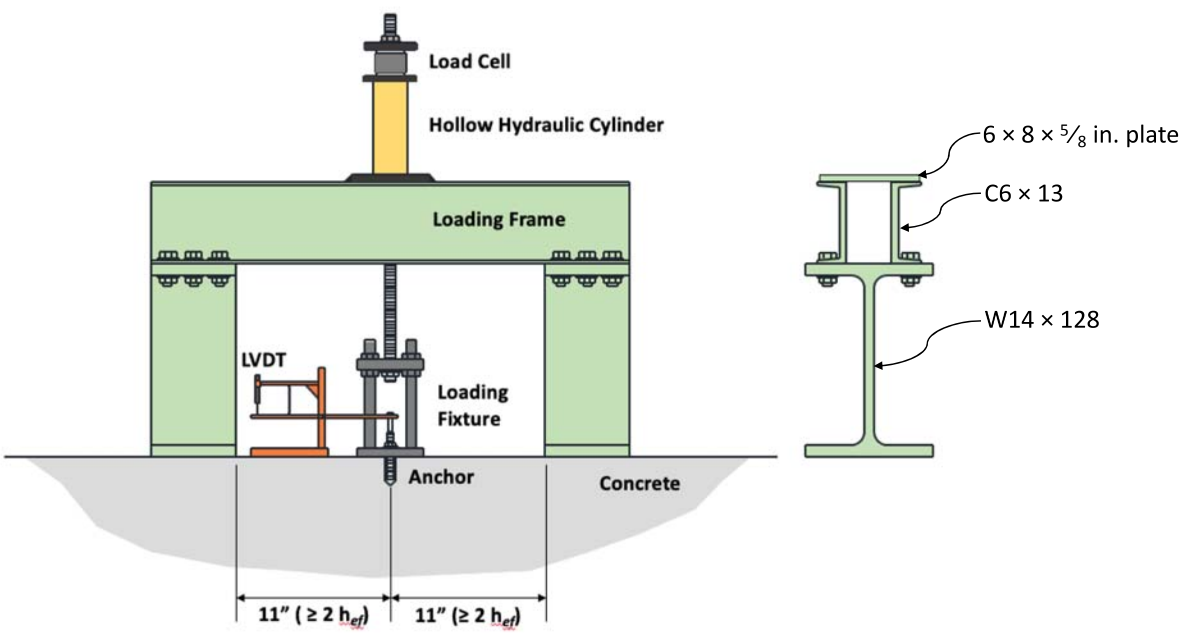


Figure 3.9: Test setup and instrumentation

3.7.1 Test Setup

In order to permit the unrestricted development of a concrete breakout failure, an unconfined test setup was developed for the tensile tests of post-installed mechanical anchors and cast-in anchors. The load frame used for the unconfined tests is pictured in Figure 3.10 and is based on the guidelines of ASTM E488. The frame consists of two W14 × 82 steel members that support two C6 × 13 steel channels. A 6 in. by 8 in. steel plate with a thickness of ⅝ in. was welded to the two channels. A 1-in. diameter hole is located at the center of the plate. For the tests, a 6 in. by 6 in. steel bearing plate with a thickness of 1.25 in. and a 1-in. diameter hole was positioned on the load frame along with a 27.6-kip capacity hollow hydraulic cylinder with a 3-in. stroke. A 20-kip capacity load cell was then placed on the hydraulic cylinder to monitor the applied load throughout the tests. A ¾-in. diameter Grade B7 steel threaded rod passed through the assembly and was connected to a loading fixture, shown in Figure 3.11.

Figure 3.10: Load frame used for unconfined tests

Figure 3.11: Loading fixture

The loading fixture, presented in Figure 3.11, was used to transfer tensile force between the anchor and the threaded rod of the load frame. The loading fixture consists of two 5-in. diameter discs made of 4140 alloy steel connected by three ¾-in. diameter Grade B7 steel threaded rods. A center removable insert made from a 2-in. diameter 4140 steel threaded rod machined to a thickness of ¾ in. served as the connection between the anchors and the loading fixture. For each test, the removable insert was secured on the concrete anchor. A 2-in. diameter threaded hole in the bottom disc of the loading fixture allowed the fixture to be threaded onto the insert. To ensure that the rods and discs of the loading fixture remained secure during the anchor tests, a tensile force exceeding the expected strengths of the anchors to be tested was applied to the fixture and the nuts were tightened prior to releasing the tensile force. In other words, the threaded rods were post-tensioned at the connections with the discs.

An electronic hydraulic pump was used to apply pressure to the hydraulic cylinder. To control the flow of hydraulic fluid to the cylinder and to maintain the control of the pressure gain in the system, a needle valve and a pressure regulator valve were installed in series at the outlet of the pump. The system avoided the risk of an abrupt peak in pressure being supplied to the hydraulic cylinder that would cause the anchors to fail suddenly. The hydraulic system used during the experimental program is shown in Figure 3.12.

Figure 3.12: Hydraulic system

3.7.2 Instrumentation

To continuously measure the displacement of the anchors during each test, a linear variable differential transducer (LVDT) was used. The LVDT was attached to the end of the measuring arm of a displacement measuring device pictured in Figure 3.13. The length of the measuring arm was 14.5 in., greater than the expected radius of the concrete breakout cone, allowing the base of the measuring device to be placed outside the cone. The space between the two discs of the loading fixture allowed the measuring arm of the displacement measuring device to rest on the top of the anchor during each test. A picture of the measuring device after the failure of an anchor is shown in Figure 3.14. The device was calibrated using a Fowler-Trimos electronic height gauge with the LVDT fixed to the measuring arm.

Figure 3.13: Displacement measuring device

Figure 3.14: Displacement measuring device after failure of an anchor

A 20-kip capacity load cell was used in the test frame to monitor the force applied to the anchors. A pressure transducer was installed in-line with the hydraulic cylinder for verification of the load cell reading. Information from the transducer, however, were not used in the data analyses.

The load cell, LVDT, and pressure transducer were monitored continuously throughout each test using a data acquisition system. Considering the brittle nature of concrete breakout failures, the data were recorded every of 0.01 second by the system.

3.8 General Testing Procedure

A video camera was used to record the entirety of each anchor test. Multiple photographs were also taken of the anchor and failure cone after each test. A method of measuring angles of the concrete breakout cones is described in Section 4.3.5. The general procedure followed for the anchor tests is provided below:

a. Install the anchor following the procedure described in Section 3.6.
b. Prepare the test setup and the displacement measuring device.
c. Reset the data acquisition system (i.e., “zero” the sensor readings).
d. Close the needle valve and pressure regulator valve.
e. Perform load test:
    - e1. Turn on the electric hydraulic pump and release the flow control valve to allow a low flow rate.
    - e2. Preload the anchor to 150 lbf by slowly turning the pressure regulator valve.
    - e3. Close the needle valve once the system approximately reaches the preload of 150 lbf as an initial load specified in ASTM E488.
    - e4. Open the needle valve to increase the load at a consistent rate that allows the anchors to reach the ultimate load after 1 to 3 minutes from the start of testing in accordance with ASTM E488.

e5. Maintaining the loading rate, turn the pressure regulator valve to increase pressure in the hydraulic cylinder until failure occurs.

3.9 Summary

The details of the experimental program focused on determining the tensile strengths of anchors in lightweight concrete were described in this chapter, including the specimen design, anchor installation procedures, and concrete mixture designs. Trail batches were performed prior to finalizing the mixture designs to be used to cast the slab specimens. To perform the unconfined tensile tests and record the applied load and displacement of anchors, a test setup and displacement measuring device were fabricated specifically for the test program.

Detailed results of the anchor tests along with the material test results are reported in Chapter 4. The analysis of the test results and comparison among different anchor types in seven types of concrete are presented in Chapter 5.

CHAPTER 4. EXPERIMENTAL RESULTS

4.1 Introduction

The results of the experimental program focused on the strength of post-installed and cast-in anchors in lightweight concrete are presented in this chapter. First, relevant material properties of the seven types of concrete used to fabricate the slab specimens are provided in detail. The results of the 200 tension tests on cast-in and post-installed anchors are then presented. Key details of each test and the ultimate loads applied to the anchors are summarized in tabular format. The general load-deflection response of the anchors is also discussed along with the failure behavior.

4.2 Material Test Results

4.2.1 Concrete Density

The density of the freshly mixed concrete was measured during each cast of the lightweight concrete slabs based on ASTM C138. A 0.25 ft^3 aluminum cylindrical container and a 12 in. by 12 in. acrylic strike-off plate with a thickness of ½ in. were used to measure the densities of the freshly mixed lightweight concrete that contained shale and slate aggregate. A 0.45 ft^3 steel cylindrical container and a 1-in. thick wooden strike-off plate with a non-absorbent surface were used to measure the density of the clay sand- and all-lightweight concrete mixtures. Although a wooden strike-off plate is not allowed by ASTM C138, the potential error in the measured density values is assumed to be negligible. A summary of the fresh concrete densities of the six lightweight mixtures is presented in Table 4.1. The 0.25 ft^3 measure before and after being filled with concrete is shown in Figure 4.1.

Table 4.1: Fresh concrete density

Concrete Type	**Lightweight Aggregate Material**	**Mass of Empty Measure, M_m (lb)**	**Mass of Measure Filled with Concrete, M_c (lb)**	**Volume of Measure, V_m (ft^3)**	**Density of Freshly Mixed Concrete, $D = (M_c - M_m)/V_m$ (lb/ft^3)**
Sand-Lightweight	Shale	8.53	40.83	0.25	129.2
	Clay	41.35	99.90	0.45	130.1
	Slate	8.60	38.75	0.25	120.6
All-Lightweight	Shale	8.61	35.31	0.25	106.8
	Clay	41.41	89.94	0.45	107.8
	Slate	8.60	35.04	0.25	105.8

(a) Before filled with concrete (b) After filled with concrete

Figure 4.1: Fresh concrete density test

4.2.2 Equilibrium Density

Concrete cylinders were cast along with the slabs to later determine the equilibrium densities of the lightweight concrete. Equilibrium density for each type of lightweight concrete was measured on the day indicated in Table 4.2 after the concrete was cast. In accordance with ASTM

C567, the approximate equilibrium density can be calculated from the measured oven-dry density. This value is calculated as follows and presented in Table 4.2:

$$E_c = O_m + 3\ lb/ft^3 \tag{4-1}$$

where:

E_c = calculated equilibrium density (lb/ft^3)

O_m = measured oven-dry density (lb/ft^3)

Table 4.2: Equilibrium density

Concrete Type	Lightweight Aggregate Material	Concrete Age (days)	Calculated Equilibrium Density, E_c (lb/ft^3)			
			Cylinder 1	Cylinder 2	Cylinder 3	Avg.
Sand-Lightweight	Shale	176	121.9	120.8	122.2	121.6
	Clay	197	118.6	118.9	116.8	118.1
	Slate	63	119.3	118.9	118.6	118.9
All-Lightweight	Shale	57	96.5	96.9	97.4	96.9
	Clay	196	91.1	92.6	93.7	92.5
	Slate	64	98.2	98.2	99.3	98.6

4.2.3 Compressive and Tensile Strengths

To determine the concrete compressive strengths of the slab specimens, several cylinders were cast along with the slabs (see Section 3.5.2). For each concrete type, three cylinders were tested in compression in accordance with ASTM C39 at an age of 28 days as well as on the first day and last day of the anchor tests for that particular concrete. Before conducting each test, the top and bottom faces of the cylinder were ground flat to avoid stress concentrations and inaccurate strength measurements. The compressive strengths of the three cylinders were averaged. The resulting values are provided in Table 4.3. For the concrete compressive strengths representing the strengths of the slab specimens during the anchor tests, the results from all of the compression tests conducted from the first to the last day of the anchor tests were averaged considering the relatively short period over which the anchor tests were conducted and that the compressive strength data exhibit scatter. For the torque-controlled anchors tested on the finished side of the slab specimens, the concrete was tested on a different day, as indicated in Table 4.3. Figure 4.2 shows a typical compressive strength test before and after failure of the cylinder.

The tensile strength of lightweight concrete is a critical parameter affecting the capacity of anchors that fail due to concrete breakout. Split cylinder tests were performed in accordance with ASTM C496 to determine the tensile strengths of the concrete. Three cylinders were tested on the first and last days of the anchor tests for each concrete type. Figure 4.3 shows a typical splitting tensile test setup before and after failure of the cylinder. The average splitting tensile strengths of the three cylinders are provided in Table 4.3. Additionally, the factors relating the compressive and splitting tensile strengths of the concrete are included in the table. This value is calculated as follows:

$$\frac{f_t}{\sqrt{f_c}} \tag{4-2}$$

Table 4.3: Summary of concrete properties

Concrete Type	Aggregate Material	Compressive Strength at 28 days, f_c (psi)	Time (days)	Compressive Strength, f_c (psi)	Splitting Tensile Strength, f_t (psi)	$\frac{f_t}{\sqrt{f_c}}$
Normalweight	--	7740	160[1][2]	7410	630	7.32
			208[3]	7570	520	6.01
Sand-Lightweight	Shale	7430	141[1][2]	8520	620	6.74
			183[3]	7840	630	7.13
	Clay	5930	150[1] to 156[2]	5930	550	7.17
			204[3]	5930	510	6.61
	Slate	8120	34[1] to 37[2]	8120	615	6.83
			72[3]	8090	520	5.81
All-Lightweight	Shale	6280	28[1] to 31[2]	6190	535	6.81
			66[3]	6250	530	6.70
	Clay	5000	161[1][2]	5670	415	5.51
			203[3]	4880	310	4.43
	Slate	5530	35[1] to 38[2]	5590	480	6.41
			73[3]	5440	400	5.46

[1] *First day of testing*
[2] *Last day of testing*
[3] *Testing day of torque-controlled anchors on finished side*

(a) Before failure (b) After failure

Figure 4.2: Typical compression test

(a) Before failure (b) After failure

Figure 4.3: Typical splitting tensile test

4.3 Results of Tension Tests on Post-Installed and Cast-In Anchors

4.3.1 Post-Installed Anchor Test Results

The experimental results of the tension tests on all 147 post-installed anchors are summarized in Table 4.4 through Table 4.10. The test ID labeling scheme used in the tables is described in Figure 3.1. Each table corresponds to one of the seven types of concrete included in the test program. The ultimate failure load, N_{test}, reported in the tables is defined as the maximum load applied to the anchor during the test as measured by the load cell. The concrete compressive strength, f_c, was calculated by averaging the results from all of the compression tests conducted from the first to the last day of the anchor tests, considering the relatively short period over which the anchor tests were conducted and that the compressive strength data exhibit scatter. The compressive strengths corresponding to the torque-controlled expansion anchors tested on the finished side of the slab specimens were measured on a single day. The effective embedment depth, h_{ef}, of each anchor is included in the tables. All anchors had a nominal diameter, d_a, of ½ in., and all anchors failed by concrete breakout.

Table 4.4: Results of post-installed anchor tests in normalweight concrete

Test ID	Concrete Compressive Strength, f_c (psi)	Concrete Splitting Tensile Strength, f_t (psi)	Anchor Type	Effective Embed-ment, h_{ef} (in.)	h_{ef}/d_a	N_{test} (lbf)
NW-T-B1	7410	630	½" dia. Torque-controlled	2.00	4.00	8236
NW-T-C1				2.00	4.00	9781
NW-T-D1				2.00	4.00	7472
NW-T-A1				2.00	4.00	9394
NW-T-B2				1.56	3.12	6599
NW-T-B3*	7570	520		2.00	4.00	7702
NW-T-C2*				2.00	4.00	7109
NW-T-D2*				2.00	4.00	5617
NW-T-A2*				2.00	4.00	6767
NW-T-B4*				2.00	4.00	7307
NW-D-B1	7410	630	½" dia. Displacement-controlled	2.00	4.00	9259
NW-D-C1				2.00	4.00	9723
NW-D-D1				2.00	4.00	10,070
NW-D-A1				2.00	4.00	9307
NW-D-B2				2.00	4.00	9678
NW-S-B1	7410	630	½" dia. Screw anchor	2.16	4.32	9223
NW-S-C1				2.14	4.28	6895
NW-S-D1				2.17	4.34	9863
NW-S-A1				2.40	4.80	9923
NW-S-B2				2.16	4.32	10,072
NW-S-D2				2.17	4.34	9849

** Anchor tested on finished side of slab*

Table 4.5: Results of post-installed anchor tests in shale sand-lightweight concrete

Test ID	Concrete Compressive Strength, f_c (psi)	Concrete Splitting Tensile Strength, f_t (psi)	Anchor Type	Effective Embed-ment, h_{ef} (in.)	h_{ef}/d_a	N_{test} (lbf)
SL-SH-T-B1	8520	620	½” dia. Torque-controlled	1.75	3.50	6714
SL-SH-T-C1				1.50	3.00	5711
SL-SH-T-D1				1.50	3.00	4453
SL-SH-T-A1				1.375	2.75	4651
SL-SH-T-A2				1.375	2.75	4524
SL-SH-T-B2*	7840	630		2.00	4.00	6426
SL-SH-T-C2*				2.00	4.00	5142
SL-SH-T-D2*				2.00	4.00	5727
SL-SH-T-A3*				2.00	4.00	5686
SL-SH-T-C3*				2.00	4.00	5217
SL-SH-D-B1	8520	620	½” dia. Displacement-controlled	2.00	4.00	7817
SL-SH-D-C1				2.00	4.00	9377
SL-SH-D-D1				2.00	4.00	7646
SL-SH-D-A1				2.00	4.00	8173
SL-SH-D-A2				2.00	4.00	8226
SL-SH-S-B1	8520	620	½” dia. Screw anchor	2.16	4.32	7841
SL-SH-S-C1				2.14	4.28	5304
SL-SH-S-D1				2.17	4.34	7189
SL-SH-S-A1				2.40	4.80	8123
SL-SH-S-D2				2.17	4.34	7049

** Anchor tested on finished side of slab*

Table 4.6: Results of post-installed anchor tests in clay sand-lightweight concrete

Test ID	Concrete Compressive Strength, f_c (psi)	Concrete Splitting Tensile Strength, f_t (psi)	Anchor Type	Effective Embed-ment, h_{ef} (in.)	h_{ef}/d_a	N_{test} (lbf)
SL-CL-T-B1	5930	550	½" dia. Torque-controlled	2.00	4.00	6062
SL-CL-T-C1				2.00	4.00	5780
SL-CL-T-D1				1.88	3.75	5590
SL-CL-T-A1				1.73	3.46	5517
SL-CL-T-B2				2.00	4.00	6430
SL-CL-T-C2				1.56	3.13	5778
SL-CL-T-D2				2.00	4.00	6250
SL-CL-T-B3*	5930	510		2.00	4.00	5583
SL-CL-T-C3*				2.00	4.00	6089
SL-CL-T-D3*				2.00	4.00	4938
SL-CL-T-A2*				2.00	4.00	5458
SL-CL-T-D4*				2.00	4.00	5489
SL-CL-D-A1	5930	550	½" dia. Displacement-controlled	2.00	4.00	7868
SL-CL-D-B1				2.00	4.00	7897
SL-CL-D-C1				2.00	4.00	8960
SL-CL-D-D1				2.00	4.00	7008
SL-CL-D-A2				2.00	4.00	8554
SL-CL-S-C1	5930	550	½" dia. Screw anchor	2.14	4.28	6681
SL-CL-S-D1				2.17	4.30	6871
SL-CL-S-A1				2.40	4.80	6611
SL-CL-S-B1				2.16	4.32	6950
SL-CL-S-B2*				2.16	4.32	6669
SL-CL-S-A1*				2.40	4.80	5853

** Anchor tested on finished side of slab*

Table 4.7: Results of post-installed anchor tests in slate sand-lightweight concrete

Test ID	Concrete Compressive Strength, f_c (psi)	Concrete Splitting Tensile Strength, f_t (psi)	Anchor Type	Effective Embed-ment, h_{ef} (in.)	h_{ef}/d_a	N_{test} (lbf)
SL-SL-T-B1	8120	615	½" dia. Torque-controlled	1.75	3.50	6373
SL-SL-T-C1				1.50	3.00	5484
SL-SL-T-D1				1.50	3.00	4743
SL-SL-T-A1				1.375	2.75	4218
SL-SL-T-C2				1.50	3.00	4798
SL-SL-T-B2*	8090	520		2.00	4.00	6824
SL-SL-T-C3*				2.00	4.00	6900
SL-SL-T-D2*				2.00	4.00	5363
SL-SL-T-A2*				2.00	4.00	6548
SL-SL-T-B3*				2.00	4.00	6546
SL-SL-D-B1	8120	615	½" dia. Displacement-controlled	2.00	4.00	7458
SL-SL-D-C1				2.00	4.00	9160
SL-SL-D-D1				2.00	4.00	7670
SL-SL-D-A1				2.00	4.00	8691
SL-SL-D-C2				2.00	4.00	9625
SL-SL-D-C3				2.00	4.00	8746
SL-SL-S-B1	8120	615	½" dia. Screw anchor	2.16	4.32	7345
SL-SL-S-C1				2.14	4.28	4757
SL-SL-S-D1				2.17	4.34	8019
SL-SL-S-A1				2.40	4.80	4872
SL-SL-S-C2				2.14	4.28	5414

** Anchor tested on finished side of slab*

Table 4.8: Results of post-installed anchor tests in shale all-lightweight concrete

Test ID	Concrete Compressive Strength, f_c (psi)	Concrete Splitting Tensile Strength, f_t (psi)	Anchor Type	Effective Embed-ment, h_{ef} (in.)	h_{ef}/d_a	N_{test} (lbf)
AL-SH-T-B1	6190	535	½" dia. Torque-controlled	1.75	3.50	4634
AL-SH-T-C1				1.50	3.00	3346
AL-SH-T-D1				1.50	3.00	3561
AL-SH-T-A1				1.375	2.75	2761
AL-SH-T-B2				1.75	3.50	4576
AL-SH-T-B3*	6250	530		2.00	4.00	4902
AL-SH-T-C2*				2.00	4.00	4294
AL-SH-T-D2*				2.00	4.00	4213
AL-SH-T-A2*				2.00	4.00	4841
AL-SH-T-C3*				2.00	4.00	4485
AL-SH-D-B1	6190	535	½" dia. Displacement-controlled	2.00	4.00	5674
AL-SH-D-C1				2.00	4.00	6476
AL-SH-D-D1				2.00	4.00	5594
AL-SH-D-A1				2.00	4.00	6587
AL-SH-D-B2				2.00	4.00	5920
AL-SH-S-B1	6190	535	½" dia. Screw anchor	2.16	4.32	5479
AL-SH-S-C1				2.14	4.28	3924
AL-SH-S-D1				2.17	4.34	4974
AL-SH-S-A1				2.40	4.80	4432
AL-SH-S-B2				2.16	4.32	4502

** Anchor tested on finished side of slab*

Table 4.9: Results of post-installed anchor tests in clay all-lightweight concrete

Test ID	Concrete Compressive Strength, f_c (psi)	Concrete Splitting Tensile Strength, f_t (psi)	Anchor Type	Effective Embed-ment, h_{ef} (in.)	h_{ef}/d_a	N_{test} (lbf)
AL-CL-T-B1	5670	415	½” dia. Torque-controlled	1.75	3.50	3544
AL-CL-T-C1				1.50	3.00	3498
AL-CL-T-D1				1.50	3.00	2749
AL-CL-T-A1				1.375	2.75	2557
AL-CL-T-C2				1.50	3.00	3238
AL-CL-T-B2*	4875	310		2.00	4.00	4435
AL-CL-T-C3*				2.00	4.00	4579
AL-CL-T-D2*				2.00	4.00	3746
AL-CL-T-A2*				2.00	4.00	3903
AL-CL-T-C4*				2.00	4.00	3982
AL-CL-D-B1	5670	415	½” dia. Displacement-controlled	2.00	4.00	3992
AL-CL-D-C1				2.00	4.00	4020
AL-CL-D-D1				2.00	4.00	3886
AL-CL-D-A1				2.00	4.00	5092
AL-CL-D-D2				2.00	4.00	4769
AL-CL-S-B1	5670	415	½” dia. Screw anchor	2.16	4.32	4550
AL-CL-S-C1				2.14	4.28	4466
AL-CL-S-D1				2.17	4.34	3881
AL-CL-S-A1				2.40	4.80	5412
AL-CL-S-A2				2.40	4.80	4810

* *Anchor tested on finished side of slab*

Table 4.10: Results of post-installed anchor tests in slate all-lightweight concrete

Test ID	**Concrete Compressive Strength, f_c (psi)**	**Concrete Splitting Tensile Strength, f_t (psi)**	**Anchor Type**	**Effective Embed-ment, h_{ef} (in.)**	h_{ef}/d_a	N_{test} **(lbf)**
AL-SL-T-B1	5590	480	½" dia. Torque-controlled	1.75	3.50	4779
AL-SL-T-C1				1.50	3.00	4343
AL-SL-T-D1				1.50	3.00	3708
AL-SL-T-A1				1.375	2.75	3476
AL-SL-T-D2				1.50	3.00	3787
AL-SL-T-B2*	5440	400		2.00	4.00	5431
AL-SL-T-C2*				2.00	4.00	4861
AL-SL-T-D3*				2.00	4.00	4923
AL-SL-T-A2*				2.00	4.00	4273
AL-SL-T-D4*				2.00	4.00	4846
AL-SL-D-B1	5590	480	½" dia. Displacement-controlled	2.00	4.00	6175
AL-SL-D-C1				2.00	4.00	7615
AL-SL-D-D1				2.00	4.00	5097
AL-SL-D-A1				2.00	4.00	6758
AL-SL-D-D2				2.00	4.00	6705
AL-SL-D-D3				2.00	4.00	6599
AL-SL-S-B1	5590	480	½" dia. Screw anchor	2.16	4.32	6380
AL-SL-S-C1				2.14	4.28	4914
AL-SL-S-D1				2.17	4.34	5590
AL-SL-S-A1				2.40	4.80	5121
AL-SL-S-D2				2.17	4.34	6069
AL-SL-S-A2				2.40	4.80	4870

** Anchor tested on finished side of slab*

4.3.2 Cast-In Anchor Test Results

Table 4.11 includes the results of the tension tests conducted on all 53 cast-in anchors. In the table, values given for the ultimate failure load, N_{test}; the concrete compressive strength, f_c; and the concrete splitting tensile strength, f_t, were acquired using the same methods described in Section 4.3.1. Effective embedment depth, h_{ef}, for the anchors calculated as explained in Section 3.6.4 are provided in the table. As with the post-installed anchors, all cast-in anchors had a nominal diameter, d_a, of ½ in., and all anchors failed by concrete breakout.

Table 4.11: Results of cast-in anchor tests (½-in. diameter anchors with 2.07-in. effective embedment depth; h_{ef}/d_a = 4.14)

Test ID	**Concrete Type**	**Concrete Compressive Strength, f_c (psi)**	**Concrete Splitting Tensile Strength, f_t (psi)**	**N_{test} (lbf)**
NW-C-1	Normalweight	7410	630	9548
NW-C-2				9534
NW-C-3				9649
NW-C-4				10,263
NW-C-5				9449
NW-C-6				10,116
NW-C-7				10,314
NW-C-8				9620
SL-SH-C-1	Shale Sand-Lightweight	8520	620	7078
SL-SH-C-2				7013
SL-SH-C-3				7401
SL-SH-C-4				7068
SL-SH-C-5				7651
SL-SH-C-6				7887
SL-SH-C-7				6842
SL-SH-C-8				6866
SL-CL-C-1	Clay Sand-Lightweight	5930	550	7254
SL-CL-C-2				7653
SL-CL-C-3				7104
SL-CL-C-4				6803
SL-CL-C-5				7064
SL-CL-C-6				7451
SL-CL-C-7				6936
SL-CL-C-8				6958
SL-SL-C-1	Slate Sand-Lightweight	8120	615	7504
SL-SL-C-2				7550
SL-SL-C-3				7704
SL-SL-C-4				8339
SL-SL-C-5				8065
SL-SL-C-6				7569
SL-SL-C-7				7629
AL-SH-C-1	Shale All-Lightweight	6190	535	4986
AL-SH-C-2				5727
AL-SH-C-3				5441
AL-SH-C-4				5239
AL-SH-C-5				5166
AL-SH-C-6				5085
AL-SH-C-7				5325

Table 4.11: Results of cast-in anchor tests (½-in. diameter anchors with 2.07-in. effective embedment depth; h_{ef}/d_a = 4.14) (Continued)

Test ID	**Concrete Type**	**Concrete Compressive Strength, f_c (psi)**	**Concrete Splitting Tensile Strength, f_t (psi)**	**N_{test} (lbf)**
AL-CL-C-1	Clay All-Lightweight	5670	415	3917
AL-CL-C-2				4863
AL-CL-C-3				4338
AL-CL-C-4				4377
AL-CL-C-5				4475
AL-CL-C-6				4608
AL-CL-C-7				3915
AL-CL-C-8				4646
AL-SL-C-1	Slate All-Lightweight	5590	480	5759
AL-SL-C-2				6310
AL-SL-C-3				6255
AL-SL-C-4				6187
AL-SL-C-5				6098
AL-SL-C-6				6161
AL-SL-C-7				6163

4.3.3 Load-Deflection Response

4.3.3.1 Typical Load-Displacement Behavior of Anchors Experiencing Concrete Breakout Failure

A general load-displacement curve for the four types of anchors experiencing a concrete breakout failure is shown in Figure 4.4. In the figure, Point A on the curve indicates the peak value of the applied load, N_{test}, and Point B indicates the moment when the displacement of the anchor began to increase rapidly and the concrete breakout cone began to develop. From the beginning of loading the anchor to Point B, no noticeable slipping of the anchor occurred.

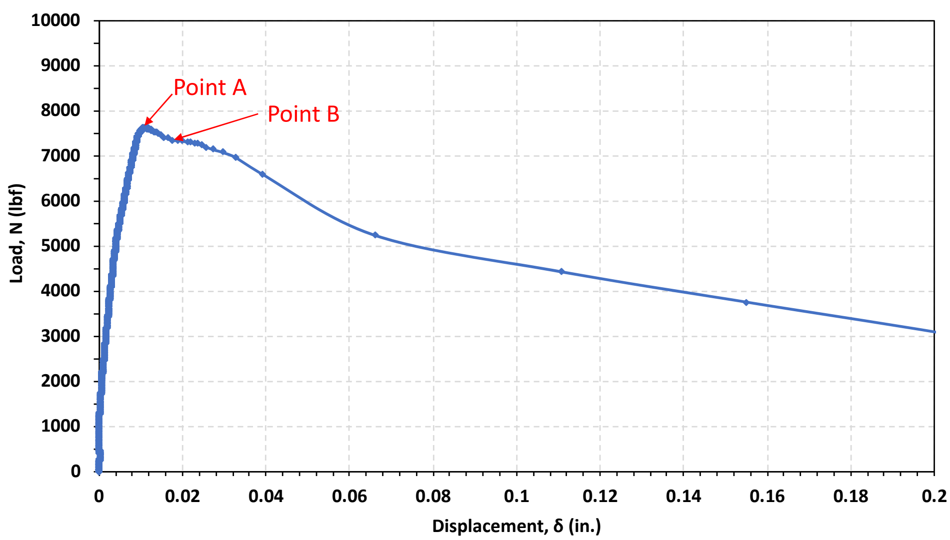


Figure 4.4: Typical load-displacement behavior of anchors experiencing concrete breakout failure

4.3.3.2 Typical Load-Displacement Behavior of Displacement-Controlled Expansion Anchors with Abrupt Slips

Seven of the displacement-controlled anchors in this study exhibited a different behavior that was characterized by abrupt slipping of the anchor. A typical example of this behavior is shown in Figure 4.5. The drop-in anchor slipped within the hole in which it was installed three distinct times. Each time the anchor slipped, a loud sound was produced due to the friction between the anchor and concrete. In Figure 4.5, Point A is the peak value of the applied load, N_{test}, and Point B represents the moment at which the concrete breakout cone developed. After Point B, displacement of the anchor increased rapidly, and the applied load dropped significantly. The data after this moment is not shown in the plot of Figure 4.5 because the displacement measuring device (i.e., LVDT stand) moved from its position due to the abrupt displacement of the anchor when the cone formed.

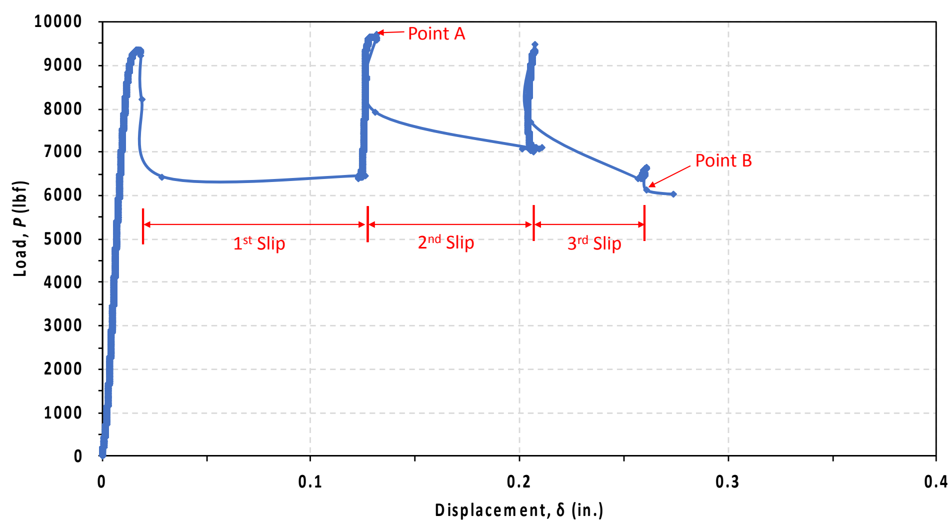


Figure 4.5: Load-displacement behavior of displacement-controlled anchors with abrupt slips

The other displacement-controlled anchors exhibited a different behavior. One of the displacement-controlled anchors in shale all-lightweight concrete and four of the anchors in clay all-lightweight concrete behaved similar to the load-displacement behavior described in Section 4.3.3.3. The rest of the displacement-controlled anchors behaved similar to the typical load-displacement behavior for concrete breakout failures (Section 4.3.3.1).

4.3.3.3 Load-Displacement Behavior of Anchors with Large Slip

Some of the anchors exhibited a behavior characterized by a large slip during the test. This behavior was observed for anchors of all four anchor types. Nevertheless, a majority of the anchors experienced the typical behavior of anchors with concrete breakout failures, as described in Section 4.3.3.1. Figure 4.6 shows an example of load-displacement curve for a torque-controlled expansion anchor the experienced a large slip. As shown in the figure, after a load of approximate 3000 lbf (Point C) was applied to the anchor, the anchor began to gradually slip. The rate of the displacement increased as the applied load increased. For the torque-controlled anchors, it is expected that the expansion clip of the anchor experienced additional expansion due to the cone of the anchor pulling farther into the clip. Finally, near the end of the test, the anchor experienced a concrete breakout failure. Point A in Figure 4.6 is the maximum applied load, N_{test}, and Point B represents the moment when the concrete breakout cone developed. There is no significant load drop that can be observed between Points A and B.

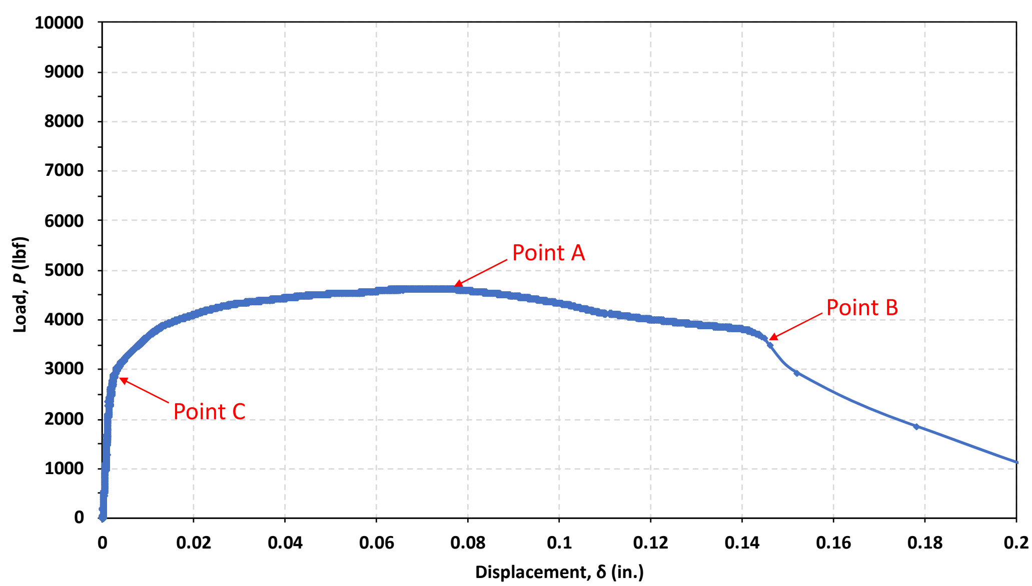


Figure 4.6: Load-displacement behavior for an anchor with large slip

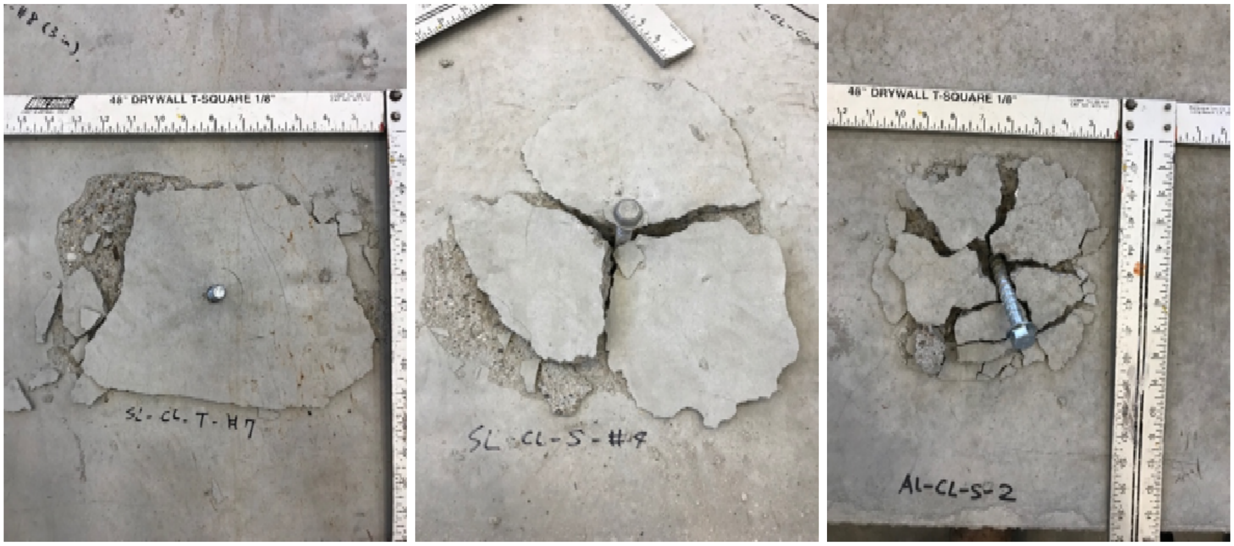
4.3.4 Concrete Breakout Failure

Concrete breakout is a brittle failure mechanism and results in a complete loss of load-carrying capacity. A concrete breakout failure is characterized by the formation of a concrete breakout cone. Figure 4.7 shows an anchor before and after the development of a breakout cone.

(a): Before concrete breakout failure (b): After concrete breakout failure

Figure 4.7: Typical concrete breakout failure of anchor in tension

Examples of typical concrete breakout cones are shown in Figure 4.8(a) and Figure 4.9(a). Unlike the uncracked surface of the cone shown in Figure 4.8(a), some concrete breakout cones experience cracks that radiate from the center of the breakout cone where the anchor is installed, as shown in Figure 4.8(b). The concrete breakout cones in the clay all-lightweight concrete specimens broke into many pieces, as shown in Figure 4.8(c). Additional discussion of the clay all-lightweight specimens is provided in Section 4.3.6.



(a) Typical concrete breakout

(b) Cracks through concrete breakout cone

(c) Concrete breakout of clay all-lightweight concrete

Figure 4.8: Top side of concrete breakout cones

(a) Upside-down concrete breakout cone

(b) Concrete breakout cone of screw anchor

Figure 4.9: Concrete breakout cones

A typical concrete breakout cone of a screw anchor tested during the experimental program is shown in Figure 4.9(b). Unlike the typical concrete breakout cone presented in Figure 4.9(a) for other anchor types, the concrete breakout cone does not initiate near the tip of the anchor but farther along its length, resulting in a smaller cone.

4.3.5 Angles of Concrete Breakout Failure Cones

The angle of each concrete breakout cone was measured using an angle finder protractor. The angle of each concrete breakout cone, θ, illustrated in Figure 4.10 was measured at four locations separated by 90 degrees around the cone. The four values were averaged to calculate the value of θ_{avg} for the cone. The value of θ_{avg} for each cone is provided in Table 4.12 through Table 4.15. Furthermore, the average angle considering each breakout cone for a specific anchor and concrete type is presented in the tables. In the Concrete Capacity Design (CCD) Method introduced by Fuchs et al. (1995), the breakout strength calculations for anchors in normalweight concrete is based on a model of an idealized breakout cone with an angle of approximately 35 degrees. As presented in the tables, the breakout cones of most anchors had an angle of less than 35 degrees. The most distinct trend is exhibited by the angles corresponding to the tests on cast-in anchors. The angles of the concrete breakout cones in the all-lightweight concrete are smaller than those of the sand-lightweight concrete. The normalweight concrete resulted in the largest angles on average.

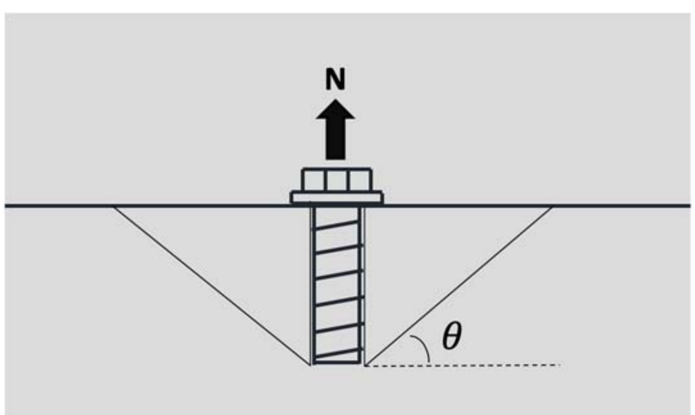


Figure 4.10 Angle, θ, of concrete breakout cone

Table 4.12: Averaged concrete breakout angles, θ_{avg}, of torque-controlled anchors

Normalweight Concrete (NW)		**ID**	T1	T2	T3	T4	T5				Avg
		$\boldsymbol{\theta_{avg}}$	37	19	33	33	24				29
		ID	T11	T12	T13	T14	T15				Avg
		$\boldsymbol{\theta_{avg}}$	33	33	28	35	29				32
Sand-Lightweight (SL)	**Shale (SH)**	**ID**	T1	T2	T3	T4	T5				Avg
		$\boldsymbol{\theta_{avg}}$	30	29	24	30	30				28
		ID	T11	T12	T13	T14	T16				Avg
		$\boldsymbol{\theta_{avg}}$	29	34	22	25	22				26
	Clay (CL)	**ID**	T1	T2	T3	T4	T5	T6	T7		Avg
		$\boldsymbol{\theta_{avg}}$	27	25	27	35	23	32	30		29
		ID	T11	T12	T13	T14	T15				Avg
		$\boldsymbol{\theta_{avg}}$	48	44	29	30	38				38
	Slate (SL)	**ID**	T1	T2	T3	T4	T6				Avg
		$\boldsymbol{\theta_{avg}}$	33	19	21	38	41				30
		ID	T11	T12	T13	T14	T15				Avg
		$\boldsymbol{\theta_{avg}}$	29	26	24	34	26				28
All-Lightweight (AL)	**Shale (SH)**	**ID**	T1	T2	T3	T4	T5				Avg
		$\boldsymbol{\theta_{avg}}$	19	33	22	25	22				30
		ID	T11	T12	T13	T14	T16				Avg
		$\boldsymbol{\theta_{avg}}$	33	27	32	24	33				24
	Clay (CL)	**ID**	T1	T2	T3	T4	T6				Avg
		$\boldsymbol{\theta_{avg}}$	36	36	33	41	46				38
		ID	T11	T12	T13	T14	T16				Avg
		$\boldsymbol{\theta_{avg}}$	26	24	29	26	30				27
	Slate (SL)	**ID**	T1	T2	T3	T4	T7				Avg
		$\boldsymbol{\theta_{avg}}$	32	47	24	56	27				37
		ID	T11	T12	T13	T14	T17				Avg
		$\boldsymbol{\theta_{avg}}$	25	40	38	44	50				38

Table 4.13: Averaged concrete breakout angles, θ_{avg}, of displacement-controlled anchors

Normalweight Concrete (NW)		**ID**	D1	D2	D4	D5	D6	D7			Avg
		$\boldsymbol{\theta_{avg}}$	36	38	40	24	19	22			30
Sand-Lightweight (SL)	**Shale (SH)**	**ID**	D1	D2	D3	D4	D8				Avg
		$\boldsymbol{\theta_{avg}}$	29	25	22	20	30				25
	Clay (CL)	**ID**	D1	D2	D3	D4	D5	D6	D7		Avg
		$\boldsymbol{\theta_{avg}}$	24	33	26	38	23	33	25		29
	Slate (SL)	**ID**	D1	D2	D3	D4	D8				Avg
		$\boldsymbol{\theta_{avg}}$	14	19	23	22	25				21
All-Lightweight (AL)	**Shale (SH)**	**ID**	D1	D2	D3	D4	D5				Avg
		$\boldsymbol{\theta_{avg}}$	15	16	21	16	37				21
	Clay (CL)	**ID**	D1	D2	D3	D4	D7				Avg
		$\boldsymbol{\theta_{avg}}$	40	34	54	29	44				40
	Slate (SL)	**ID**	D1	D2	D3	D4	D7				Avg
		$\boldsymbol{\theta_{avg}}$	21	21	45	15	18				24

Table 4.14: Averaged concrete breakout angles, θ_{avg}, of screw anchors

Normalweight Concrete (NW)		**ID**	S1	S2	S4	S5	S7				Avg
		$\boldsymbol{\theta_{avg}}$	34	27	26	36	29				31
Sand-Lightweight (SL)	**Shale (SH)**	**ID**	S1	S2	S3	S4	S7				Avg
		$\boldsymbol{\theta_{avg}}$	17	27	31	17	22				24
	Clay (CL)	**ID**	S2	S3	S4	S5	S6				Avg
		$\boldsymbol{\theta_{avg}}$	34	31	34	30	33				31
	Slate (SL)	**ID**	S1	S2	S3	S4	S6				Avg
		$\boldsymbol{\theta_{avg}}$	38	33	23	33	25				30
All-Lightweight (AL)	**Shale (SH)**	**ID**	S1	S2	S3	S4	S5				Avg
		$\boldsymbol{\theta_{avg}}$	24	26	28	23	32				27
	Clay (CL)	**ID**	S1	S2	S3	S4	S8				Avg
		$\boldsymbol{\theta_{avg}}$	36	34	37	27	40				35
	Slate (SL)	**ID**	S1	S2	S3	S4	S5				Avg
		$\boldsymbol{\theta_{avg}}$	22	28	25	26	27				25

Table 4.15: Averaged concrete breakout angles, θ_{avg}, of cast-in anchors

Concrete	Aggregate										
Normalweight Concrete (NW)		**ID**	C1	C2	C3	C4	C5	C6	C7	C8	Avg
		$\boldsymbol{\theta_{avg}}$	36	25	36	25	31	33	36	38	32
Sand-Lightweight (SL)	**Shale (SH)**	**ID**	C1	C2	C3	C4	C5	C6	C7	C8	Avg
		$\boldsymbol{\theta_{avg}}$	19	24	24	30	28	24	27	29	29
	Clay (CL)	**ID**	C1	C2	C3	C4	C5	C6	C7	C8	Avg
		$\boldsymbol{\theta_{avg}}$	29	21	31	25	26	25	27	27	26
	Slate (SL)	**ID**	C1	C2	C3	C4	C5	C6	C7		Avg
		$\boldsymbol{\theta_{avg}}$	28	28	28	23	30	22	31		27
All-Lightweight (AL)	**Shale (SH)**	**ID**	C1	C2	C3	C4	C5	C6	C7		Avg
		$\boldsymbol{\theta_{avg}}$	25	26	22	17	23	23	21		22
	Clay (CL)	**ID**	C1	C2	C3	C4	C5	C6	C7	C8	Avg
		$\boldsymbol{\theta_{avg}}$	27	19	24	19	21	16	28	20	22
	Slate (SL)	**ID**	C1	C2	C3	C4	C5	C6	C7		Avg
		$\boldsymbol{\theta_{avg}}$	19	34	28	28	21	31	22		26

4.3.6 Cracking of Clay All-Lightweight Specimens

The clay all-lightweight slabs suffered cracking during curing and/or storage prior to being transported to the laboratory. As shown in Figure 4.11(a), the surface of the slabs had a random crack pattern. The cracks were initially believed to be due to crazing and likely to be relatively shallow. However, after coring cylinders with 4-in. diameters, the cracks were observed to have depths of up to 3 in. along the edges of the cylinders. The cracks in a cored cylinder are shown in Figure 4.11(b). The cracking was determined to be likely caused by freezing and thawing early in the life of the concrete. Similar to the crumbled concrete in Figure 4.8(c), all of the other anchors tested in the clay all-lightweight slabs resulted in cones that broke into several pieces. All results of the anchors tested in the clay all-lightweight slabs are reported in Chapter 4 and included for comparison purposes in Chapter 5. However, these results are not included in the calculations leading to recommended reduction factors considering that the ultimate loads applied to the anchors are relatively low and were likely affected by the cracking.

(a) Slab specimen (b) Cored cylinder

Figure 4.11: Cracking of clay all-lightweight specimen (cracks have been marked for visibility)

4.4 Summary

The details of the test results, including ultimate failure loads, for each anchor of the experimental program were presented in this chapter along with measured properties of the seven types of concrete. Moreover, typical load-displacement curves representative of the behavior of the anchors were provided as well as descriptions and angles corresponding to the concrete breakout cones. In Chapter 5, comprehensive, in-depth analyses and comparisons of the test results are presented.

For the clay all-lightweight concrete specimens, cracks on the surface of the concrete likely developed due to freezing and thawing. Although the results of the anchor tests in clay all-lightweight concrete are presented in Chapter 5, the results will be excluded from the development of recommended reduction factors.

CHAPTER 5. ANALYSIS OF TEST RESULTS

5.1 Introduction

The results of the anchor tests performed in seven types of concrete are compared and discussed in detail in this chapter. A basic method to analyze the strength data from anchor tests collected during the experimental program and gathered from other sources was the Concrete Capacity Design (CCD) Method, introduced in Section 1.4. This method allows for normalization of the data to facilitate comparison of results from various anchors installed in different concrete types included in this research. In the chapter, broad and in-depth comparisons for both post-installed and cast-in anchors across different concrete types and anchor manufacturers are presented.

5.2 Analysis Method

To analyze the test data, the CCD method as presented in Equation 1-2 was used. In this equation, the value of f'_c is taken as the average of the concrete compressive strength test results as indicated in Table 4.3. Furthermore, the values of h_{ef} used in the equation were obtained from data reported in Table 4.4 through Table 4.11. The value of N_{no} has been calculated for each anchor and is presented in Table 5.1 through Table 5.6.

5.2.1 Modification Factor, λ_{LWF}, for Anchors in Lightweight Concrete

A modification factor, λ_{LWF}, can be calculated by dividing the experimental capacity of an anchor, N_{test}, by the predicted strength, N_{no}, based on the CCD method. The modification factor, λ_{LWF}, represents a reduction in strength of an anchor due to the influence of lightweight concrete. The expression for λ_{LWF} is presented as follows:

$$\lambda_{LWF} = \frac{N_{test}}{N_{no}} \tag{5-1}$$

Here, the value of k_{nc} in the function for N_{no} in Equation 1-2 is based on the mean strength of anchors in tension with concrete breakout failures (i.e., 35 for post-installed anchors and 40 for cast-in anchors; see Section 1.4). The modification factor, λ_{LWF}, for each anchor of the test program is provided in Table 5.1 to Table 5.6. By calculating λ_{LWF}, the result of each anchor test is effectively normalized by the concrete compressive strength (in the form of $\sqrt{f_c'}$) and the effective embedment depth of the anchor (in the form of $h_{ef}^{1.5}$). This allows for direct comparisons to be made between different anchors installed in different types of concrete. Values of λ_{LWF} are also calculated for the tests in normalweight concrete. The values will be used to normalize the data from tests in lightweight concrete to the results of tests in normalweight concrete when calculating recommended reduction factors.

5.2.2 Reduction Factor, *R*, for Anchors in Lightweight Concrete

As explained in Section 1.3, the values of λ_a specified in Section 17.2.4.1 of ACI 318-19 for anchors in lightweight concrete consist of the lightweight concrete modification factor, λ, also specified in the code, multiplied by an additional factor (currently 1.0 for cast-in anchors and 0.8 for expansion and screw anchors). Analogous to this additional factor, a reduction factor, *R*, can be calculated for each anchor test by dividing the modification factor λ_{LWF} by the value of λ as defined in ACI 318-19. The expression for *R* is presented as follows:

$$R = \frac{\lambda_{LWF}}{\lambda} \tag{5-2}$$

The factor, *R*, represents a potential reduction in the strength of an anchor beyond the reduction defined by λ, which may be needed due to different mechanisms of interaction between different types of anchors and concretes. The reduction factor, *R*, for each anchor is presented in Table 5.1 through Table 5.6. Here, the value of λ is determined in accordance with Table 19.2.4.1(b) of ACI 318-19 (see Table 1.1 in this thesis). The values of *R* calculated using the λ values based on concrete equilibrium density (see Table 1.2) are discussed in Section 5.8.2.

Table 5.1: Analysis results of tests on torque-controlled anchors

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Concrete Type	**Test ID**	**N_{test} (lbf)**	**N_{no} (lbf)**	**λ_{LWF} Col (3) / Col (4)**	**λ**	***R* Col (5) / Col (6)**
Normalweight	NW-T-B1	8236	8520	0.967	1.00	0.967
	NW-T-C1	9781	8520	1.148		1.148
	NW-T-D1	7472	8520	0.877		0.877
	NW-T-A1	9394	8520	1.103		1.103
	NW-T-B2	6559	5884	1.122		1.122
	NW-T-B3*	7702	8610	0.894		0.894
	NW-T-C2*	7109	8610	0.826		0.826
	NW-T-D2*	5617	8610	0.652		0.652
	NW-T-A2*	6767	8610	0.786		0.786
	NW-T-B4*	7307	8610	0.849		0.849

** Anchor tested on finished side of slab*

Table 5.2: Analysis results of tests on torque-controlled anchors (Continued)

(1) Concrete Type	(2) Test ID	(3) N_{test} (lbf)	(4) N_{no} (lbf)	(5) λ_{LWF} Col (3) / Col (4)	(6) λ	(7) *R* Col (5) / Col (6)
Shale Sand-Lightweight	SL-SH-T-B1	6714	7478	0.898	0.85	1.056
	SL-SH-T-C1	5711	5933	0.963		1.132
	SL-SH-T-D1	4453	5934	0.750		0.883
	SL-SH-T-A1	4651	5208	0.893		1.051
	SL-SH-T-A2	4524	5208	0.869		1.022
	SL-SH-T-B2*	6426	8763	0.733		0.863
	SL-SH-T-C2*	5142	8763	0.587		0.690
	SL-SH-T-D2*	5727	8763	0.654		0.769
	SL-SH-T-A3*	5686	8763	0.649		0.763
	SL-SH-T-C3*	5217	8763	0.595		0.700
Clay Sand-Lightweight	SL-CL-T-B1	6062	7625	0.795	0.85	0.935
	SL-CL-T-C1	5780	7625	0.758		0.892
	SL-CL-T-D1	5590	6922	0.808		0.950
	SL-CL-T-A1	5517	6134	0.899		1.058
	SL-CL-T-B2	6430	7625	0.843		0.992
	SL-CL-T-C2	5778	5265	1.097		1.291
	SL-CL-T-D2	6250	7625	0.820		0.964
	SL-CL-T-B3*	5583	7623	0.732		0.862
	SL-CL-T-C3*	6089	7623	0.799		0.940
	SL-CL-T-D3*	4938	7623	0.648		0.762
	SL-CL-T-A2*	5458	7623	0.716		0.842
	SL-CL-T-D4*	5489	7623	0.720		0.847
Slate Sand-Lightweight	SL-SL-T-B1	6373	7303	0.873	0.85	1.027
	SL-SL-T-C1	5484	5795	0.946		1.113
	SL-SL-T-D1	4743	5795	0.818		0.963
	SL-SL-T-A1	4218	5086	0.829		0.976
	SL-SL-T-C2	4798	5795	0.828		0.974
	SL-SL-T-B2*	6824	8902	0.767		0.902
	SL-SL-T-C3*	6900	8902	0.775		0.912
	SL-SL-T-D2*	5363	8902	0.602		0.709
	SL-SL-T-A2*	6548	8902	0.736		0.865
	SL-SL-T-B3*	6546	8902	0.735		0.865

** Anchor tested on finished side of slab*

Table 5.3: Analysis results of tests on torque-controlled anchors (Continued)

(1) Concrete Type	(2) Test ID	(3) N_{test} (lbf)	(4) N_{no} (lbf)	(5) λ_{LWF} Col (3) / Col (4)	(6) λ	(7) *R* Col (5) / Col (6)
Shale All-Lightweight	AL-SH-T-B1	4634	6376	0.727	0.75	0.969
	AL-SH-T-C1	3346	5060	0.661		0.882
	AL-SH-T-D1	3561	5060	0.704		0.938
	AL-SH-T-A1	2761	4441	0.622		0.829
	AL-SH-T-B2	4576	6376	0.718		0.957
	AL-SH-T-B3*	4902	7824	0.627		0.835
	AL-SH-T-C2*	4294	7824	0.549		0.732
	AL-SH-T-D2*	4213	7824	0.538		0.718
	AL-SH-T-A2*	4841	7824	0.619		0.825
	AL-SH-T-C3*	4485	7824	0.573		0.764
Clay All-Lightweight	AL-CL-T-B1	3544	6102	0.581	0.75	0.774
	AL-CL-T-C1	3498	4842	0.722		0.963
	AL-CL-T-D1	2749	4842	0.568		0.757
	AL-CL-T-A1	2557	4250	0.602		0.802
	AL-CL-T-C2	3238	4842	0.669		0.892
	AL-CL-T-B2*	4435	6912	0.642		0.856
	AL-CL-T-C3*	4579	6912	0.662		0.883
	AL-CL-T-D2*	3746	6912	0.542		0.723
	AL-CL-T-A2*	3903	6912	0.565		0.753
	AL-CL-T-C4*	3982	6912	0.576		0.768
Slate All-Lightweight	AL-SL-T-B1	4779	6056	0.789	0.75	1.052
	AL-SL-T-C1	4343	4806	0.904		1.205
	AL-SL-T-D1	3708	4806	0.772		1.029
	AL-SL-T-A1	3476	4218	0.824		1.099
	AL-SL-T-D2	3787	4806	0.788		1.051
	AL-SL-T-B2*	5431	7301	0.744		0.992
	AL-SL-T-C2*	4861	7301	0.666		0.888
	AL-SL-T-D3*	4923	7301	0.674		0.899
	AL-SL-T-A2*	4273	7301	0.585		0.780
	AL-SL-T-D4*	4846	7301	0.664		0.885

** Anchor tested on finished side of slab*

Table 5.4: Analysis results of tests on displacement-controlled anchors

(1) Concrete Type	(2) Test ID	(3) N_{test} (lbf)	(4) N_{no} (lbf)	(5) λ_{LWF} Col (3) / Col (4)	(6) λ	(7) *R* Col (5) / Col (6)
Normalweight	NW-D-B1	9259	8520	1.087	1.00	1.087
	NW-D-C1	9723	8520	1.141		1.141
	NW-D-D1	10,070	8520	1.182		1.182
	NW-D-A1	9307	8520	1.092		1.092
	NW-D-B2	9678	8520	1.136		1.136
Shale Sand-Lightweight	SL-SH-D-B1	7817	9135	0.856	0.85	1.007
	SL-SH-D-C1	9377	9135	1.026		1.208
	SL-SH-D-D1	7646	9135	0.837		0.985
	SL-SH-D-A1	8173	9135	0.895		1.053
	SL-SH-D-A2	8226	9135	0.900		1.059
Clay Sand-Lightweight	SL-CL-D-A1	7868	7625	1.032	0.85	1.214
	SL-CL-D-B1	7897	7625	1.036		1.218
	SL-CL-D-C1	8960	7625	1.175		1.382
	SL-CL-D-D1	7008	7625	0.919		1.081
	SL-CL-D-A2	8554	7625	1.122		1.320
Slate Sand-Lightweight	SL-SL-D-B1	7458	8923	0.836	0.85	0.983
	SL-SL-D-C1	9160	8923	1.027		1.208
	SL-SL-D-D1	7670	8923	0.860		1.011
	SL-SL-D-A1	8691	8923	0.974		1.146
	SL-SL-D-C2	9625	8923	1.079		1.269
	SL-SL-D-C3	8746	8923	0.980		1.153
Shale All-Lightweight	AL-SH-D-B1	5674	7790	0.728	0.75	0.971
	AL-SH-D-C1	6476	7790	0.831		1.108
	AL-SH-D-D1	5594	7790	0.718		0.957
	AL-SH-D-A1	6587	7790	0.846		1.127
	AL-SH-D-B2	5920	7790	0.760		1.013
Clay All-Lightweight	AL-CL-D-B1	3992	7455	0.535	0.75	0.714
	AL-CL-D-C1	4020	7455	0.539		0.719
	AL-CL-D-D1	3886	7455	0.521		0.695
	AL-CL-D-A1	5092	7455	0.683		0.911
	AL-CL-D-D2	4769	7455	0.640		0.853
Slate All-Lightweight	AL-SL-D-B1	6175	7399	0.835	0.75	1.113
	AL-SL-D-C1	7615	7399	1.029		1.372
	AL-SL-D-D1	5097	7399	0.689		0.919
	AL-SL-D-A1	6758	7399	0.913		1.218
	AL-SL-D-D2	6705	7399	0.906		1.208
	AL-SL-D-D3	6599	7399	0.892		1.189

Table 5.5: Analysis results of tests on screw anchors

(1) Concrete Type	(2) Test ID	(3) N_{test} (lbf)	(4) N_{no} (lbf)	(5) λ_{LWF} Col (3) / Col (4)	(6) λ	(7) *R* Col (5) / Col (6)
Normalweight	NW-S-B1	9223	9563	0.964	1.00	0.964
	NW-S-C1	6895	9414	0.732		0.732
	NW-S-D1	9863	9630	1.024		1.024
	NW-S-A1	9923	11,200	0.886		0.886
	NW-S-B2	10,072	9563	1.053		1.053
	NW-S-D2	9849	9630	1.023		1.023
Shale Sand-Lightweight	SL-SH-S-B1	7841	10,253	0.765	0.85	0.900
	SL-SH-S-C1	5304	10,093	0.526		0.618
	SL-SH-S-D1	7189	10,324	0.696		0.819
	SL-SH-S-A1	8123	12,008	0.676		0.796
	SL-SH-S-D2	7049	10,324	0.683		0.803
Clay Sand-Lightweight	SL-CL-S-C1	6681	8425	0.793	0.85	0.933
	SL-CL-S-D1	6871	8618	0.797		0.938
	SL-CL-S-A1	6611	10,024	0.660		0.776
	SL-CL-S-B1	6950	8558	0.812		0.955
	SL-CL-S-B2*	6669	8558	0.779		0.917
	SL-CL-S-A1*	5853	10,024	0.584		0.687
Slate Sand-Lightweight	SL-SL-S-B1	7345	10,015	0.733	0.85	0.863
	SL-SL-S-C1	4757	9859	0.483		0.568
	SL-SL-S-D1	8019	10,084	0.795		0.936
	SL-SL-S-A1	4872	11,729	0.415		0.489
	SL-SL-S-C2	5414	9859	0.549		0.646
Shale All-Lightweight	AL-SH-S-B1	5479	8743	0.627	0.75	0.836
	AL-SH-S-C1	3924	8607	0.456		0.608
	AL-SH-S-D1	4974	8804	0.565		0.753
	AL-SH-S-A1	4432	10,240	0.433		0.577
	AL-SH-S-B2	4502	8743	0.515		0.687
Clay All-Lightweight	AL-CL-S-B1	4550	8367	0.544	0.75	0.725
	AL-CL-S-C1	4466	8237	0.542		0.723
	AL-CL-S-D1	3881	8425	0.461		0.614
	AL-CL-S-A1	5412	9800	0.552		0.736
	AL-CL-S-A2	4810	9800	0.491		0.654
Slate All-Lightweight	AL-SL-S-B1	6380	8304	0.768	0.75	1.024
	AL-SL-S-C1	4914	8175	0.601		0.801
	AL-SL-S-D1	5590	8362	0.669		0.891
	AL-SL-S-A1	5121	9726	0.527		0.702
	AL-SL-S-D2	6069	8362	0.726		0.968
	AL-SL-S-A2	4870	9726	0.501		0.668

** Anchor tested on finished side of slab*

Table 5.6: Analysis results of tests on cast-in anchors

(1) Concrete Type	(2) Test ID	(3) N_{test} (lbf)	(4) N_{no} (lbf)	(5) λ_{LWF} Col (3) / Col (4)	(6) λ	(7) *R* Col (5) / Col (6)
Normalweight	NW-C-1	9548	10,253	0.931	1.00	0.931
	NW-C-2	9534	10,253	0.930		0.930
	NW-C-3	9649	10,253	0.941		0.941
	NW-C-4	10,263	10,253	1.001		1.001
	NW-C-5	9449	10,253	0.922		0.922
	NW-C-6	10,116	10,253	0.987		0.987
	NW-C-7	10,314	10,253	1.006		1.006
	NW-C-8	9620	10,253	0.938		0.938
Shale Sand-Lightweight	SL-SH-C-1	7078	10,993	0.644	0.85	0.758
	SL-SH-C-2	7013	10,993	0.638		0.751
	SL-SH-C-3	7401	10,993	0.673		0.792
	SL-SH-C-4	7068	10,993	0.643		0.756
	SL-SH-C-5	7651	10,993	0.696		0.819
	SL-SH-C-6	7887	10,993	0.717		0.844
	SL-SH-C-7	6842	10,993	0.622		0.732
	SL-SH-C-8	6866	10,993	0.625		0.735
Clay Sand-Lightweight	SL-CL-C-1	7254	9176	0.791	0.85	0.930
	SL-CL-C-2	7653	9176	0.834		0.981
	SL-CL-C-3	7104	9176	0.774		0.911
	SL-CL-C-4	6803	9176	0.741		0.872
	SL-CL-C-5	7064	9176	0.770		0.906
	SL-CL-C-6	7451	9176	0.812		0.955
	SL-CL-C-7	6936	9176	0.756		0.889
	SL-CL-C-8	6958	9176	0.758		0.892
Slate Sand-Lightweight	SL-SL-C-1	7504	10,737	0.699	0.85	0.822
	SL-SL-C-2	7550	10,737	0.703		0.827
	SL-SL-C-3	7704	10,737	0.717		0.844
	SL-SL-C-4	8339	10,737	0.777		0.914
	SL-SL-C-5	8065	10,737	0.751		0.884
	SL-SL-C-6	7569	10,737	0.705		0.829
	SL-SL-C-7	7629	10,737	0.711		0.836

Table 5.6: Analysis results of tests on cast-in anchors (Continued)

(1) Concrete Type	(2) Test ID	(3) N_{test} (lbf)	(4) N_{no} (lbf)	(5) λ_{LWF} Col (3) / Col (4)	(6) λ	(7) *R* Col (5) / Col (6)
Shale All-Lightweight	AL-SH-C-1	4986	9374	0.532	0.75	0.709
	AL-SH-C-2	5727	9374	0.611		0.815
	AL-SH-C-3	5441	9374	0.580		0.774
	AL-SH-C-4	5239	9374	0.559		0.745
	AL-SH-C-5	5166	9374	0.551		0.735
	AL-SH-C-6	5085	9374	0.542		0.723
	AL-SH-C-7	5325	9374	0.568		0.757
Clay All-Lightweight	AL-CL-C-1	3917	8971	0.437	0.75	0.582
	AL-CL-C-2	4863	8971	0.542		0.723
	AL-CL-C-3	4338	8971	0.484		0.645
	AL-CL-C-4	4377	8971	0.488		0.651
	AL-CL-C-5	4475	8971	0.499		0.665
	AL-CL-C-6	4608	8971	0.514		0.685
	AL-CL-C-7	3915	8971	0.436		0.582
	AL-CL-C-8	4646	8971	0.518		0.691
Slate All-Lightweight	AL-SL-C-1	5759	8904	0.647	0.75	0.862
	AL-SL-C-2	6310	8904	0.709		0.945
	AL-SL-C-3	6255	8904	0.703		0.937
	AL-SL-C-4	6187	8904	0.695		0.927
	AL-SL-C-5	6098	8904	0.685		0.913
	AL-SL-C-6	6161	8904	0.692		0.923
	AL-SL-C-7	6163	8904	0.692		0.923

5.3 Comparison of Anchors in Concrete with Three Aggregate Types

A total of 47 post-installed anchors and 23 cast-in anchors were tested on the formed side of the sand-lightweight concrete slab specimens. A histogram of λ_{LWF} for all of the post-installed anchors and cast-in anchors tested on the formed side of the slab specimens during the experimental program in the three sand-lightweight concrete types is shown in Figure 5.1. The three types of coarse aggregate used in the mixtures are differentiated by color. From the histogram, it is observed that the different lightweight aggregate types influenced the performance of the anchors to some degree. As shown in the figure, the anchors in clay sand-lightweight experienced better performance compared to other two types of aggregate. Only one test performed in clay sand-lightweight concrete resulted in a λ_{LWF} value less than 0.7. A total of 11 tests performed in shale sand-lightweight aggregate correspond to values of λ_{LWF} less than 0.7. The results from the tests in slate sand-lightweight concrete includes two tests with λ_{LWF} values less than 0.5, with a minimum value of 0.415. Overall, based on the comparison, the effects of different lightweight aggregate types within sand-lightweight concrete mixtures should be considered further.

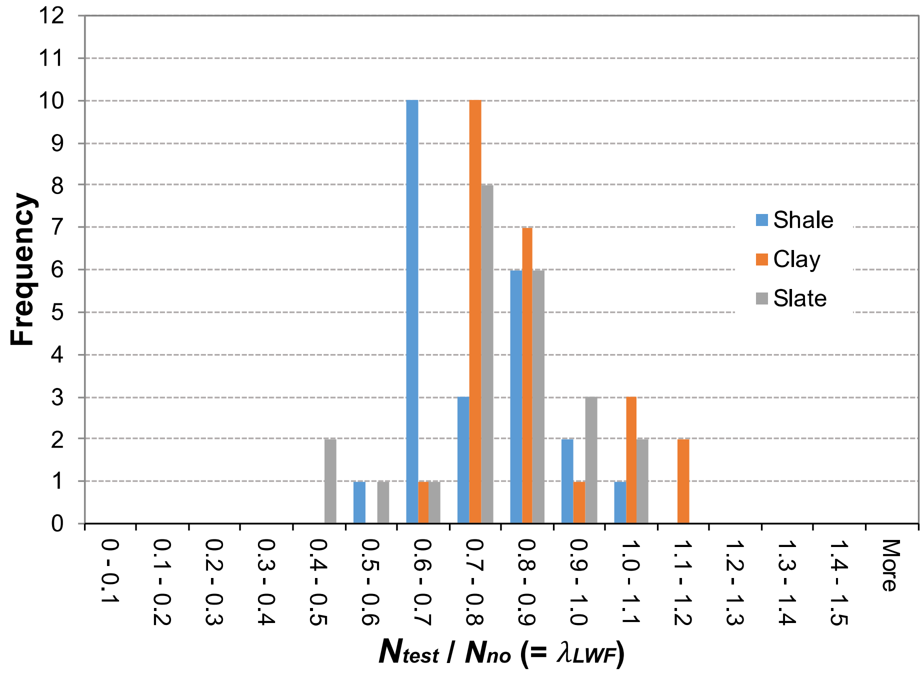


Figure 5.1: Histogram of λ_{LWF} for four anchor types in sand-lightweight concrete (tested on formed side)

A similar histogram of λ_{LWF} for 47 post-installed anchors and 22 cast-in anchors tested on the formed side of the all-lightweight concrete slab specimens with three aggregate types is presented in Figure 5.2. Comparing the data for anchors in shale and slate all-lightweight concrete, the values of λ_{LWF} for tests in slate all-lightweight concrete are generally greater than the values for tests in shale all-lightweight concrete. The relatively small values of λ_{LWF} for anchors in clay all-lightweight concrete were likely influenced by the cracking of the slab specimens (see Section 4.3.6). Again, the data suggest that the anchors were affected by the different aggregate types of the all-lightweight concrete mixtures.

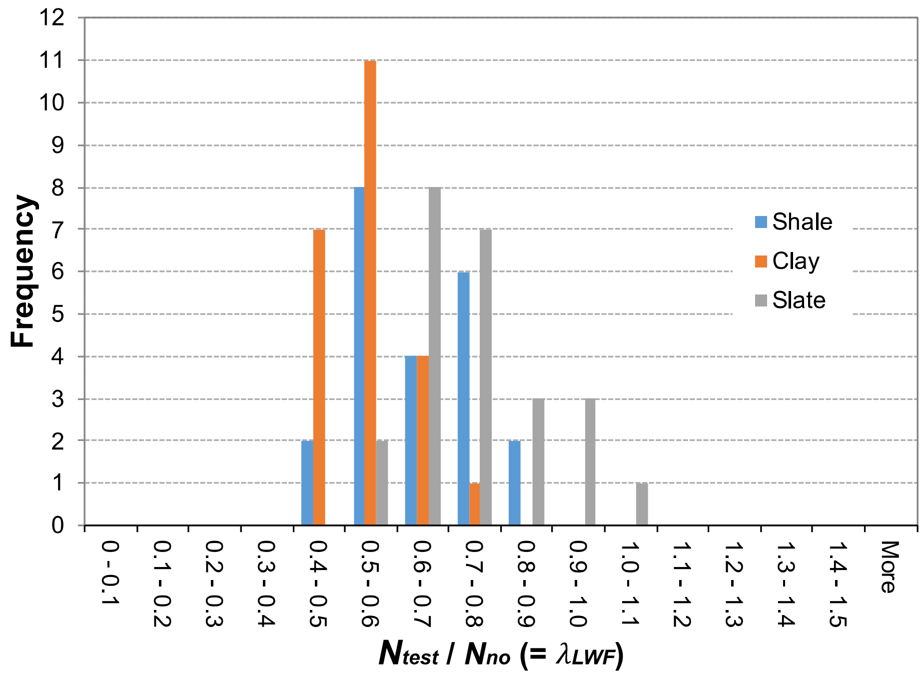
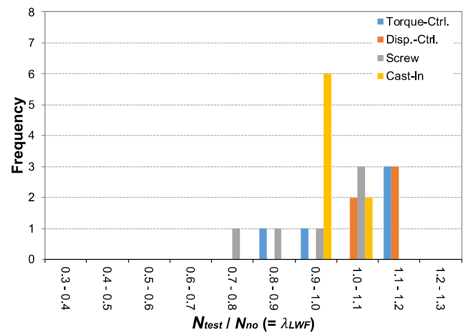


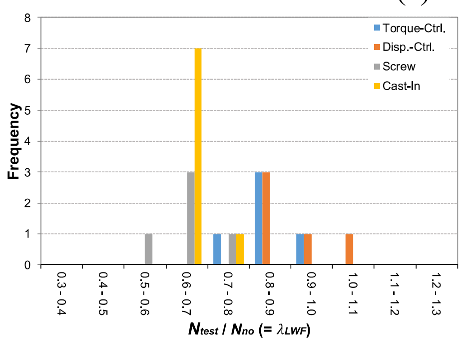
Figure 5.2: Histogram of λ_{LWF} for four anchor types in all-lightweight concrete (tested on formed side)

5.4 Comparison of Four Anchor Types in Seven Concrete Mixtures (Tested on Formed Side)

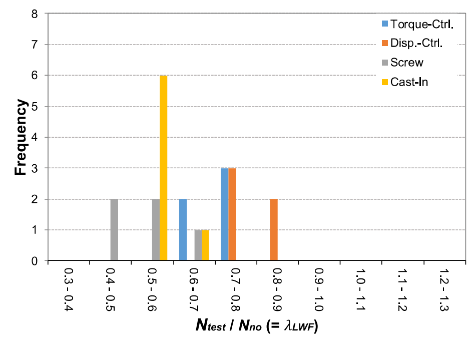
In this section, the data from the four anchor types tested on the formed side of the slab specimens in each of the seven concrete mixtures are compared. Histograms are presented in Figure 5.3 that provide the values of λ_{LWF} for the three types of post-installed anchors and the cast-in anchors in each of the seven types of concrete included in the experimental program. The four anchor types are differentiated by color.



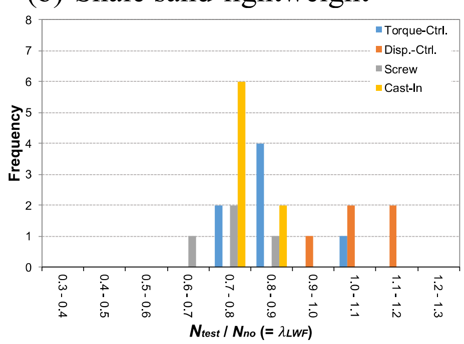
(a) Normalweight



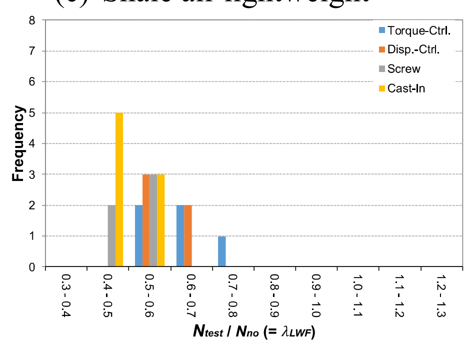
(b) Shale sand-lightweight



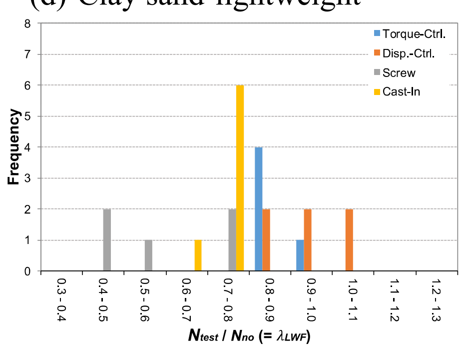
(c) Shale all-lightweight



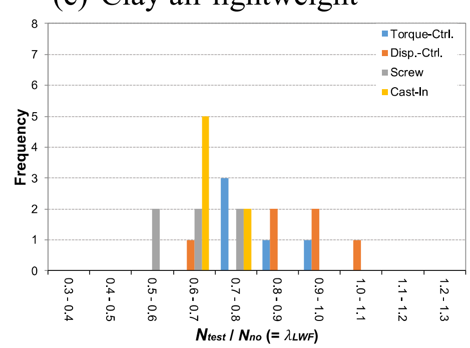
(d) Clay sand-lightweight



(e) Clay all-lightweight



(f) Slate sand-lightweight



(g) Slate all-lightweight

Figure 5.3: Histograms of λ_{LWF} for four anchor types in different concrete mixtures (tested on formed side)

From the plots, it can be observed that the concrete screw anchors generally have the lowest values of λ_{LWF} for the lightweight concrete mixtures compared to the other three types of anchors. Furthermore, the displacement-controlled anchors generally have higher λ_{LWF} values than the other three anchors types in lightweight concrete. Compared to the two types of expansion anchors, cast-in anchors consistently resulted in lower λ_{LWF} values. The tests in the clay all-lightweight concrete demonstrate somewhat different trends, likely due to the effect of the cracking that was observed (see Section 4.3.6). Compared to the other five types of lightweight concrete, the histogram for the normalweight concrete is unique (Figure 5.3(a)). Here, the screw anchor data are more closely aligned with the expansion anchor data when compared to the results from the tests in lightweight concrete. The displacement-controlled anchors, however, continue to present a higher average λ_{LWF} value compared to the other anchor types. A summary of the average values of λ_{LWF} and R for each anchor type in each concrete mixture is presented in Table 5.7. The coefficient of variation (COV) for the λ_{LWF} values is also provided. In general, the screw anchors exhibited a larger COV compared to the expansion and cast-in anchors.

Table 5.7: Summary of four anchor types in each type of concrete (tested on formed side)

Concrete	Anchor	$\lambda_{LWF,avg.}$	COV	Number of Tests	$R_{avg.}$
Normalweight	Torque-Controlled	1.043	11.2%	5	1.043
	Displacement-Controlled	1.128	3.5%	5	1.128
	Screw	0.947	12.8%	6	0.947
	Cast-In	0.957	3.6%	8	0.957
Shale Sand-Lightweight	Torque-Controlled	0.874	8.9%	5	1.029
	Displacement-Controlled	0.903	8.2%	5	1.062
	Screw	0.669	13.1%	5	0.787
	Cast-In	0.657	5.3%	8	0.773
Clay Sand-Lightweight	Torque-Controlled	0.860	13.3%	7	1.012
	Displacement-Controlled	1.057	9.3%	5	1.243
	Screw	0.768	9.3%	4	0.901
	Cast-In	0.780	4.0%	8	0.917
Slate Sand-Lightweight	Torque-Controlled	0.859	6.2%	5	1.010
	Displacement-Controlled	0.959	9.8%	6	1.128
	Screw	0.595	27.4%	5	0.700
	Cast-In	0.723	4.1%	7	0.851

Table 5.7: Summary of four anchor types in each type of concrete (tested on formed side) (Continued)

Concrete	**Anchor**	$\lambda_{LWF,avg.}$	**COV**	**Number of Tests**	$R_{avg.}$
Shale All-Lightweight	Torque-Controlled	0.686	6.4%	5	0.915
	Displacement-Controlled	0.777	7.6%	5	1.036
	Screw	0.519	15.3%	5	0.692
	Cast-In	0.563	4.7%	7	0.751
Clay All-Lightweight	Torque-Controlled	0.628	10.4%	5	0.838
	Displacement-Controlled	0.584	12.5%	5	0.778
	Screw	0.518	7.8%	5	0.691
	Cast-In	0.490	7.7%	8	0.653
Slate All-Lightweight	Torque-Controlled	0.815	6.5%	5	1.087
	Displacement-Controlled	0.877	12.8%	6	1.170
	Screw	0.632	17.0%	6	0.842
	Cast-In	0.689	2.9%	7	0.918

A comparison between the four anchor types in the seven concrete mixtures is presented in a different manner in Figure 5.4. In the figure, each bar corresponds with a row in Table 5.7. The general reduction in strength of anchors in lightweight concrete compared to those in normalweight concrete is evident. Furthermore, the general reduction of anchors in all-lightweight concrete compared to sand-lightweight concrete is observed. Considering the sand-lightweight concrete mixtures, the clay sand-lightweight concrete resulted in the largest values of λ_{LWF} for the displacement-controlled, screw, and cast-in anchors, but the shale sand-lightweight concrete resulted in a slightly larger λ_{LWF} value for the torque-controlled anchors compared to the clay and slate sand-lightweight mixtures. Considering the three types of all-lightweight concrete, the slate all-lightweight concrete provided superior performance when compared to shale and clay all-lightweight concrete. Only small differences exist between the anchor performance in slate sand-lightweight concrete and slate all-lightweight concrete. In fact, the average value of λ_{LWF} for screw anchors in slate all-lightweight concrete is larger than the λ_{LWF} value for screw anchors in slate sand-lightweight concrete.

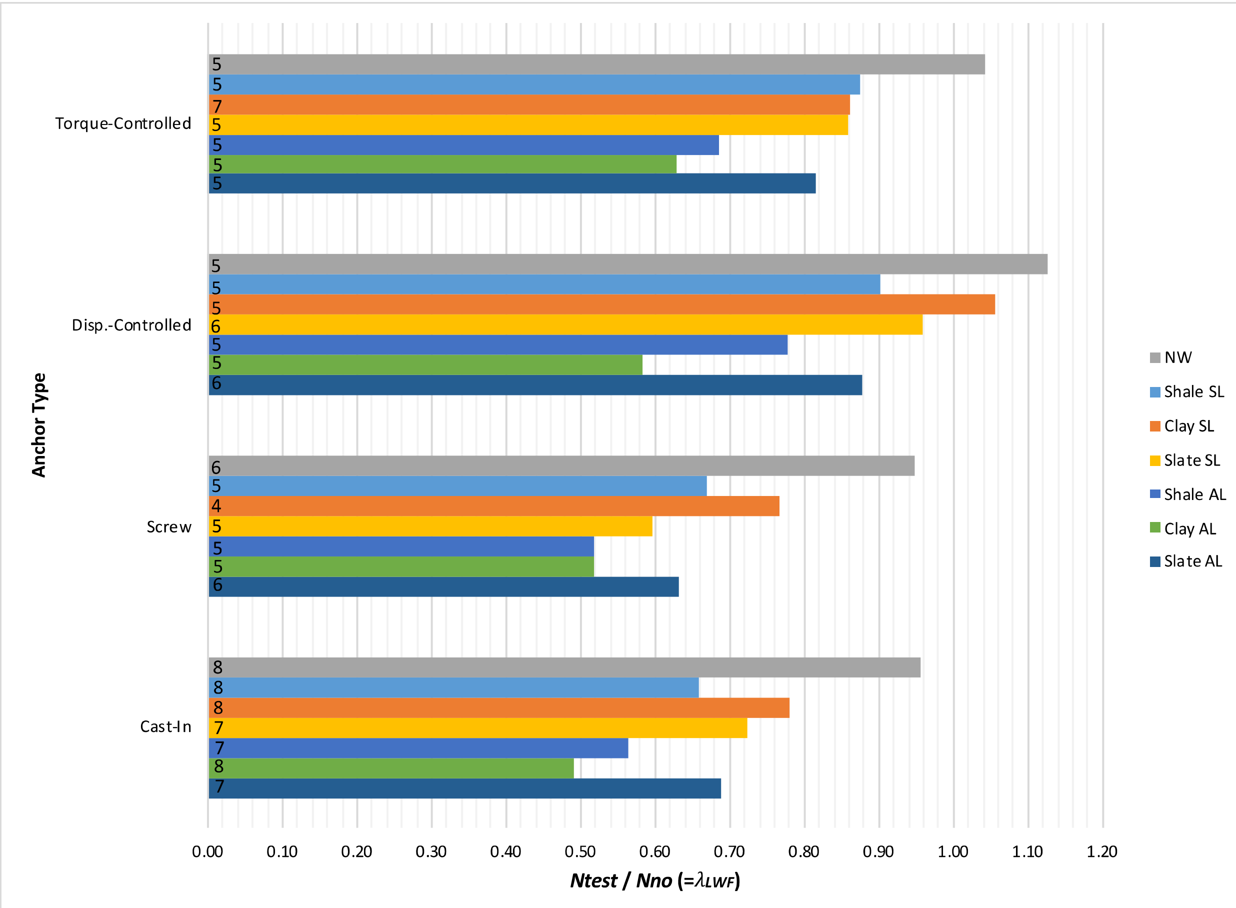


Figure 5.4: Bar chart of four anchor types in seven concrete types (tested on formed side)

The results presented in Figure 5.3, Figure 5.4, and Table 5.7 all seem to indicate that the strengths of screw anchors are more affected by the presence of lightweight concrete compared to the expansion anchors. The data for the cast-in anchors also demonstrate more of an impact with the use of lightweight concrete relative to the expansion anchors. Due to the difference in test results for each anchor type, torque-controlled anchors, displacement-controlled anchors, screw anchors, and cast-in anchors will be discussed and considered separately when determining recommended strength reduction factors.

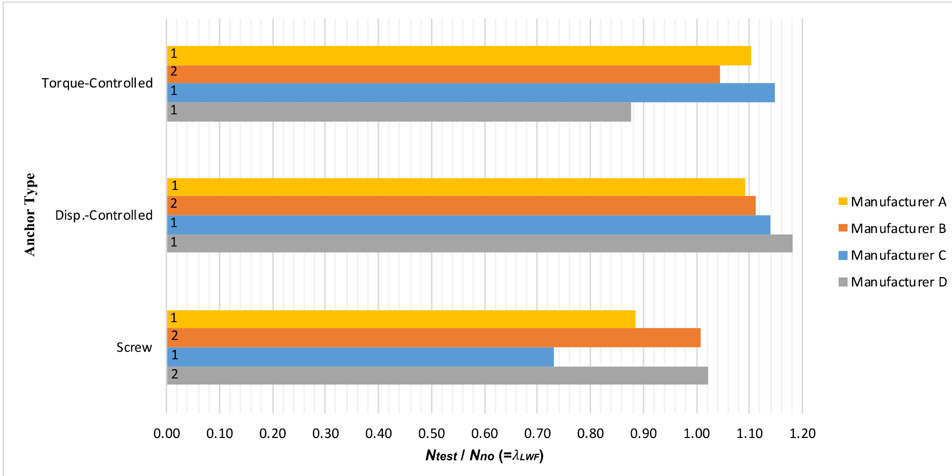
5.5 Comparison of Post-Installed Anchors

5.5.1 Comparison of Three Post-Installed Anchor Types from Four Manufacturers (Tested on Formed Side)

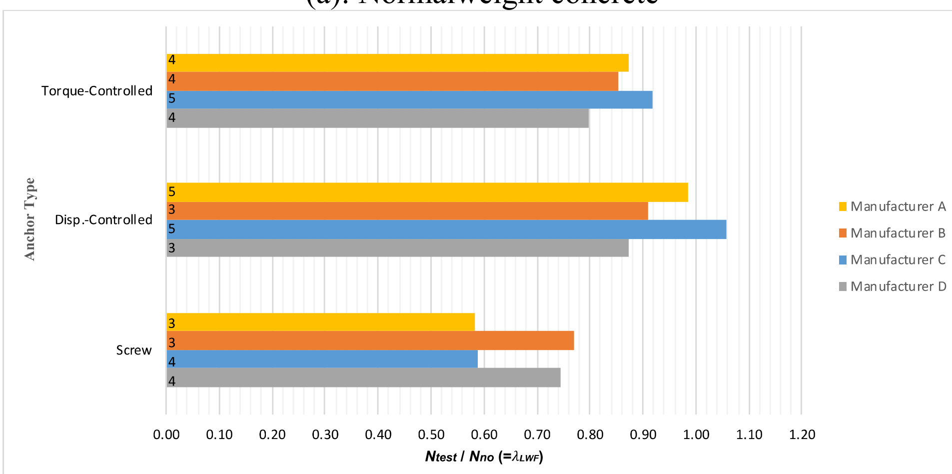
Torque-controlled, displacement-controlled, and screw anchors from the four anchor manufacturers included in the experimental study are compared in Figure 5.5. The data are separated by concrete type: normalweight, sand-lightweight, and all-lightweight concrete. The bars represent the average value of λ_{LWF} for anchors of a particular type from a specific manufacturer. The clay all-lightweight concrete is excluded from the comparison in this section due to the effect of the cracking experienced by the slab specimens.

Considering that all anchors experienced failure governed by the concrete (i.e., concrete breakout failure), large differences between the anchors from the various manufacturers were not expected. However, some trends were identified. For example, considering the torque-controlled anchors, the anchors from Manufacturer C resulted in the largest values of λ_{LWF} in all three types of concrete.

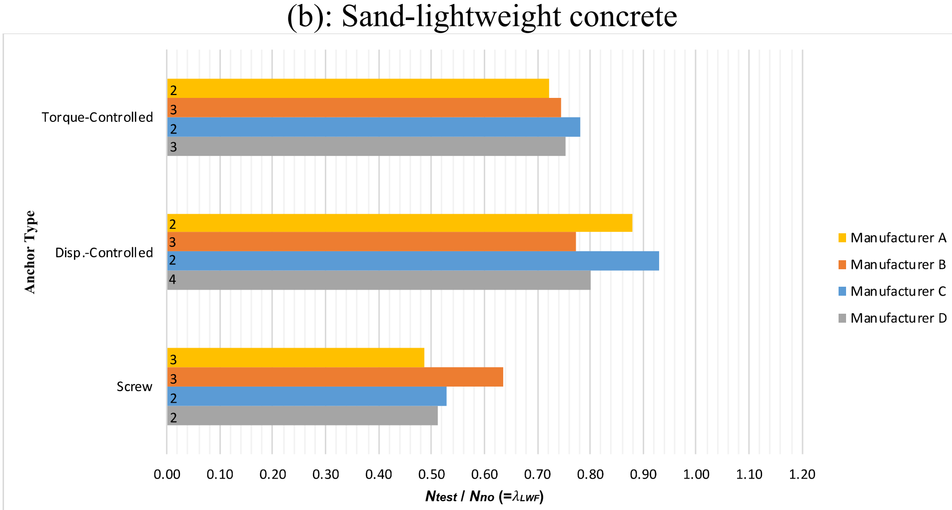
Consistent with previous observations, the displacement-controlled anchor data shown in Figure 5.5 have the largest λ_{LWF} values compared to the other anchor types in lightweight concrete. Considering the displacement-controlled anchors, the anchors from Manufacturer D resulted in the largest λ_{LWF} values in normalweight concrete but the smallest λ_{LWF} values in sand-lightweight concrete. The same anchors resulted in the second smallest values of λ_{LWF} in all-lightweight concrete. In sand-lightweight and all-lightweight concrete, the anchors from Manufacturer C provided the largest λ_{LWF} values among the four manufacturers.



(a): Normalweight concrete



(b): Sand-lightweight concrete



(c): All-lightweight concrete (excluding clay all-lightweight)

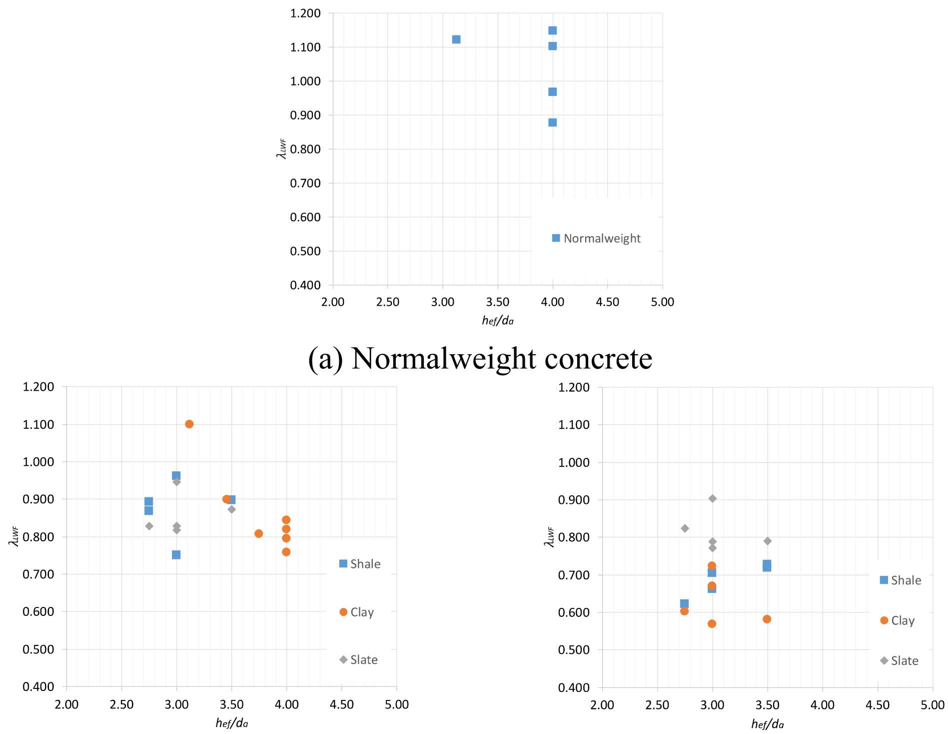
Figure 5.5: Comparison of three post-installed anchor types from four manufacturers in normalweight, sand-lightweight, and all-lightweight concrete (tested on formed side)

Among the three types of anchors, it can again be observed that the screw anchors were influenced the most by the use of lightweight concrete. The screw anchors from Manufacturer B resulted in the largest values of λ_{LWF} compared to the other three manufacturers in both types of lightweight concrete. The same anchors provided the second largest values in normalweight concrete. Although all screw anchors experienced a concrete breakout failure, the value of λ_{LWF} for the anchor from Manufacturer C in normalweight concrete seems relatively low (see Figure 5.5(a)). However, the same anchor provided results similar to anchors from other manufacturers in the sand-lightweight and all-lightweight concrete. While making observations based on Figure 5.5, the small sample sizes for some of the anchors should be considered.

Overall, the comparisons between the four manufacturers gives no indication that any specific anchors should be excluded from the analysis due to unexpected performance in comparison to other anchors.

5.5.2 Evaluation of Shallow Embedment of Torque-Controlled Anchors (Tested on Formed Side)

A total of 37 torque-controlled anchors were tested on the formed side of the slab specimens, of which 29 were installed with an effective embedment depth of less than 2 in. (h_{ef}/d_a < 4). To evaluate any potential effects of these relatively shallow embedment depths on the performance of the anchors, scatter plots of λ_{LWF} versus h_{ef}/d_a for the 37 tests on torque-controlled anchors are shown in Figure 5.6. The plots are separated based on the concrete type (normalweight, sand-lightweight, and all-lightweight concrete). For the sand-lightweight and all-lightweight concrete, the three aggregate types are differentiated by color. Overall, the data shown in the plots are scattered with no clear trends. Therefore, the data from tests on anchors with relatively shallow embedment depths were determined to be viable for inclusion with the data from tests on anchors with deeper embedment depths ($h_{ef}/d_a \geq 4$).



(a) Normalweight concrete

(c) Sand-lightweight concrete (b) All-lightweight concrete

Figure 5.6: λ_{LWF} versus h_{ef}/d_a for torque-controlled anchor tested on formed side

5.5.3 Evaluation of Torque-Controlled and Screw Anchors Tested on the Finished Side of the Slab Specimens

A total of 35 torque-controlled expansion anchors and 2 screw anchors, both with ½-in. diameters, were tested on the finished side of the concrete slab specimens. These anchors are denoted by an asterisk in Table 5.1, Table 5.2, Table 5.3, and Table 5.5. All 35 torque-controlled anchors were installed with an effective embedment depth of 2 in., and the effective embedment depths of the two screw anchors were 2.16 in. and 2.40 in. The average values of λ_{LWF} and R for the torque-controlled anchors are provided in Table 5.8. The values of λ_{LWF} and R for the two screw anchors tested on the finished side of the slab specimens are provided in Table 5.9.

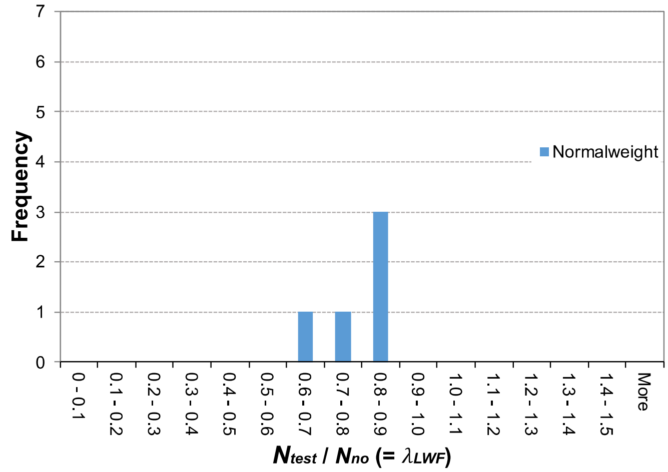
Table 5.8: Summary of torque-controlled anchors tested on the finished side of the slab specimens

Concrete	$\lambda_{LWF,avg.}$	COV	Number of Tests	R_{avg}
Normalweight	0.801	11.5%	5	0.801
Shale Sand-Lightweight	0.644	9.1%	5	0.757
Clay Sand-Lightweight	0.723	7.4%	5	0.851
Slate Sand-Lightweight	0.723	9.6%	5	0.851
Shale All-Lightweight	0.581	6.9%	5	0.775
Clay All-Lightweight	0.597	8.7%	5	0.796
Slate All-Lightweight	0.667	8.4%	5	0.889

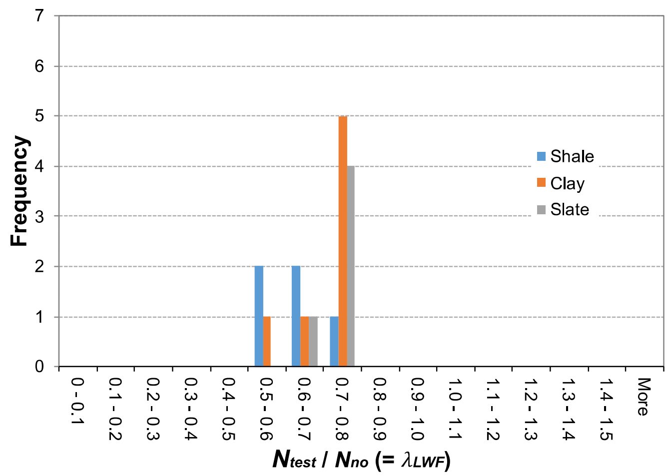
Table 5.9: Summary of screw anchors tested on the finished side of the slab specimens

Test ID	λ_{LWF}	R
SL-CL-S-6	0.779	0.917
SL-CL-S-8	0.584	0.687

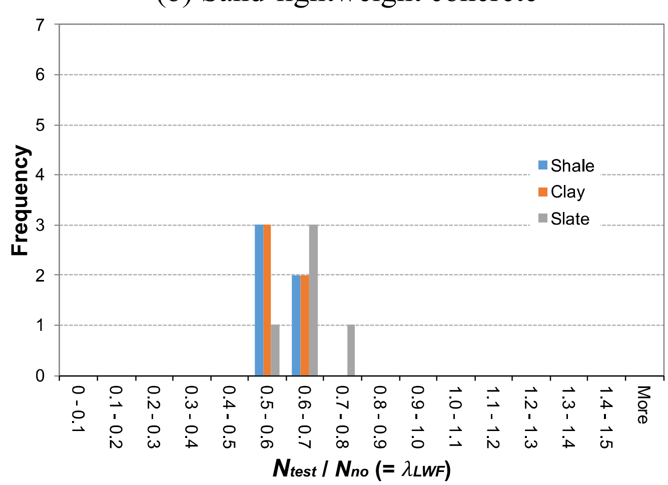
Histograms of the values of λ_{LWF} for the torque-controlled anchors in normalweight, sand-lightweight, and all-lightweight concrete, with each aggregate type differentiated by color, are presented in Figure 5.7. The expected trend for the influence of lightweight concrete is visible, with the anchors in normalweight concrete corresponding to the largest λ_{LWF} values and the anchors in all-lightweight concrete corresponding to the smallest λ_{LWF} values. Considering Figure 5.7(b), the anchors in shale sand-lightweight concrete demonstrated inferior performance compared to the anchors in the two other concrete types. Again, the anchors in the slate all-lightweight concrete generally performed better than the anchors in the other two all-lightweight concrete types.



(a) Normalweight concrete



(b) Sand-lightweight concrete



(c) All-lightweight concrete

Figure 5.7: Histogram of λ_{LWF} for torque-controlled anchors tested on the finished side of the slab specimens

A comparison of the torque-controlled anchors tested on the finished sides and the formed sides of the slab specimens is provided in Figure 5.8. The λ_{LWF} values for the anchors tested on the formed side are notably larger than the λ_{LWF} values for the anchors tested on the finished side. For example, the average value of λ_{LWF} for the tests on the formed side of the normalweight concrete specimens is approximately 30% greater than the value corresponding to the finished side. The discrepancy may be due to a depth effect in the 12-in. thick slabs. Despite the difference in the two cases, the overall trends within each set are comparable. However, because the use of the two slab surfaces introduces a variable to the test data, the two sets of data are not combined. Instead, to develop recommended strength reduction factors, the results of the tests in lightweight concrete will be normalized with respect to the tests conducted on the same side (formed or finished side) of the normalweight slab specimens.

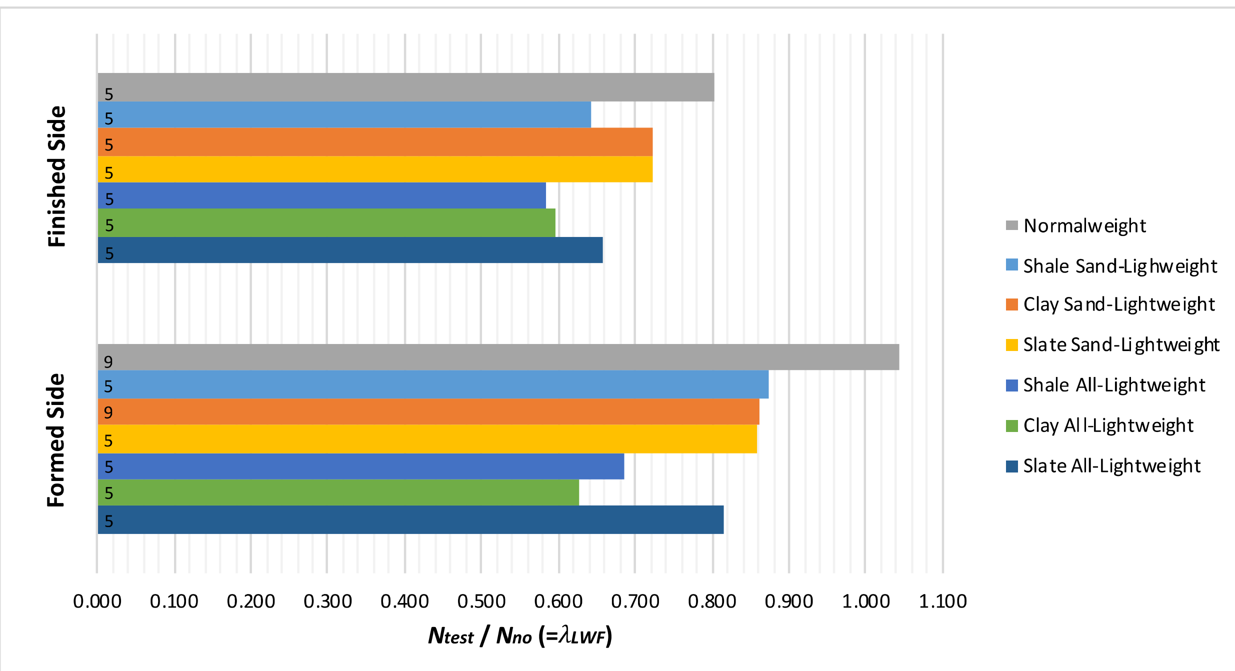


Figure 5.8: Comparison of torque-controlled anchors in seven types of concrete tested on the formed and finished sides of the slab specimens

Because the two tests on screw anchors installed on the finished side of the slab specimens do not have corresponding companion tests conducted on the finished side of normalweight specimens, the data from the tests will not be included in the analysis leading to recommended reduction factors.

5.5.4 Comparison of Anchors from Manufacturer D in Sand-Lightweight Concrete and Results from Tests Performed at Virginia Tech

In 2009, a total of 63 post-installed anchor tests were conducted at Virginia Tech, including 31 tests on torque-controlled expansion anchors and 32 tests on screw anchors. Slate sand-lightweight concrete was used as the base concrete material for all 63 tests, and the anchors were from Manufacturer D. Table 5.10 presents a summary of the result from the torque-controlled and screw anchors tested at Virginia Tech. A histogram of λ_{LWF} for the test results, calculated as explained in Section 5.2.1, is shown in Figure 5.9. The average values of λ_{LWF} for each anchor type and diameter is provided in Table 5.10. As seem from the data presented in Table 5.10, the torque-controlled anchors with ⅝-in. diameter and two types of screw anchors have λ_{LWF} values of approximately 0.85. In contrast, the average λ_{LWF} value for the torque-controlled anchors with ½-in. diameter is lower. Nevertheless, the anchor tests within each of the four groups of anchors in Table 5.10 are relatively consistent based on the coefficients of variation and the histogram plot in Figure 5.9. The reduction factors, *R*, for the tests calculated by dividing λ_{LWF} by 0.85, the modification factor, λ (see Section 5.2.2), for sand-lightweight concrete, are included in the table.

Table 5.10: Summary of results for tests performed at Virginia Tech

Anchor	Diameter (in.)	$\lambda_{LWF,avg.}$	COV	Number of Tests	R_{avg}
Torque-Controlled	½	0.651	8.2%	20	0.766
	⅝	0.842	5.0%	11	0.990
Screw	½	0.857	9.1%	17	1.009
	⅝	0.883	9.5%	15	1.039

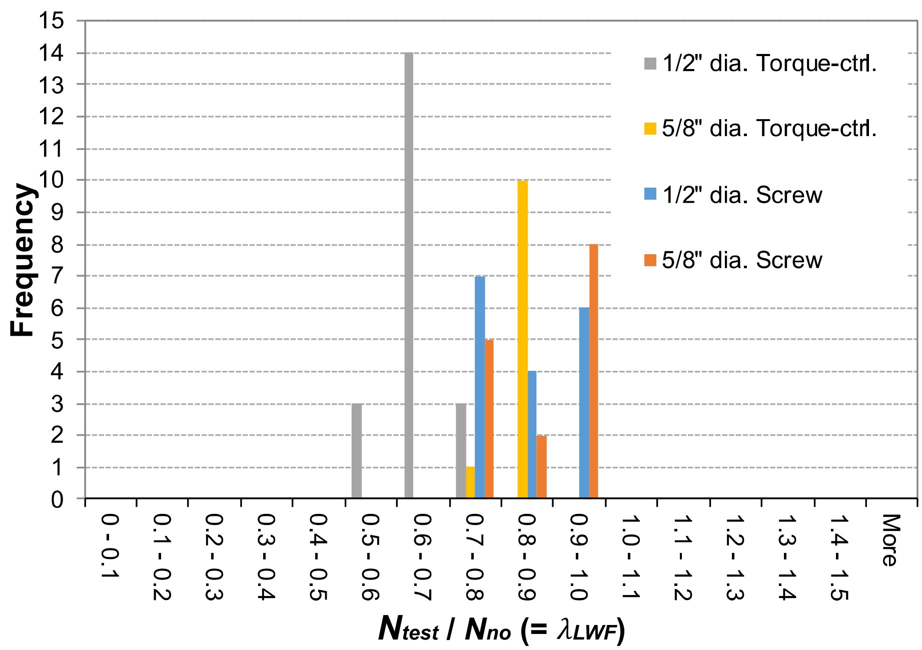


Figure 5.9: Histogram of λ_{LWF} for anchors tested at Virginia Tech

5.5.4.1 Comparison of Torque-Controlled Anchors in Sand-Lightweight Concrete

The torque-controlled expansion anchor (ID: SL-SL-T-D1) tested in slate sand-lightweight concrete as part of the experimental program described in this thesis is the same anchor product tested at Virginia Tech. The resulting value of λ_{LWF} from the test is 0.818. A histogram comparing the λ_{LWF} values for the torque-controlled anchors tested at Virginia Tech and the torque-controlled anchors tested in sand-lightweight concrete as part of the current research is shown in Figure 5.10. The data are separated based on the side of the slab specimens on which the tests were conducted. The result of test SL-SL-T-D1 is also indicated in the figure. The λ_{LWF} value for test SL-SL-T-D1 is higher than the ½-in. diameter torque-controlled anchors tested at Virginia Tech but slightly less than the average λ_{LWF} value of 0.842 for the ⁵⁄₈-in. diameter torque-controlled anchors. Overall, the values of λ_{LWF} for the ½-in. diameter anchors tested at Virginia Tech are notably lower than the λ_{LWF} values for the torque-controlled anchors tested on the formed side of the sand-lightweight concrete specimens during the current study. Moreover, the anchors tested on the finished side of the slabs during the current study generally resulted in larger λ_{LWF} values than the ½-in diameter torque-controlled anchors tested at Virginia Tech. Furthermore, the tests on the ⁵⁄₈-in. diameter anchors demonstrated better performance compared to the tests conducted on the finished side.

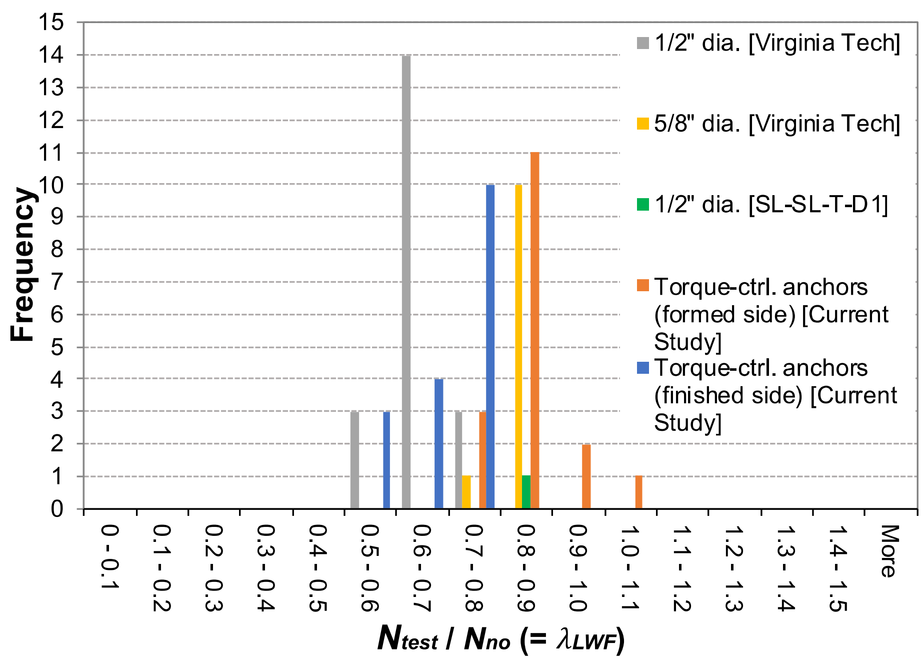


Figure 5.10: Histogram of λ_{LWF} for torque-controlled anchors in sand-lightweight concrete

The results from the tests performed at Virginia Tech are again compared in Figure 5.11 to all torque-controlled expansion anchors tested in sand-lightweight concrete during the current experimental program. In the figure, the average λ_{LWF} values for all torque-controlled expansion anchors tested on the formed and the finished side in sand-lightweight concrete during the current study and the torque-controlled anchors tested at Virginia Tech are presented. The anchors tested on the formed side of the slab specimens during the current study all resulted in similar average λ_{LWF} values regardless of the aggregate type, and the anchors tested on the finished side of the slate and clay sand-lightweight slab specimens resulted in similar λ_{LWF} values as well. The average value of λ_{LWF} for the ⅝-in. diameter anchors tested at Virginia Tech is slightly less than the λ_{LWF} values for the anchors tested on the formed side of the slabs but approximately 16% larger than the anchors tested on the finished side during the current study. The average λ_{LWF} value for the ½-in. diameter anchors tested at Virginia Tech, however, is significantly less (approximately equal to 76% of the values for the clay and slate sand-lightweight concrete) than the values for the other data sets except the anchors tested on the finished side of shale sand-lightweight concrete.

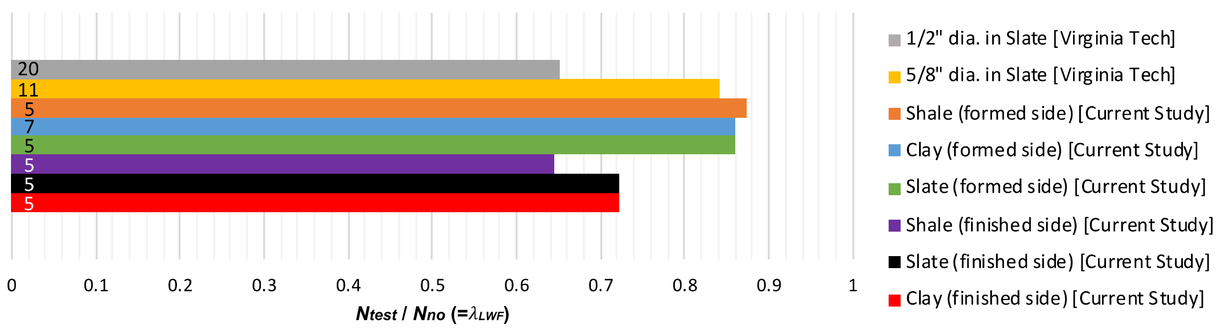


Figure 5.11: Comparison of λ_{LWF} for torque-controlled anchors in sand-lightweight concrete

When comparing the results from the current study with those performed at Virginia Tech, the potential effects of interlaboratory variability should be considered. However, no known relevant interlaboratory studies are available in the literature to determine the expected interlaboratory variability of anchors tested in lightweight concrete. Considering the variability of the data from the different sources, the data from Virginia Tech are kept separate from the data of the current study.

5.5.4.2 Comparison of Screw Anchors in Slate Sand-Lightweight Concrete

The screw anchors from Manufacturer D tested at Virginia Tech, which are a different product from the screw anchors tested as part of the current study, resulted in average λ_{LWF} values of 0.857 and 0.883 for ½-in. and ⅝-in. diameter anchors, respectively. A histogram shown in Figure 5.12 compares the results of the screw anchor tests conducted at Virginia Tech to the screw anchor from Manufacturer D (ID: SL-SL-S-D1) tested in slate sand-lightweight concrete as part of the current research. In the figure, the λ_{LWF} value of 0.795 for test SL-SL-S-D1 is lower than many of the λ_{LWF} values from the tests performed at Virginia Tech. Furthermore, compared to the results of all tests of the current study performed on screw anchors from the four manufacturers in sand-lightweight concrete, the tests conducted at Virginia Tech generally provide superior results. The data for screw anchors in sand-lightweight concrete displayed in Figure 5.5(b) indicate that various screw anchor products can provide results that are significantly different from each other. The data from the tests performed at Virginia tech represent 32 tests on the same product with two different diameters. Including the data in further analysis could result in a bias based on one screw anchor product and lead to unconservative design recommendations. The bias could potentially be significant due to the large number of tests on the same screw anchor product. Therefore, the screw anchor test data from the tests performed at Virginia Tech will not be considered in the formulation of recommended strength reduction factors.

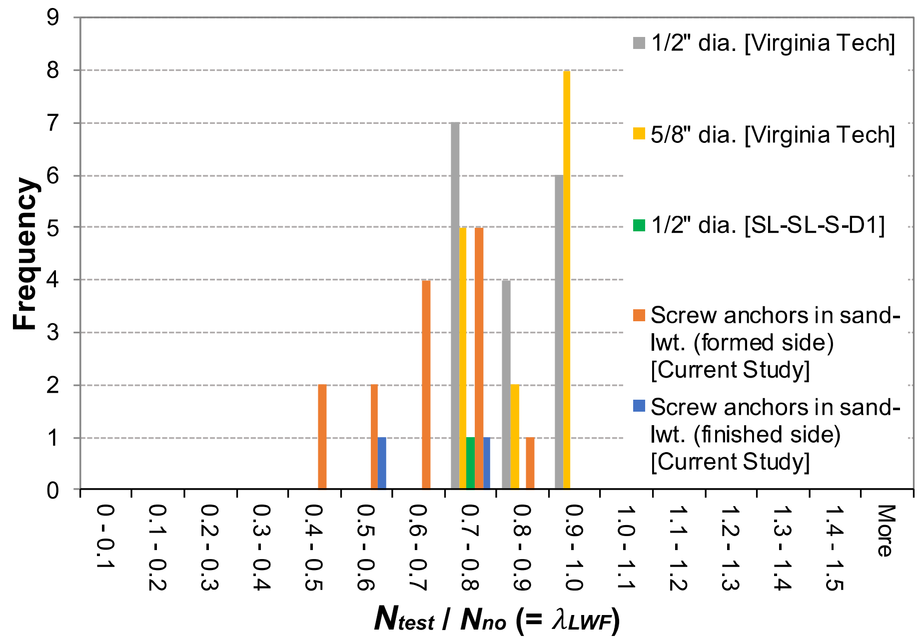


Figure 5.12: Histogram of λ_{LWF} for screw anchors in sand-lightweight concrete

5.6 Comparison of Cast-In Anchors in Sand-Lightweight Concrete with McMackin et al. (1973) Test Data

McMackin et al. (1973) performed two tests on cast-in anchors in sand-lightweight concrete. Table 5.11 presents a comparison of the data collected by McMackin et al. and the tests on anchors in lightweight concrete of the current study.

Table 5.11: Comparison of cast-in anchors in sand-lightweight concrete and tests from McMackin et al. (1973)

Data Source	Concrete	$\lambda_{LWF,avg.}$	R_{avg}
Current Study	Sand-Lightweight	0.720	0.847
McMackin et al. (1973)	Sand-Lightweight	0.502	0.591

As shown in the table, the McMackin et al. (1973) test results provide an average λ_{LWF} value that is significantly (approximately 30%) lower than the results from the current study. The average λ_{LWF} value for the tests from McMackin et al. is only slightly greater (0.502 compared to 0.490) than the value resulting from the tests on cast-in anchors in clay all-lightweight concrete of the current study (see Table 5.7). Although the strength data collected from McMackin et al. is relatively low, there is no reason to believe that the data are not viable. The data are therefore included in the calculations for determining recommended strength reduction factors.

5.7 Comparison of All Anchor Types in Normalweight, Sand-Lightweight, and All-Lightweight Concrete (Tested on Formed Side)

All data discussed in the previous sections from tests performed on the formed side of the slab specimens are summarized in Figure 5.13. In the figure, the values of λ_{LWF} for all four anchor types in normalweight, sand-lightweight, and all-lightweight concrete are presented. As previously discussed, the results from the two tests on cast-in anchors reported in McMackin et al. are included. The data from the tests on torque-controlled expansion anchors performed at Virginia Tech will be considered separately in Section 5.8.5. The results of anchors tested in the clay all-lightweight concrete are not included in the plot. As shown in Figure 5.13, the values of λ_{LWF} corresponding to the four types of anchors demonstrate the same trend for each type of concrete. The displacement-controlled expansion anchors correspond to the largest values of λ_{LWF} in all three types of concrete, and the λ_{LWF} values for the torque-controlled anchors are the second largest. The values of λ_{LWF} for the screw anchors are the smallest among the three types of concrete. The influence of lightweight concrete can obviously be observed in the plot. The anchors in normalweight concrete have the greatest λ_{LWF} values, and the anchors in all-lightweight concrete have the smallest λ_{LWF} values.

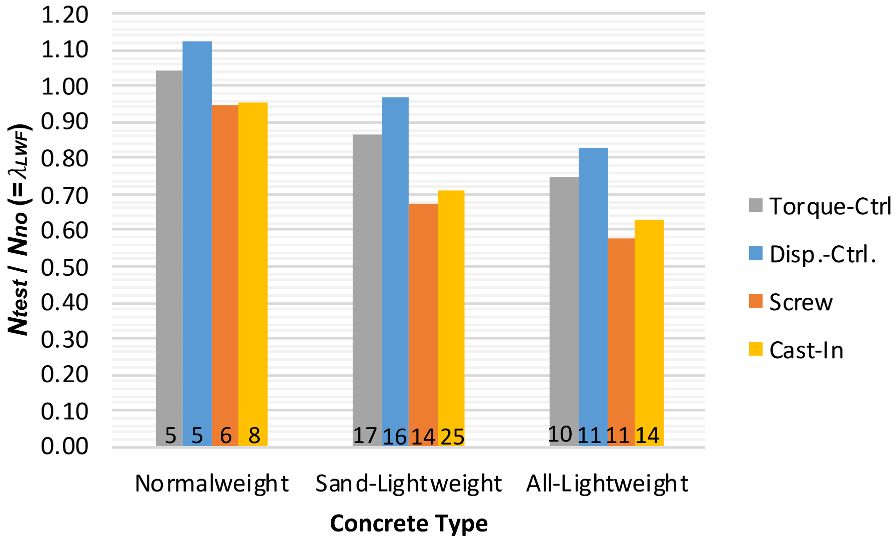


Figure 5.13: Summary of data – λ_{LWF} for four anchor types in three types of concrete (tested on formed side)

5.8 Reduction Factors, *R*, from Test Data

5.8.1 Reduction Factors, *R*, for Four Anchor Types Tested on Formed Side of Specimens (λ = 0.85 for Sand-Lightweight and 0.75 for All-Lightweight Concrete)

The *R* values for the four types of anchors in six types of concrete mixtures (clay all-lightweight excluded) tested on the formed side of the slab specimens are shown in Table 5.12. As described in Section 5.2.2, the *R* values are calculated by dividing λ_{LWF} by the lightweight concrete modification factor, λ, specified in Table 19.2.4.1(b) of ACI 318-19 (0.85 for sand-lightweight concrete and 0.75 for all-lightweight concrete). The *R* values represent an additional reduction factor that applies to anchors due to the influence of lightweight concrete and are analogous to the additional strength reduction factors multiplied by λ that are specified in Section 17.2.4.1 of ACI 318-19. The results in Table 5.12 indicate that the influence of lightweight concrete further reduces the strength of screw and cast-in anchors beyond what is captured by the λ-factor. Furthermore, the results reflect that the types of aggregate in the lightweight concrete have different degrees of influence on the four types of anchors.

Table 5.12: Reduction factor, *R*, from test data (λ = 0.85 for sand-lightweight and 0.75 for all-lightweight concrete)

Anchor	**Normalweight Concrete**	**Sand-Lightweight Concrete**			**All-Lightweight Concrete**	
		Shale	Clay	Slate	Shale	Slate
Torque-Controlled	1.04	1.03	1.01	1.01	0.92	1.09
Displacement-Controlled	1.13	1.06	1.24	1.13	1.04	1.17
Screw	0.95	0.79	0.90	0.70	0.69	0.84
Cast-In	0.96	0.77	0.92	0.85	0.75	0.92

Note: Clay all-lightweight concrete is not included.

In Table 5.14, the *R*-factor for each anchor type in six concrete mixtures is normalized with respect to the *R*-factor for normalweight concrete. In the current code provisions of ACI 318-19 (Section 17.2.4), no reduction factor is applied to anchors governed by concrete failure in normalweight concrete. Assuming the accuracy and reliability of current code provisions and the values of k_{nc} in the CCD method (see Section 1.4) which are related to design constants specified in ACI 318-19, normalizing the values of *R* with respect to the factors resulting from the tests in normalweight concrete is justified.

Table 5.13: Normalized reduction factor, *R*, from test data (λ = 0.85 for sand-lightweight and 0.75 for all-lightweight concrete)

Anchor	Normalweight Concrete	Sand-Lightweight Concrete			All-Lightweight Concrete	
		Shale	Clay	Slate	Shale	Slate
Torque-Controlled	1.00	0.99	0.97	0.97	0.88	1.04
Displacement-Controlled	1.00	0.94	1.10	1.00	0.92	1.04
Screw	1.00	0.83	0.95	0.74	0.73	0.89
Cast-In	1.00	0.81	0.96	0.89	0.79	0.96

Note: Clay all-lightweight concrete is not included, considering lower strength due to the cracking.

5.8.2 Reduction Factors, *R*, for Four Anchor Types Tested on Formed Side of Specimens (λ Based on Equilibrium Density)

A summary of equilibrium density and corresponding λ values based on Table 19.2.4.1(a) of ACI 318-19 (see Table 1.2 in this thesis) for different concrete mixtures is provided in Table 5.14. The *R* values based on the λ values in the table for the four types of anchors tested on the formed side of the slab specimens are provided in Table 5.15.

Table 5.14: Summary of λ values based on equilibrium density

Concrete	Aggregate	Equilibrium Density w_c, lb/ft^3	λ
Normalweight	--	--	1
Sand-Lightweight	Shale	122	0.92
	Clay	118	0.89
	Slate	119	0.89
All-Lightweight	Shale	97	0.75
	Slate	99	0.75

Table 5.15: Reduction factor, *R*, from test data (λ based on equilibrium density)

Anchor	Normalweight Concrete	Sand-Lightweight Concrete			All-Lightweight Concrete	
		Shale	Clay	Slate	Shale	Slate
Torque-Controlled	1.04	0.96	0.97	0.96	0.92	1.09
Displacement-Controlled	1.13	0.99	1.19	1.07	1.04	1.17
Screw	0.95	0.73	0.86	0.67	0.69	0.84
Cast-In	0.96	0.72	0.88	0.81	0.75	0.92

Note: Clay all-lightweight concrete is not included, considering lower strength due to the cracking.

In the same manner as described Section 5.8.1, the *R* values normalized with respect to normalweight concrete are provided in Table 5.16. Comparing the values in Table 5.13 and Table 5.16, the *R* values for the four types of anchors in sand-lightweight concrete in Table 5.16 are smaller than the values in Table 5.13 due to larger λ values based on equilibrium density. For all-lightweight concrete in Table 5.16, the *R* values are the same as in Table 5.13 because the equilibrium densities of the two types of all-lightweight concrete are less than 100 lb/ft^3.

Table 5.16: Normalized reduction factor, *R*, from test data (λ based on equilibrium density)

Anchor	Normalweight Concrete	Sand-Lightweight Concrete			All-Lightweight Concrete	
		Shale	Clay	Slate	Shale	Slate
Torque-Controlled	1.00	0.92	0.93	0.92	0.88	1.04
Displacement-Controlled	1.00	0.88	1.06	0.95	0.92	1.04
Screw	1.00	0.77	0.91	0.70	0.73	0.89
Cast-In	1.00	0.75	0.92	0.85	0.79	0.96

Note: Clay all-lightweight concrete is not included, considering lower strength due to the cracking.

The small differences in the equilibrium densities of the three sand-lightweight concrete mixtures result in only small variations in the value of λ calculated in accordance with Table 19.2.4.1(a) of ACI 318-19. Incorporation of these λ values based on equilibrium densities do not capture the variations in performance of the anchors in concrete with different aggregates. For this reason, the remaining discussion of *R* values will be based on the values of λ specified in Table 19.2.4.1(b) of ACI 318-19 (0.85 for sand-lightweight concrete and 0.75 for all-lightweight concrete).

5.8.3 Summary of Reduction Factors, *R*, for Four Anchor Types Tested on Formed Side of Specimens

Despite the influence of the aggregate type on the performance of the anchors, it is interesting to evaluate the performance of the CCD method for predicting the strengths of anchors if *R* values are selected that do not consider specific aggregate types. Values of *R* are calculated in this section without consideration of specific aggregate types. The performance of the CCD method incorporating these reduction factors will be evaluated in the following subsections.

The *R* values for the four types of anchors tested on the formed side of the slab specimens are shown graphically in Figure 5.14. The same information is provided numerically in Table 5.17. The results in Figure 5.14 and Table 5.17 indicate that the influence of lightweight concrete further reduces the strength of screw and cast-in anchors beyond what is captured by the λ-factor. The data imply that displacement-controlled and torque-controlled expansion anchors, however, do not require an additional strength reduction.

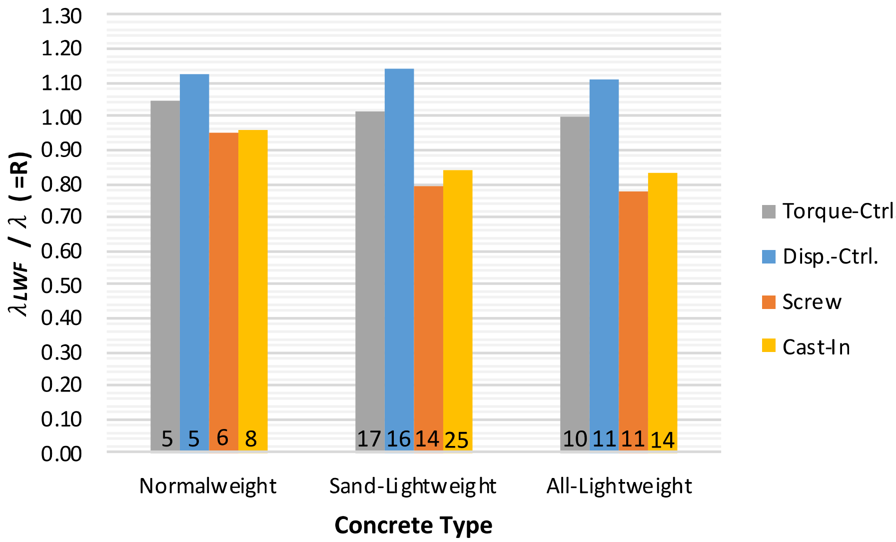


Figure 5.14: Summary of data – *R*-factors for four anchor types in three types of concrete (tested on formed side)

Table 5.17: Reduction factor, *R*, from test data (tested on formed side)

Anchor	**Normalweight Concrete**	**Sand-Lightweight Concrete**	**All-Lightweight Concrete**
Torque-Controlled	1.04	1.02	1.00
Displacement-Controlled	1.13	1.14	1.11
Screw	0.95	0.79	0.77
Cast-In	0.96	0.84	0.83

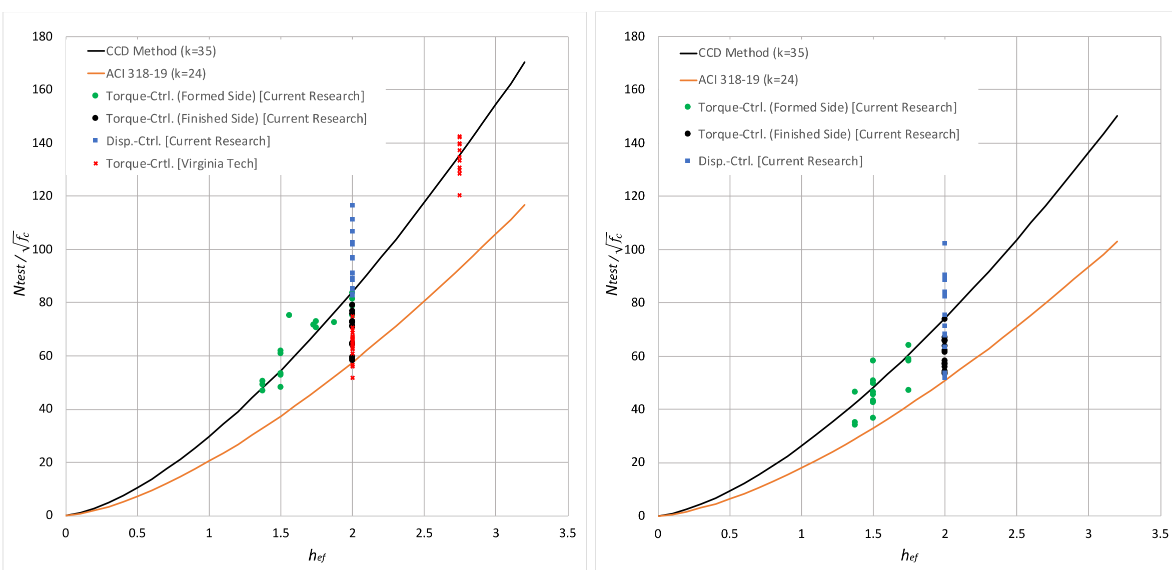
In Table 5.18, the *R*-factor for each anchor type in sand-lightweight and all-lightweight concrete is normalized with respect to the *R*-factor for normalweight concrete. These factors will be incorporated into the CCD method in the following subsections.

Table 5.18: Normalized reduction factor, *R*, from test data (tested on formed side)

Anchor	**Normalweight Concrete**	**Sand-Lightweight Concrete**	**All-Lightweight Concrete**
Torque-Controlled	1.00	0.97	0.96
Displacement-Controlled	1.00	1.01	0.98
Screw	1.00	0.83	0.82
Cast-In	1.00	0.87	0.87

5.8.3.1 Reduction Factors, λ_a, for Torque-Controlled and Displacement-Controlled Anchors in Sand-Lightweight and All-Lightweight Concrete

In Figure 5.15, scatter plots of the torque-controlled and displacement-controlled test data from the current research and the data from the tests performed at Virginia Tech are presented. Based on the *R* values in Table 5.18, a reduction factor of 1.0λ for torque-controlled anchors is selected. Two curves representing the CCD method (Fuchs et al., 1995) and the design strength calculated in accordance with ACI 318-19 provisions (see Section 1.4) are presented in Figure 5.15. The reduction factor of 1.0λ is incorporated into the two curves. In Figure 5.15(a), three data points from the tests on ½-in. diameter torque-controlled anchors conducted at Virginia Tech fall below the curve for the ACI 318-19 design strength. However, the test data from Virginia Tech were not included in the calculation of the reduction factors in Table 5.18. For the anchors in all-lightweight concrete (see Figure 5.15(b)), all of the data points for torque-controlled and displacement-controlled anchors are conservatively estimated by the ACI 318-19 design equation with a reduction factor of 1.0λ.

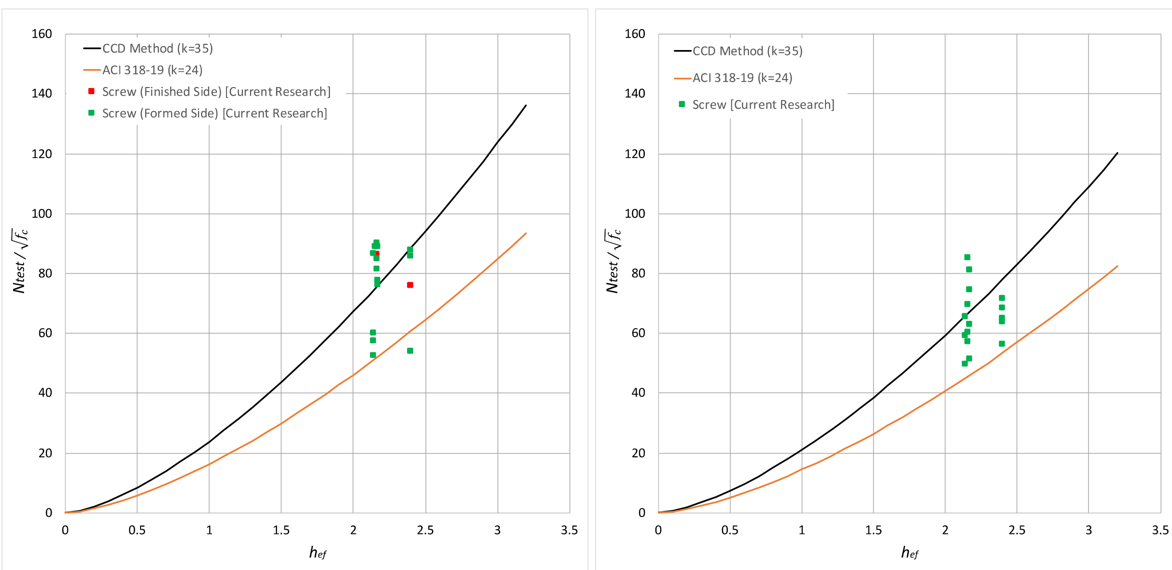


(a) Sand-lightweight concrete (b) All-lightweight concrete

Figure 5.15: Test data from torque-controlled and displacement-controlled anchor tests compared to calculated capacities

5.8.3.2 Reduction Factors, λ_a, for Screw Anchors in Sand-Lightweight and All-Lightweight Concrete

In the same manner as indicated in Section 5.8.3.1, the results from the tests on screw anchors in sand-lightweight concrete and all-lightweight concrete conducted during the current study are presented in Figure 5.16. Based on the *R* values in Table 5.18, a reduction factor of 0.8λ for screw anchors is selected and incorporated into strengths calculated in accordance with the CCD method and the design equations in ACI 318-19. As shown in the Figure 5.16(a), only one data point for the screw anchors tested in sand-lightweight concrete falls below the curve for the ACI 318-19 design strength. All of the screw anchors tested during the current study in all-lightweight concrete are conservatively estimated by the ACI 318-19 design equation with a reduction factor of 0.8λ, as shown in Figure 5.16(b).

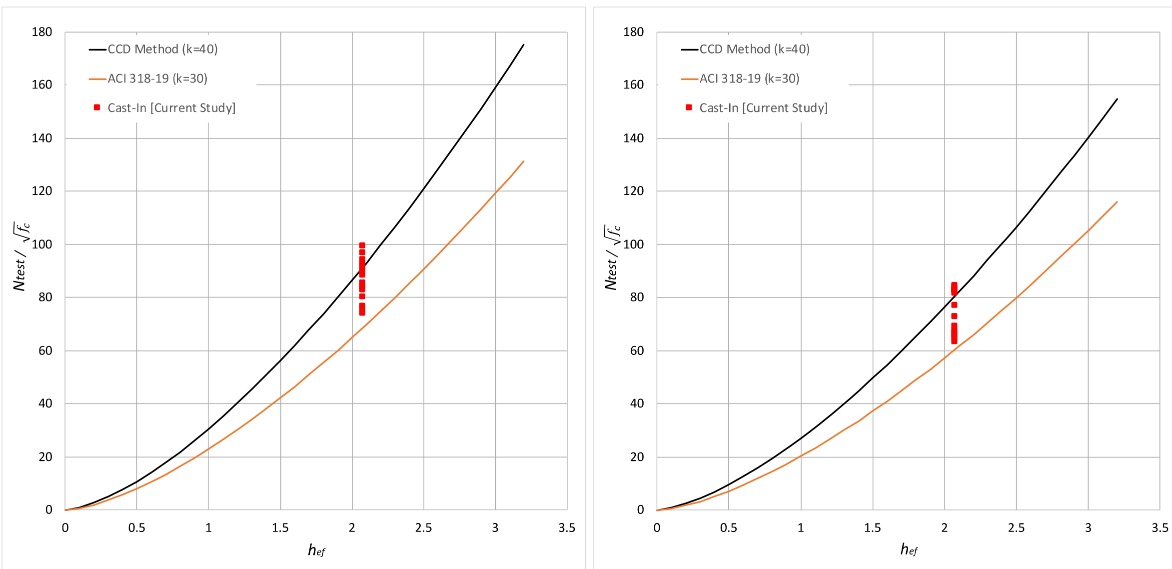


(a) Sand-lightweight concrete (b) All-lightweight concrete

Figure 5.16: Test data from screw anchor tests compared to calculated capacities

5.8.3.3 *Reduction Factors, λ_a, for Cast-In Anchors in Sand-Lightweight and All-Lightweight Concrete*

Figure 5.17 presents the results from tests on cast-in anchors in sand-lightweight concrete and all-lightweight concrete performed during the current study. Based on the *R* values in Table 5.18, a reduction factor of 0.9λ for cast-in anchors is selected. As shown in the figure, none of data points from the cast-in anchors tested in both sand-lightweight and all-lightweight concrete falls below the curve for the ACI 318-19 strength design with a reduction factor of 0.9λ.



(a) Sand-lightweight concrete (b) All-lightweight concrete

Figure 5.17: Test data from cast-in anchor tests compared to calculated capacities

Overall, the reduction factors selected based on the values in Table 5.18 provide satisfactory results when incorporated into current design provisions. Nevertheless, the test results from the current study demonstrate varying anchor performance based on aggregate type. Incorporating the effects of aggregate type will result in *R* values that are more accurate. Recommended reduction factors based on aggregate type are presented in Section 5.8.6.

5.8.4 Reduction Factors, *R*, for Torque-Controlled Anchors Tested on Finished Side of Specimens

The *R*-factors for the torque-controlled anchors tested on the finished side of the slab specimens in three types of concrete are presented in Table 5.19. The *R*-factors normalized with respect to the *R*-factor for normalweight concrete is also given. The normalized values of *R* for sand-lightweight and all-lightweight concrete are slightly greater than 1.00. The results are comparable to the results presented in Section 5.8.3 for the torque-controlled anchors tested on the formed side of the slab specimens.

Table 5.19: Reduction factor, *R*, for torque-controlled anchors tested on the finished side of the slab specimens

Anchor	Normalweight Concrete	Sand-Lightweight Concrete	All-Lightweight Concrete
R	0.80	0.81	0.82
Normalized *R*	1.00	1.01	1.03

5.8.5 Reduction Factors, *R*, for Torque-Controlled Anchors Tested at Virginia Tech

In Table 5.20, the reduction factors, *R*, for torque-controlled anchors with ½-in. and ⅝-in. diameters tested at Virginia Tech are presented. The results of the tests on ⅝-in. diameter torque-controlled anchors give an *R* value of 0.99. However, the *R*-factor for torque-controlled anchors with ½-in. diameter is significantly (approximately 22%) less than the other results. However, without companion tests in normalweight concrete, interpretation of the low value of *R* is not possible.

Table 5.20: Reduction factor, *R*, for tests conducted at Virginia Tech

Data Source	Anchor	Concrete	*R*
Virginia Tech	⅝" dia. Torque-Controlled	Sand-Lightweight	0.99
	½" dia. Torque-Controlled		0.77

5.8.6 Recommended Reduction Factor, λ_a

As indicated in Section 5.3, various types of concrete mixtures result in different anchor performance. For the most accurate results, the recommend reduction values should be evaluated by considering the different types of aggregate. A comparison of recommended values of λ_a based on different anchor types and aggregate types and the current factors specified in ACI 318-19 is shown in Table 5.21. Currently, ACI 318-19 does not differentiate between aggregate types used in lightweight concrete. Because the drop-in displacement-controlled anchors included in the research are not approved by the ICC Evaluation Service due to the performance of the anchors in cracked concrete, the recommended value of λ_a for displacement-controlled drop-in anchors is shown separately in Table 5.22. The recommended λ_a values consist of an *R*-factor multiplied by the lightweight concrete modification factor, λ. The magnitudes of the *R*-factor were selected by rounding the values presented in Table 5.13. The *R*-factor for screw anchors in slate all-lightweight concrete was selected to result in a λ_a value equal to that for screw anchors in slate sand-lightweight concrete. As indicated in Table 5.21, the factor for expansion anchors currently specified in ACI 318-19 is less than the recommended value for torque-controlled expansion anchors. The current code factor for screw anchors is less than the recommended factors for shale and clay sand-lightweight and slate all-lightweight concrete. However, the factor is greater than the recommended factors for slate sand-lightweight and shale all-lightweight concrete. For cast-in anchors, the recommended factors are less than the current factor of 1.0. The finding that the reduction factor should be as low as 0.8λ for cast-in anchors in some concrete types is a significant observation from the research program. The recommended *R*-factor for displacement-controlled drop-in expansion anchors is simply 1.0 for clay and slate sand-lightweight concrete and slate all-lightweight concrete.

Table 5.21: Comparison of recommended values of λ_a and current values in ACI 318-19

Anchor	**Sand-Lightweight Concrete**				**All-Lightweight Concrete**		
	Shale	Clay	Slate	ACI 318-19	Shale	Slate	ACI 318-19
Torque-Controlled	1.0λ	0.95λ	0.95λ	0.8λ	0.9λ	1.0λ	0.8λ
Screw	0.85λ	0.95λ	0.75λ	0.8λ	0.75λ	0.85λ	0.8λ
Cast-In	0.8λ	0.95λ	0.9λ	1.0λ	0.8λ	0.95λ	1.0λ

Table 5.22: Recommended values of λ_a for displacement-controlled expansion anchors

Anchor	**Sand-Lightweight Concrete**			**All-Lightweight Concrete**	
	Shale	Clay	Slate	Shale	Slate
Displacement-Controlled (Drop-in) Expansion	0.95λ	1.0λ	1.0λ	0.9λ	1.0λ

For some anchor types, the value of *R* in Table 5.21 (i.e., the coefficient paired with λ) is greater for all-lightweight concrete with a particular aggregate type than the value for sand-lightweight concrete with the same aggregate. This may indicate that the current values of λ specified in the code may not be appropriate for every lightweight concrete type when applied to the strength of anchors. It should be noted that the value of λ_a for a specific anchor type in sand-lightweight concrete with a particular aggregate type is greater than or equal to the value of λ_a for that same anchor type in all-lightweight concrete with the same aggregate type (considering that λ is equal to 0.85 for sand-lightweight concrete and 0.75 for all-lightweight concrete).

Although the results of the tests conducted on Virginia Tech on ½-in. torque-controlled expansion anchors were not considered in the above recommendations, the average *R* value of 0.77 presented in Table 5.20 should not be forgotten. The value indicates the need for an interlaboratory study to determine possible variations in anchor tests in lightweight concrete. The current value of λ_a in ACI 318-19 for torque-controlled expansion anchors is conservative in accordance with the recommendations in Table 5.21. Until further tests are conducted, maintaining the current factor would be a conservative approach.

5.9 Summary

In this chapter, values of λ_{LWF} representative of normalized test data were calculated for each anchor test and were used for comparing test results based on anchor types, concrete types, and anchor manufacturers. The comparisons revealed that the displacement-controlled anchors generally resulted in the largest λ_{LWF} values compared to other anchor types. Furthermore, the λ_{LWF} values of the screw anchors were more significantly influenced by the effects of lightweight concrete compared to the displacement-controlled and torque-controlled expansion anchors.

Comparing the influence of different concrete types, the anchor tests generally resulted in the largest λ_{LWF} values in normalweight concrete and the smallest λ_{LWF} values in all-lightweight concrete, as expected. From the histograms of the anchors in concretes with different aggregate types, it is observed that the anchors are influenced by different aggregates types in the sand-lightweight and all-lightweight concrete mixtures.

The reduction factor, R, was calculated for every test conducted during the current study and for data collected from previous research. Recommended R values for torque-controlled expansion anchors, displacement-controlled drop-in anchors, screw anchors, and cast-in anchors were proposed and compared to current factors in ACI 318-19. An interlaboratory study is recommended to verify the proposed factors.

CHAPTER 6. SUMMARY AND CONCLUSIONS

6.1 Summary

For the efficient design and implementation of post-installed and cast-in anchors in lightweight concrete in practice, it is essential that the influence of lightweight concrete on the concrete breakout strength of the anchors in tension be accurately known. Data from past tests on anchors in lightweight concrete provide limited data and have not incorporated the various lightweight aggregate types used in the United States for structural concrete. A study was therefore conducted to evaluate the strength of post-installed and cast-in anchors by performing a series of tension tests on four types of anchors in six types of lightweight concrete as well as in one normalweight concrete. Comparisons were also made between the anchor test data that was generated and the results of past tests. The following aspects of anchor performance were of primary interest during the study:

1. Performance of different types of post-installed anchors (i.e., torque-controlled expansion, displacement-controlled expansion, and screw anchors) and cast-in anchors (i.e., headed stud cast-in anchors) in lightweight concrete
2. Effect of three types of concrete (i.e., normalweight, sand-lightweight, and all-lightweight concrete) on anchor capacity
3. Influence of different aggregate types (i.e., expanded shale, clay, and slate) in sand-lightweight and all-lightweight concrete on anchor capacity
4. Performance of three types of post-installed anchors from four different manufacturers

In this thesis, an introduction to anchors installed in lightweight concrete was presented and the modification factor, λ_a, specified in ACI 318-19 for cast-in and post-installed anchors in lightweight concrete were introduced. Relevant tension tests that were previously conducted on cast-in and post-installed anchors were presented. Much of the data from past tests available to the author were incomplete and not suitable for further analysis. Complete results from a series of tests conducted at Virginia Tech, however, were included in further analysis and comparisons with the results of the current study.

Considering the wide variety of post-installed anchors used in practice, three types of post-installed anchors in addition to cast-in headed studs were selected for inclusion in the study. Three types of lightweight aggregates commonly used in the United States were chosen to develop six unique lightweight concrete mixtures (three sand-lightweight concrete mixtures and three all-lightweight concrete mixtures). To provide comprehensive details of the tests that were conducted as part of the current study, concrete material test results, including fresh density, approximate equilibrium density, compressive strength, and splitting tensile strength, were presented for each concrete type. Then, detailed results from a total of 200 anchor tests on the post-installed and cast-in anchors were reported.

Finally, comparisons of anchor performance with regard to the different types of anchors, concrete mixtures, and aggregates were provided. Strength reduction factors for each type of anchor in lightweight concrete calculated from the test data were then summarized.

6.2 Conclusions

The primary observations and conclusions from the research on post-installed and cast-in anchors in lightweight concrete are summarized below:

- **Influence of lightweight concrete on capacities of post-installed and cast-in anchors with concrete breakout failures:** As expected, the strengths of post-installed and cast-in anchors experiencing concrete breakout failures are influenced by lightweight concrete. In general, anchors in sand-lightweight concrete resulted in lower strengths than anchors in normalweight concrete. Similarly, anchors in all-lightweight concrete generally had lower strengths than anchors in sand-lightweight concrete. The lightweight concrete modification factor, λ, specified in Table 19.2.4.1(b) of ACI 318-19 reflects the fact that differences in tensile capacity between sand-lightweight and all-lightweight concrete are expected.

- **Effect of aggregate type on the strengths of anchors in sand-lightweight and all-lightweight concrete:** The test data revealed differences in anchor strengths due to the type of lightweight aggregate used in the sand-lightweight and all-lightweight concrete mixtures. For example, anchors in slate all-lightweight concrete generally resulted in larger values of λ_{LWF} compared to anchors in the other types of all-lightweight concrete. Due to these differences, the recommended reduction factors were selected to differentiate between different lightweight aggregate types.
- **Performance of the four types of anchors among different types of lightweight concrete:** Comparing the anchors tested on the formed side of the slab specimens, the displacement-controlled expansion anchors resulted in larger values of λ_{LWF} in normalweight, sand-lightweight, and all-lightweight concrete compared to the torque-controlled expansion anchors, screw anchors, and cast-in anchors. The screw anchors generally provided the smallest values of λ_{LWF} and presented more scatter compared to the other anchor types. Overall, the strengths of the screw anchors were more significantly affected by the influence of lightweight concrete compared to the expansion anchors.
- **Strengths of torque-controlled anchors on formed and finished sides of the slab specimens:** Significant differences between the results of the torque-controlled anchors

tested on the formed side and finished side of slab specimens was observed. Comparing the two sets of torque-controlled anchors tested on different sides of the specimens, the results from the anchors tested on the formed side resulted in λ_{LWF} values approximately 20% larger on average than the values for the anchors tested on the finished side.

- **Comparison of results from tests on torque-controlled expansion anchors of current study with results from tests performed at Virginia Tech:** In general, the tests on ½-in. diameter torque-controlled anchors conducted at Virginia Tech resulted in smaller λ_{LWF} values compared to the ½-in. diameter torque-controlled anchors tested during the current study on both the formed and finished sides of the slab specimens. The tests on ⅝-in. diameter torque-controlled anchors conducted at Virginia Tech, however, demonstrated better performance compared to the tests conducted on the finished side during the current study.
- **Strength reduction factor for post-installed and cast-in anchors in lightweight concrete:** Based on the analysis of the test results, strength reduction factors, *R*, to be multiplied by λ to modify the predicted strengths of anchors in lightweight concrete were calculated. Due to differences in performance of the anchor types, reduction factors were calculated for each type of anchor. Moreover, the recommended reduction factors, *R*, are different for different types of aggregate used in concrete mixtures. For cast-in anchors, the recommended reduction factors are less than those currently specified in ACI 318-19, indicating that the current provisions could be unconservative.

6.3 Future Work

Due to the discrepancies between the data from the current study and the tests performed at Virginia Tech, additional tests are needed to determine the expected interlaboratory variability for anchors tested in lightweight concrete.

As part of the current study, tension tests were also performed on adhesive anchors to determine the influence of lightweight concrete on the effects of bond strength. The data from the adhesive anchor tests will be summarized in a future report.

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APPENDIX I: TEST DATA

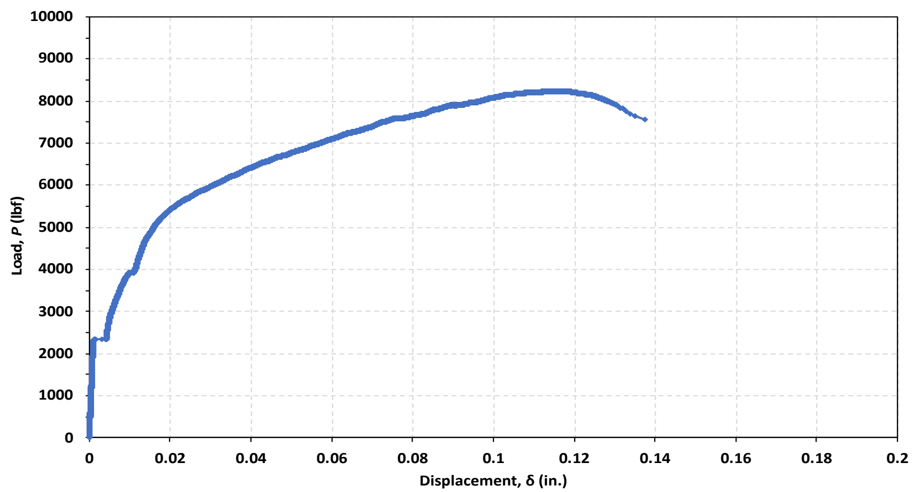
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
			Specimen Details			Anchor Details							Concrete Detials				Test Results
Count	ID	Cast-in / Post-installed	Concrete Type	Aggregate Type	Equlibrium Density	Manufacturer	Anchor Types	Diameter, d_a	Effective Embedment Depth, h_{ef}	h_{ef}/d_a	Installation Torque	Installation Turns	Compressive Strength at 28 Days, f_c	Compressive Strength on Testing Day, f_c	Tensilie Splitting Strength on Testing Day, f_t	$\frac{f_t}{\sqrt{f_c}}$	N_{test}
			NW/SLW/ALW	Shale/Clay/ Slate (Expanded Aggregate)	pcf		Torque-Crtl.(T)/ Disp.-Ctrl.(D)/ Screw(S)/Cast-In(C)	in.	in.	Col(9) / Col(8)	ft-lbf	Number	psi	psi	psi	Col(15) / [Col(14)]^0.5	lb
1	NW-T-B1	Post-installed	NW	n/a	-	B	T	0.5	2.00	4.00	39.70	4.00	7740	7408	630	7.32	8236
2	NW-T-C1	Post-installed	NW	n/a	-	C	T	0.5	2.00	4.00	59.30	6.25	7740	7408	630	7.32	9781
3	NW-T-D1	Post-installed	NW	n/a	-	D	T	0.5	2.00	4.00	39.60	5.00	7740	7408	630	7.32	7472
4	NW-T-A1	Post-installed	NW	n/a	-	A	T	0.5	2.00	4.00	55.00	6.00	7740	7408	630	7.32	9394
5	NW-T-B2	Post-installed	NW	n/a	-	B	T	0.5	1.56	3.13	40.00	4.50	7740	7408	630	7.32	6599
6	NW-T-B3*	Post-installed	NW	n/a	-	B	T	0.5	2.00	4.00	39.20	2.25	7740	7565	520	5.98	7702
7	NW-T-C2*	Post-installed	NW	n/a	-	C	T	0.5	2.00	4.00	60.00	4.50	7740	7565	520	5.98	7109
8	NW-T-D2*	Post-installed	NW	n/a	-	D	T	0.5	2.00	4.00	39.60	4.00	7740	7565	520	5.98	5617
9	NW-T-A2*	Post-installed	NW	n/a	-	A	T	0.5	2.00	4.00	54.10	6.25	7740	7565	520	5.98	6767
10	NW-T-B4*	Post-installed	NW	n/a	-	B	T	0.5	2.00	4.00	39.10	2.00	7740	7565	520	5.98	7307
11	NW-D-B1	Post-installed	NW	n/a	-	B	D	0.5	2.00	4.00	-	-	7740	7408	630	7.32	9259
12	NW-D-C1	Post-installed	NW	n/a	-	C	D	0.5	2.00	4.00	-	-	7740	7408	630	7.32	9723
13	NW-D-D1	Post-installed	NW	n/a	-	D	D	0.5	2.00	4.00	-	-	7740	7408	630	7.32	10070
14	NW-D-A1	Post-installed	NW	n/a	-	A	D	0.5	2.00	4.00	-	-	7740	7408	630	7.32	9307
15	NW-D-B2	Post-installed	NW	n/a	-	B	D	0.5	2.00	4.00	-	-	7740	7408	630	7.32	9678
16	NW-S-B1	Post-installed	NW	n/a	-	B	S	0.5	2.16	4.32	45.00	-	7740	7408	630	7.32	9223
17	NW-S-C1	Post-installed	NW	n/a	-	C	S	0.5	2.14	4.28	64.40	-	7740	7408	630	7.32	6895
18	NW-S-D1	Post-installed	NW	n/a	-	D	S	0.5	2.17	4.34	44.00	-	7740	7408	630	7.32	9863
19	NW-S-A1	Post-installed	NW	n/a	-	A	S	0.5	2.40	4.80	45.00	-	7740	7408	630	7.32	9923
20	NW-S-B2	Post-installed	NW	n/a	-	B	S	0.5	2.16	4.32	45.50	-	7740	7408	630	7.32	10072
21	NW-S-D2	Post-installed	NW	n/a	-	D	S	0.5	2.17	4.34	44.50	-	7740	7408	630	7.32	9849
22	SL-SH-T-B1	Post-installed	SLW	Shale	121.6	B	T	0.5	1.75	3.50	40.00	3.00	7430	8518	620	6.72	6714
23	SL-SH-T-C1	Post-installed	SLW	Shale	121.6	C	T	0.5	1.50	3.00	59.30	5.85	7430	8515	620	6.72	5711
24	SL-SH-T-D1	Post-installed	SLW	Shale	121.6	D	T	0.5	1.50	3.00	40.00	4.00	7430	8518	620	6.72	4453
25	SL-SH-T-A1	Post-installed	SLW	Shale	121.6	A	T	0.5	1.38	2.75	54.00	5.00	7430	8518	620	6.72	4651
26	SL-SH-T-A2	Post-installed	SLW	Shale	121.6	A	T	0.5	1.38	2.75	54.80	5.00	7430	8518	620	6.72	4524
27	SL-SH-T-B2*	Post-installed	SLW	Shale	121.6	B	T	0.5	2.00	4.00	39.10	2.00	7430	7836	630	7.12	6426
28	SL-SH-T-C2*	Post-installed	SLW	Shale	121.6	C	T	0.5	2.00	4.00	59.20	3.75	7430	7836	630	7.12	5142
29	SL-SH-T-D2*	Post-installed	SLW	Shale	121.6	D	T	0.5	2.00	4.00	39.40	3.50	7430	7836	630	7.12	5727
30	SL-SH-T-A3*	Post-installed	SLW	Shale	121.6	A	T	0.5	2.00	4.00	54.30	4.75	7430	7836	630	7.12	5686
31	SL-SH-T-C3*	Post-installed	SLW	Shale	121.6	C	T	0.5	2.00	4.00	59.40	4.75	7430	7836	630	7.12	5217
32	SL-SH-D-B1	Post-installed	SLW	Shale	121.6	B	D	0.5	2.00	4.00	-	-	7430	8515	620	6.72	7817
33	SL-SH-D-C1	Post-installed	SLW	Shale	121.6	C	D	0.5	2.00	4.00	-	-	7430	8515	620	6.72	9377
34	SL-SH-D-D1	Post-installed	SLW	Shale	121.6	D	D	0.5	2.00	4.00	-	-	7430	8515	620	6.72	7646
35	SL-SH-D-A1	Post-installed	SLW	Shale	121.6	A	D	0.5	2.00	4.00	-	-	7430	8515	620	6.72	8173
36	SL-SH-D-A2	Post-installed	SLW	Shale	121.6	A	D	0.5	2.00	4.00	-	-	7430	8515	620	6.72	8226
37	SL-SH-S-B1	Post-installed	SLW	Shale	121.6	B	S	0.5	2.16	4.32	44.30	-	7430	8515	620	6.72	7841
38	SL-SH-S-C1	Post-installed	SLW	Shale	121.6	C	S	0.5	2.14	4.28	64.70	-	7430	8515	620	6.72	5304
39	SL-SH-S-D1	Post-installed	SLW	Shale	121.6	D	S	0.5	2.17	4.34	45.00	-	7430	8515	620	6.72	7189
40	SL-SH-S-A1	Post-installed	SLW	Shale	121.6	A	S	0.5	2.40	4.80	44.40	-	7430	8515	620	6.72	8123
41	SL-SH-S-D2	Post-installed	SLW	Shale	121.6	D	S	0.5	2.17	4.34	44.60	-	7430	8515	620	6.72	7049
42	SL-CL-T-B1	Post-installed	SLW	Clay	118.1	B	T	0.5	2.00	4.00	40.00	3.50	5930	5933	550	7.14	6062
43	SL-CL-T-C1	Post-installed	SLW	Clay	118.1	C	T	0.5	2.00	4.00	60.00	4.75	5930	5933	550	7.14	5780
44	SL-CL-T-D1	Post-installed	SLW	Clay	118.1	D	T	0.5	1.88	3.75	40.00	5.40	5930	5933	550	7.14	5590
45	SL-CL-T-A1	Post-installed	SLW	Clay	118.1	A	T	0.5	1.73	3.46	57.40	7.50	5930	5933	550	7.14	5517
46	SL-CL-T-B2	Post-installed	SLW	Clay	118.1	B	T	0.5	2.00	4.00	40.00	3.60	5930	5933	550	7.14	6430
47	SL-CL-T-C2	Post-installed	SLW	Clay	118.1	C	T	0.5	1.56	3.12	60.00	9.50	5930	5933	550	7.14	5778
48	SL-CL-T-D2	Post-installed	SLW	Clay	118.1	D	T	0.5	2.00	4.00	39.50	4.13	5930	5933	550	7.14	6250
49	SL-CL-T-B3*	Post-installed	SLW	Clay	118.1	B	T	0.5	2.00	4.00	39.00	4.75	5930	5929	510	6.62	5583
50	SL-CL-T-C3*	Post-installed	SLW	Clay	118.1	C	T	0.5	2.00	4.00	59.20	5.25	5930	5929	510	6.62	6089

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
			Specimen Details			Anchor Details							Concrete Detials				Test Results
Count	ID	Cast-in / Post-installed	Concrete Type	Aggregate Type	Equlibrium Density	Manufacturer	Anchor Types	Diameter, d_a	Effective Embedment Depth, h_{ef}	h_{ef}/d_a	Installation Torque	Installation Turns	Compressive Strength at 28 Days, f_c	Compressive Strength on Testing Day, f_c	Tensilie Splitting Strength on Testing Day, f_t	$\frac{f_t}{\sqrt{f_c}}$	N_{test}
			NW/SLW/ALW	Shale/Clay/ Slate (Expanded Aggregate)	pcf		Torque-Crtl.(T)/ Disp.-Ctrl.(D)/ Screw(S)/Cast-In(C)	in.	in.	Col(9) / Col(8)	ft-lbf	Number	psi	psi	psi	Col(15) / [Col(14)]^0.5	lb
51	SL-CL-T-D3*	Post-installed	SLW	Clay	118.1	D	T	0.5	2.00	4.00	39.20	4.50	5930	5929	510	6.62	4938
52	SL-CL-T-A2*	Post-installed	SLW	Clay	118.1	A	T	0.5	2.00	4.00	54.00	6.00	5930	5929	510	6.62	5458
53	SL-CL-T-D4*	Post-installed	SLW	Clay	118.1	D	T	0.5	2.00	4.00	39.00	4.75	5930	5929	510	6.62	5489
54	SL-CL-D-A1	Post-installed	SLW	Clay	118.1	A	D	0.5	2.00	4.00	-	-	5930	5933	550	7.14	7868
55	SL-CL-D-B1	Post-installed	SLW	Clay	118.1	B	D	0.5	2.00	4.00	-	-	5930	5933	550	7.14	7897
56	SL-CL-D-C1	Post-installed	SLW	Clay	118.1	C	D	0.5	2.00	4.00	-	-	5930	5933	550	7.14	8960
57	SL-CL-D-D1	Post-installed	SLW	Clay	118.1	D	D	0.5	2.00	4.00	-	-	5930	5933	550	7.14	7008
58	SL-CL-D-A2	Post-installed	SLW	Clay	118.1	A	D	0.5	2.00	4.00	-	-	5930	5933	550	7.14	8554
59	SL-CL-S-C1	Post-installed	SLW	Clay	118.1	C	2	0.5	2.14	4.28	64.10	-	5930	5933	550	7.14	6681
60	SL-CL-S-D1	Post-installed	SLW	Clay	118.1	D	S	0.5	2.17	4.34	49.70	-	5930	5933	550	7.14	6871
61	SL-CL-S-A1	Post-installed	SLW	Clay	118.1	A	S	0.5	2.40	4.80	44.70	-	5930	5933	550	7.14	6611
62	SL-CL-S-B1	Post-installed	SLW	Clay	118.1	B	S	0.5	2.16	4.32	44.60	-	5930	5933	550	7.14	6950
63	SL-CL-S-B2*	Post-installed	SLW	Clay	118.1	B	S	0.5	2.16	4.32	55.00	-	5930	5933	550	7.14	6669
64	SL-CL-S-A1*	Post-installed	SLW	Clay	118.1	A	S	0.5	2.40	4.80	44.20	-	5930	5933	550	7.14	5853
65	SL-SL-T-B1	Post-installed	SLW	Slate	118.9	B	T	0.5	1.75	3.50	39.90	1.25	8120	8124	615	6.82	6373
66	SL-SL-T-C1	Post-installed	SLW	Slate	118.9	C	T	0.5	1.50	3.00	59.80	5.25	8120	8124	615	6.82	5484
67	SL-SL-T-D1	Post-installed	SLW	Slate	118.9	D	T	0.5	1.50	3.00	40.00	4.50	8120	8124	615	6.82	4743
68	SL-SL-T-A1	Post-installed	SLW	Slate	118.9	A	T	0.5	1.375	2.75	45.50	6.25	8120	8124	615	6.82	4218
69	SL-SL-T-C2	Post-installed	SLW	Slate	118.9	C	T	0.5	1.50	3.00	59.70	4.25	8120	8124	615	6.82	4798
70	SL-SL-T-B2*	Post-installed	SLW	Slate	118.9	B	T	0.5	2.00	4.00	39.60	2.50	8120	8086	520	5.78	6824
71	SL-SL-T-C3*	Post-installed	SLW	Slate	118.9	C	T	0.5	2.00	4.00	59.20	4.50	8120	8086	520	5.78	6900
72	SL-SL-T-D2*	Post-installed	SLW	Slate	118.9	D	T	0.5	2.00	4.00	39.20	4.25	8120	8086	520	5.78	5363
73	SL-SL-T-A2*	Post-installed	SLW	Slate	118.9	A	T	0.5	2.00	4.00	55.00	5.25	8120	8086	520	5.78	6548
74	SL-SL-T-B3*	Post-installed	SLW	Slate	118.9	B	T	0.5	2.00	4.00	40.00	2.00	8120	8086	520	5.78	6546
75	SL-SL-D-B1	Post-installed	SLW	Slate	118.9	B	D	0.5	2.00	4.00	-	-	8120	8124	615	6.82	7458
76	SL-SL-D-C1	Post-installed	SLW	Slate	118.9	C	D	0.5	2.00	4.00	-	-	8120	8124	615	6.82	9160
77	SL-SL-D-D1	Post-installed	SLW	Slate	118.9	D	D	0.5	2.00	4.00	-	-	8120	8124	615	6.82	7670
78	SL-SL-D-A1	Post-installed	SLW	Slate	118.9	A	D	0.5	2.00	4.00	-	-	8120	8124	615	6.82	8691
79	SL-SL-D-C2	Post-installed	SLW	Slate	118.9	C	D	0.5	2.00	4.00	-	-	8120	8124	615	6.82	9625
80	SL-SL-D-C3	Post-installed	SLW	Slate	118.9	C	D	0.5	2.00	4.00	-	-	8120	8124	615	6.82	8746
81	SL-SL-S-B1	Post-installed	SLW	Slate	118.9	B	S	0.5	2.16	4.32	45.00	2.50	8120	8124	615	6.82	7345
82	SL-SL-S-C1	Post-installed	SLW	Slate	118.9	C	S	0.5	2.14	4.28	64.00	6.00	8120	8124	615	6.82	4757
83	SL-SL-S-D1	Post-installed	SLW	Slate	118.9	D	S	0.5	2.17	4.34	44.50	5.00	8120	8124	615	6.82	8019
84	SL-SL-S-A1	Post-installed	SLW	Slate	118.9	A	S	0.5	2.40	4.80	45.00	5.75	8120	8124	615	6.82	4872
85	SL-SL-S-C2	Post-installed	SLW	Slate	118.9	C	S	0.5	2.14	4.28	64.40	5.75	8120	8124	615	6.82	5414
86	AL-SH-T-B1	Post-installed	ALW	Shale	96.9	B	T	0.5	1.75	3.50	-	-	6280	6192	535	6.80	4634
87	AL-SH-T-C1	Post-installed	ALW	Shale	96.9	C	T	0.5	1.50	3.00	-	-	6280	6192	535	6.80	3346
88	AL-SH-T-D1	Post-installed	ALW	Shale	96.9	D	T	0.5	1.50	3.00	-	-	6280	6192	535	6.80	3561
89	AL-SH-T-A1	Post-installed	ALW	Shale	96.9	A	T	0.5	1.375	2.75	-	-	6280	6192	535	6.80	2761
90	AL-SH-T-B2	Post-installed	ALW	Shale	96.9	B	T	0.5	1.75	3.50	-	-	6280	6192	535	6.80	4576
91	AL-SH-T-B3*	Post-installed	ALW	Shale	96.9	B	T	0.5	2.00	4.00	-	-	6280	6247	530	6.71	4902
92	AL-SH-T-C2*	Post-installed	ALW	Shale	96.9	C	T	0.5	2.00	4.00	-	-	6280	6247	530	6.71	4294
93	AL-SH-T-D2*	Post-installed	ALW	Shale	96.9	D	T	0.5	2.00	4.00	-	-	6280	6247	530	6.71	4213
94	AL-SH-T-A2*	Post-installed	ALW	Shale	96.9	A	T	0.5	2.00	4.00	-	-	6280	6247	530	6.71	4841
95	AL-SH-T-C3*	Post-installed	ALW	Shale	96.9	C	T	0.5	2.00	4.00	-	-	6280	6247	530	6.71	4485
96	AL-SH-D-B1	Post-installed	ALW	Shale	96.9	B	D	0.5	2.00	4.00	-	-	6280	6192	535	6.80	5674
97	AL-SH-D-C1	Post-installed	ALW	Shale	96.9	C	D	0.5	2.00	4.00	-	-	6280	6192	535	6.80	6476
98	AL-SH-D-D1	Post-installed	ALW	Shale	96.9	D	D	0.5	2.00	4.00	-	-	6280	6192	535	6.80	5594
99	AL-SH-D-A1	Post-installed	ALW	Shale	96.9	A	D	0.5	2.00	4.00	-	-	6280	6192	535	6.80	6587
100	AL-SH-D-B2	Post-installed	ALW	Shale	96.9	B	D	0.5	2.00	4.00	-	-	6280	6192	535	6.80	5920

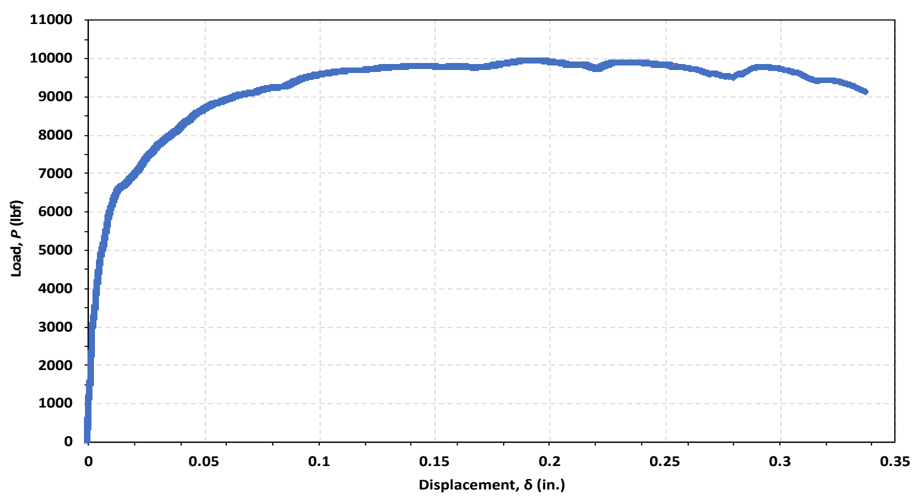
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
			Specimen Details			Anchor Details							Concrete Detials				Test Results
Count	ID	Cast-in / Post-installed	Concrete Type	Aggregate Type	Equlibrium Density	Manufacturer	Anchor Types	Diameter, d_a	Effective Embedment Depth, h_{ef}	h_{ef}/d_a	Installation Torque	Installation Turns	Compressive Strength at 28 Days, f_c	Compressive Strength on Testing Day, f_c	Tensilie Splitting Strength on Testing Day, f_t	$\frac{f_t}{\sqrt{f_c}}$	N_{test}
			NW/SLW/ALW	Shale/Clay/ Slate (Expanded Aggregate)	pcf		Torque-Crtl.(T)/ Disp.-Ctrl.(D)/ Screw(S)/Cast-In(C)	in.	in.	Col(9) / Col(8)	ft-lbf	Number	psi	psi	psi	Col(15) / [Col(14)]^0.5	lb
101	AL-SH-S-B1	Post-installed	ALW	Shale	96.9	B	S	0.5	2.16	4.32	-	-	6280	6192	535	6.80	5479
102	AL-SH-S-C1	Post-installed	ALW	Shale	96.9	C	S	0.5	2.14	4.28	-	-	6280	6192	535	6.80	3924
103	AL-SH-S-D1	Post-installed	ALW	Shale	96.9	D	S	0.5	2.17	4.34	-	-	6280	6192	535	6.80	4974
104	AL-SH-S-A1	Post-installed	ALW	Shale	96.9	A	S	0.5	2.40	4.80	-	-	6280	6192	535	6.80	4432
105	AL-SH-S-B2	Post-installed	ALW	Shale	96.9	B	S	0.5	2.16	4.32	-	-	6280	6192	535	6.80	4502
106	AL-CL-T-B1	Post-installed	ALW	Clay	92.5	B	T	0.5	1.75	3.50	40.00	2.25	5000	5671	415	5.51	3544
107	AL-CL-T-C1	Post-installed	ALW	Clay	92.5	C	T	0.5	1.50	3.00	60.00	6.50	5000	5671	415	5.51	3498
108	AL-CL-T-D1	Post-installed	ALW	Clay	92.5	D	T	0.5	1.50	3.00	40.00	6.25	5000	5671	415	5.51	2749
109	AL-CL-T-A1	Post-installed	ALW	Clay	92.5	A	T	0.5	1.375	2.75	58.80	8.50	5000	5671	415	5.51	2557
110	AL-CL-T-C2	Post-installed	ALW	Clay	92.5	C	T	0.5	1.50	3.00	59.70	5.50	5000	5671	415	5.51	3238
111	AL-CL-T-B2*	Post-installed	ALW	Clay	92.5	B	T	0.5	2.00	4.00	39.00	2.75	5000	4875	310	4.44	4435
112	AL-CL-T-C3*	Post-installed	ALW	Clay	92.5	C	T	0.5	2.00	4.00	59.20	7.50	5000	4875	310	4.44	4579
113	AL-CL-T-D2*	Post-installed	ALW	Clay	92.5	D	T	0.5	2.00	4.00	39.00	5.75	5000	4875	310	4.44	3746
114	AL-CL-T-A2*	Post-installed	ALW	Clay	92.5	A	T	0.5	2.00	4.00	54.30	6.00	5000	4875	310	4.44	3903
115	AL-CL-T-C4*	Post-installed	ALW	Clay	92.5	C	T	0.5	2.00	4.00	59.90	9.25	5000	4875	310	4.44	3982
116	AL-CL-D-B1	Post-installed	ALW	Clay	92.5	B	D	0.5	2.00	4.00	-	-	5000	5671	415	5.51	3992
117	AL-CL-D-C1	Post-installed	ALW	Clay	92.5	C	D	0.5	2.00	4.00	-	-	5000	5671	415	5.51	4020
118	AL-CL-D-D1	Post-installed	ALW	Clay	92.5	D	D	0.5	2.00	4.00	-	-	5000	5671	415	5.51	3886
119	AL-CL-D-A1	Post-installed	ALW	Clay	92.5	A	D	0.5	2.00	4.00	-	-	5000	5671	415	5.51	5092
120	AL-CL-D-D2	Post-installed	ALW	Clay	92.5	D	D	0.5	2.00	4.00	-	-	5000	5671	415	5.51	4769
121	AL-CL-S-B1	Post-installed	ALW	Clay	92.5	B	S	0.5	2.16	4.32	44.10	-	5000	5671	415	5.51	4550
122	AL-CL-S-C1	Post-installed	ALW	Clay	92.5	C	S	0.5	2.14	4.28	64.50	-	5000	5671	415	5.51	4466
123	AL-CL-S-D1	Post-installed	ALW	Clay	92.5	D	S	0.5	2.17	4.34	44.90	-	5000	5671	415	5.51	3881
124	AL-CL-S-A1	Post-installed	ALW	Clay	92.5	A	S	0.5	2.40	4.80	44.90	-	5000	5671	415	5.51	5412
125	AL-CL-S-A2	Post-installed	ALW	Clay	92.5	A	S	0.5	2.40	4.80	45.00	-	5000	5671	415	5.51	4810
126	AL-SL-T-B1	Post-installed	ALW	Slate	98.6	B	T	0.5	1.75	3.50	40.00	3.75	5530	5586	480	6.42	4779
127	AL-SL-T-C1	Post-installed	ALW	Slate	98.6	C	T	0.5	1.50	3.00	60.00	6.25	5530	5586	480	6.42	4343
128	AL-SL-T-D1	Post-installed	ALW	Slate	98.6	D	T	0.5	1.50	3.00	40.00	4.75	5530	5586	480	6.42	3708
129	AL-SL-T-A1	Post-installed	ALW	Slate	98.6	A	T	0.5	1.375	2.75	54.90	7.00	5530	5586	480	6.42	3476
130	AL-SL-T-D2	Post-installed	ALW	Slate	98.6	D	T	0.5	1.50	3.00	39.90	4.75	5530	5586	480	6.42	3787
131	AL-SL-T-B2*	Post-installed	ALW	Slate	98.6	B	T	0.5	2.00	4.00	-	-	5530	5439	400	5.42	5431
132	AL-SL-T-C2*	Post-installed	ALW	Slate	98.6	C	T	0.5	2.00	4.00	-	-	5530	5439	400	5.42	4861
133	AL-SL-T-D3*	Post-installed	ALW	Slate	98.6	D	T	0.5	2.00	4.00	-	-	5530	5439	400	5.42	4923
134	AL-SL-T-A2*	Post-installed	ALW	Slate	98.6	A	T	0.5	2.00	4.00	-	-	5530	5439	400	5.42	4273
135	AL-SL-T-D4*	Post-installed	ALW	Slate	98.6	D	T	0.5	2.00	4.00	-	-	5530	5439	400	5.42	4846
136	AL-SL-D-B1	Post-installed	ALW	Slate	98.6	B	D	0.5	2.00	4.00	-	-	5530	5586	480	6.42	6175
137	AL-SL-D-C1	Post-installed	ALW	Slate	98.6	C	D	0.5	2.00	4.00	-	-	5530	5586	480	6.42	7615
138	AL-SL-D-D1	Post-installed	ALW	Slate	98.6	D	D	0.5	2.00	4.00	-	-	5530	5586	480	6.42	5097
139	AL-SL-D-A1	Post-installed	ALW	Slate	98.6	A	D	0.5	2.00	4.00	-	-	5530	5586	480	6.42	6758
140	AL-SL-D-D2	Post-installed	ALW	Slate	98.6	D	D	0.5	2.00	4.00	-	-	5530	5586	480	6.42	6705
141	AL-SL-D-D3	Post-installed	ALW	Slate	98.6	D	D	0.5	2.00	4.00	-	-	5530	5586	480	6.42	6599
142	AL-SL-S-B1	Post-installed	ALW	Slate	98.6	B	S	0.5	2.16	4.32	44.70	-	5530	5586	480	6.42	6380
143	AL-SL-S-C1	Post-installed	ALW	Slate	98.6	C	S	0.5	2.14	4.28	60.00	-	5530	5586	480	6.42	4914
144	AL-SL-S-D1	Post-installed	ALW	Slate	98.6	D	S	0.5	2.17	4.34	45.00	-	5530	5586	480	6.42	5590
145	AL-SL-S-A1	Post-installed	ALW	Slate	98.6	A	S	0.5	2.40	4.80	45.00	-	5530	5586	480	6.42	5121
146	AL-SL-S-D2	Post-installed	ALW	Slate	98.6	D	S	0.5	2.17	4.34	45.00	-	5530	5586	480	6.42	6069
147	AL-SL-S-A2	Post-installed	ALW	Slate	98.6	A	S	0.5	2.40	4.80	44.90	-	5530	5586	480	6.42	4870
148	NW-C-1	Cast-in	NW	n/a	-	n/a	C	0.5	2.07	4.14	-	-	7740	7408	630	7.32	9548
149	NW-C-2	Cast-in	NW	n/a	-	n/a	C	0.5	2.07	4.14	-	-	7740	7408	630	7.32	9534
150	NW-C-3	Cast-in	NW	n/a	-	n/a	C	0.5	2.07	4.14	-	-	7740	7408	630	7.32	9649

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Count	ID	Cast-in / Post-installed	Specimen Details			Manufacturer	Anchor Details						Concrete Detials				Test Results
			Concrete Type	Aggregate Type	Equlibrium Density		Anchor Types	Diameter, d_a	Effective Embedment Depth, h_{ef}	h_{ef}/d_a	Installation Torque	Installation Turns	Compressive Strength at 28 Days, f_c	Compressive Strength on Testing Day, f_c	Tensilie Splitting Strength on Testing Day, f_t	$\frac{f_t}{\sqrt{f_c}}$	N_{test}
			NW/SLW/ALW	Shale/Clay/ Slate (Expanded Aggregate)	pcf		Torque-Crtl.(T)/ Disp.-Ctrl.(D)/ Screw(S)/Cast-In(C)	in.	in.	Col(9) / Col(8)	ft-lbf	Number	psi	psi	psi	Col(15) / [Col(14)]^0.5	lb
151	NW-C-4	Cast-in	NW	n/a	-	n/a	C	0.5	2.07	4.14	-	-	7740	7408	630	7.32	10263
152	NW-C-5	Cast-in	NW	n/a	-	n/a	C	0.5	2.07	4.14	-	-	7740	7408	630	7.32	9449
153	NW-C-6	Cast-in	NW	n/a	-	n/a	C	0.5	2.07	4.14	-	-	7740	7408	630	7.32	10116
154	NW-C-7	Cast-in	NW	n/a	-	n/a	C	0.5	2.07	4.14	-	-	7740	7408	630	7.32	10314
155	NW-C-8	Cast-in	NW	n/a	-	n/a	C	0.5	2.07	4.14	-	-	7740	7408	630	7.32	9620
156	SL-SH-C-1	Cast-in	SLW	Shale	121.6	n/a	C	0.5	2.07	4.14	-	-	7430	8515	620	6.72	7078
157	SL-SH-C-2	Cast-in	SLW	Shale	121.6	n/a	C	0.5	2.07	4.14	-	-	7430	8515	620	6.72	7013
158	SL-SH-C-3	Cast-in	SLW	Shale	121.6	n/a	C	0.5	2.07	4.14	-	-	7430	8515	620	6.72	7401
159	SL-SH-C-4	Cast-in	SLW	Shale	121.6	n/a	C	0.5	2.07	4.14	-	-	7430	8515	620	6.72	7068
160	SL-SH-C-5	Cast-in	SLW	Shale	121.6	n/a	C	0.5	2.07	4.14	-	-	7430	8515	620	6.72	7651
161	SL-SH-C-6	Cast-in	SLW	Shale	121.6	n/a	C	0.5	2.07	4.14	-	-	7430	8515	620	6.72	7887
162	SL-SH-C-7	Cast-in	SLW	Shale	121.6	n/a	C	0.5	2.07	4.14	-	-	7430	8515	620	6.72	6842
163	SL-SH-C-8	Cast-in	SLW	Shale	121.6	n/a	C	0.5	2.07	4.14	-	-	7430	8515	620	6.72	6866
164	SL-CL-C-1	Cast-in	SLW	Clay	118.1	n/a	C	0.5	2.07	4.14	-	-	5930	5933	550	7.14	7254
165	SL-CL-C-2	Cast-in	SLW	Clay	118.1	n/a	C	0.5	2.07	4.14	-	-	5930	5933	550	7.14	7653
166	SL-CL-C-3	Cast-in	SLW	Clay	118.1	n/a	C	0.5	2.07	4.14	-	-	5930	5933	550	7.14	7104
167	SL-CL-C-4	Cast-in	SLW	Clay	118.1	n/a	C	0.5	2.07	4.14	-	-	5930	5933	550	7.14	6803
168	SL-CL-C-5	Cast-in	SLW	Clay	118.1	n/a	C	0.5	2.07	4.14	-	-	5930	5933	550	7.14	7064
169	SL-CL-C-6	Cast-in	SLW	Clay	118.1	n/a	C	0.5	2.07	4.14	-	-	5930	5933	550	7.14	7451
170	SL-CL-C-7	Cast-in	SLW	Clay	118.1	n/a	C	0.5	2.07	4.14	-	-	5930	5933	550	7.14	6936
171	SL-CL-C-8	Cast-in	SLW	Clay	118.1	n/a	C	0.5	2.07	4.14	-	-	5930	5933	550	7.14	6958
172	SL-SL-C-1	Cast-in	SLW	Slate	118.9	n/a	C	0.5	2.07	4.14	-	-	8120	8124	615	6.82	7504
173	SL-SL-C-2	Cast-in	SLW	Slate	118.9	n/a	C	0.5	2.07	4.14	-	-	8120	8124	615	6.82	7550
174	SL-SL-C-3	Cast-in	SLW	Slate	118.9	n/a	C	0.5	2.07	4.14	-	-	8120	8124	615	6.82	7704
175	SL-SL-C-4	Cast-in	SLW	Slate	118.9	n/a	C	0.5	2.07	4.14	-	-	8120	8124	615	6.82	8339
176	SL-SL-C-5	Cast-in	SLW	Slate	118.9	n/a	C	0.5	2.07	4.14	-	-	8120	8124	615	6.82	8065
177	SL-SL-C-6	Cast-in	SLW	Slate	118.9	n/a	C	0.5	2.07	4.14	-	-	8120	8124	615	6.82	7569
178	SL-SL-C-7	Cast-in	SLW	Slate	118.9	n/a	C	0.5	2.07	4.14	-	-	8120	8124	615	6.82	7629
179	AL-SH-C-1	Cast-in	ALW	Shale	96.9	n/a	C	0.5	2.07	4.14	-	-	6280	6192	630	8.01	4986
180	AL-SH-C-2	Cast-in	ALW	Shale	96.9	n/a	C	0.5	2.07	4.14	-	-	6280	6192	630	8.01	5727
181	AL-SH-C-3	Cast-in	ALW	Shale	96.9	n/a	C	0.5	2.07	4.14	-	-	6280	6192	630	8.01	5441
182	AL-SH-C-4	Cast-in	ALW	Shale	96.9	n/a	C	0.5	2.07	4.14	-	-	6280	6192	630	8.01	5239
183	AL-SH-C-5	Cast-in	ALW	Shale	96.9	n/a	C	0.5	2.07	4.14	-	-	6280	6192	630	8.01	5166
184	AL-SH-C-6	Cast-in	ALW	Shale	96.9	n/a	C	0.5	2.07	4.14	-	-	6280	6192	630	8.01	5085
185	AL-SH-C-7	Cast-in	ALW	Shale	96.9	n/a	C	0.5	2.07	4.14	-	-	6280	6192	630	8.01	5325
186	AL-CL-C-1	Cast-in	ALW	Clay	92.5	n/a	C	0.5	2.07	4.14	-	-	5000	5671	415	5.51	3917
187	AL-CL-C-2	Cast-in	ALW	Clay	92.5	n/a	C	0.5	2.07	4.14	-	-	5000	5671	415	5.51	4863
188	AL-CL-C-3	Cast-in	ALW	Clay	92.5	n/a	C	0.5	2.07	4.14	-	-	5000	5671	415	5.51	4338
189	AL-CL-C-4	Cast-in	ALW	Clay	92.5	n/a	C	0.5	2.07	4.14	-	-	5000	5671	415	5.51	4377
190	AL-CL-C-5	Cast-in	ALW	Clay	92.5	n/a	C	0.5	2.07	4.14	-	-	5000	5671	415	5.51	4475
191	AL-CL-C-6	Cast-in	ALW	Clay	92.5	n/a	C	0.5	2.07	4.14	-	-	5000	5671	415	5.51	4608
192	AL-CL-C-7	Cast-in	ALW	Clay	92.5	n/a	C	0.5	2.07	4.14	-	-	5000	5671	415	5.51	3915
193	AL-CL-C-8	Cast-in	ALW	Clay	92.5	n/a	C	0.5	2.07	4.14	-	-	5000	5671	415	5.51	4646
194	AL-SL-C-1	Cast-in	ALW	Slate	98.6	n/a	C	0.5	2.07	4.14	-	-	5530	5586	480	6.42	5759
195	AL-SL-C-2	Cast-in	ALW	Slate	98.6	n/a	C	0.5	2.07	4.14	-	-	5530	5586	480	6.42	6310
196	AL-SL-C-3	Cast-in	ALW	Slate	98.6	n/a	C	0.5	2.07	4.14	-	-	5530	5586	480	6.42	6255
197	AL-SL-C-4	Cast-in	ALW	Slate	98.6	n/a	C	0.5	2.07	4.14	-	-	5530	5586	480	6.42	6187
198	AL-SL-C-5	Cast-in	ALW	Slate	98.6	n/a	C	0.5	2.07	4.14	-	-	5530	5586	480	6.42	6098
199	AL-SL-C-6	Cast-in	ALW	Slate	98.6	n/a	C	0.5	2.07	4.14	-	-	5530	5586	480	6.42	6161
200	AL-SL-C-7	Cast-in	ALW	Slate	98.6	n/a	C	0.5	2.07	4.14	-	-	5530	5586	480	6.42	6163

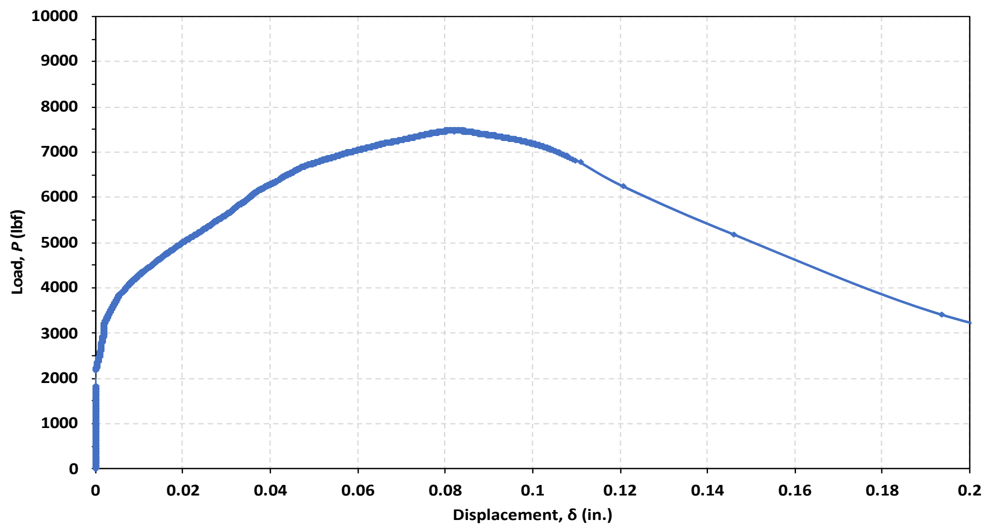
APPENDIX II: LOAD-DEFLECTION PLOTS



NW-T-B1



NW-T-C1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9000
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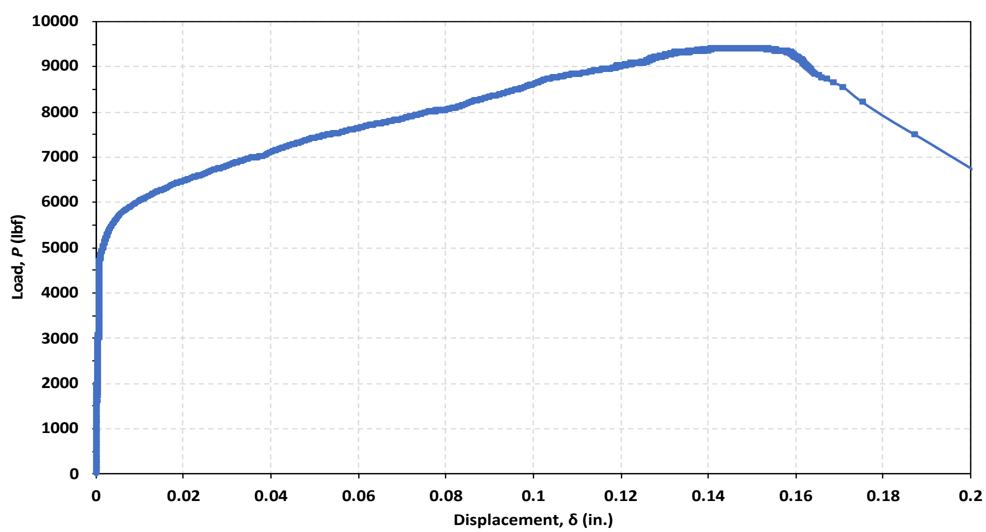
5000
4000
3000
2000
1000
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-T-D1


Load, P (lbf)
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9000
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6000
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4000
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2000
1000
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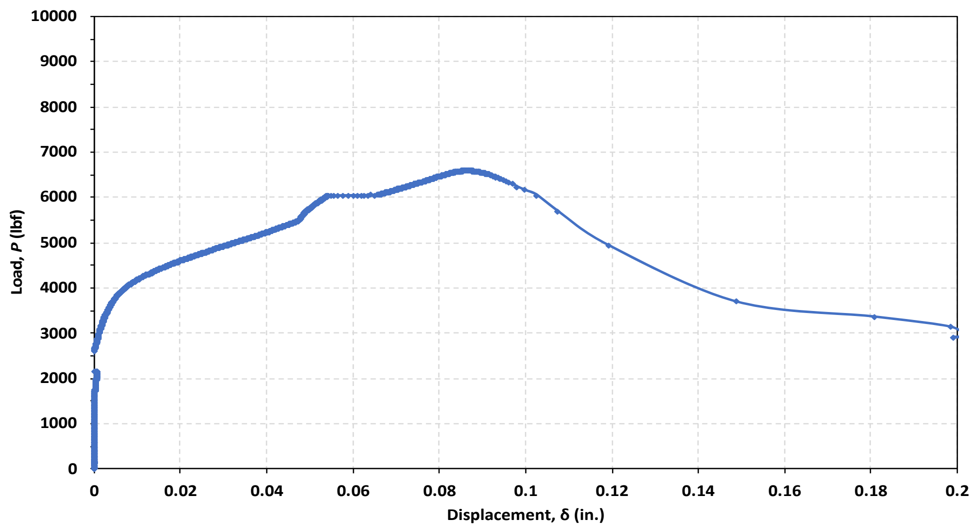
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-T-A1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Displacement, δ (in.)
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7000
6000
5000
4000
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2000
1000
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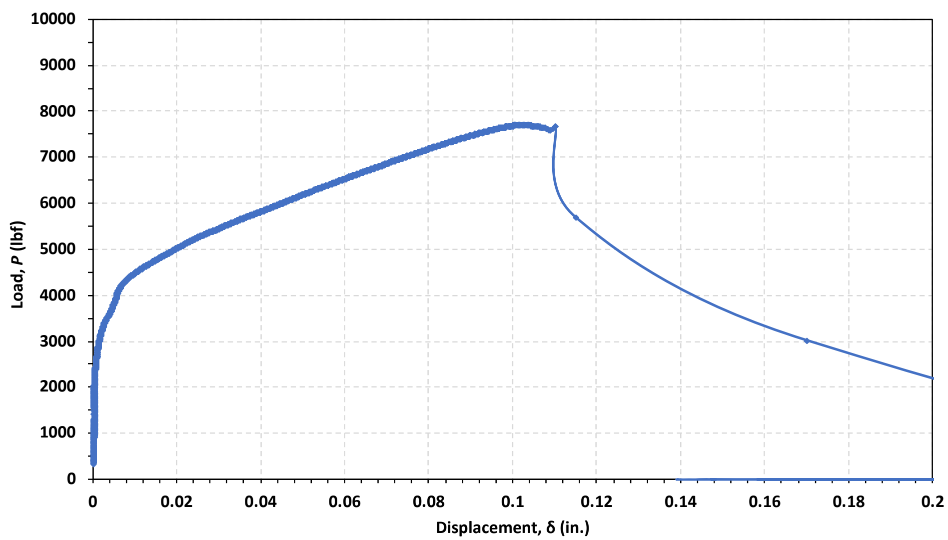
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

NW-T-B2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Displacement, δ (in.)
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9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
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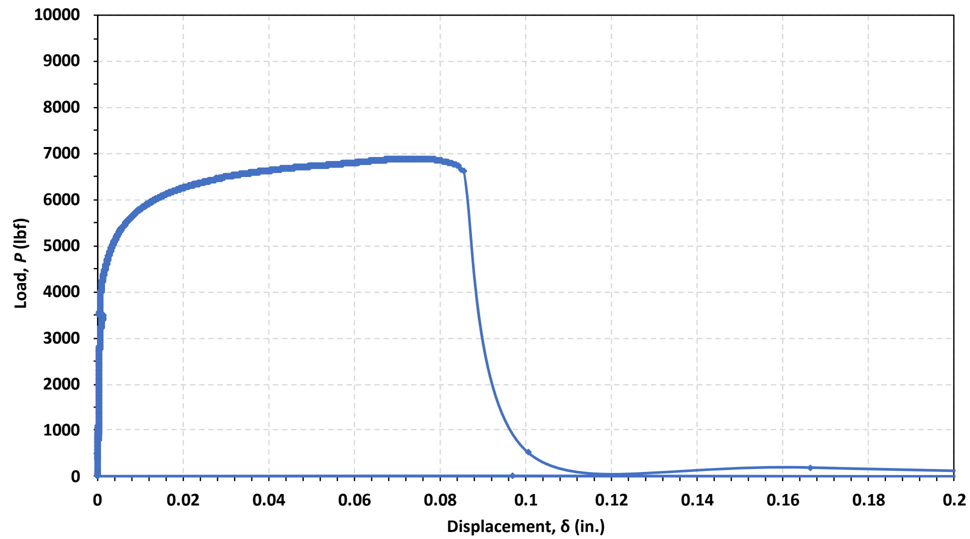
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

NW-T-B3*


Load, P (lbf)
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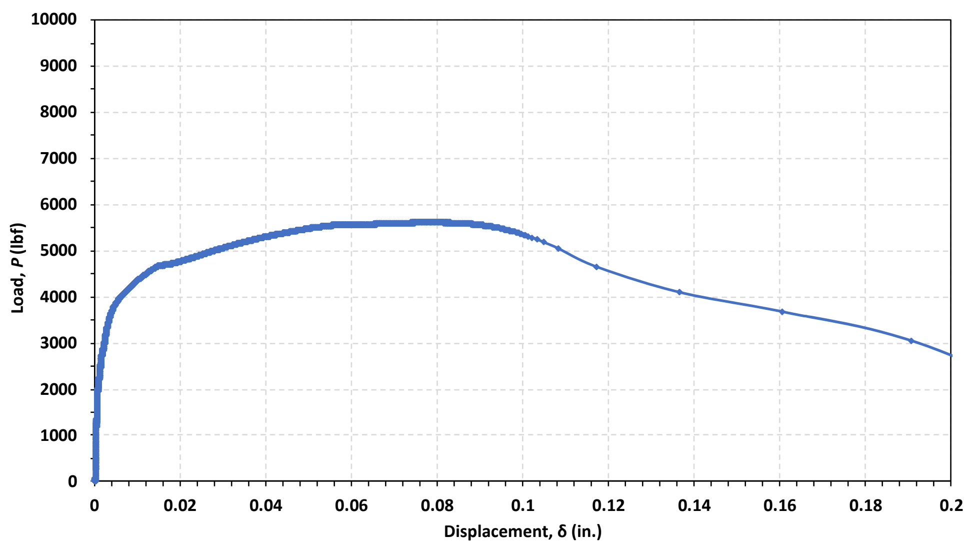
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-T-C2*


Load, P (lbf)
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9000
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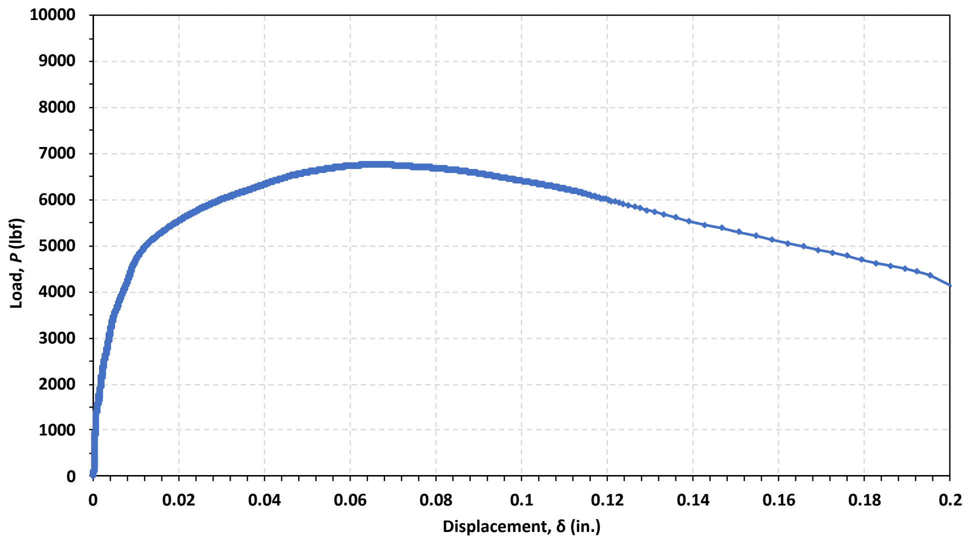
7000
6000
5000
4000
3000
2000
1000
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-T-D2*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6000
5000
4000
3000
2000
1000
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Load, P (lbf)
0
0.02
0.04
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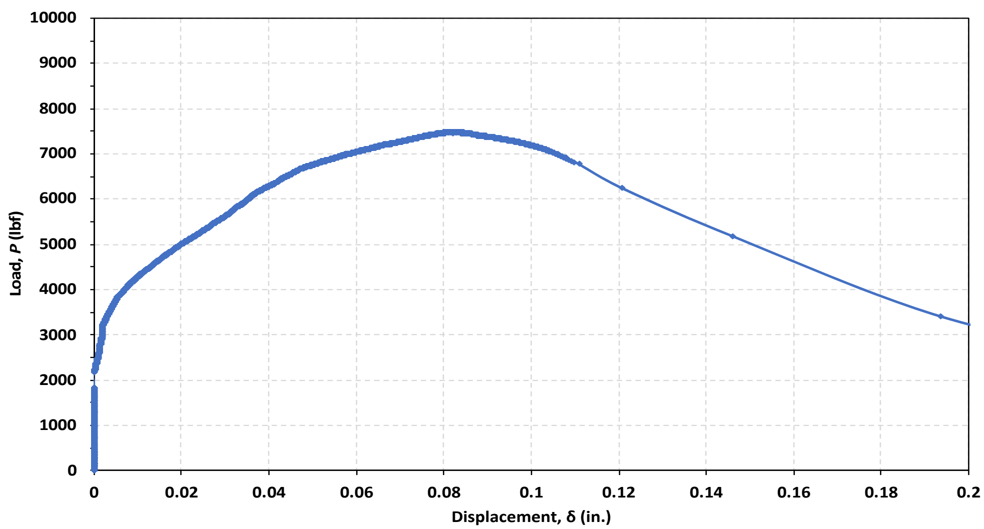
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-T-A2*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1000
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Load, P (lbf)
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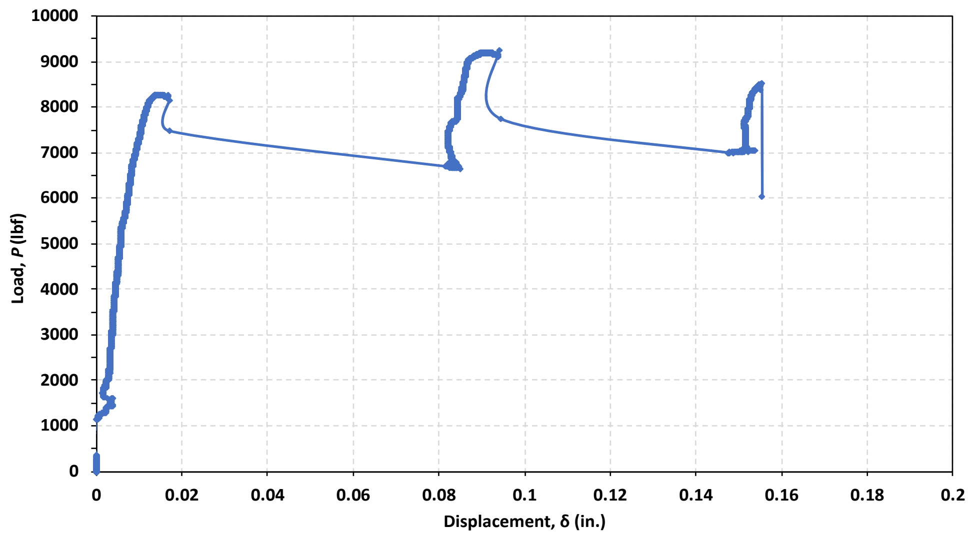
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-T-B4*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6000
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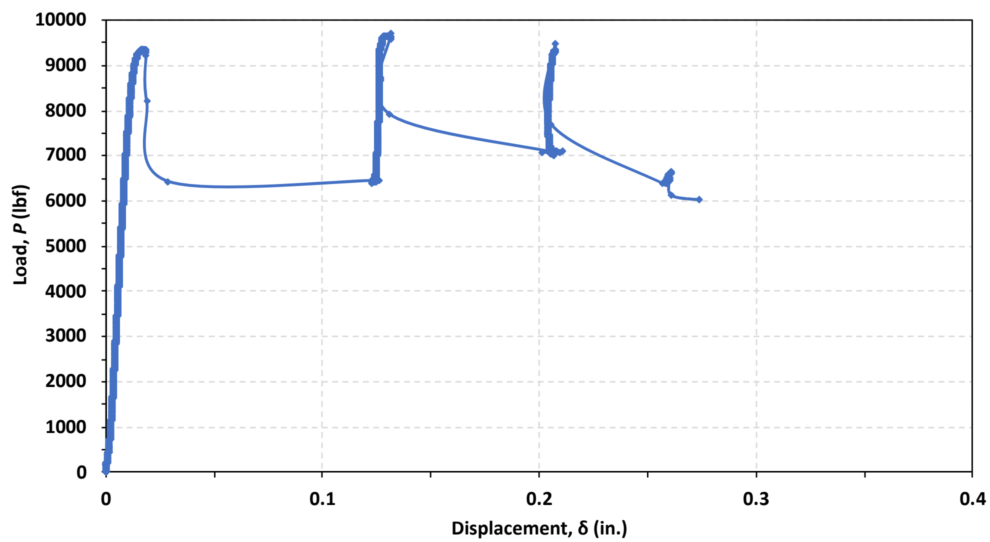
2000
1000
0
Load, P (lbf)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-D-B1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7000
6000
5000
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3000
2000
1000
0
Load, P (lbf)
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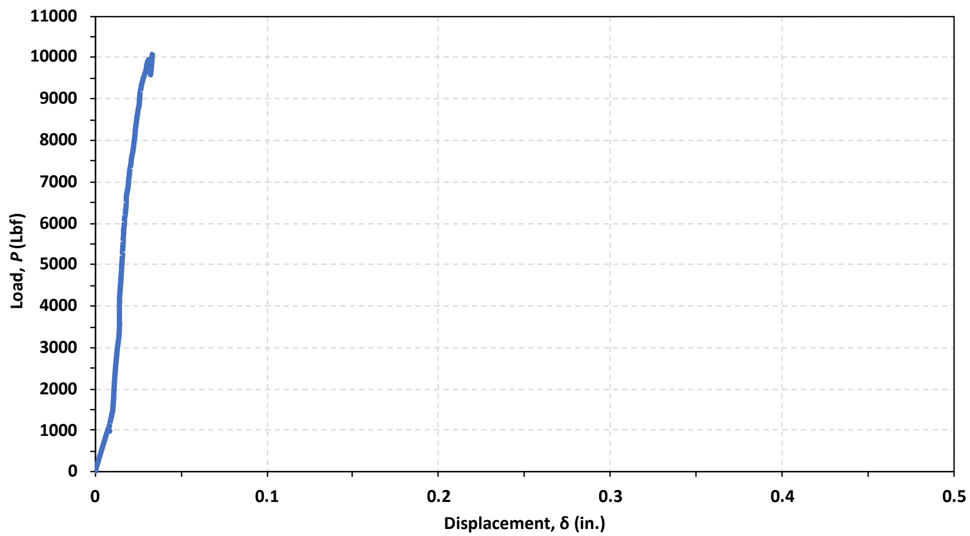
0.1
0.2
0.3
0.4
Displacement, δ (in.)

NW-D-C1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8000
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6000
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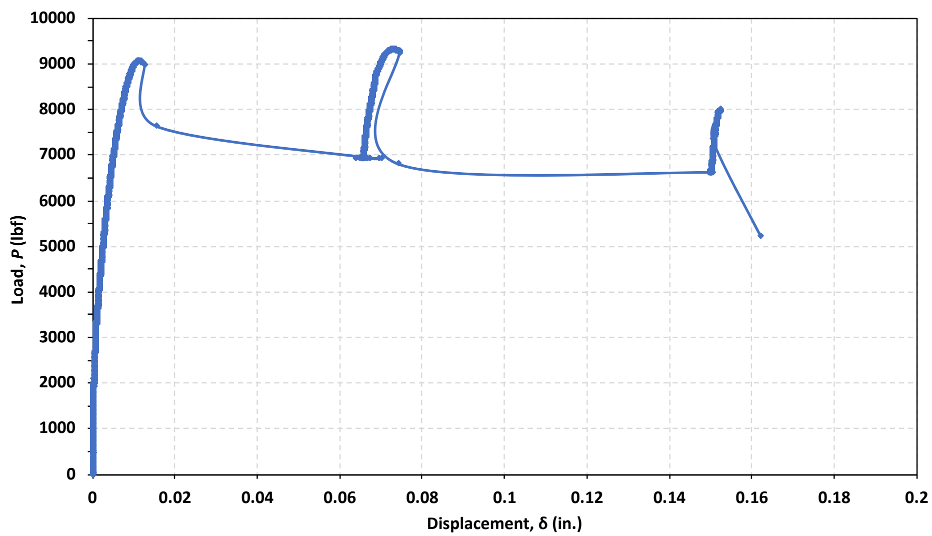
4000
3000
2000
1000
0
Load, P (Lbf)
0
0.1
0.2
0.3
0.4
0.5
Displacement, δ (in.)

NW-D-D1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Load, P (lbf)
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0.02
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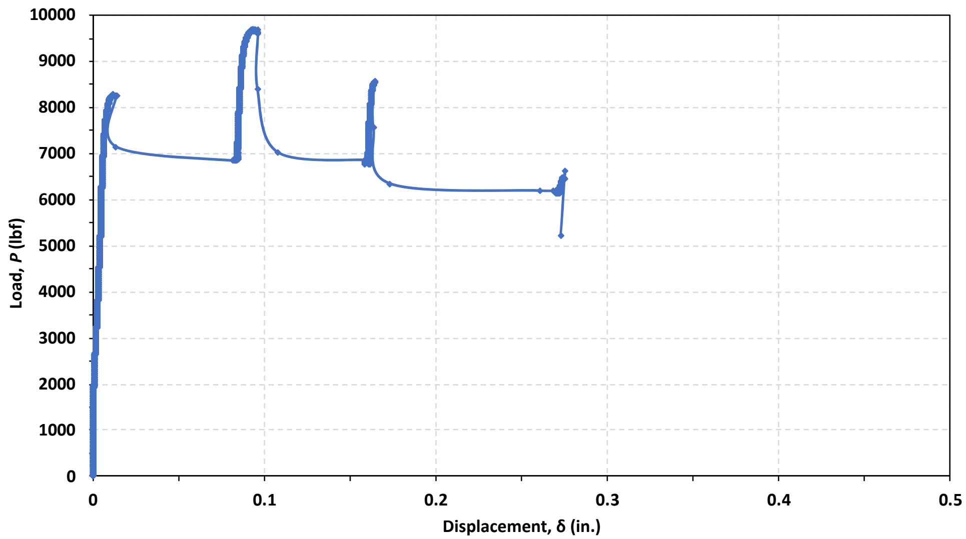
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-D-A1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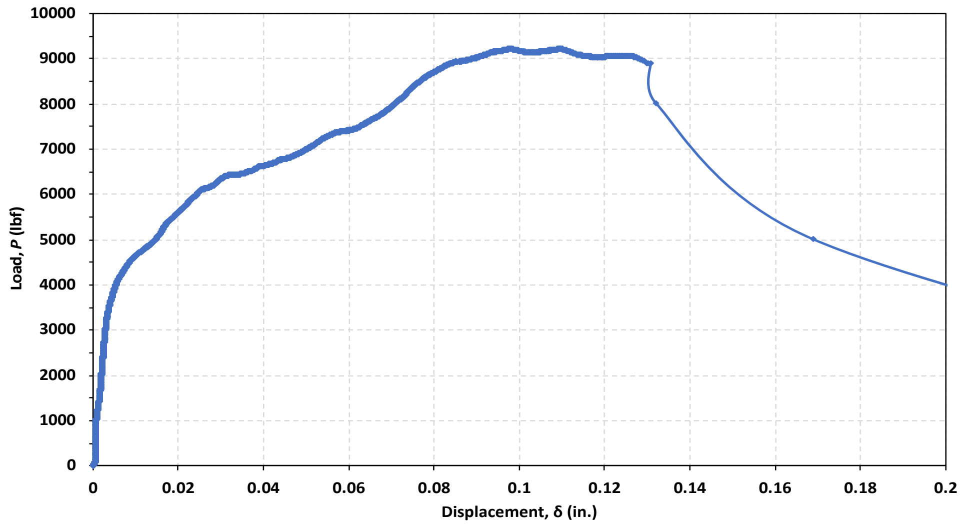
0.2
0.3
0.4
0.5
Displacement, δ (in.)

NW-D-B2



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1000
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0.02
0.04
0.06
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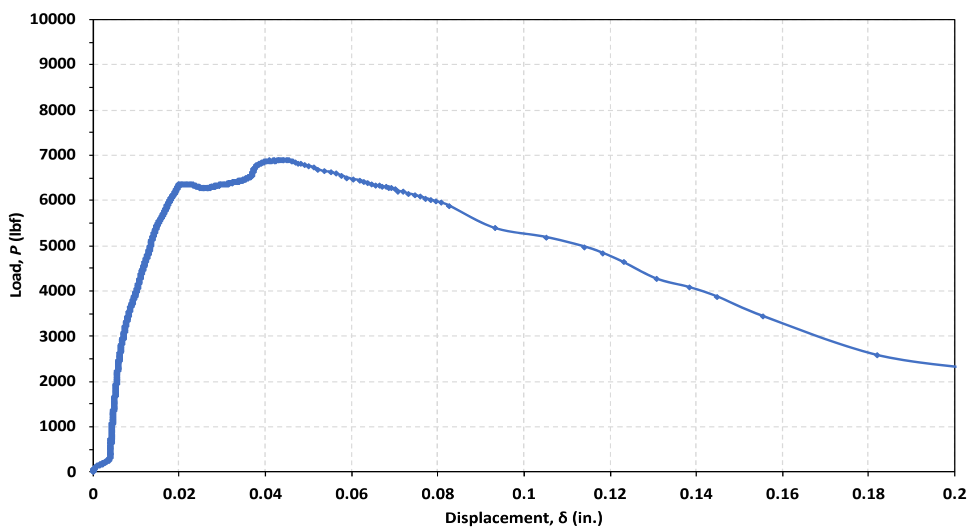
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-S-B1



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Load, P (lbf)
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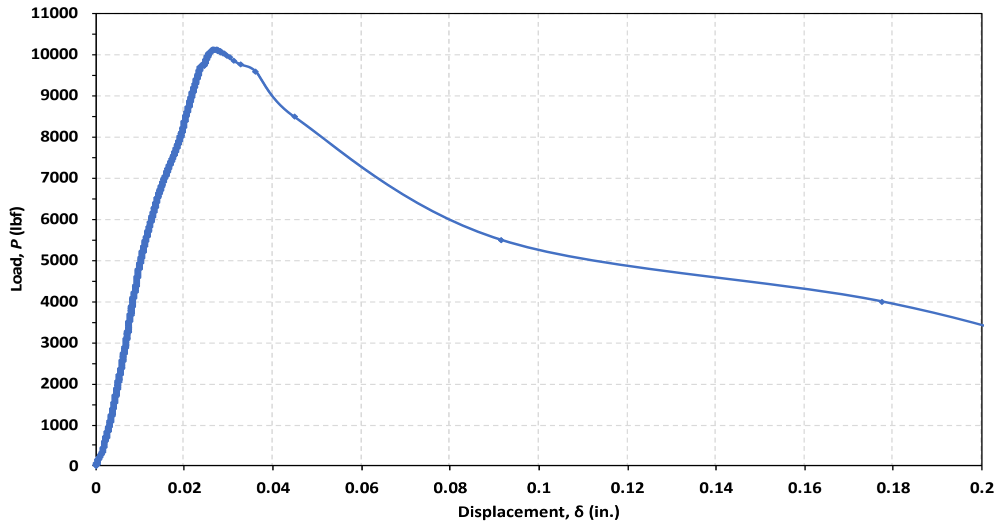
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-S-C1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Load, P (lbf)
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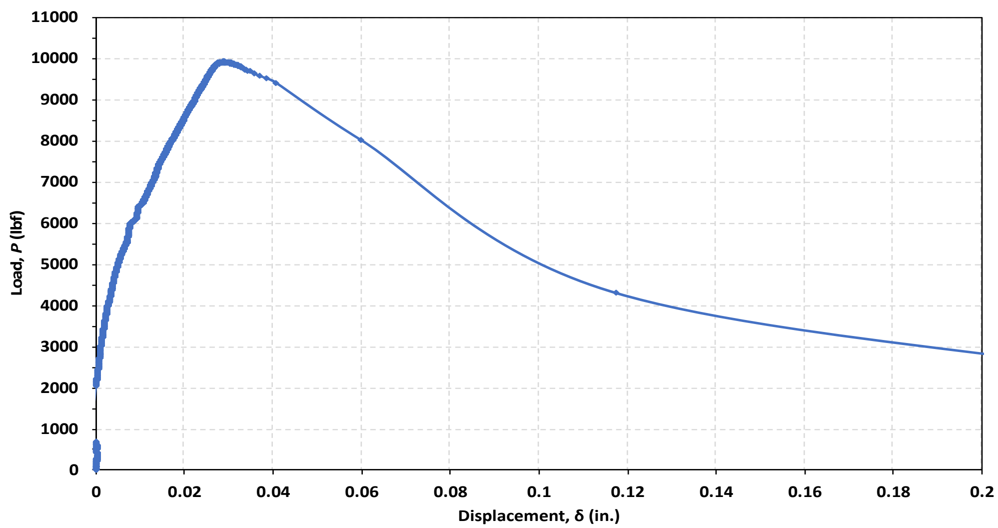
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-S-D1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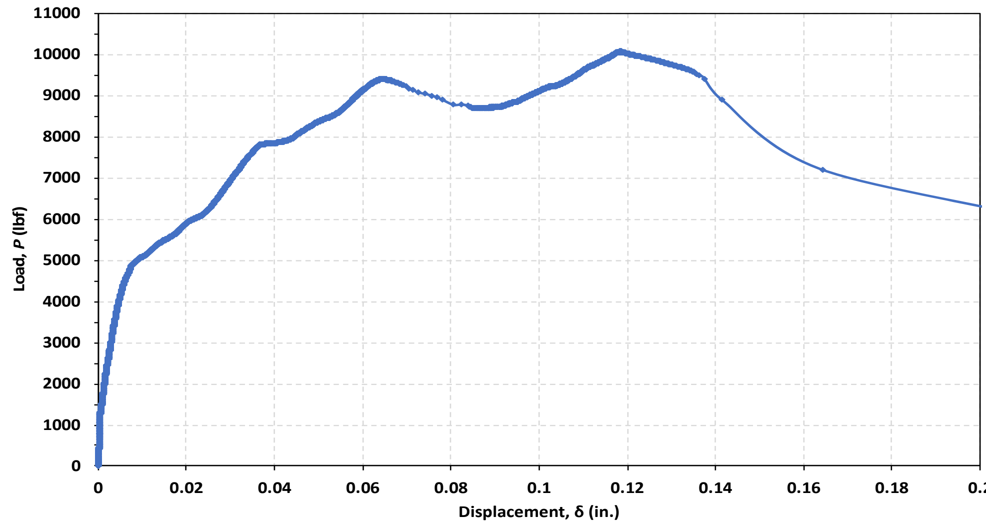
2000
1000
0
Load, P (lbf)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-S-A1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9000
10000
11000
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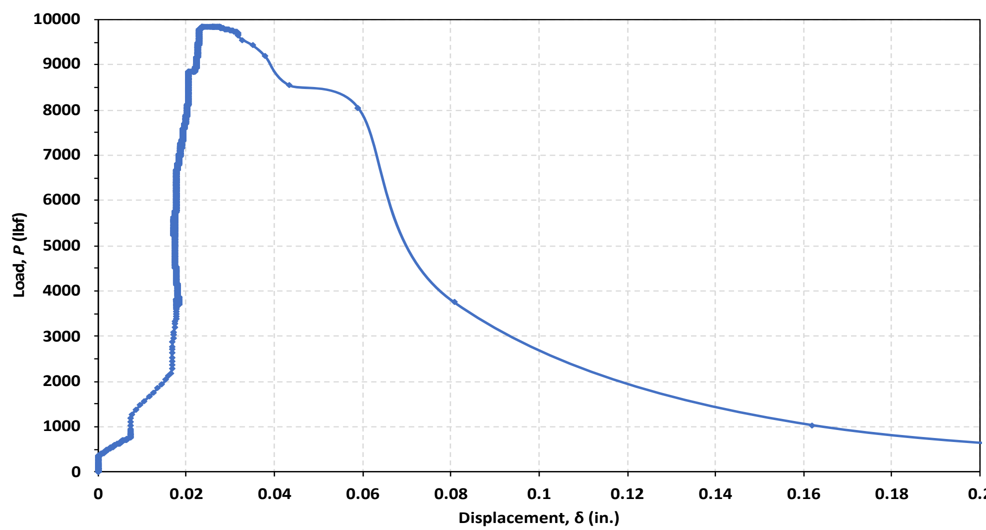
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

NW-S-B2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0.08
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0.12
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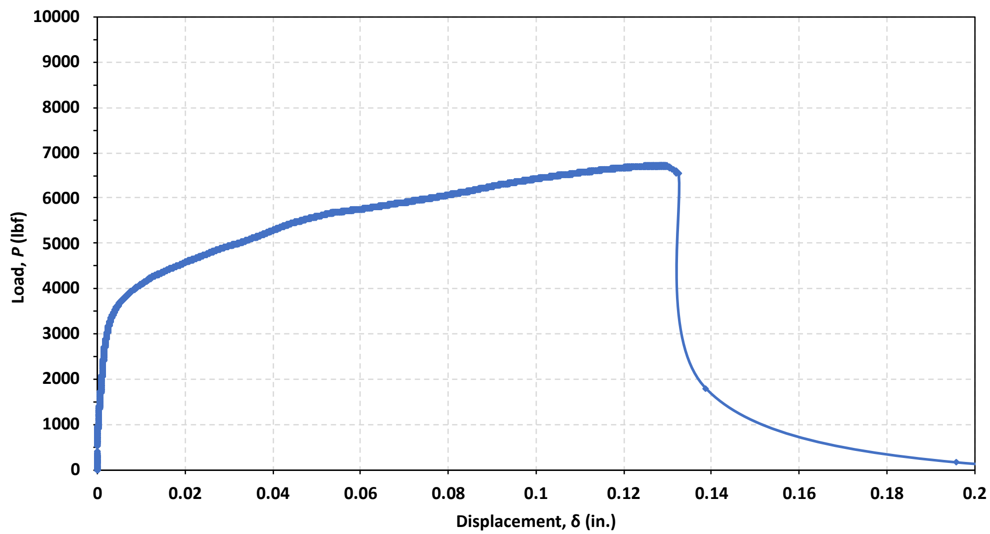
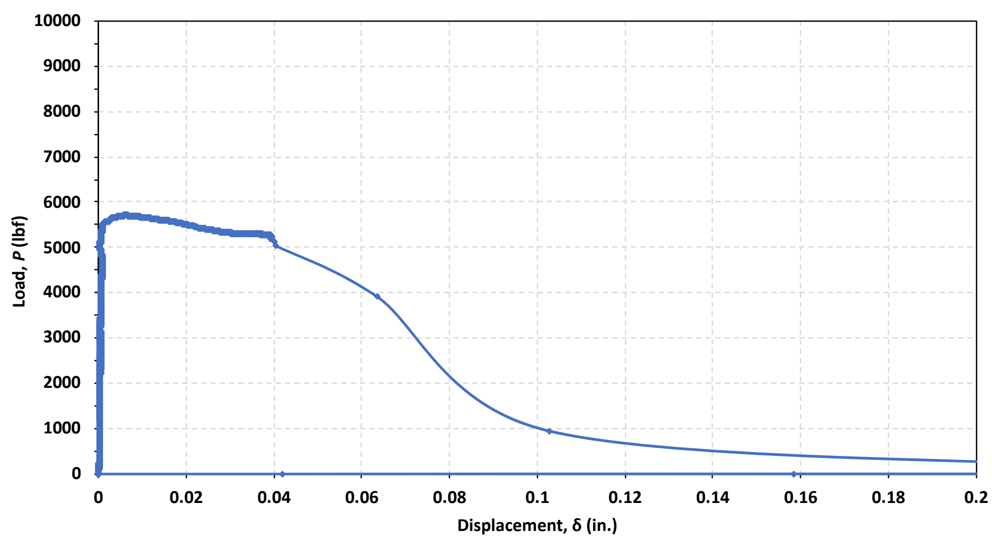
0.16
0.18
0.2

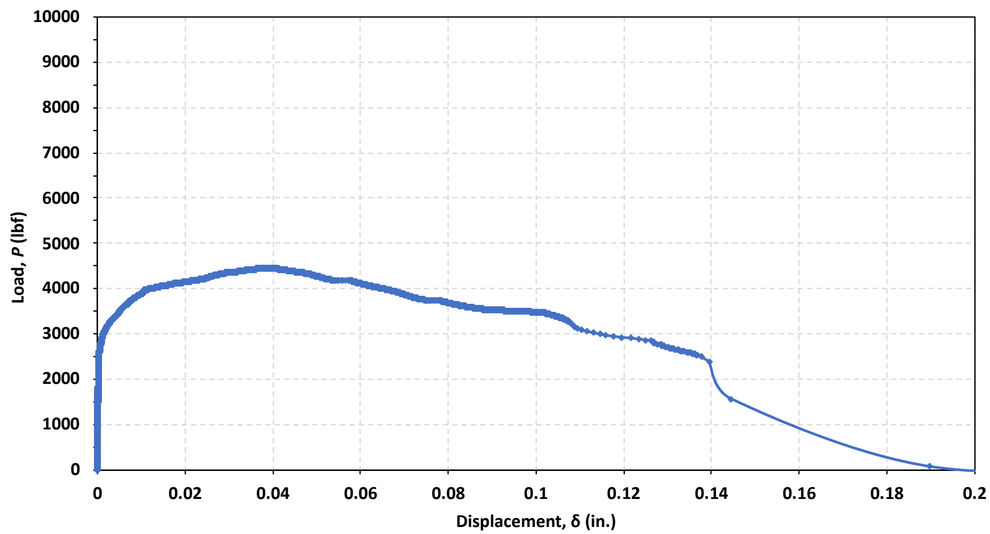
NW-S-D2



SL-SH-T-B1



SL-SH-T-C1



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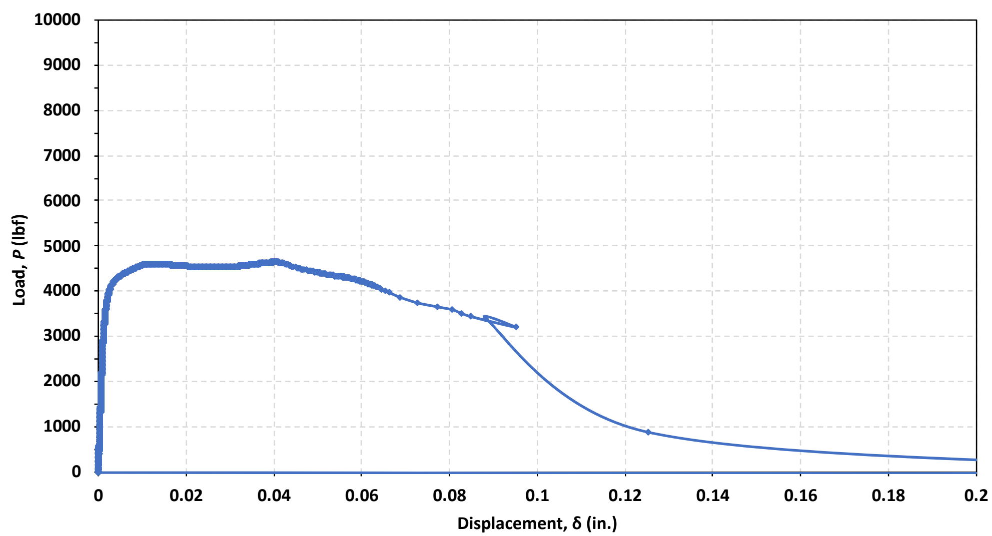

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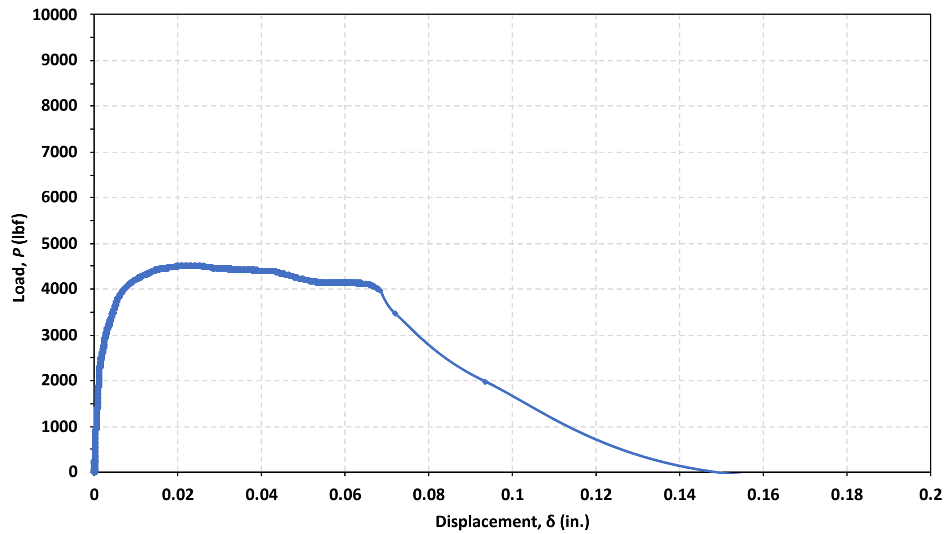

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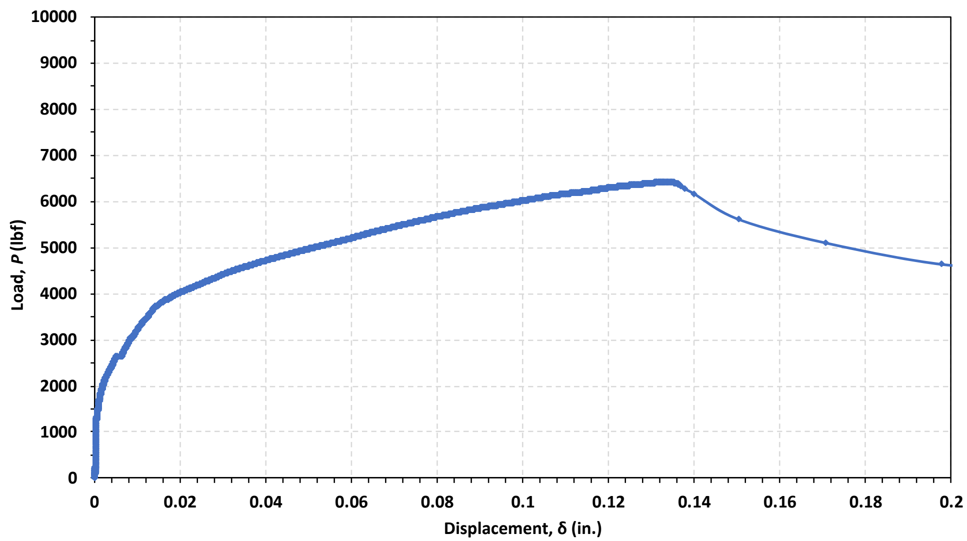
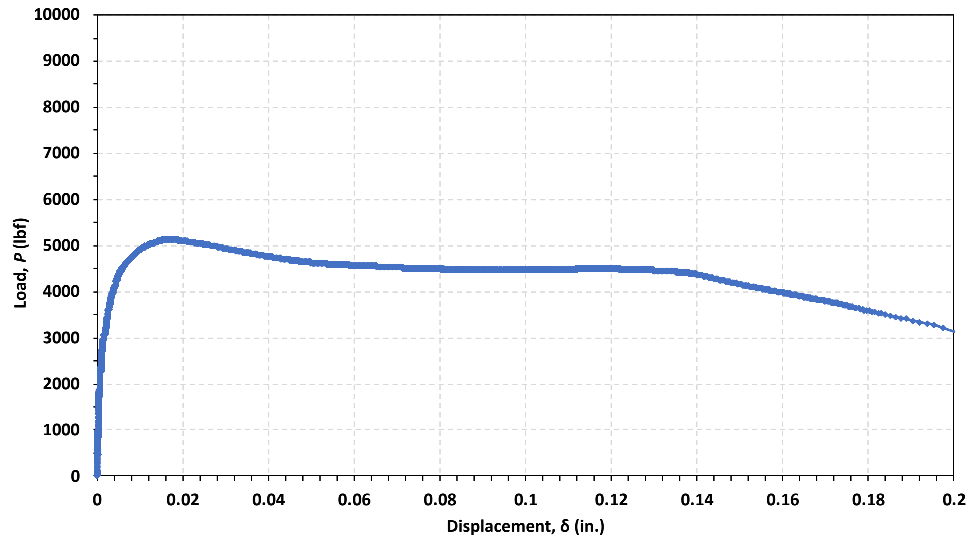
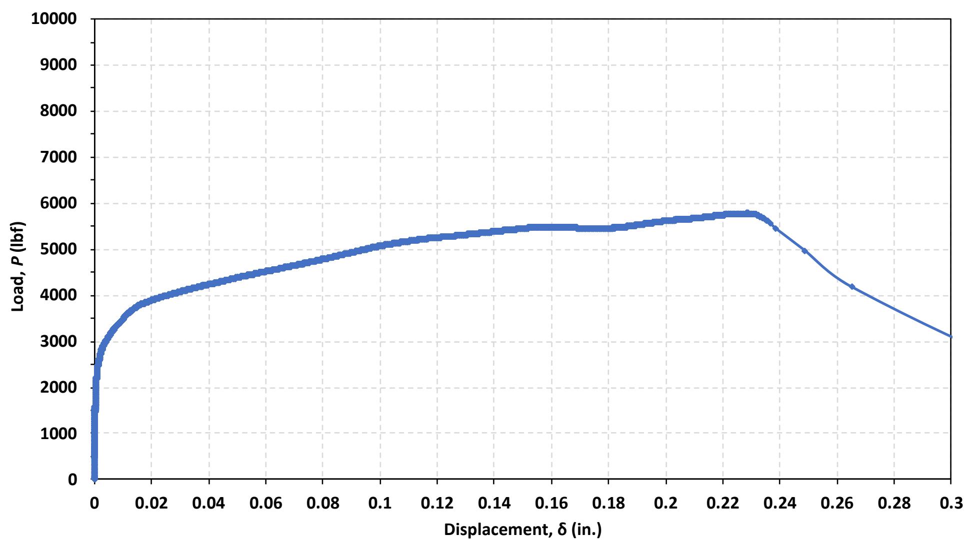


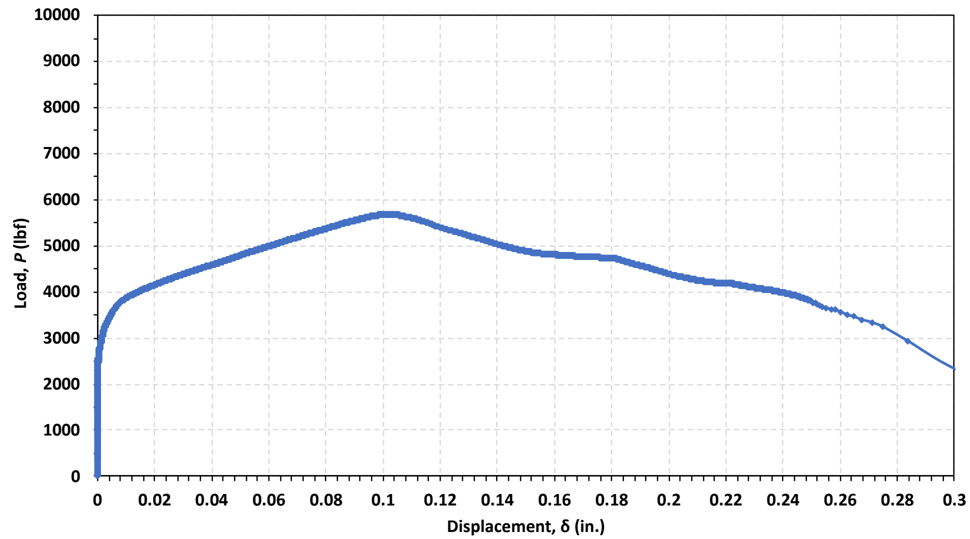
SL-SH-T-B2*



SL-SH-T-C2*



SL-SH-T-D2*



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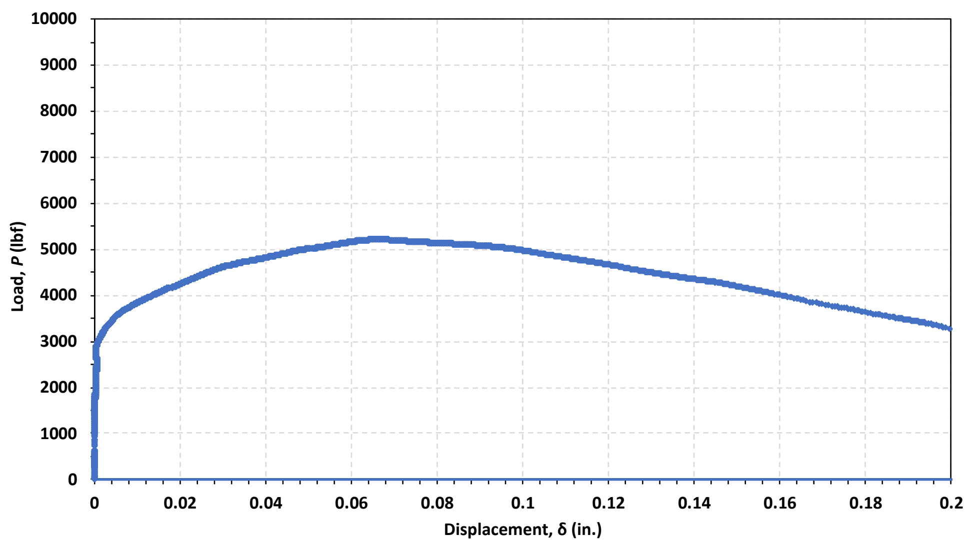

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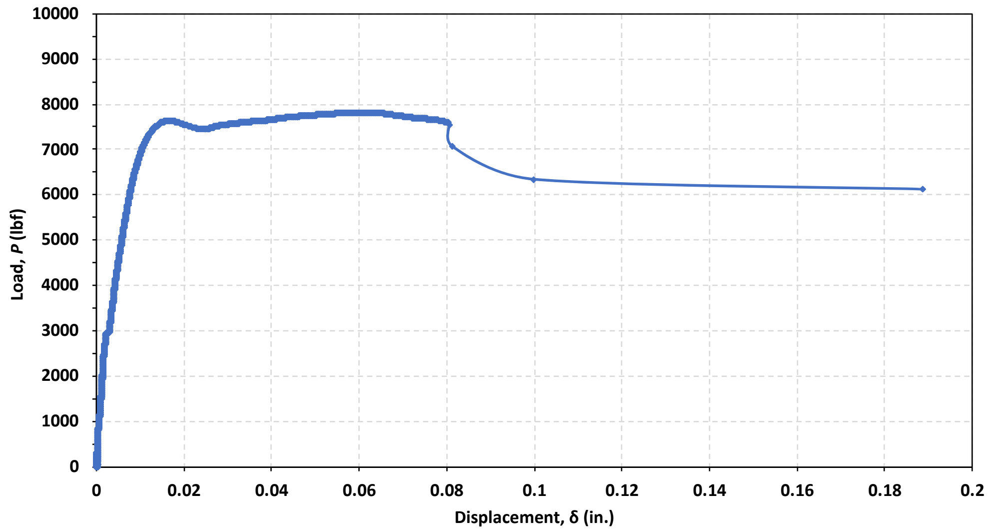
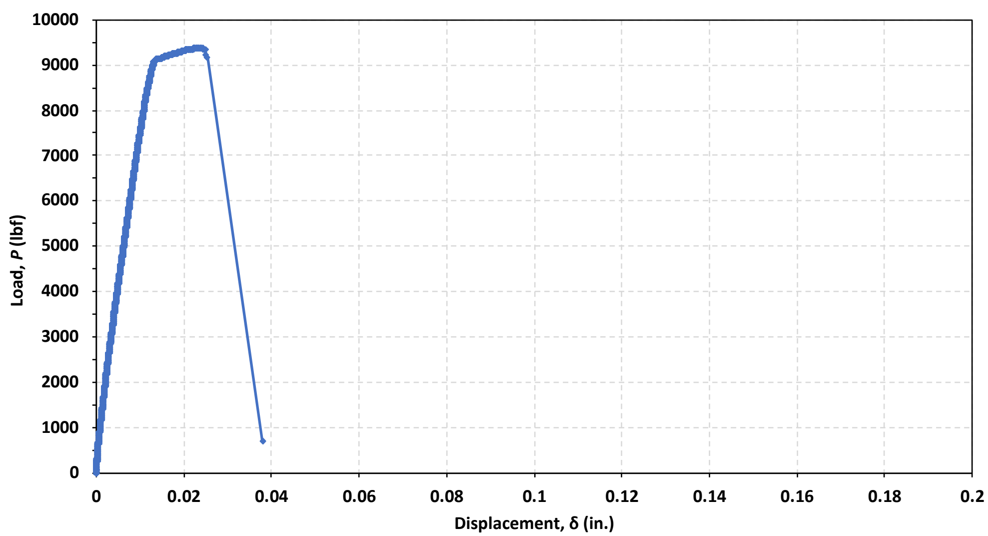
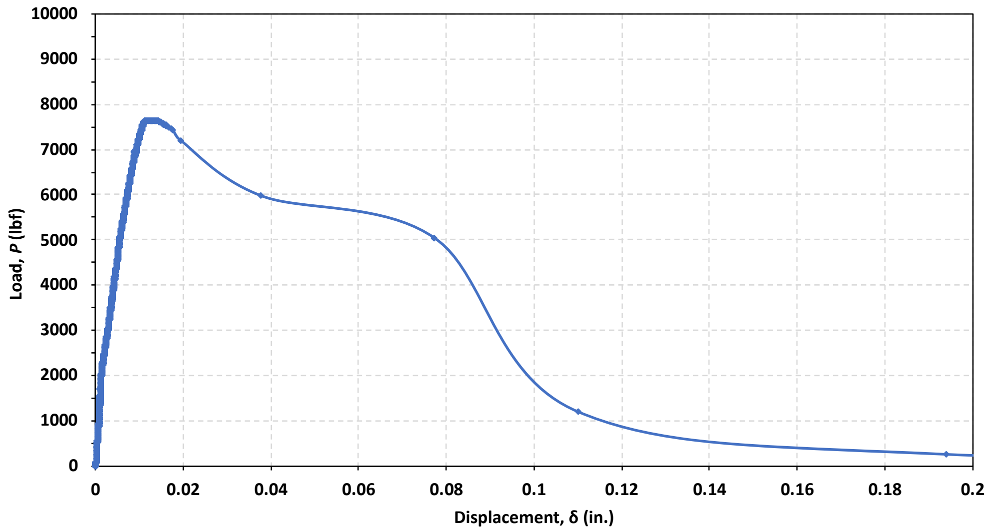


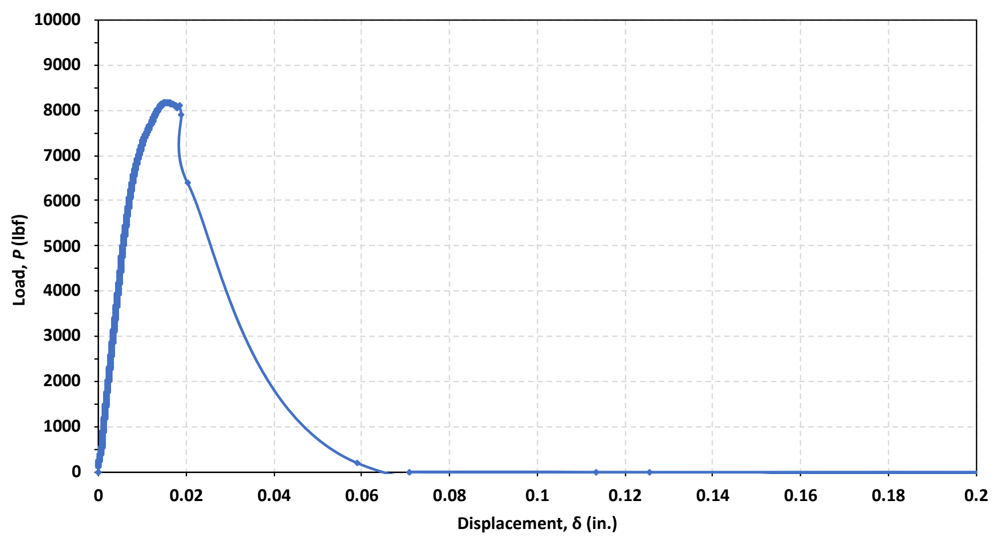
SL-SH-D-B1



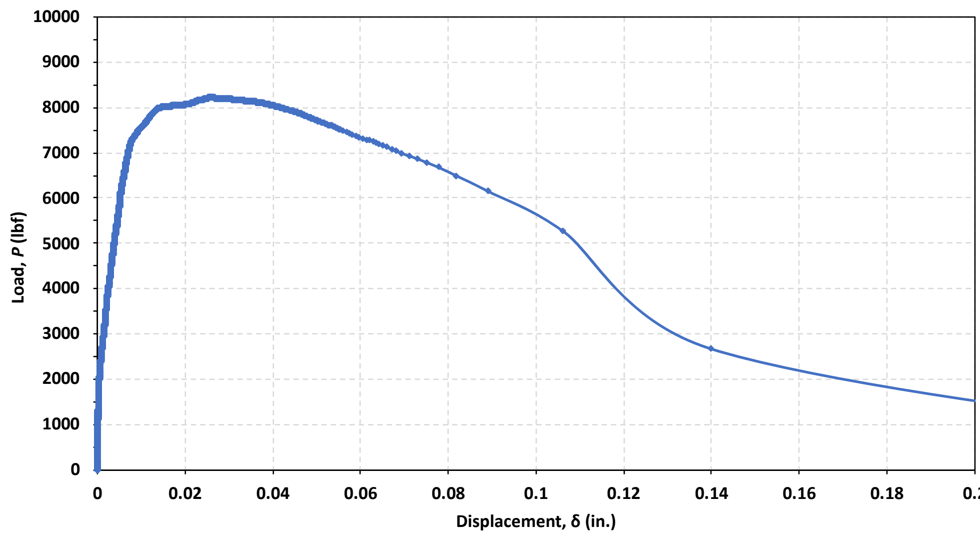
SL-SH-D-C1



SL-SH-D-D1



SL-SH-D-A1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1000
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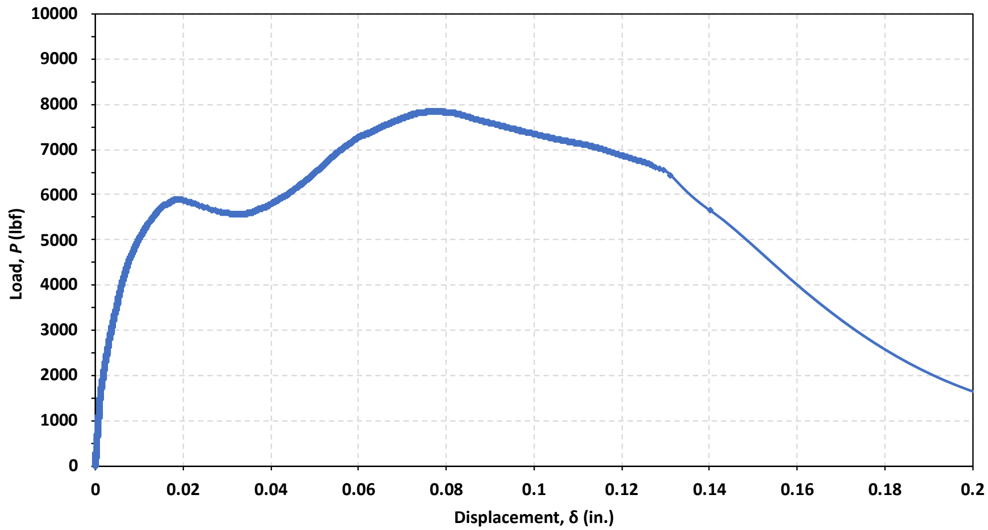
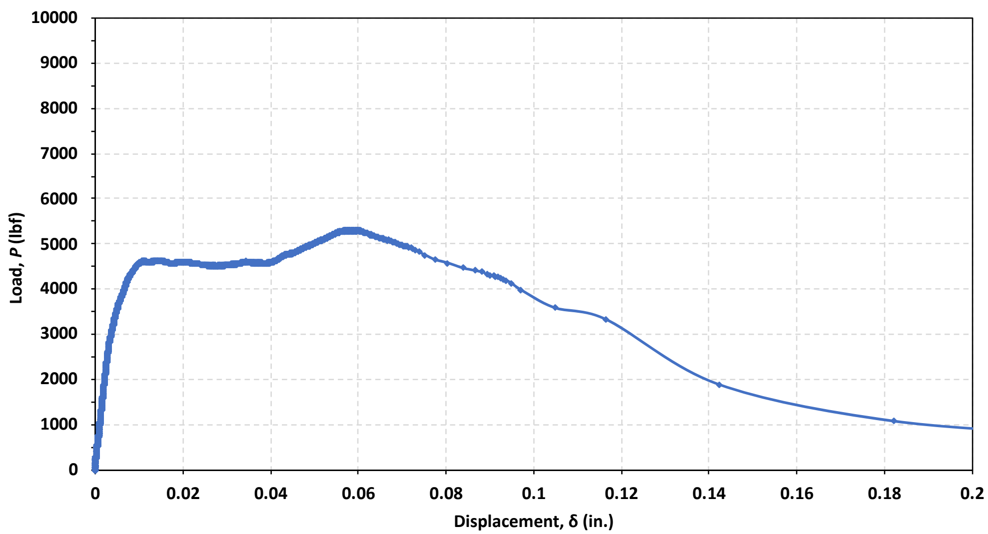
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

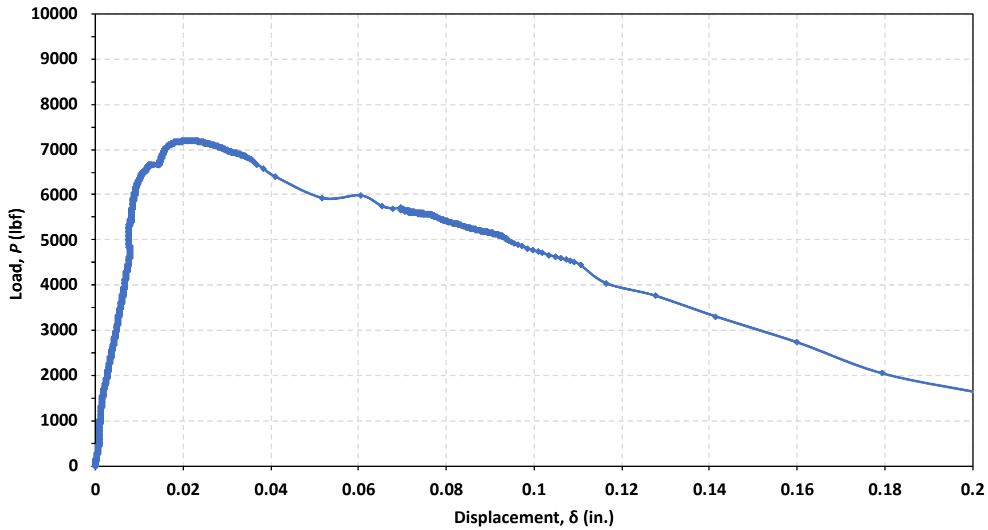
SL-SH-D-A2



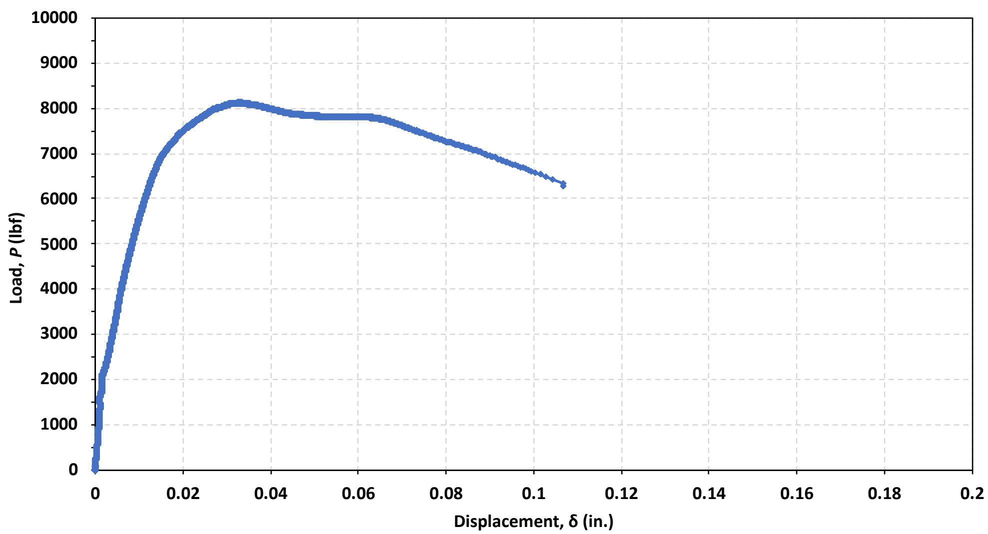
SL-SH-S-B1



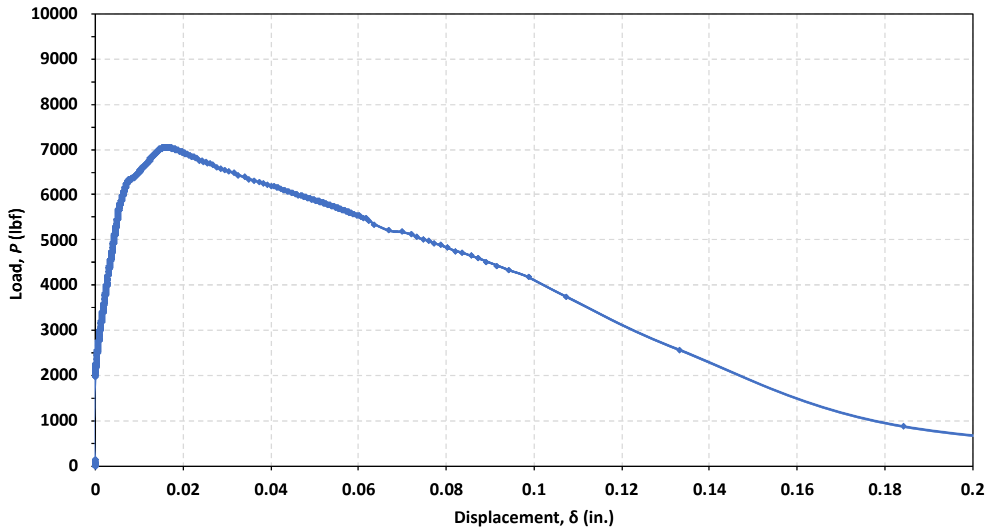
SL-SH-S-C1



SL-SH-S-D1



SL-SH-S-A1


Load, P (lbf)
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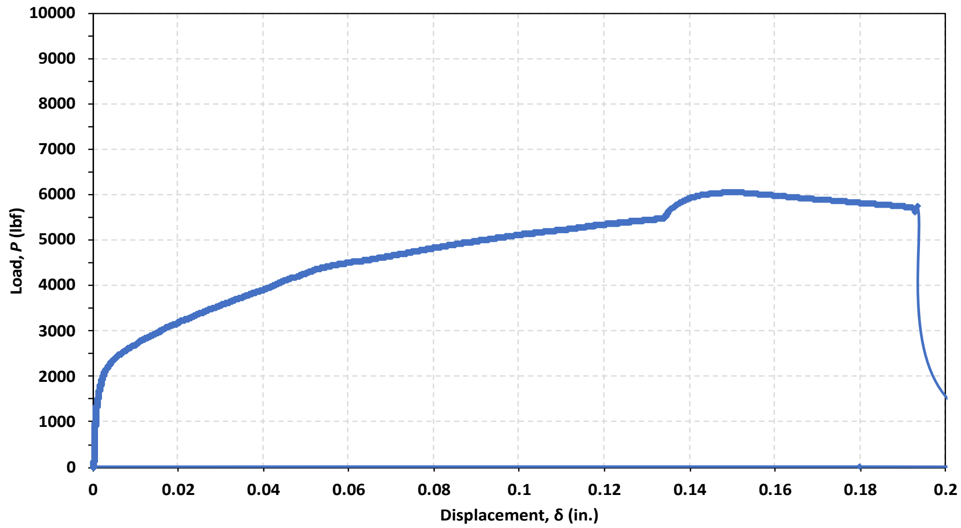
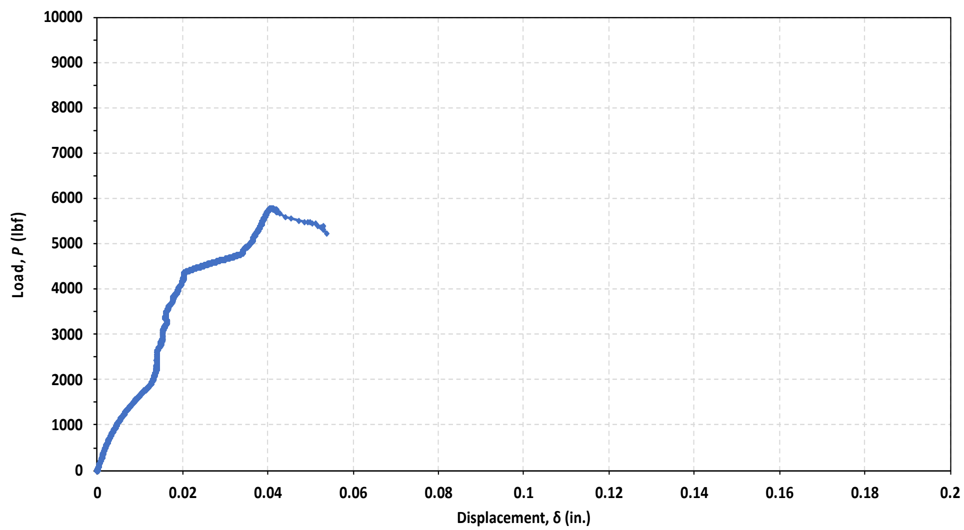
Displacement, δ (in.)

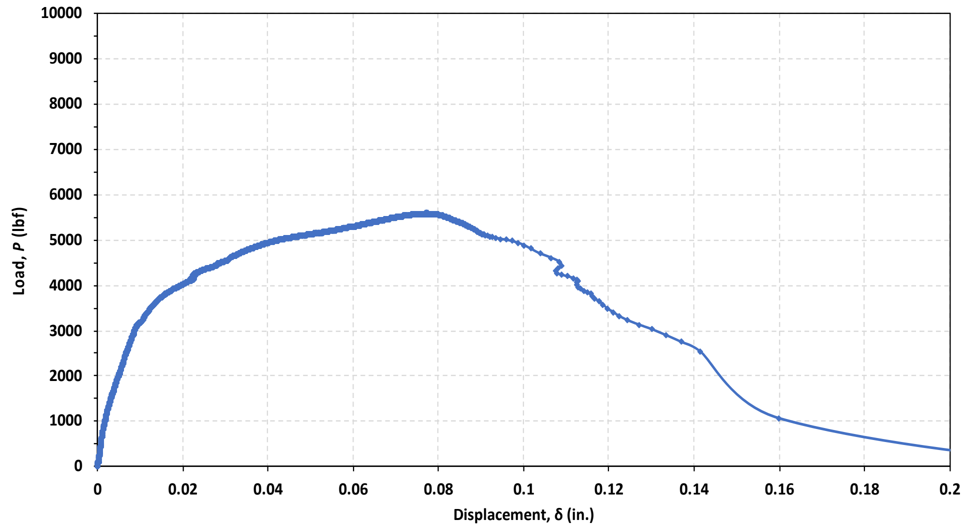
SL-SH-S-D2



SL-CL-T-B1



SL-CL-T-C1



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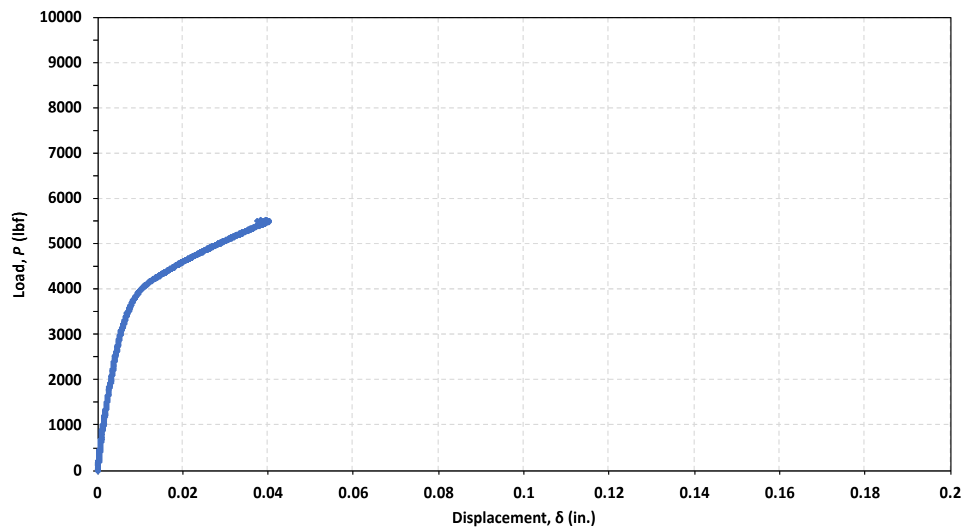

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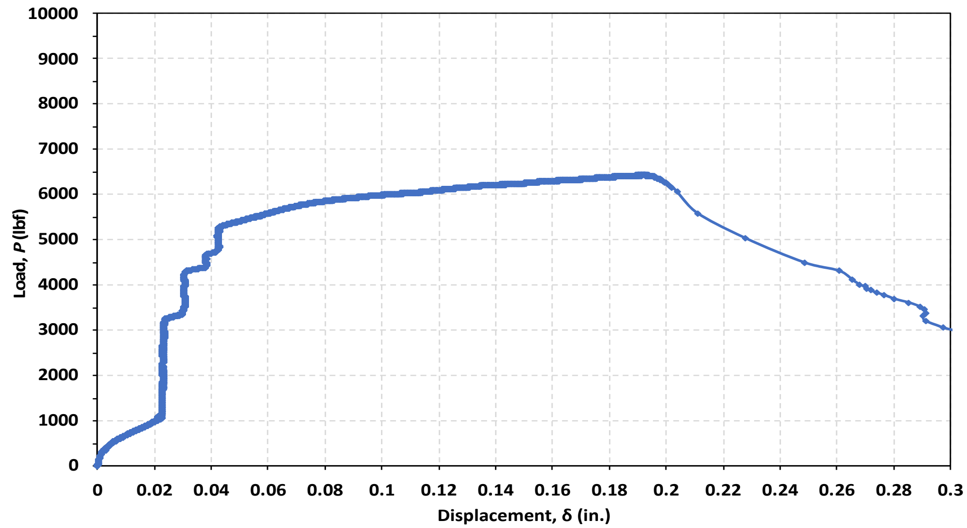

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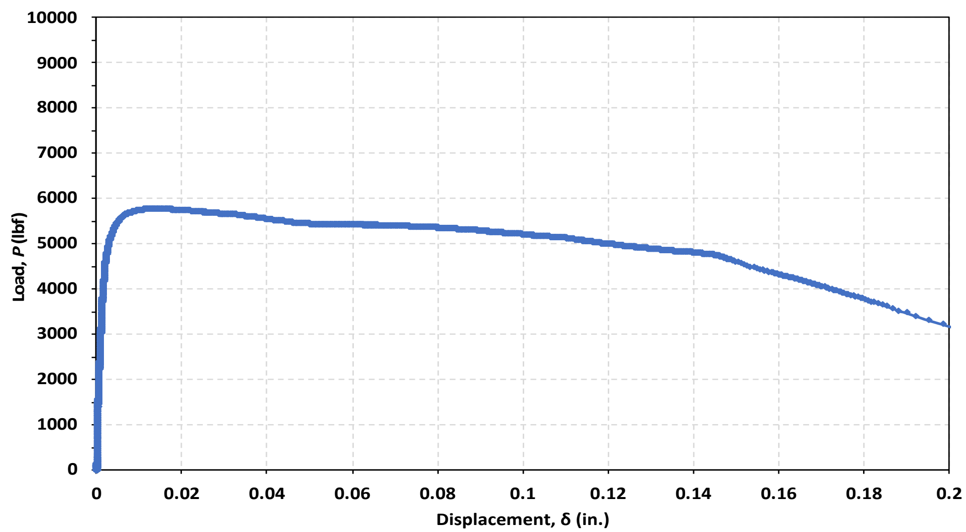

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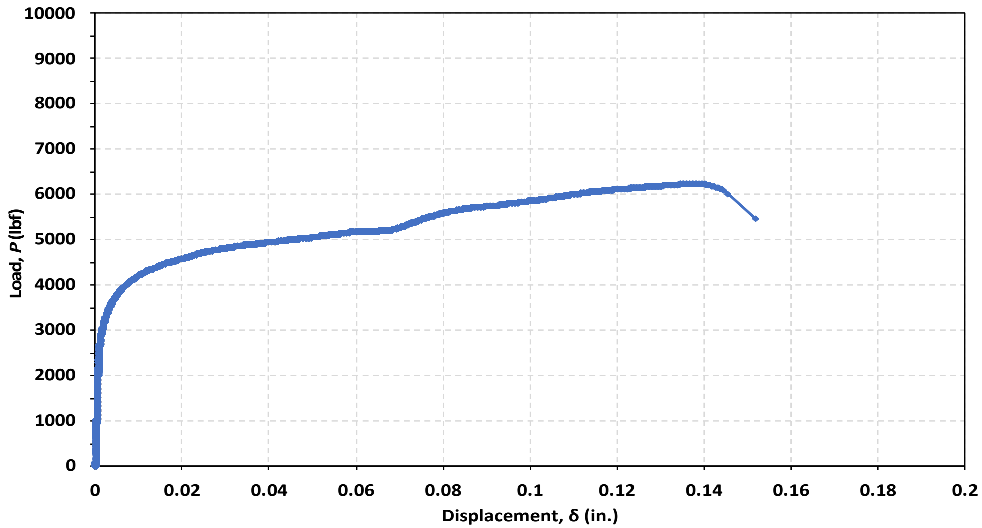

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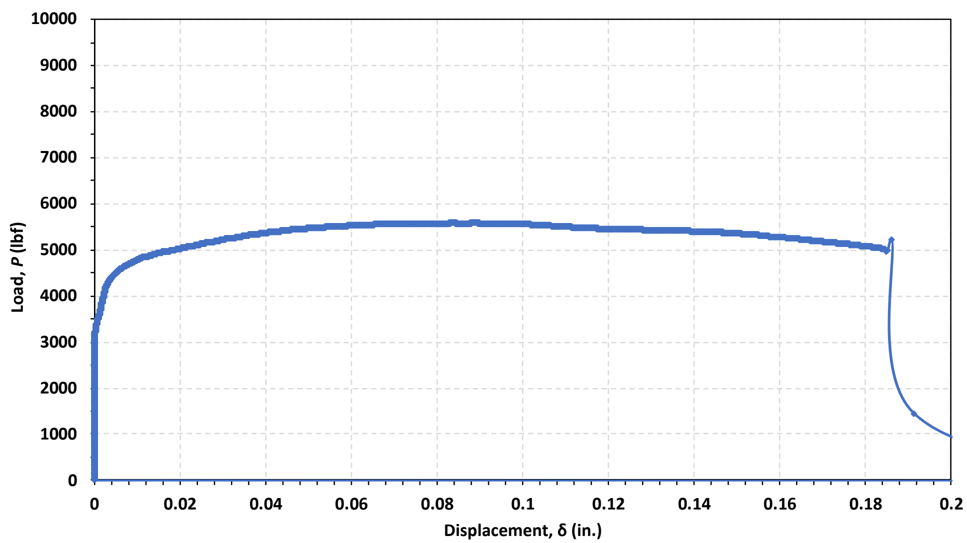

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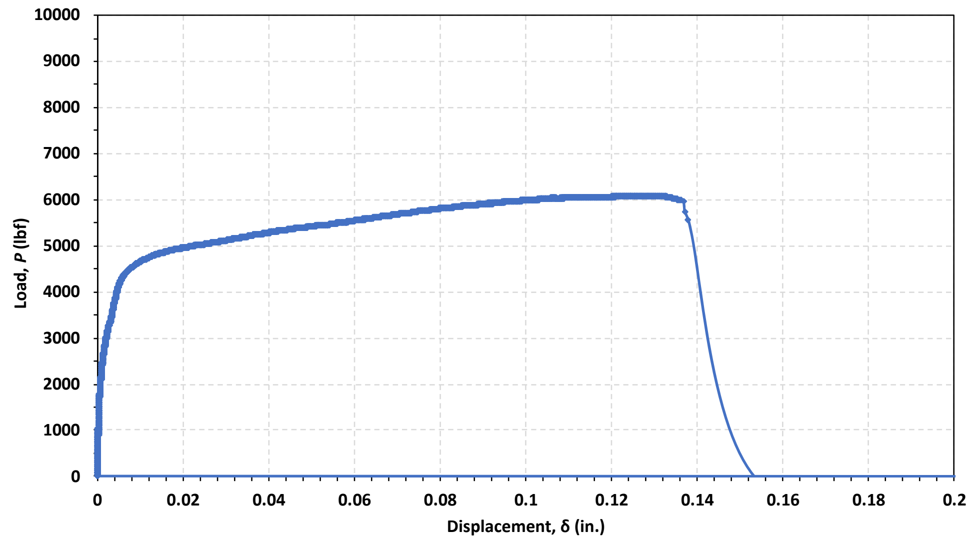

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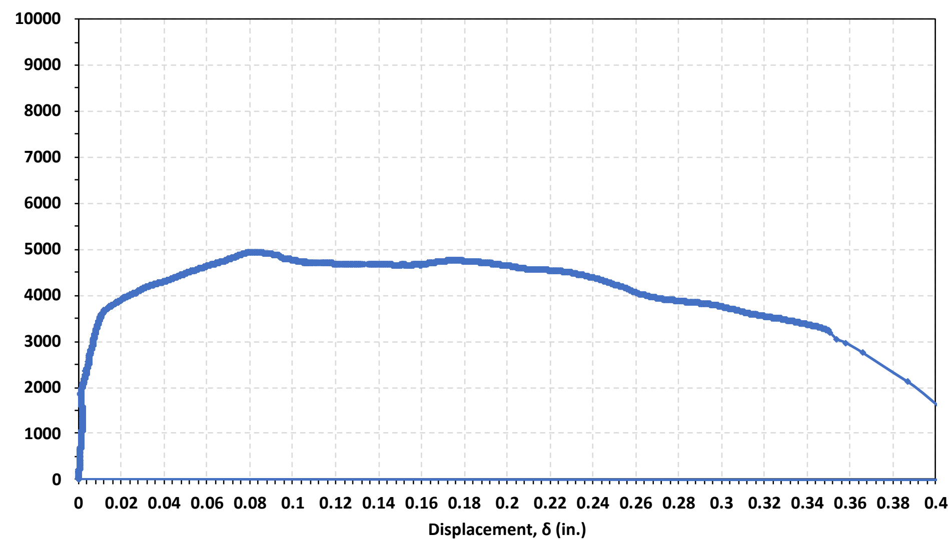

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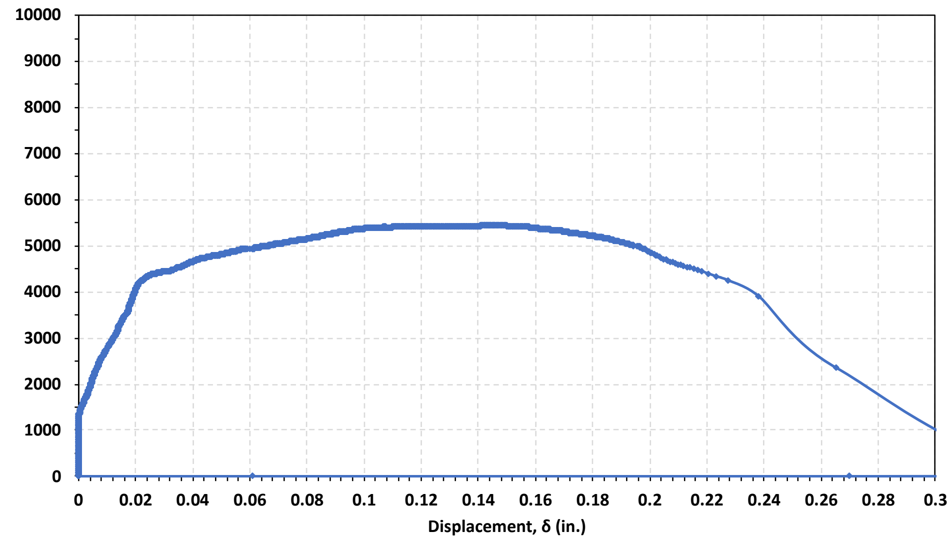

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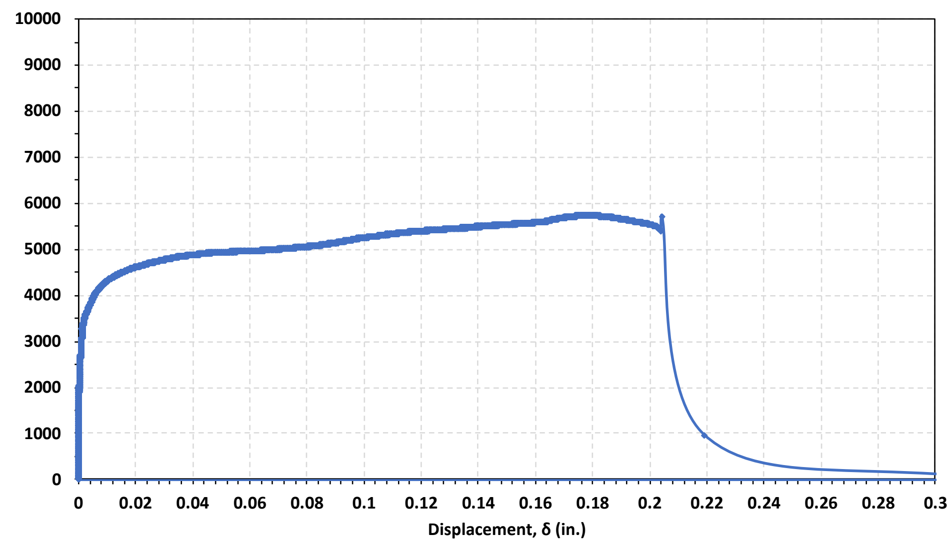

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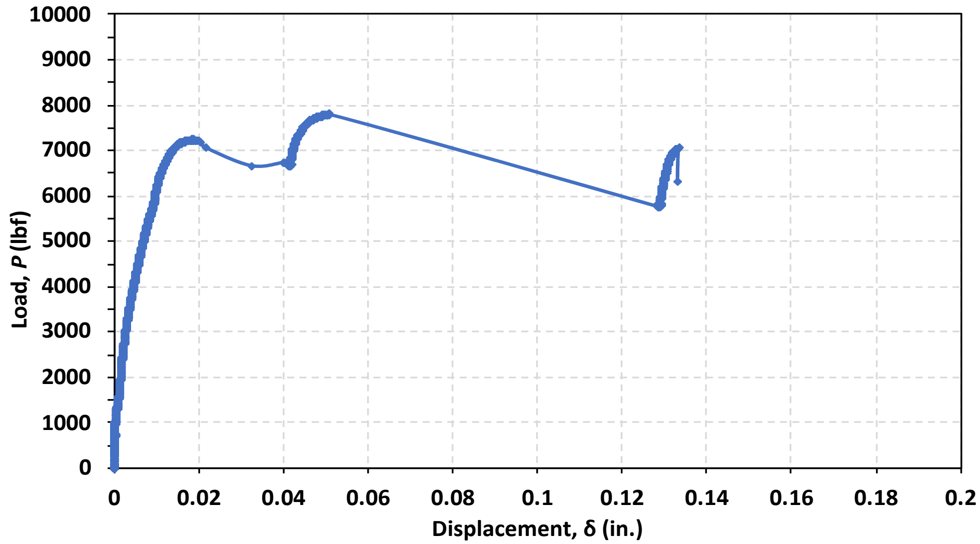

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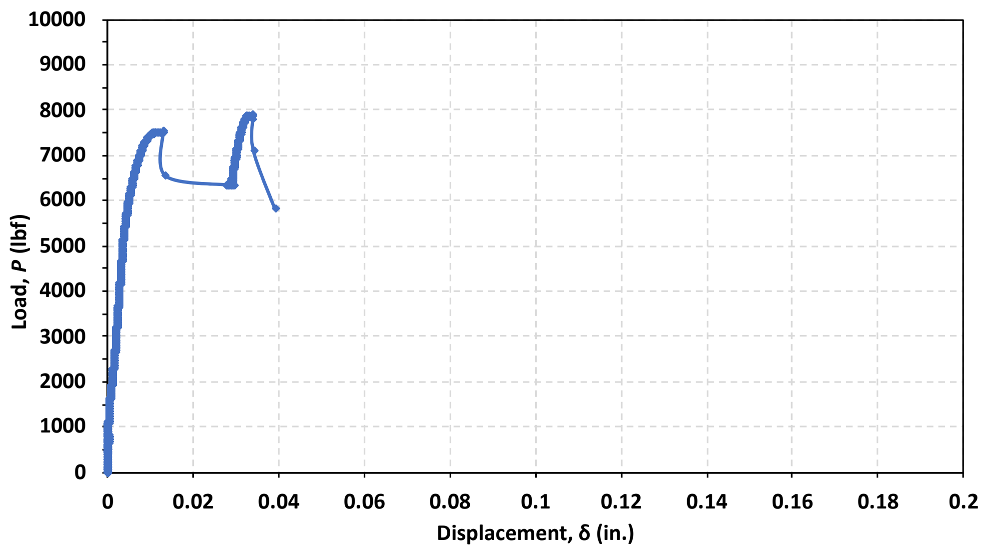

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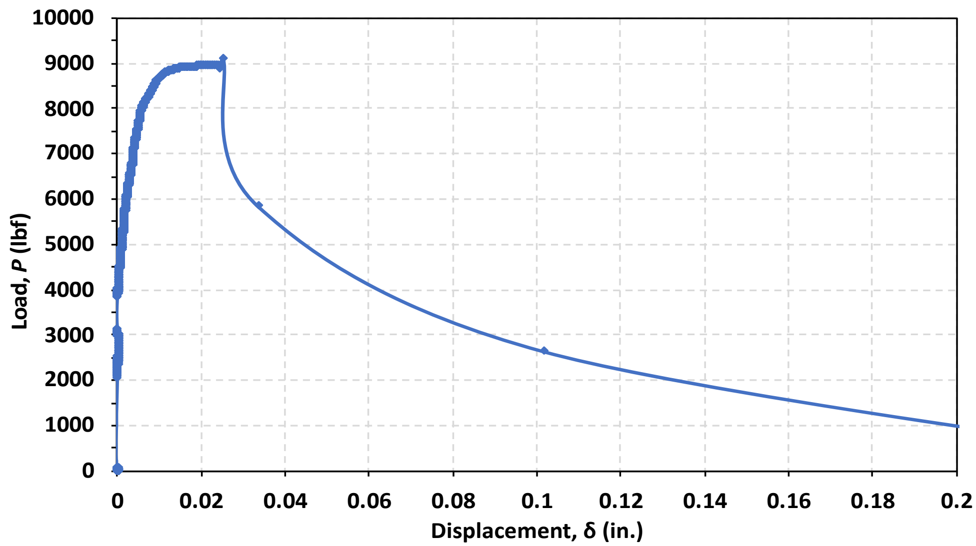

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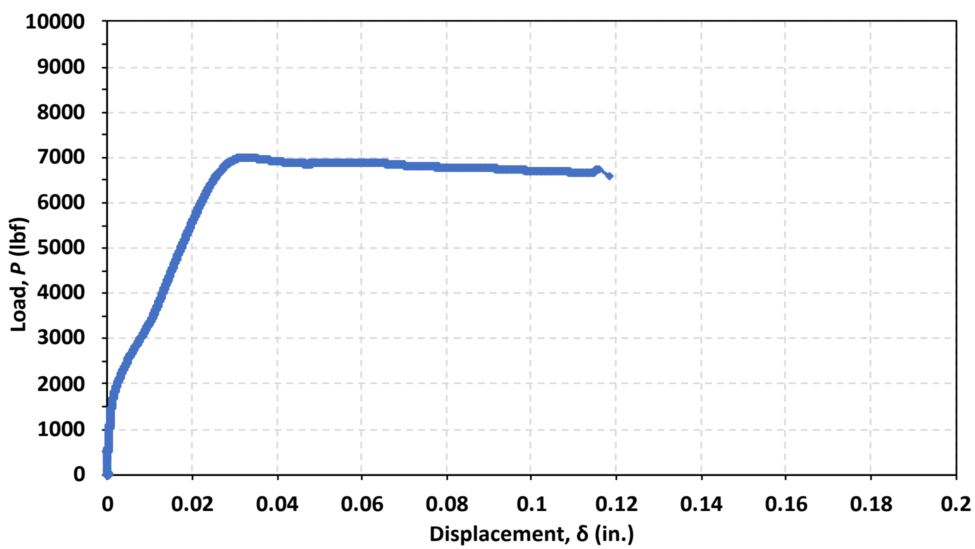

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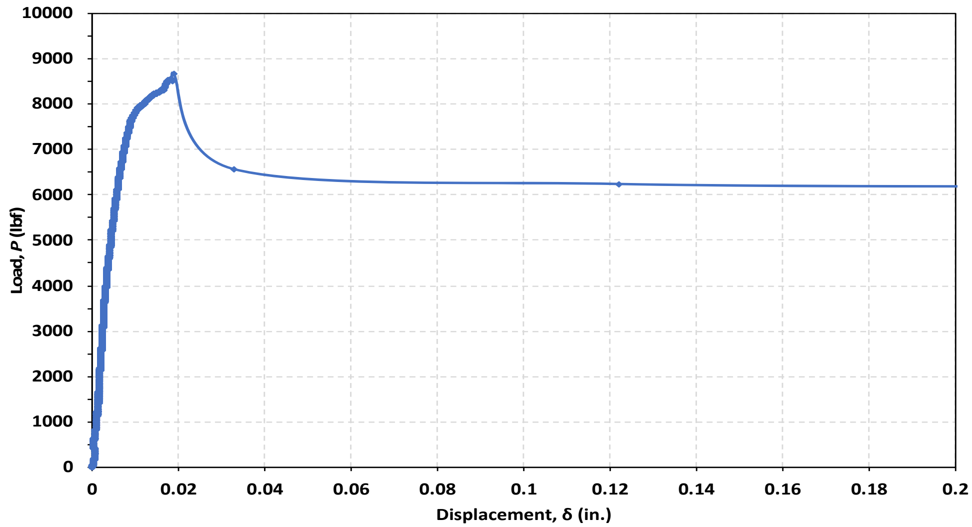
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Load, P (lbf)
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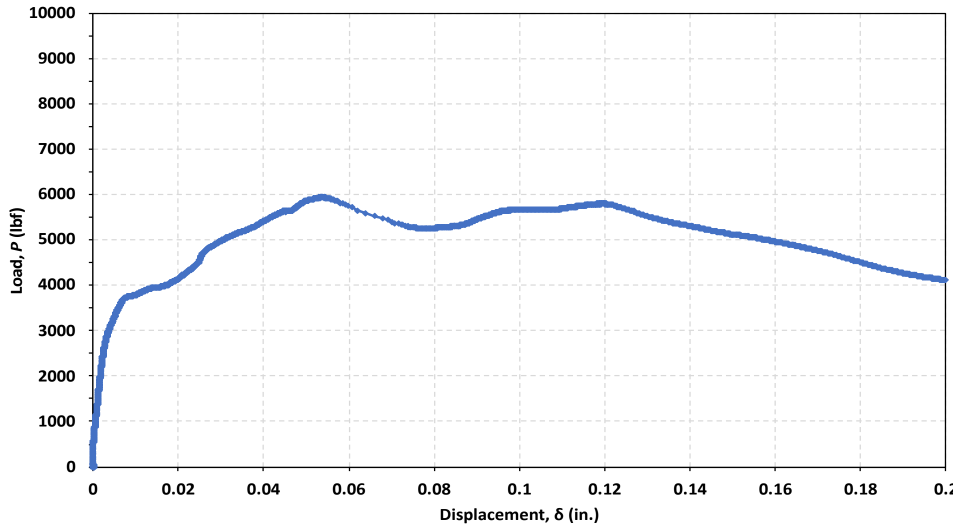
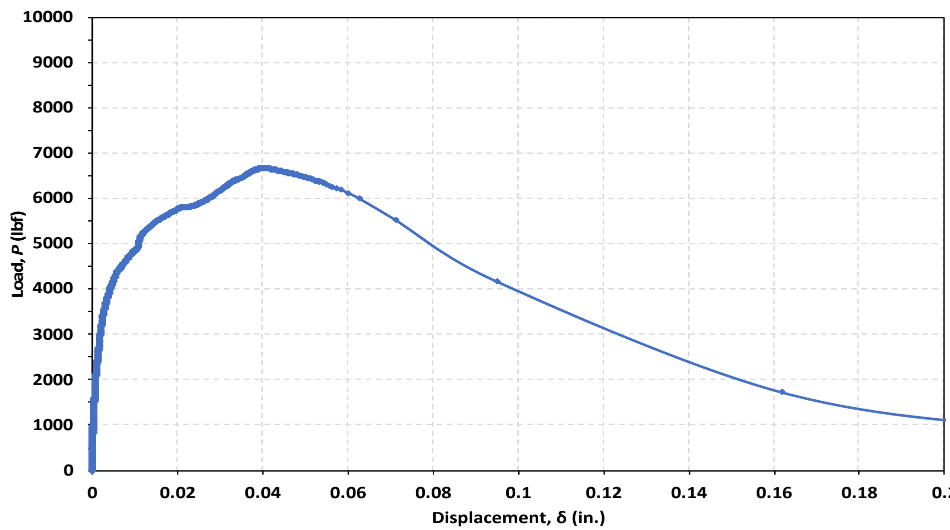
0.2
Displacement, δ (in.)

SL-CL-D-A2



SL-CL-S-C1



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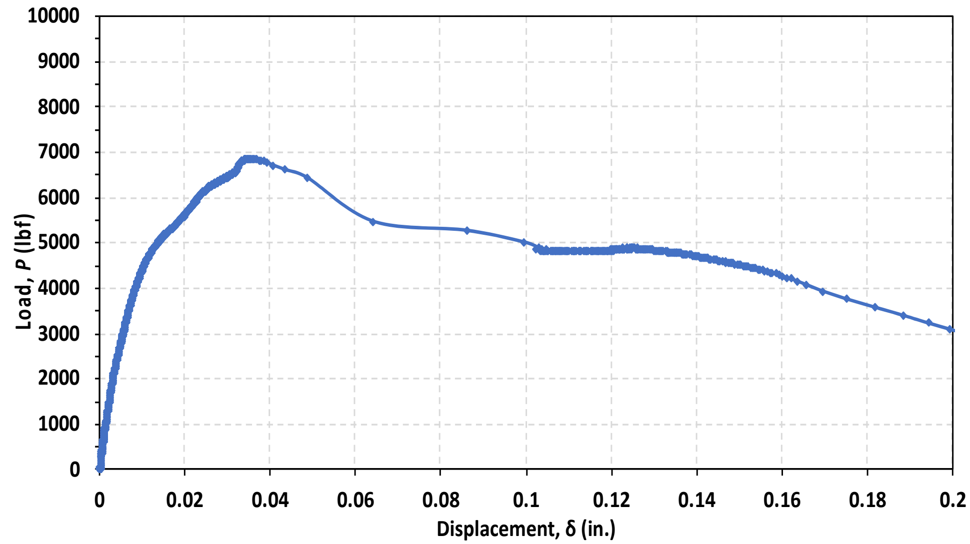

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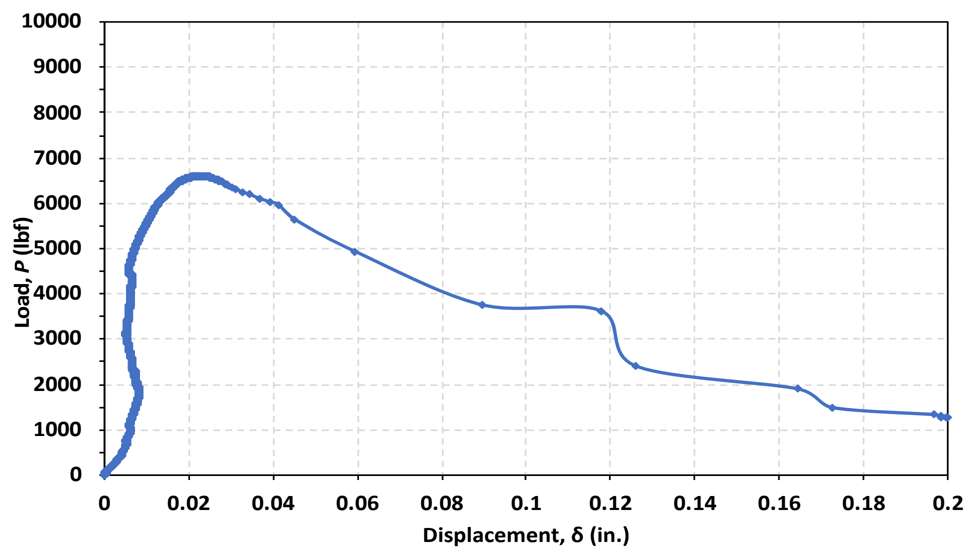

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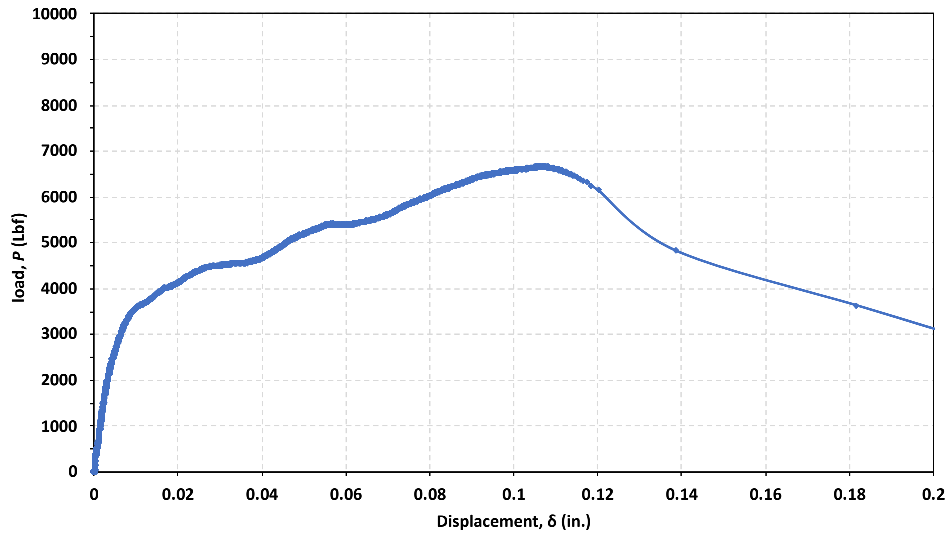

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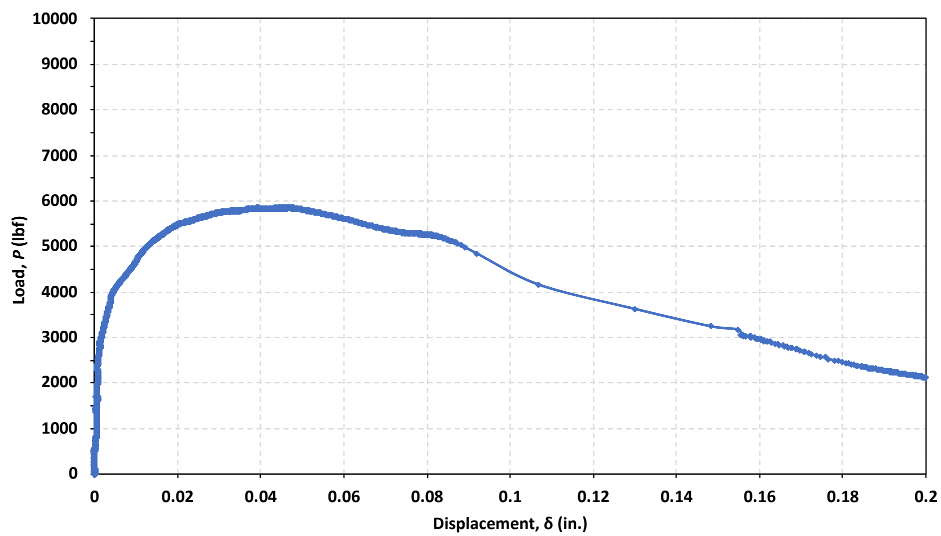

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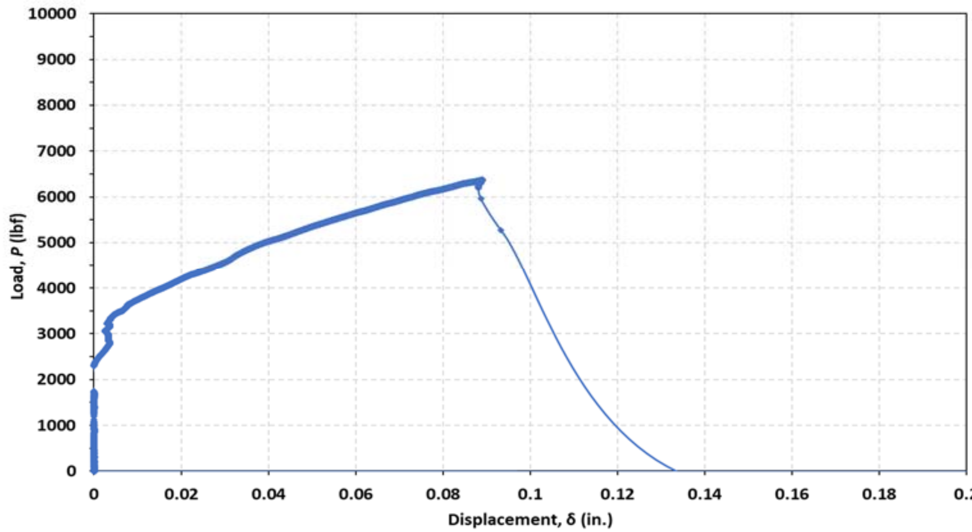

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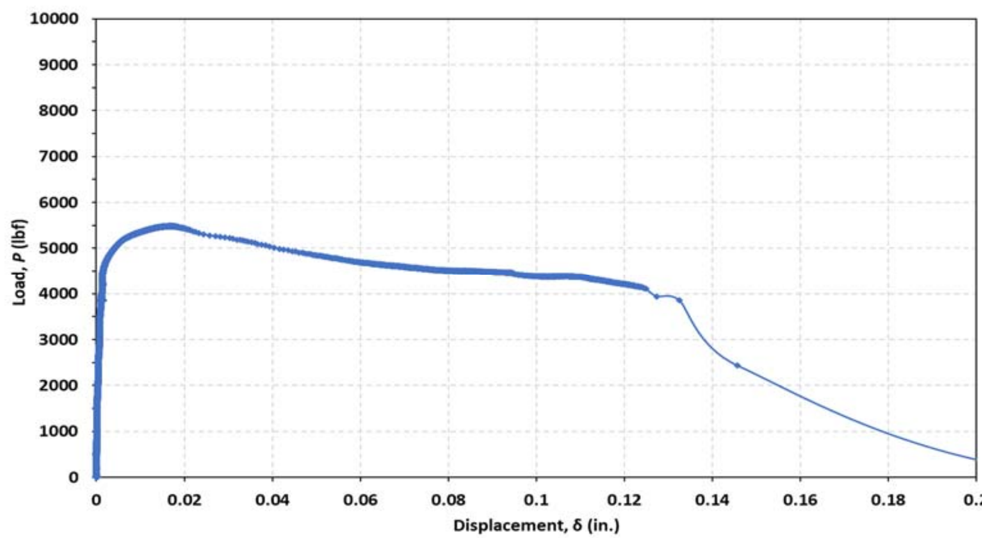

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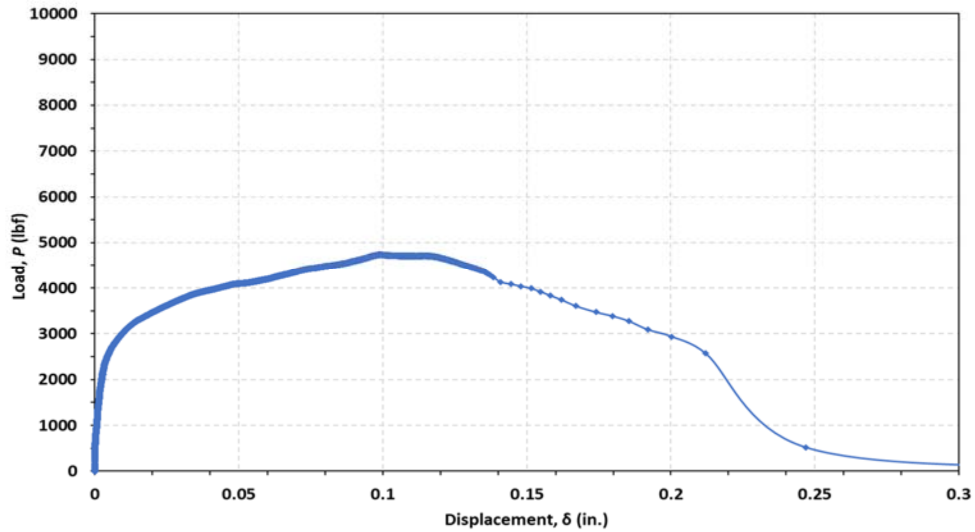

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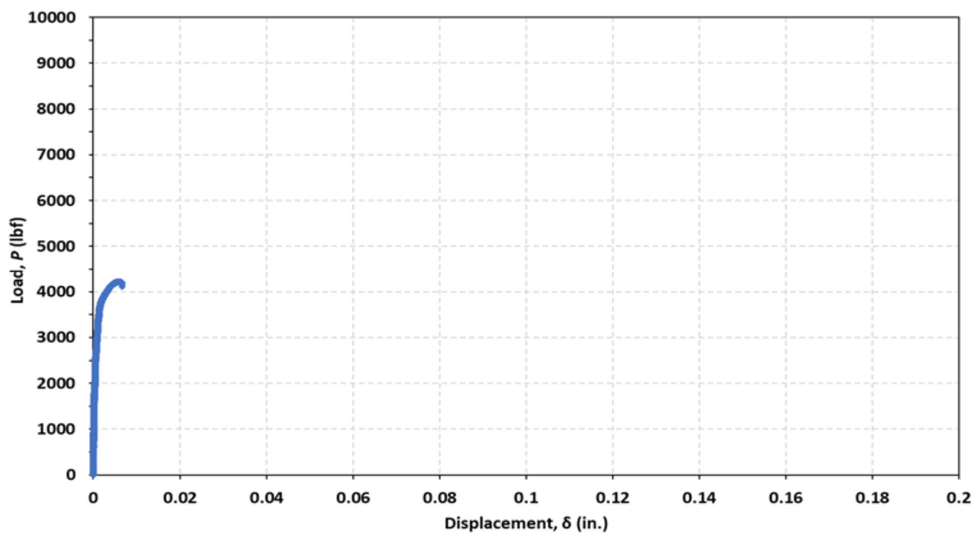

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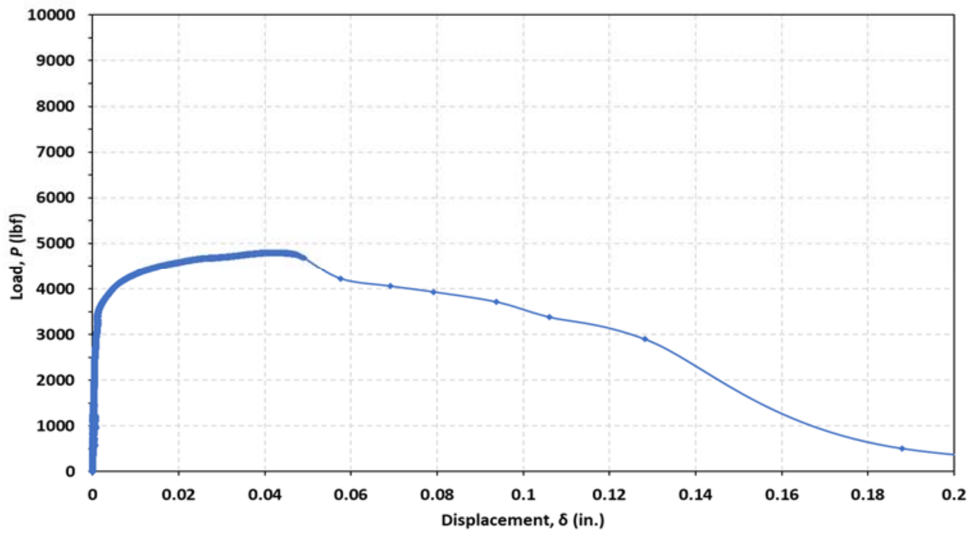

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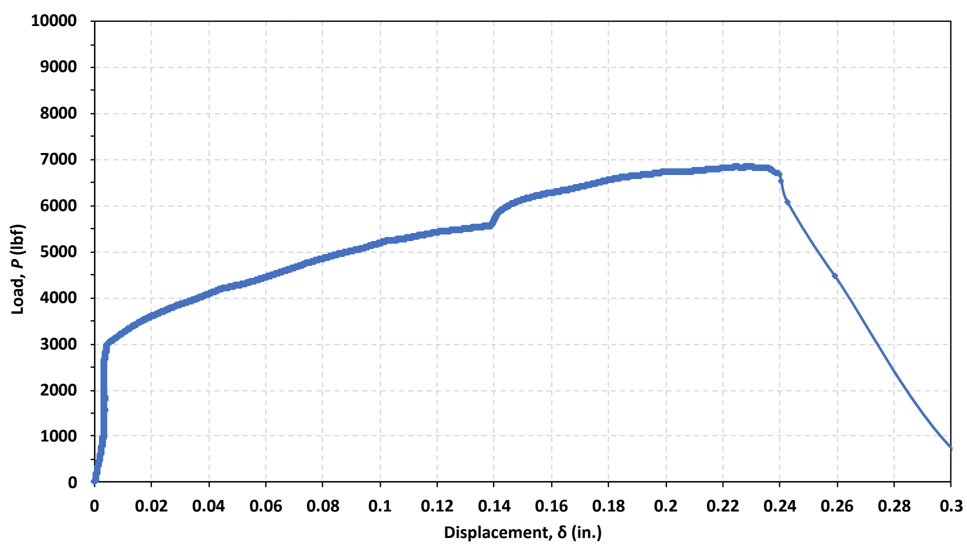

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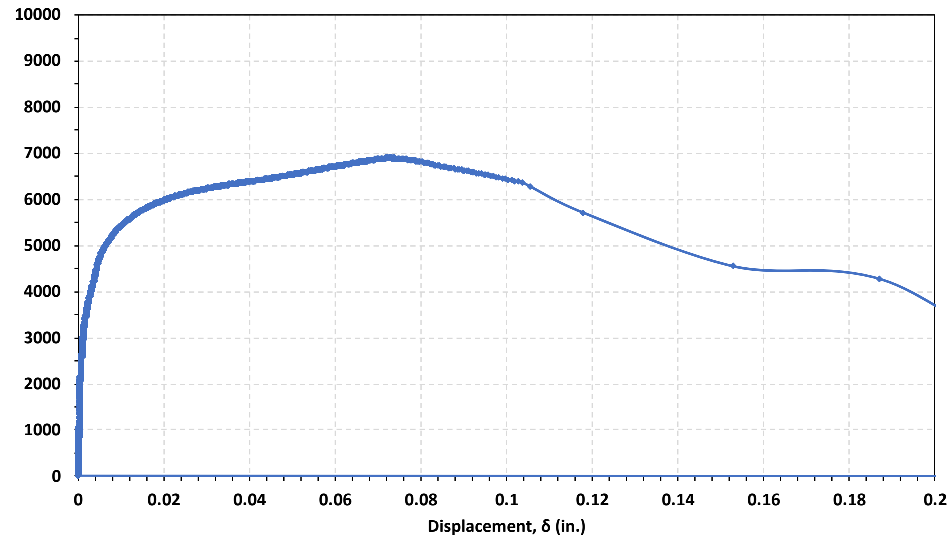

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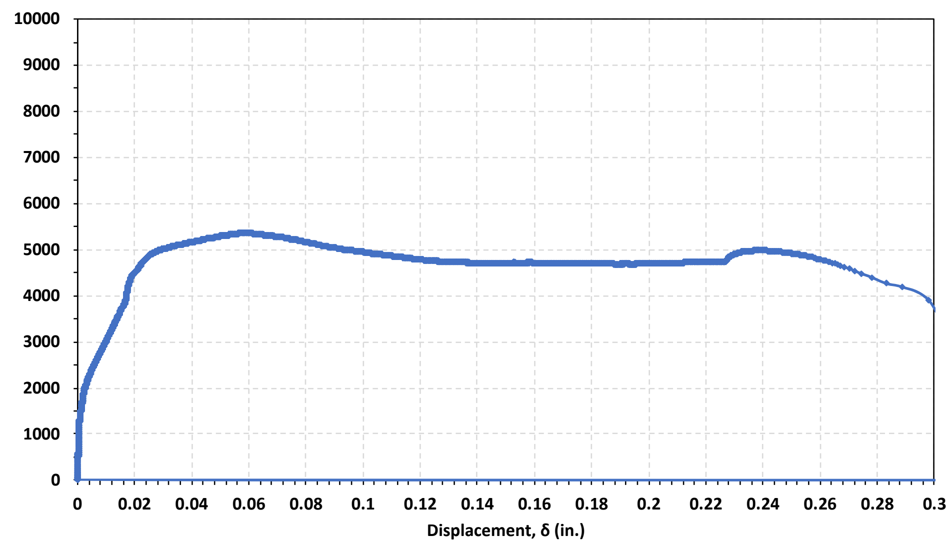

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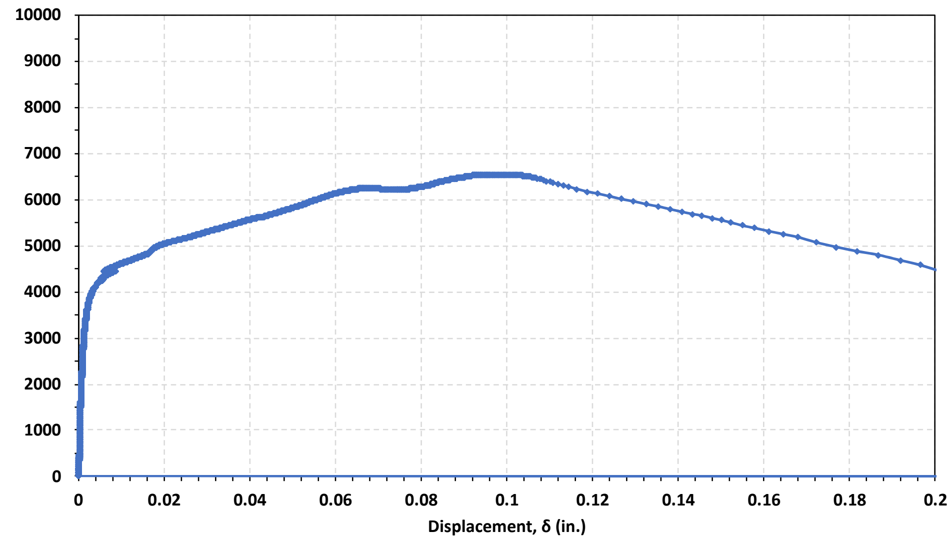

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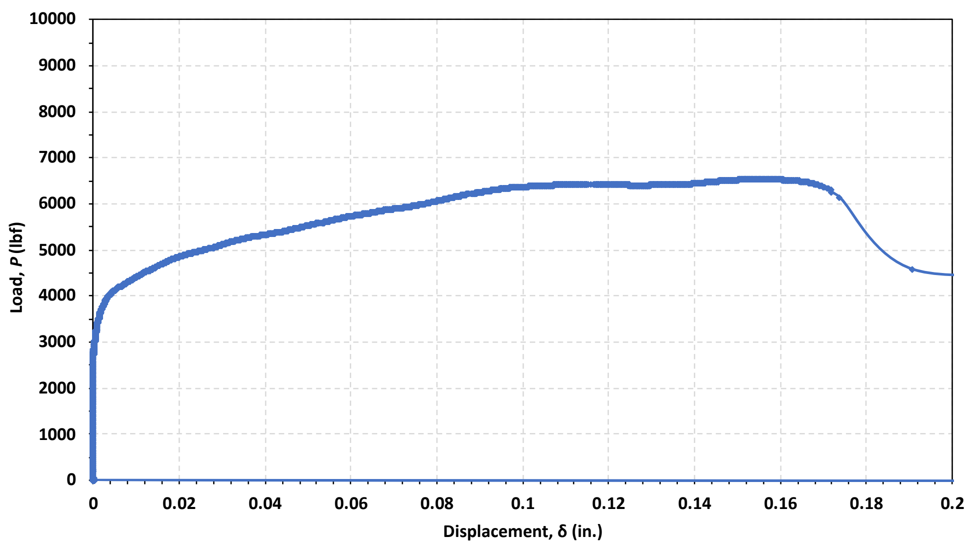

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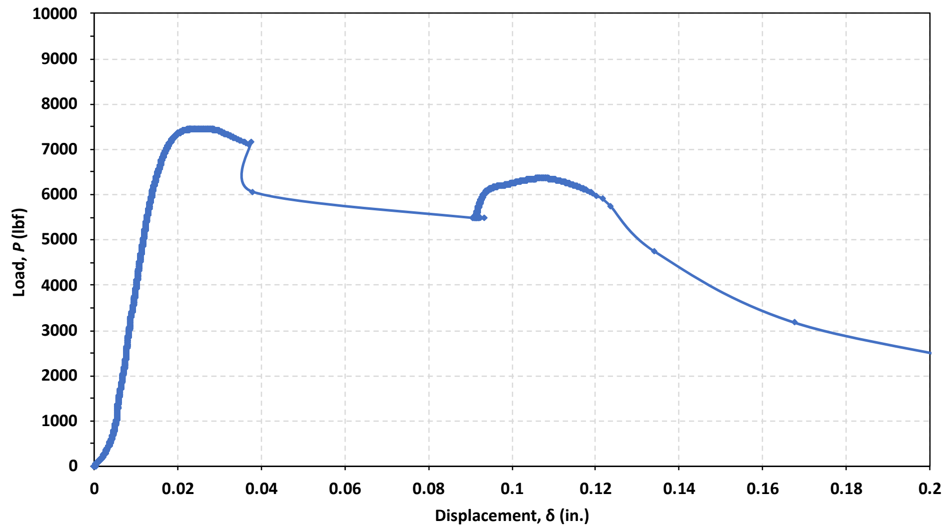

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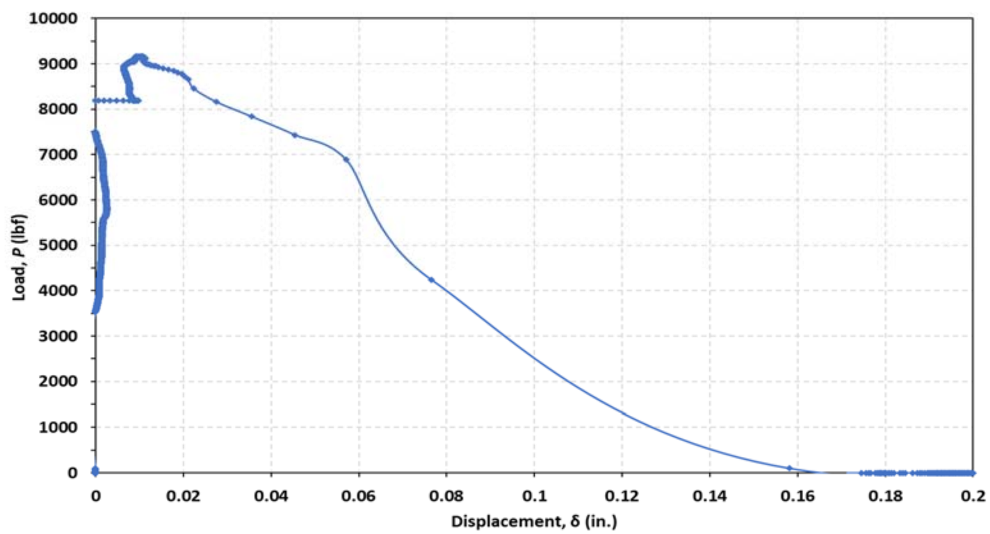

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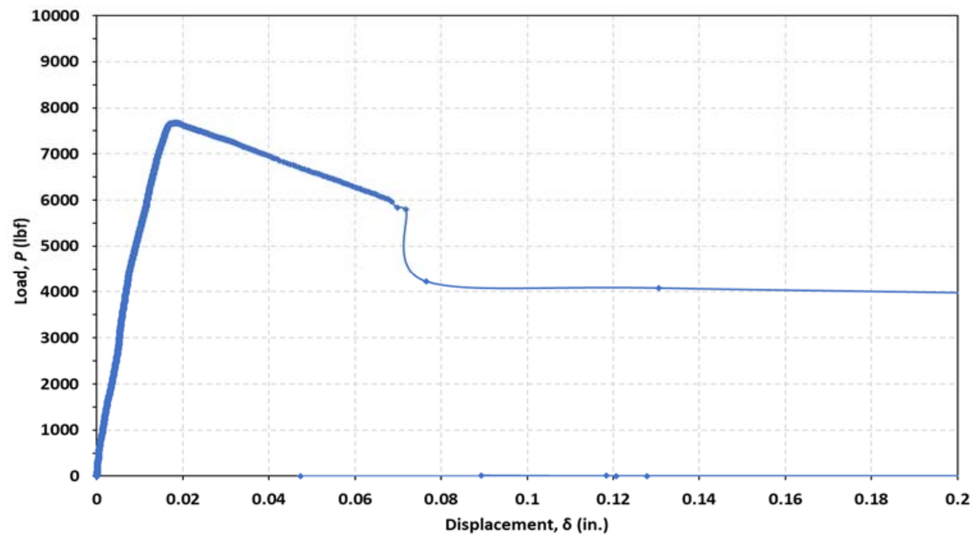

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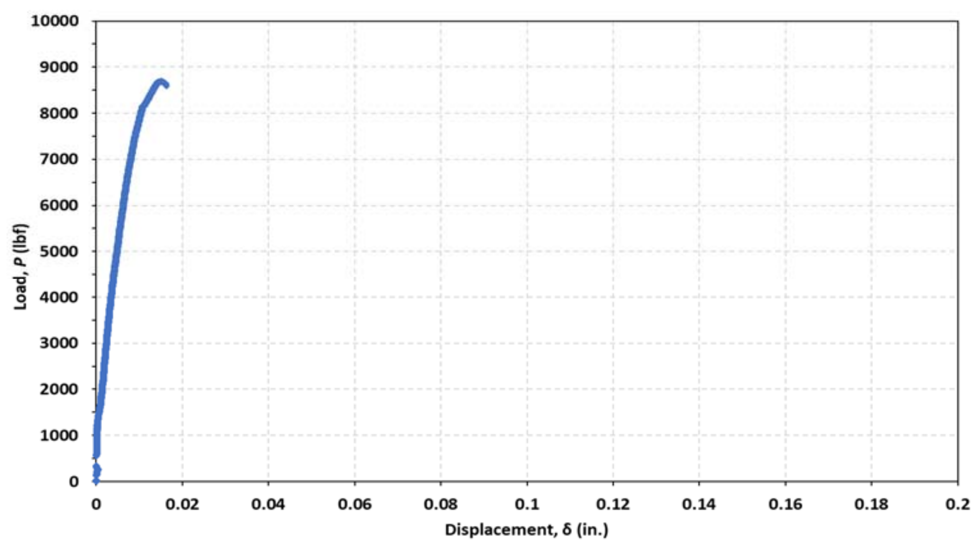

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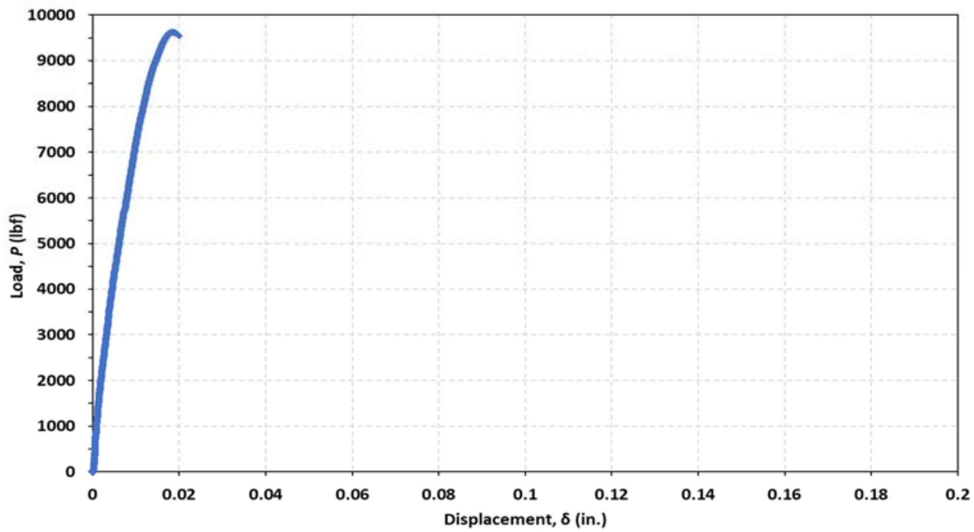

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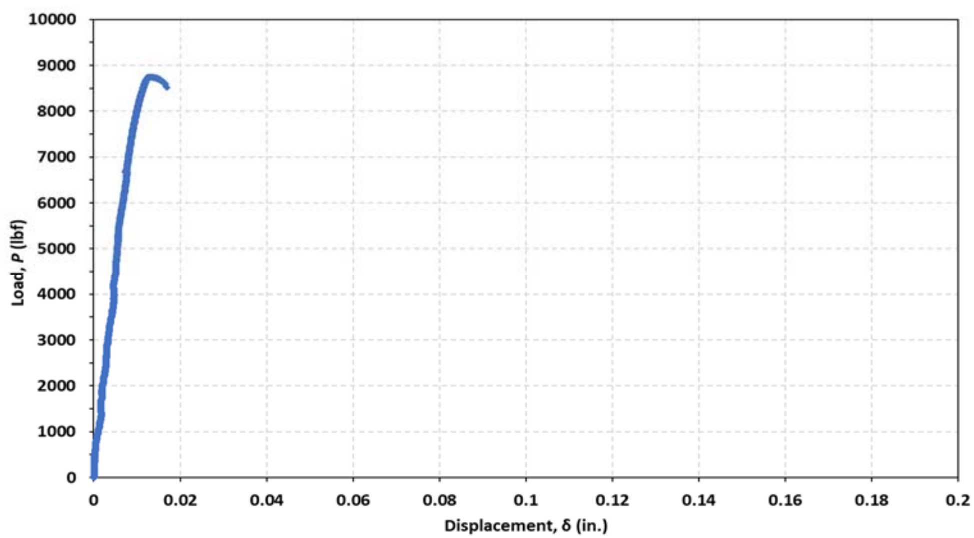

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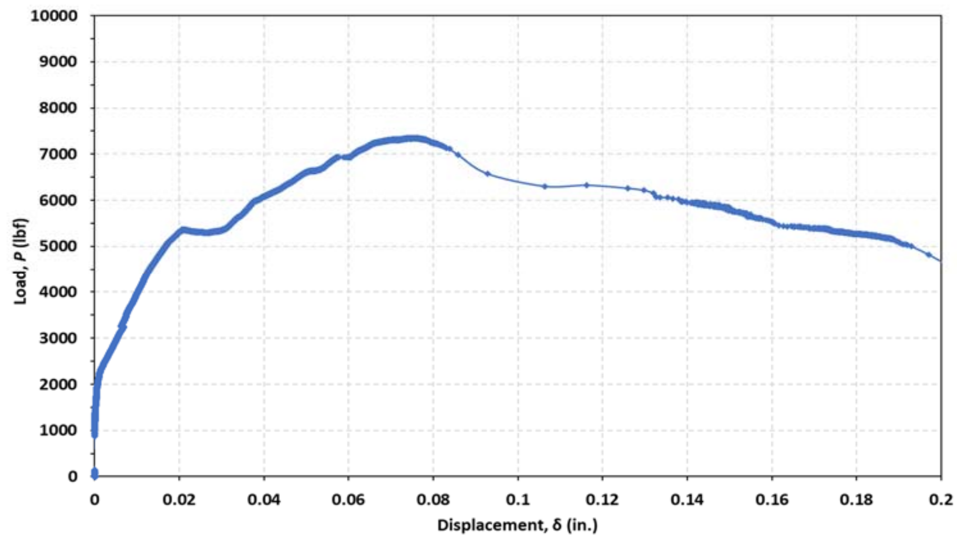
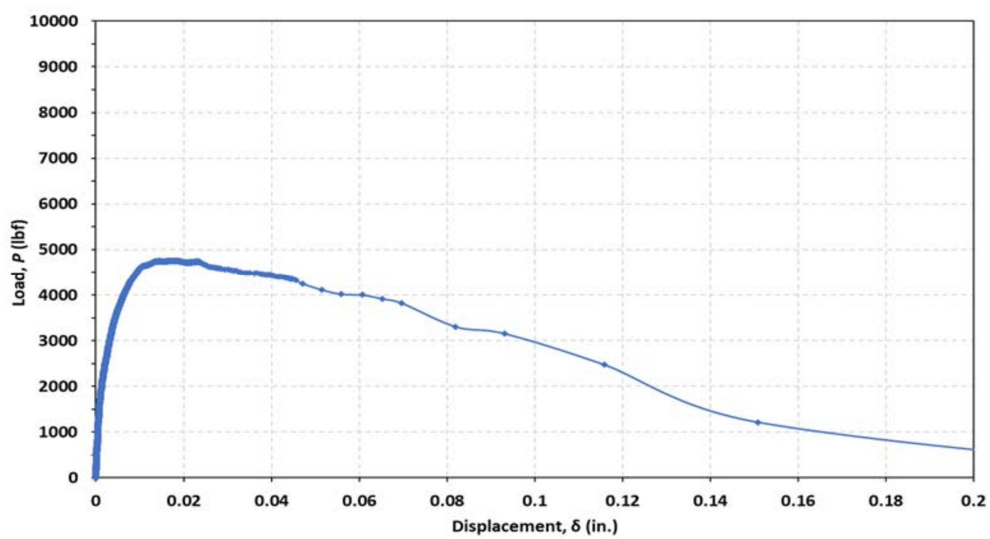


SL-SL-S-B1



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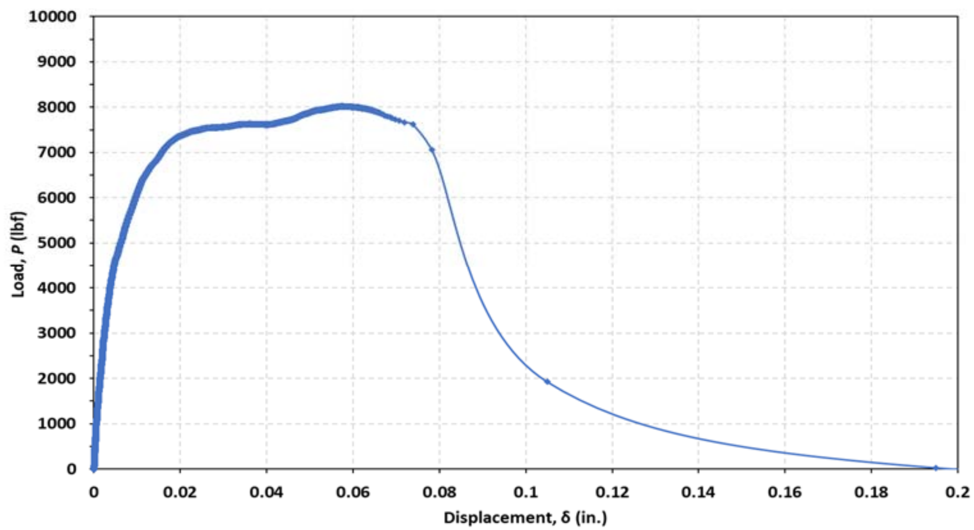

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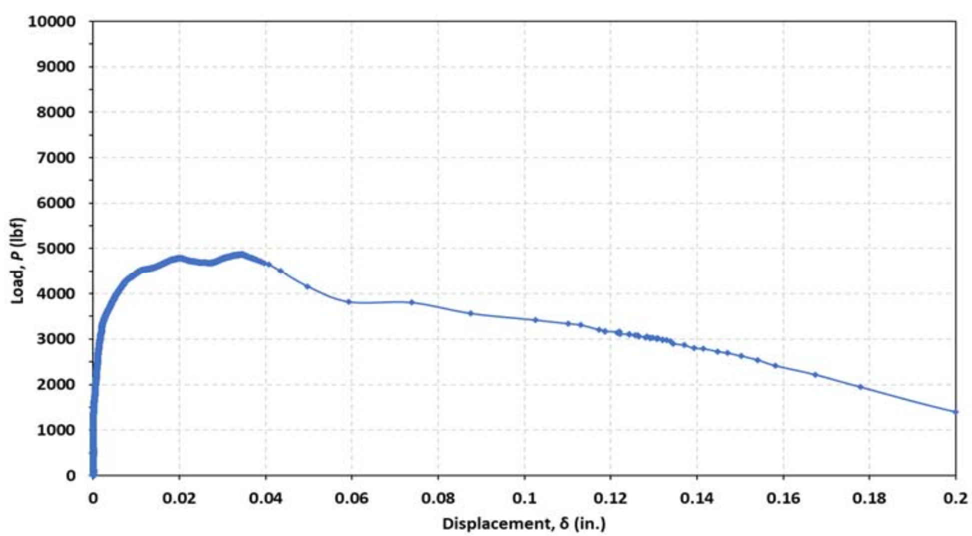

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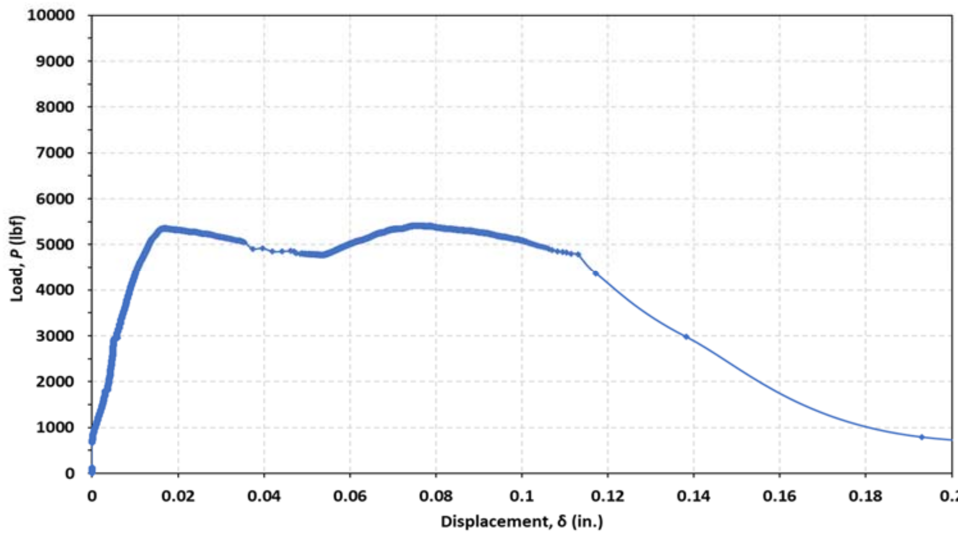
Load, P (lbf)
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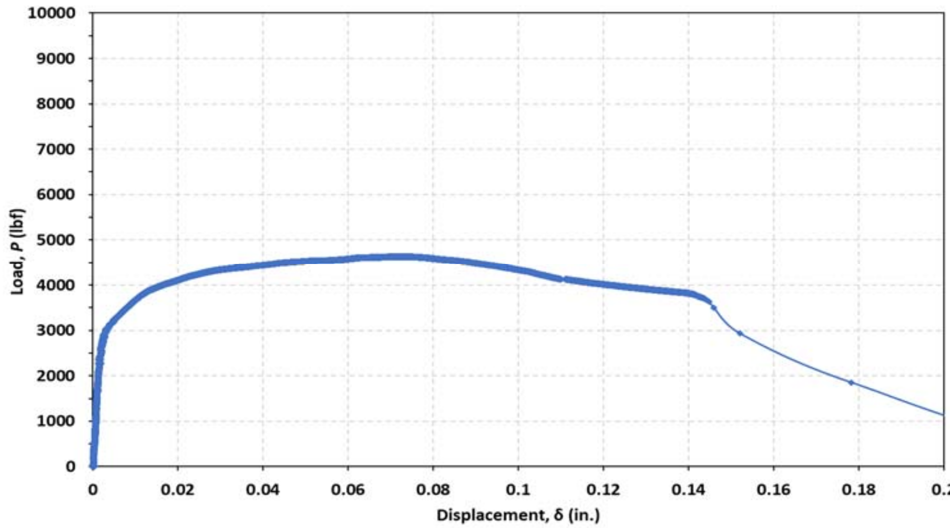
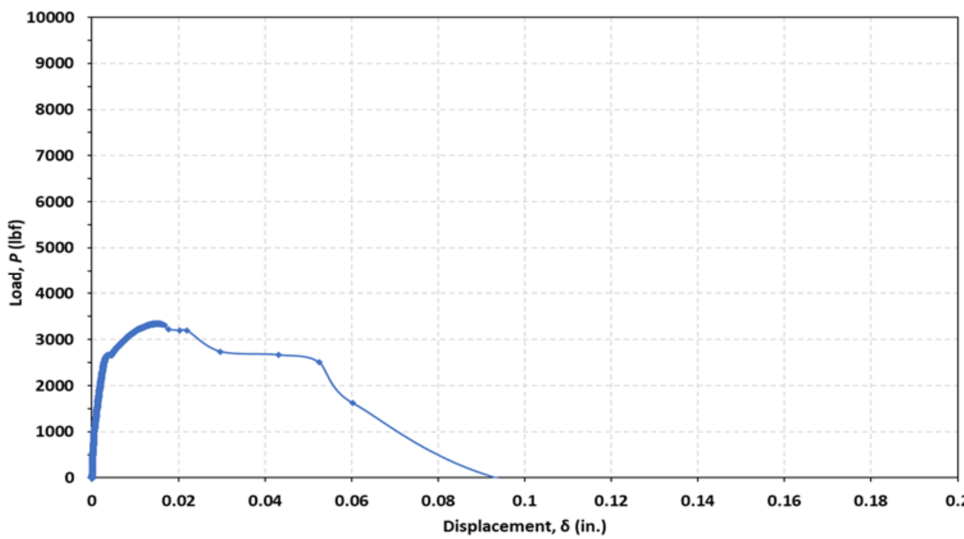
Displacement, δ (in.)

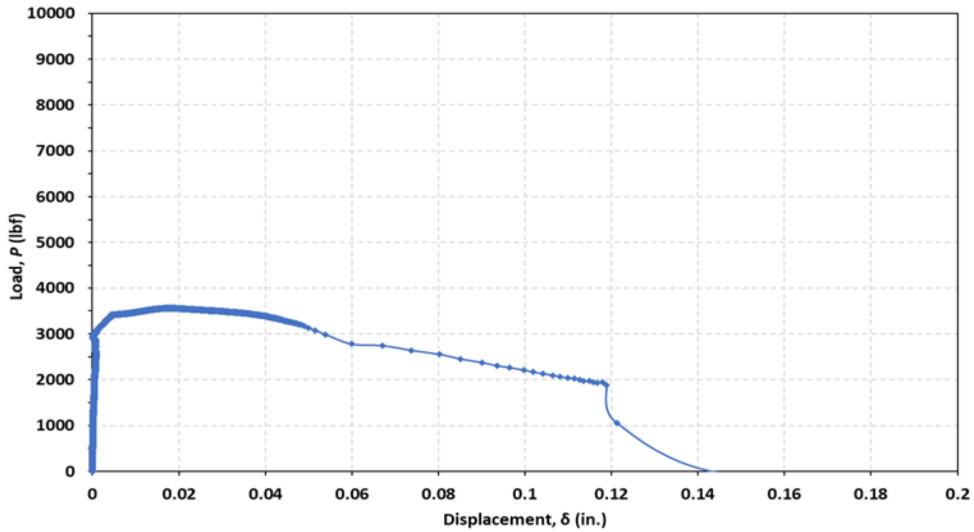
SL-SL-S-C2



AL-SH-T-B1



AL-SH-T-C1



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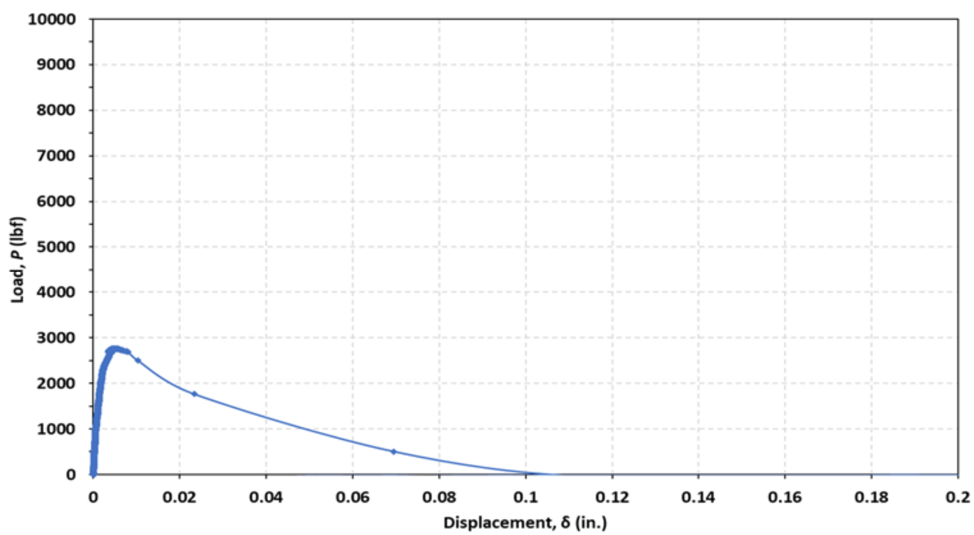
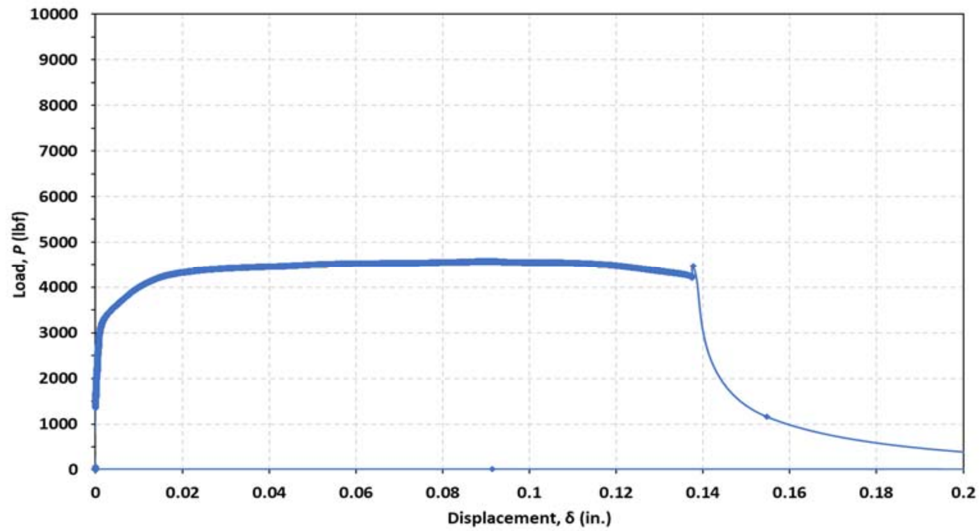
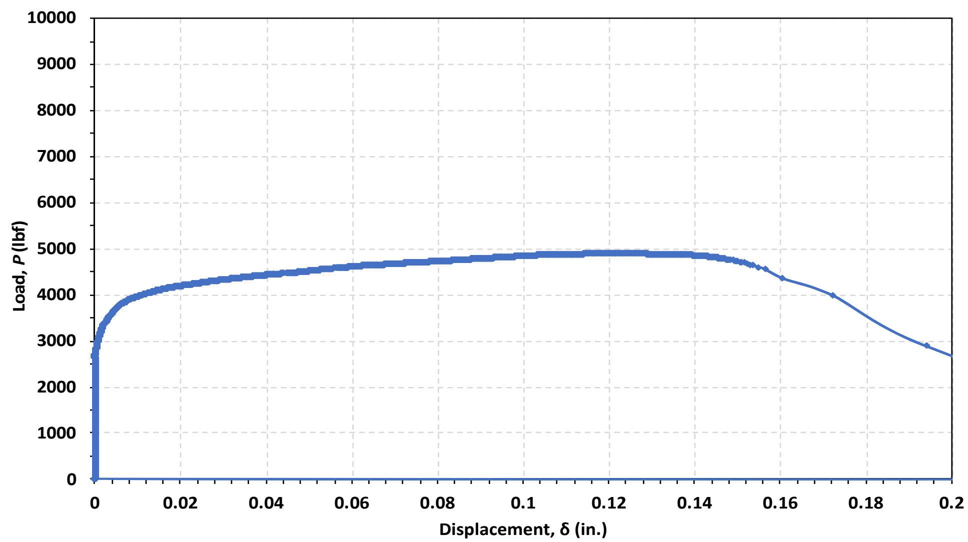


AL-SH-T-A1



AL-SH-T-B2



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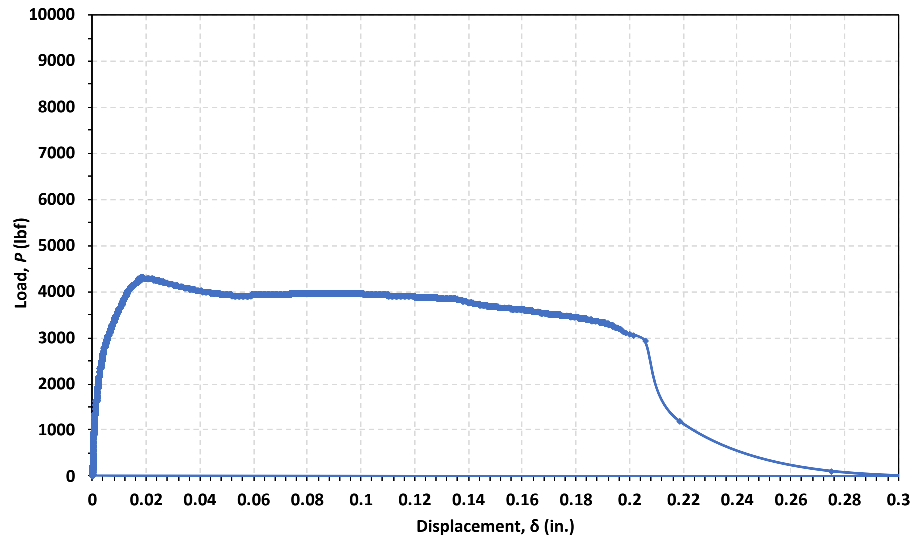

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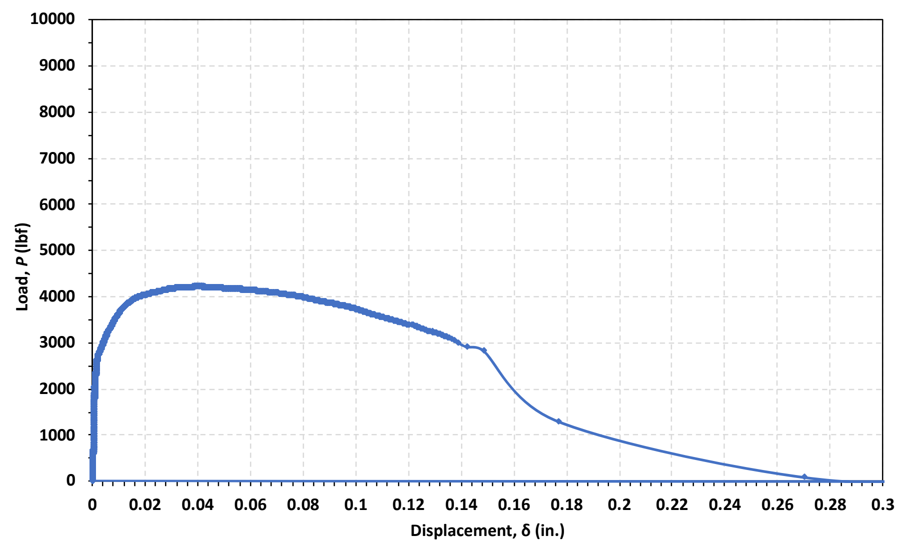

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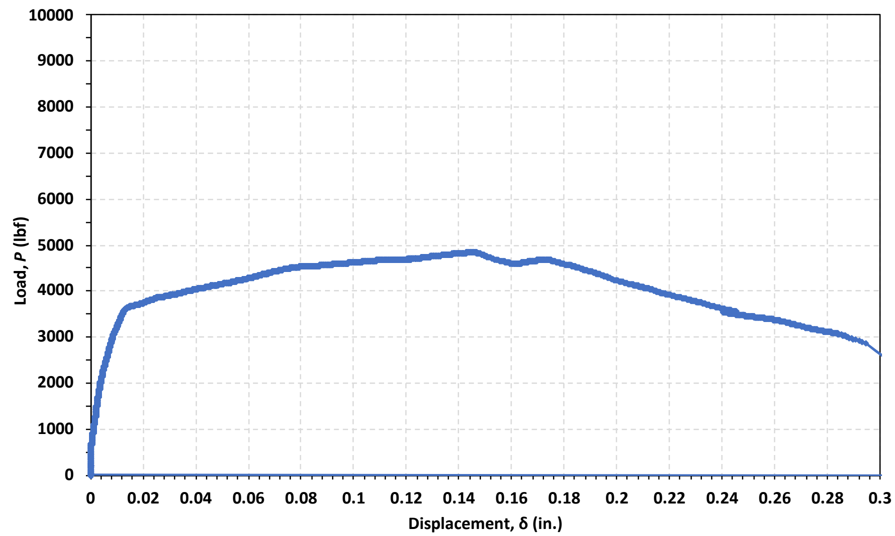

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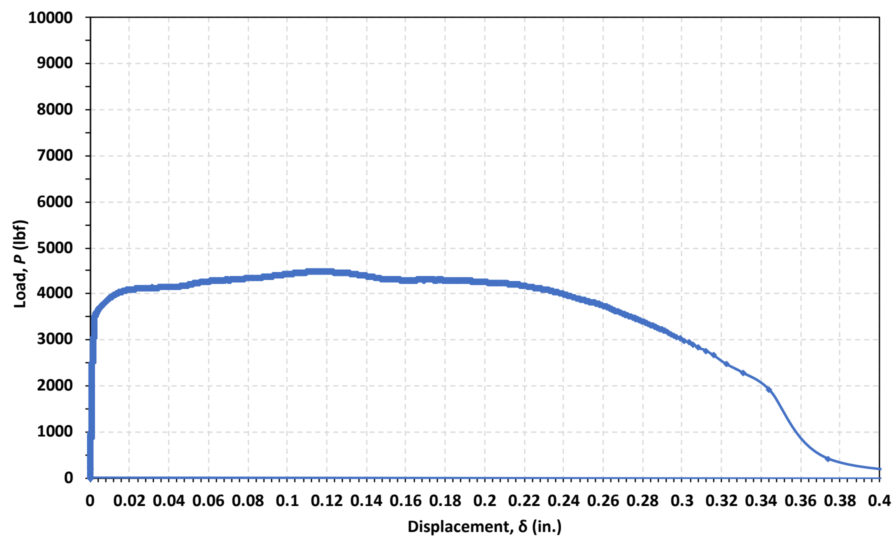

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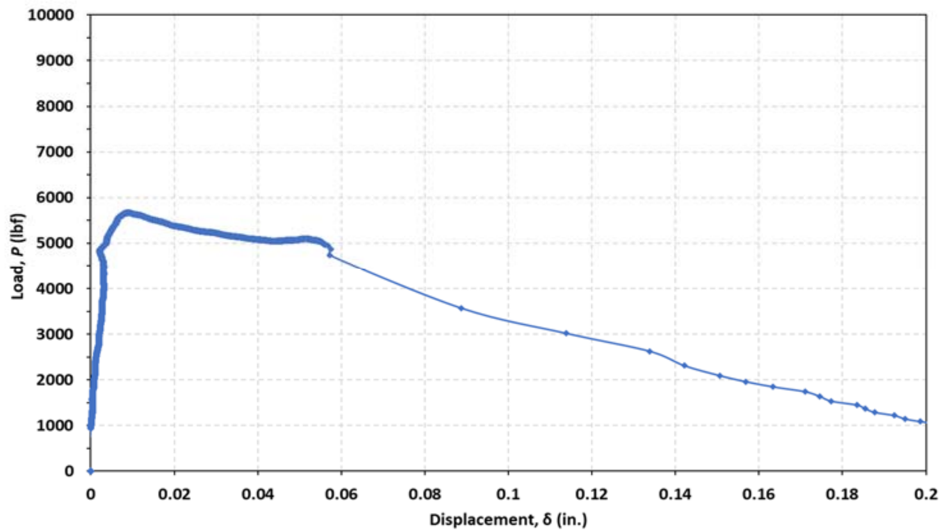

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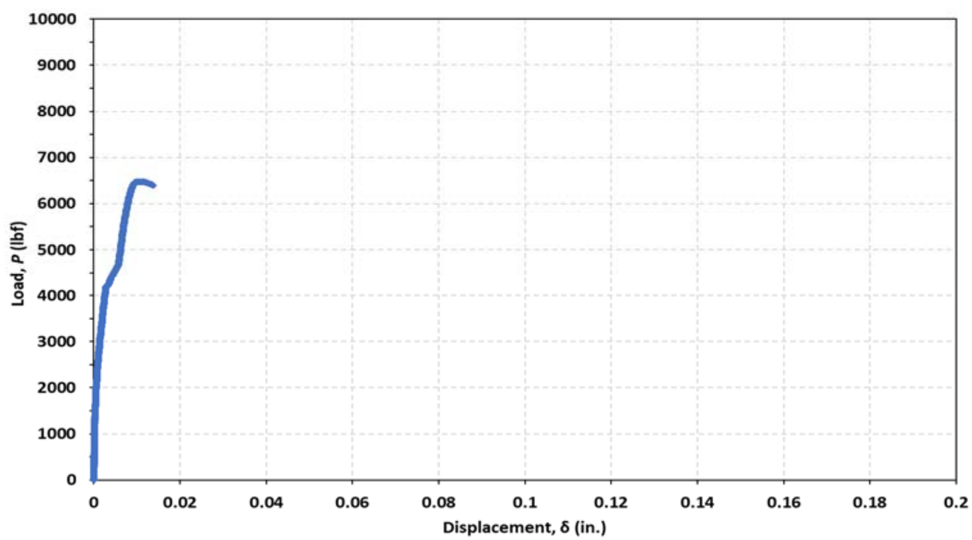

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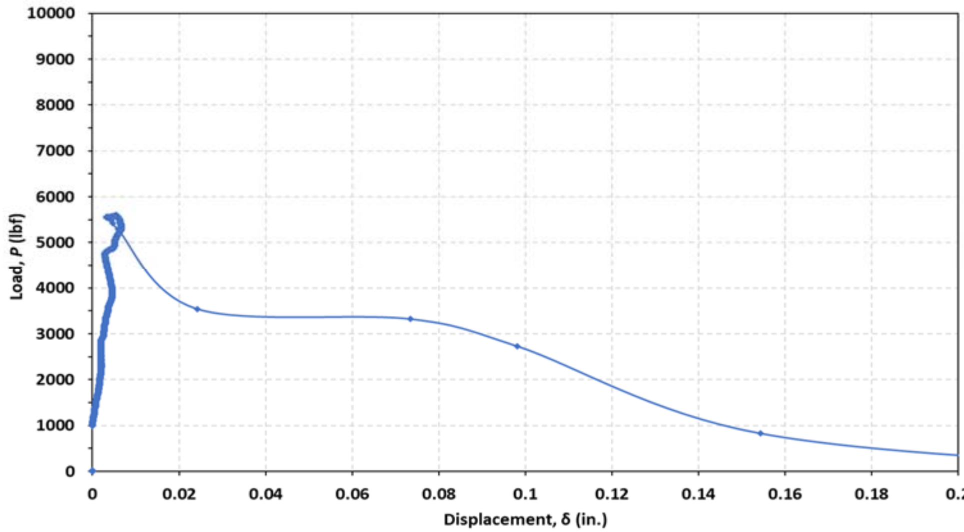

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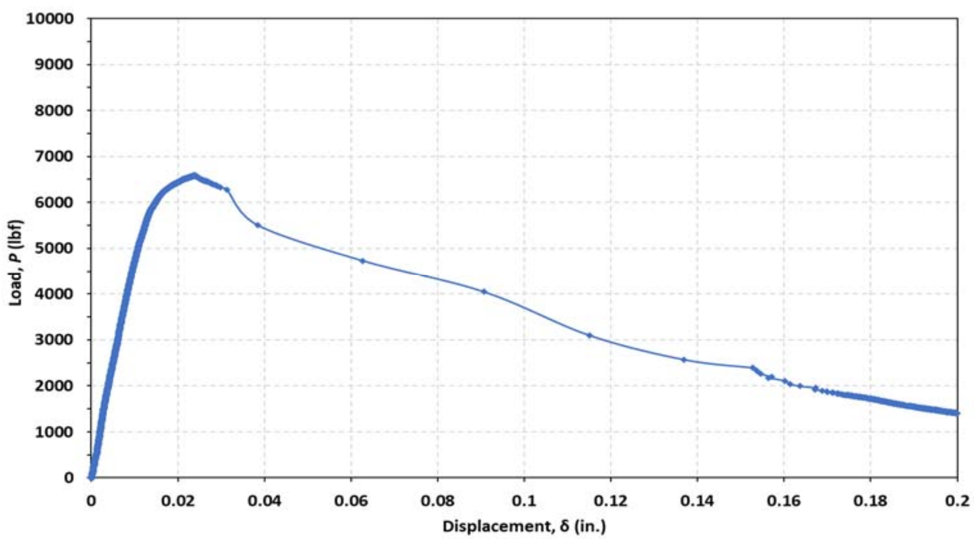

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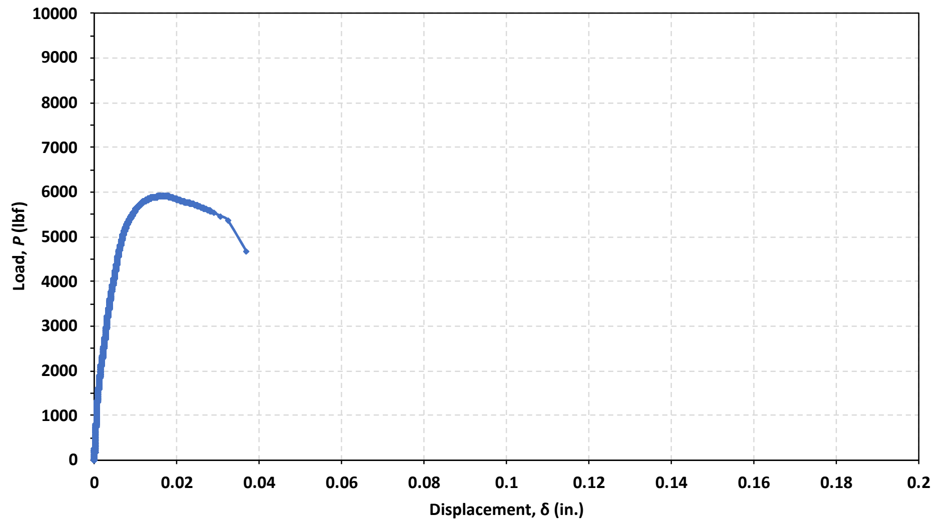
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Load, P (lbf)
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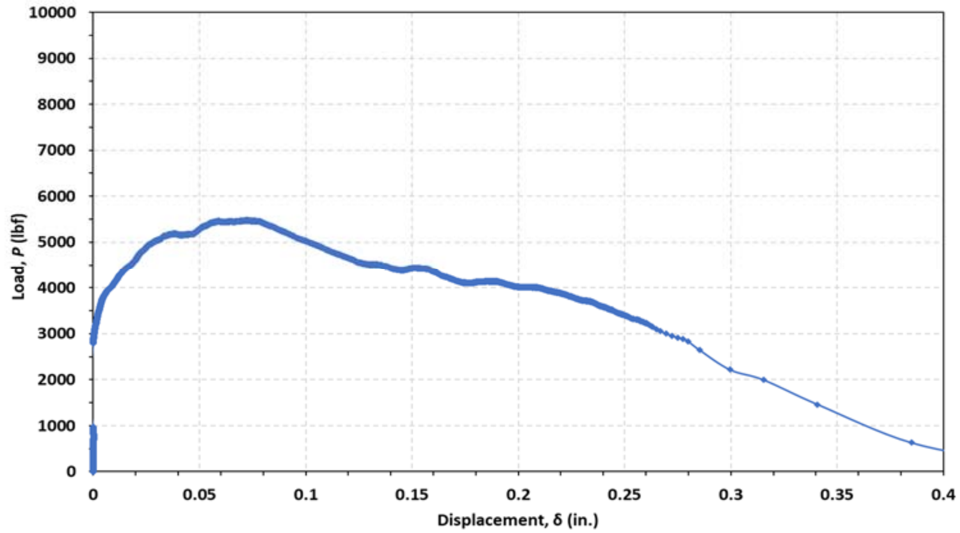
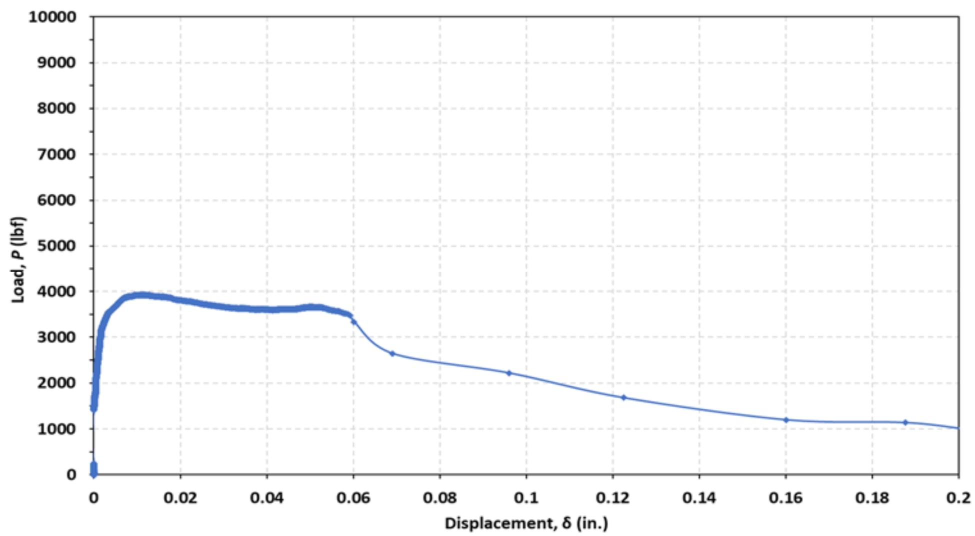
0.18
0.2
Displacement, δ (in.)

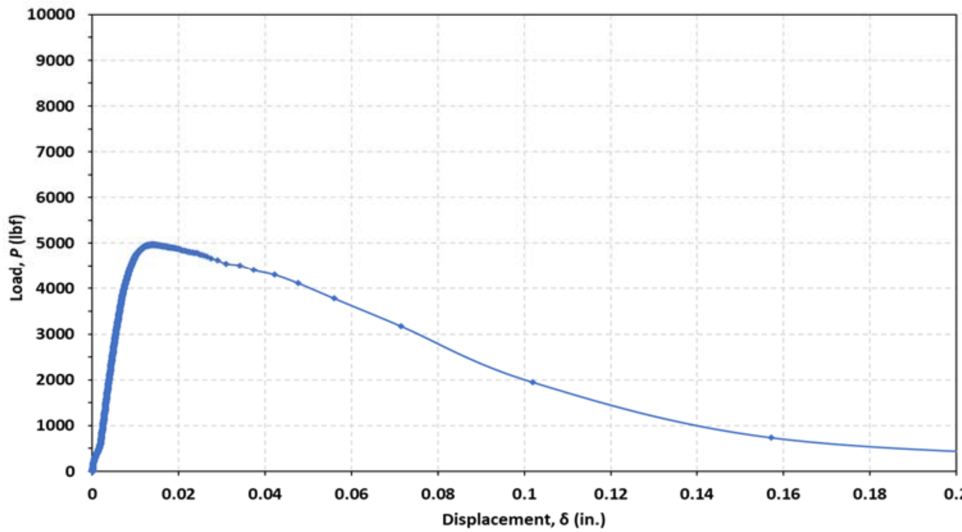
AL-SH-D-B2



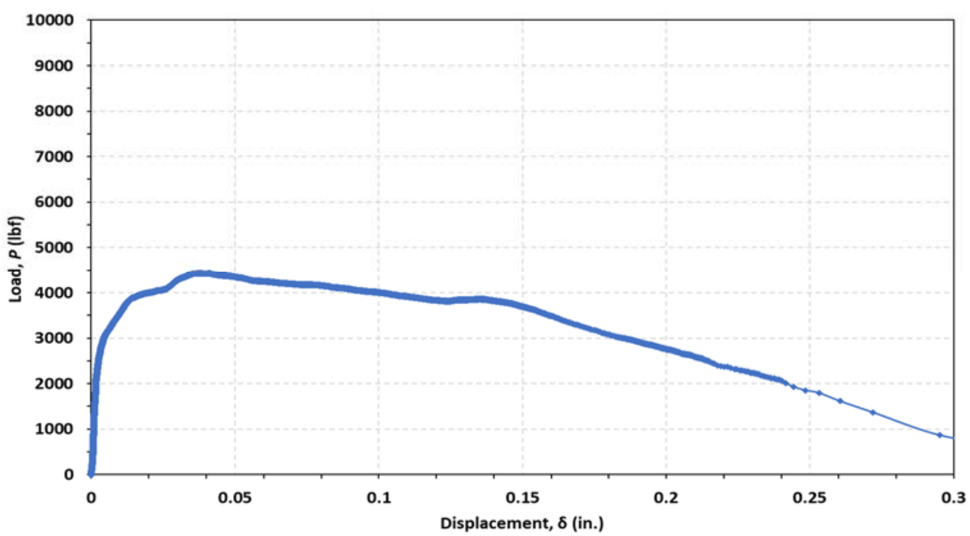
AL-SH-S-B1



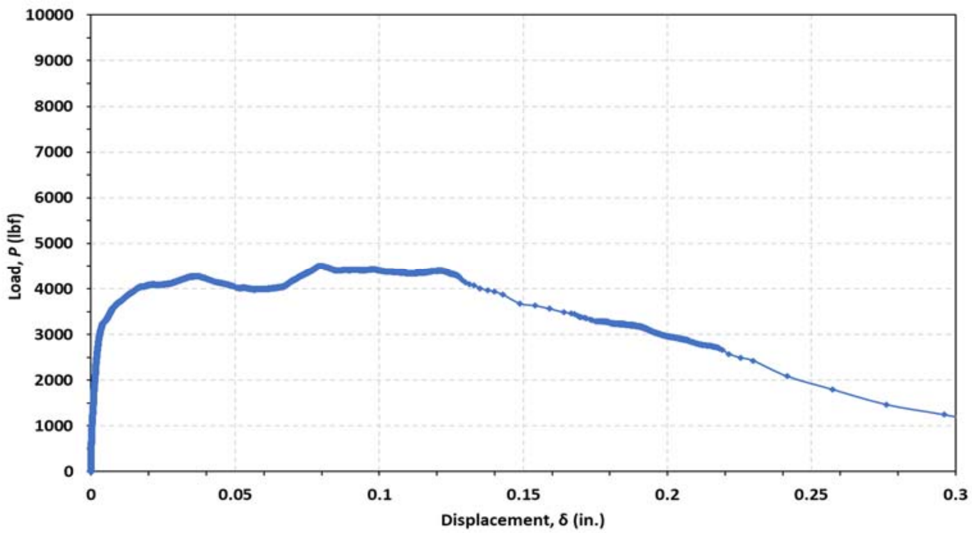
AL-SH-S-C1



AL-SH-S-D1



AL-SH-S-A1


10000
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6000
5000
4000
3000
2000
1000
0
Load, P (lbf)
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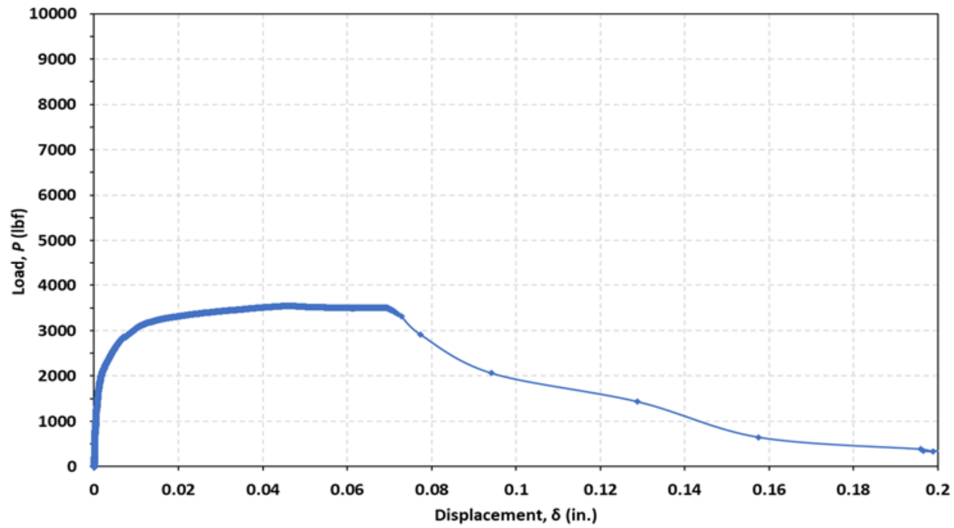
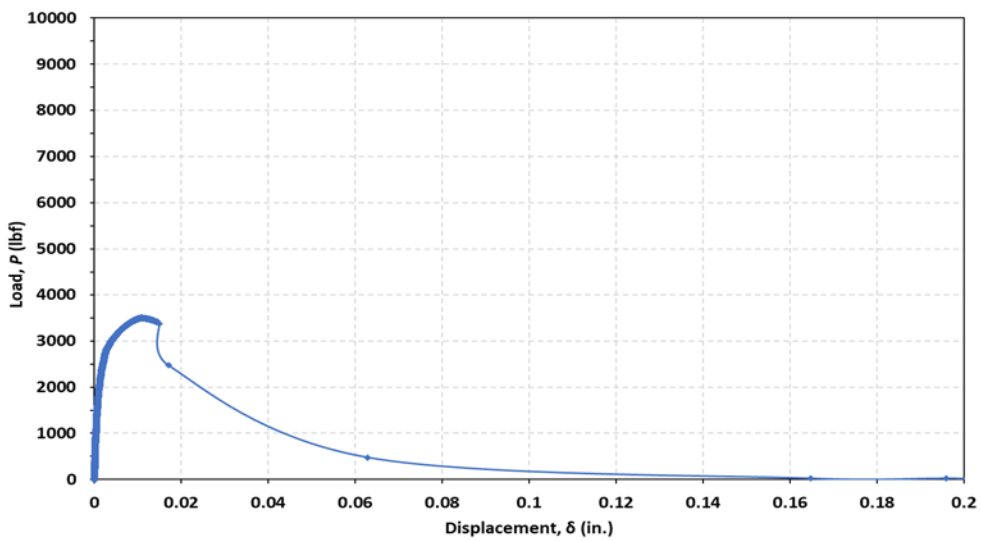
0.05
0.1
0.15
0.2
0.25
0.3
Displacement, δ (in.)

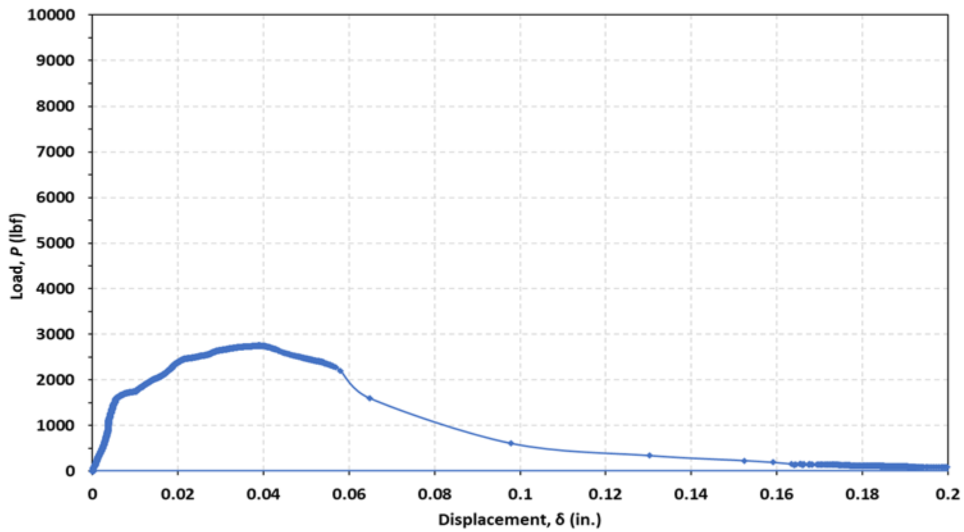
AL-SH-S-B2



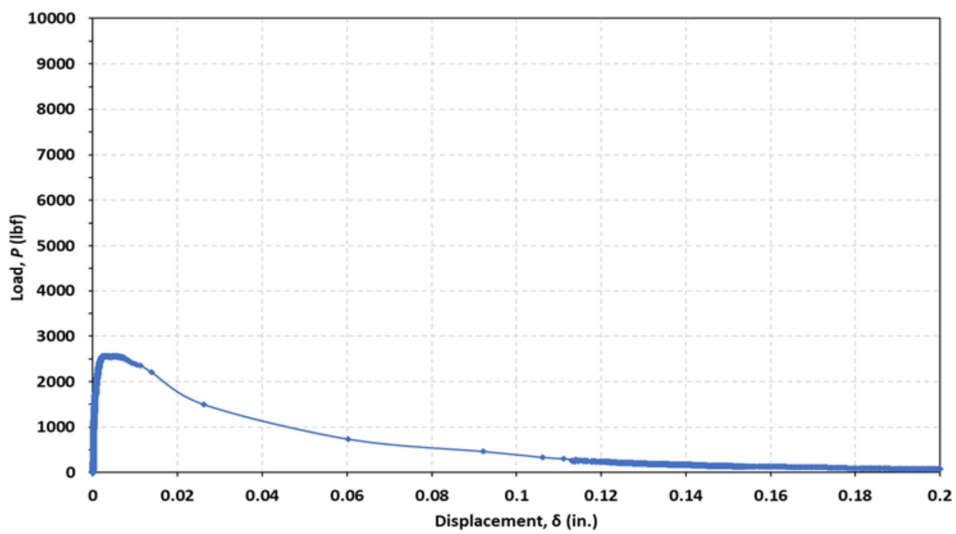
AL-CL-T-B1



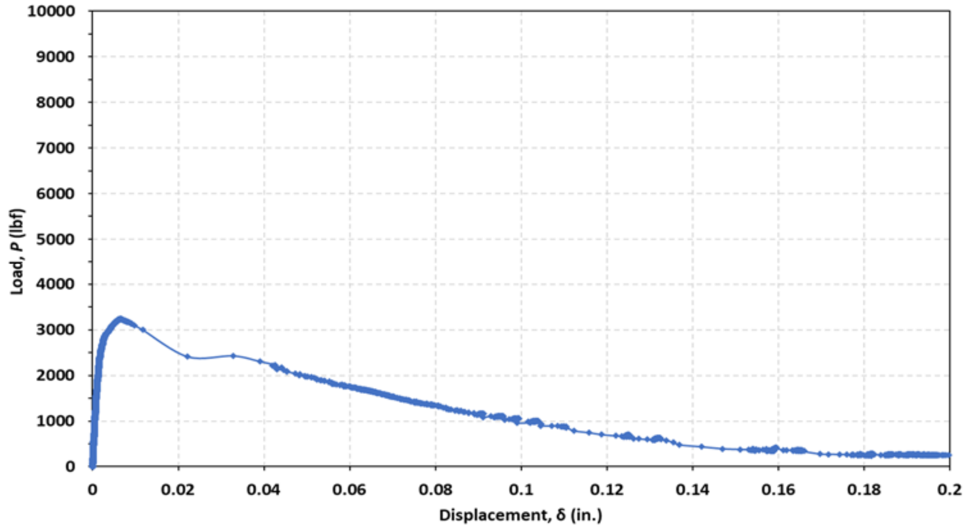
AL-CL-T-C1



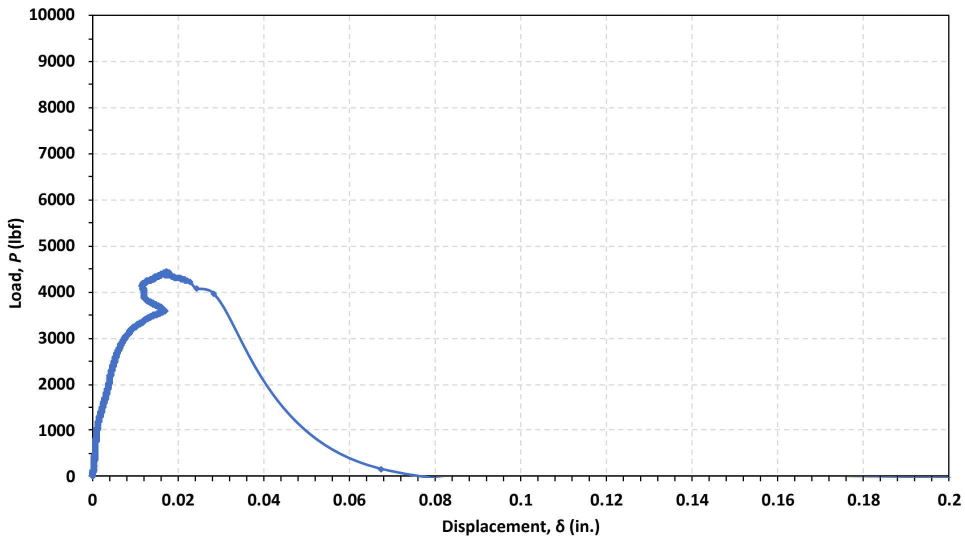
AL-CL-T-D1



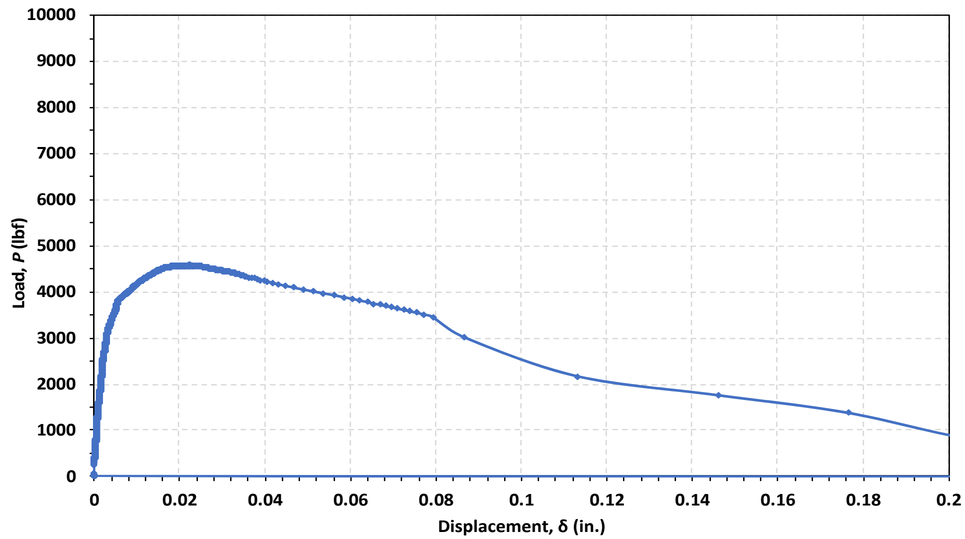
AL-CL-T-A1



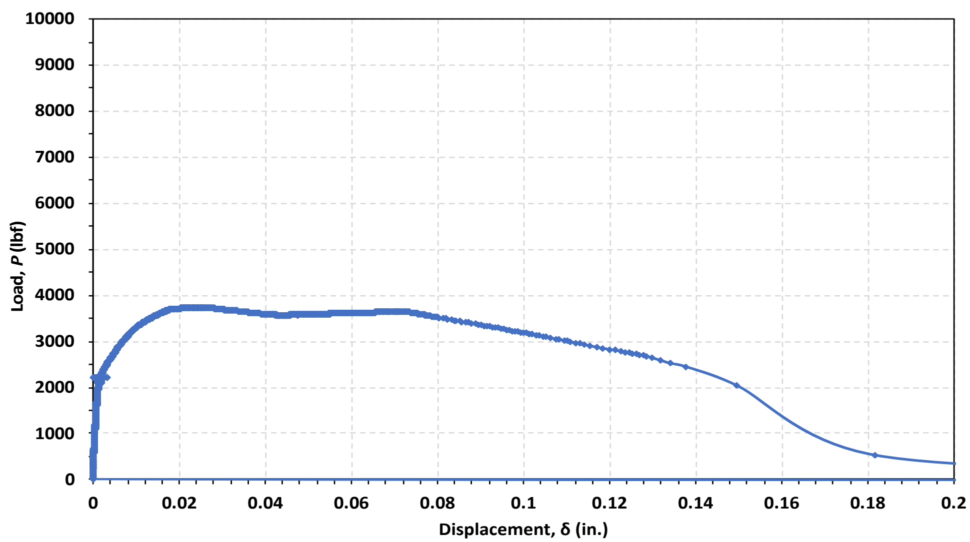
AL-CL-T-C2



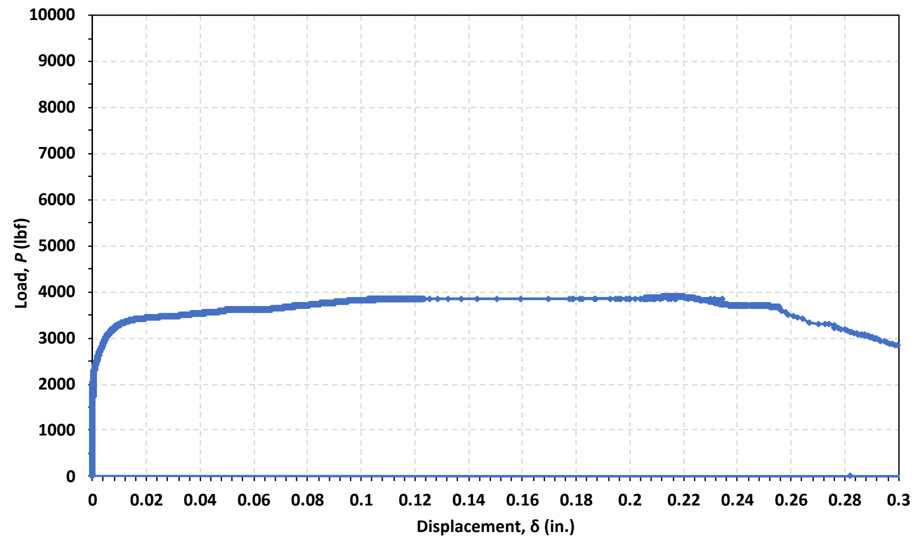
AL-CL-T-B2*



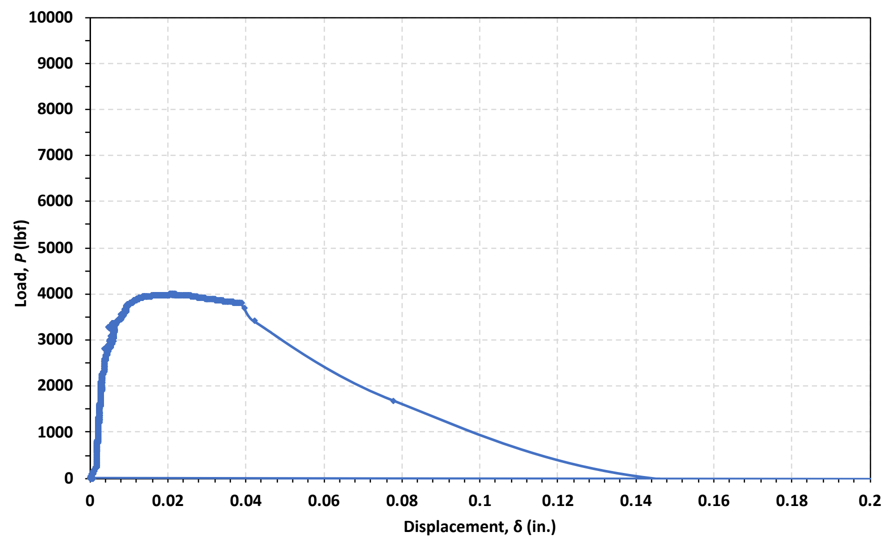
AL-CL-T-C3*



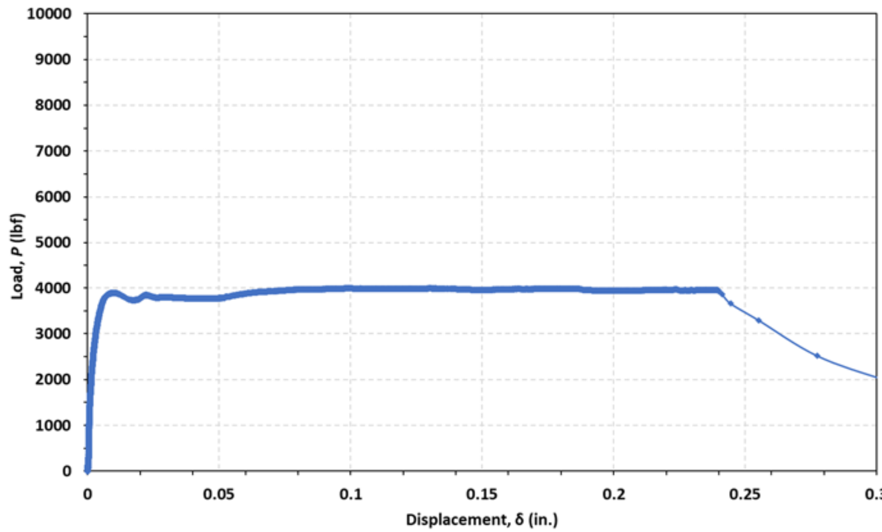
AL-CL-T-D2*



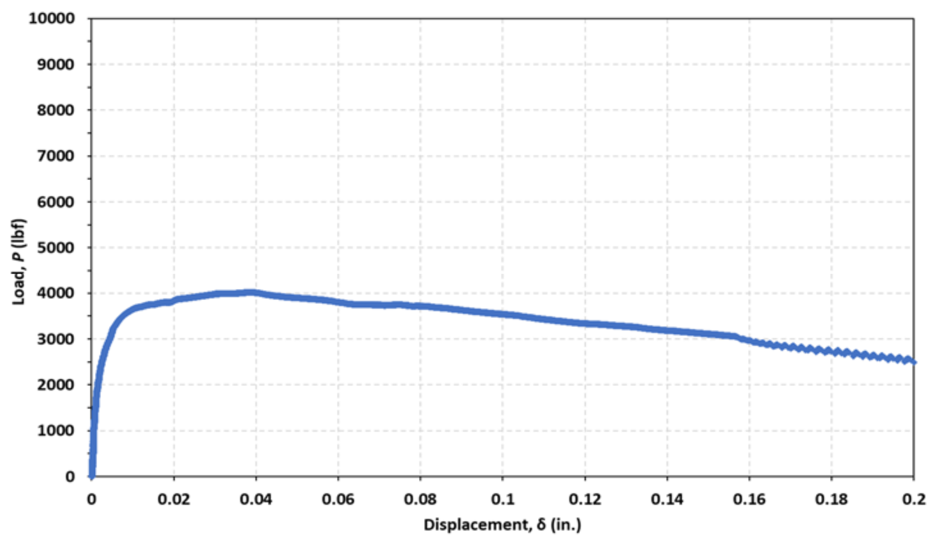
AL-CL-T-A2*



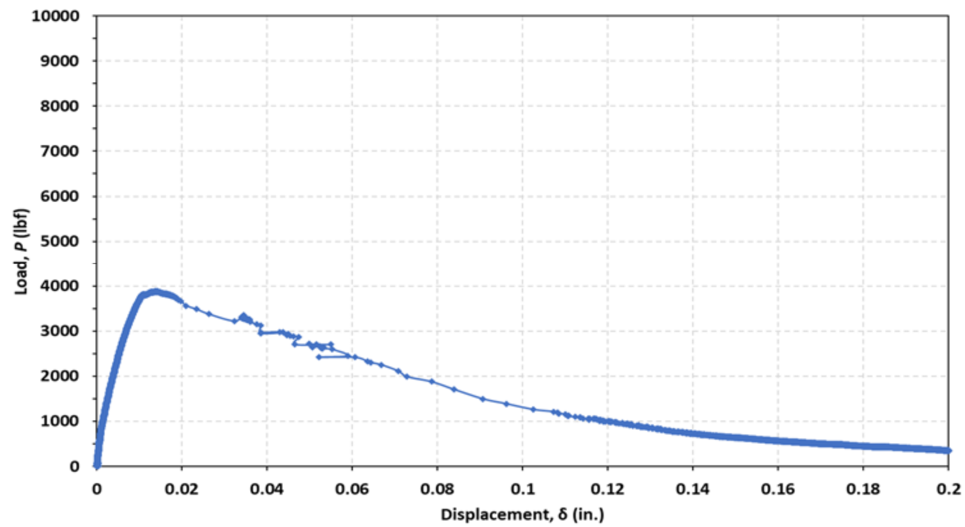
AL-CL-T-C4*



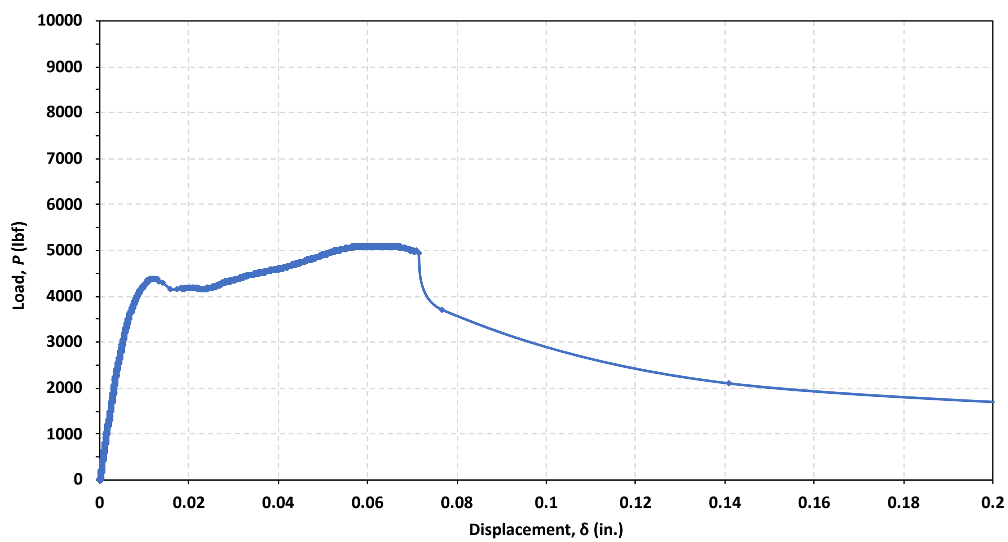
AL-CL-D-B1



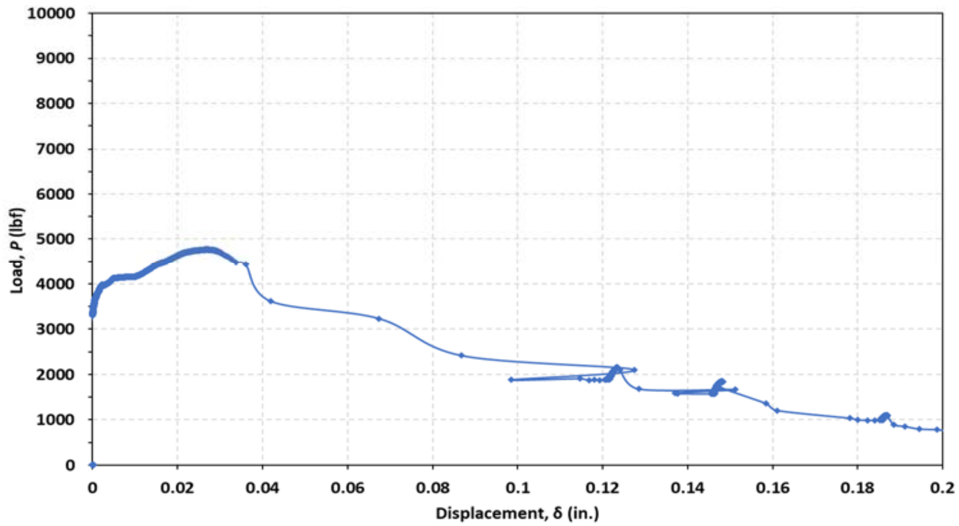
AL-CL-D-C1



AL-CL-D-D1



AL-CL-D-A1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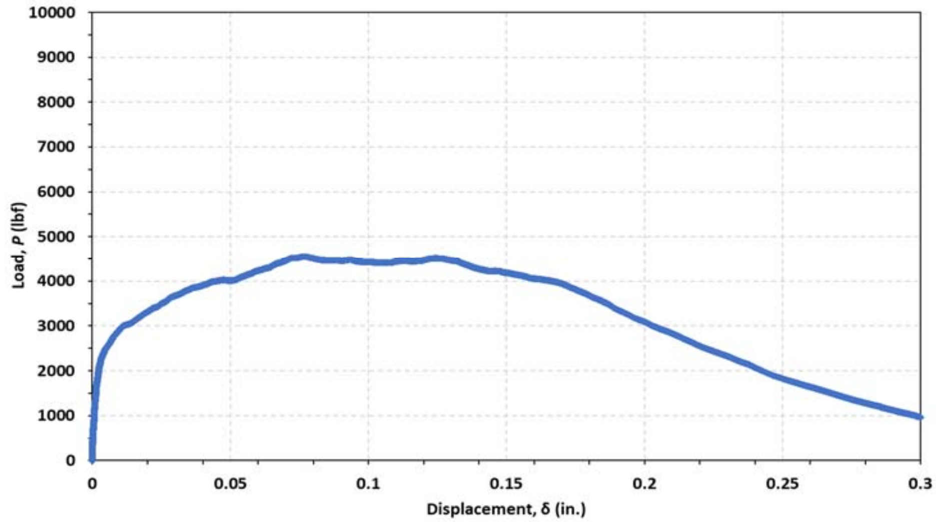
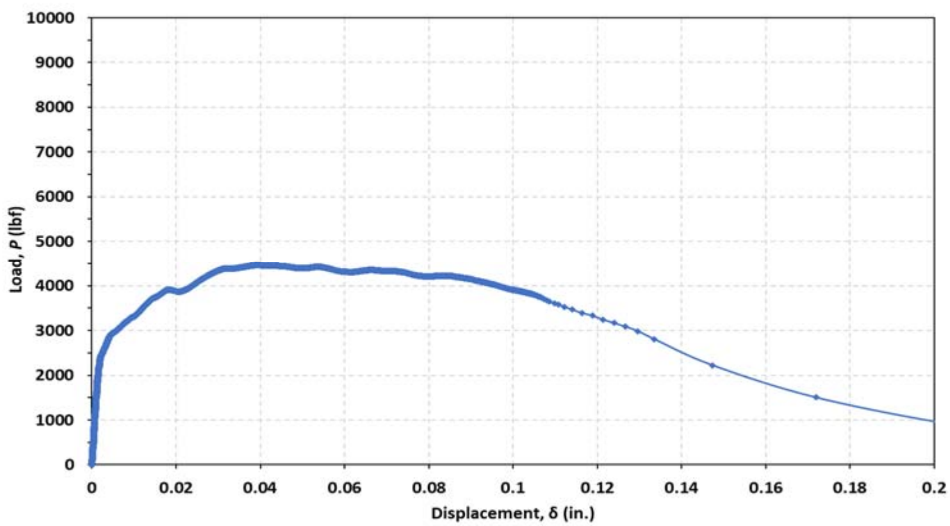
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Load, P (lbf)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

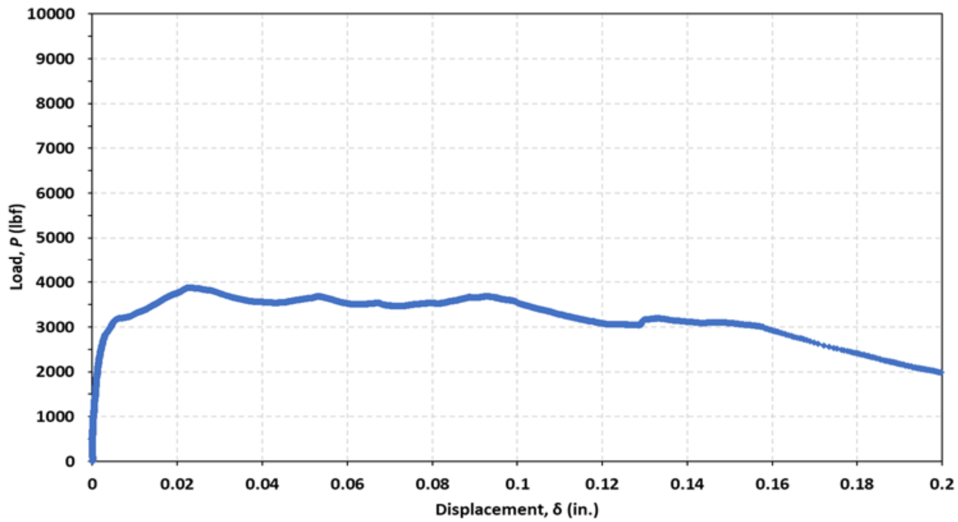
AL-CL-D-D2



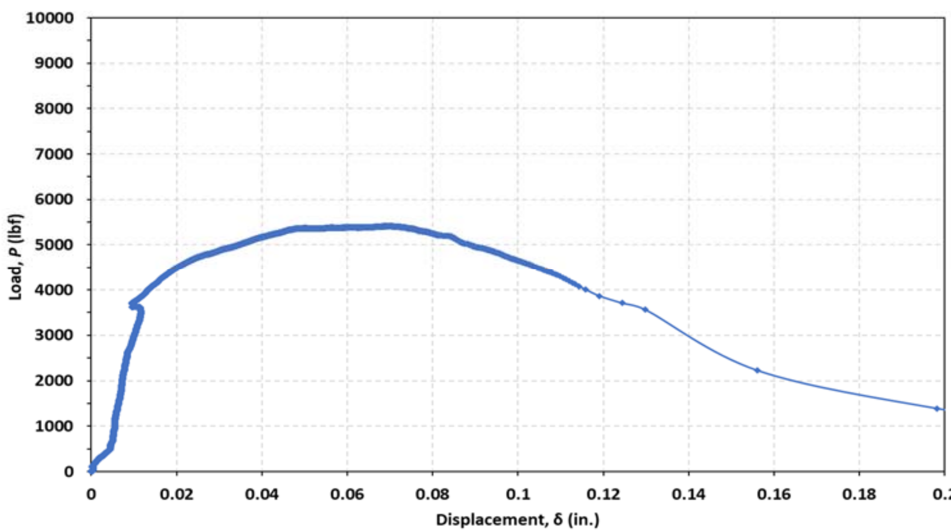
AL-CL-S-B1



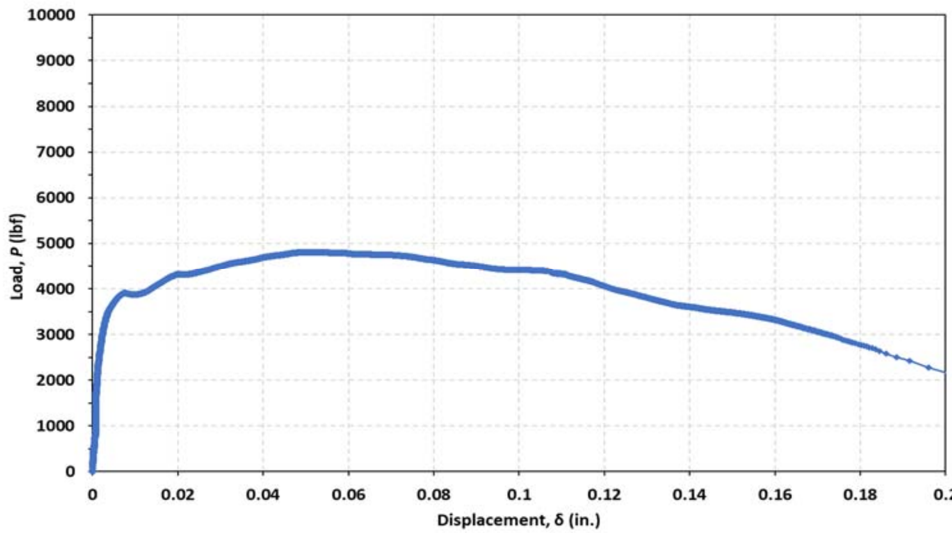
AL-CL-S-C1



AL-CL-S-D1



AL-CL-S-A1


Load, P (lbf)
10000
9000
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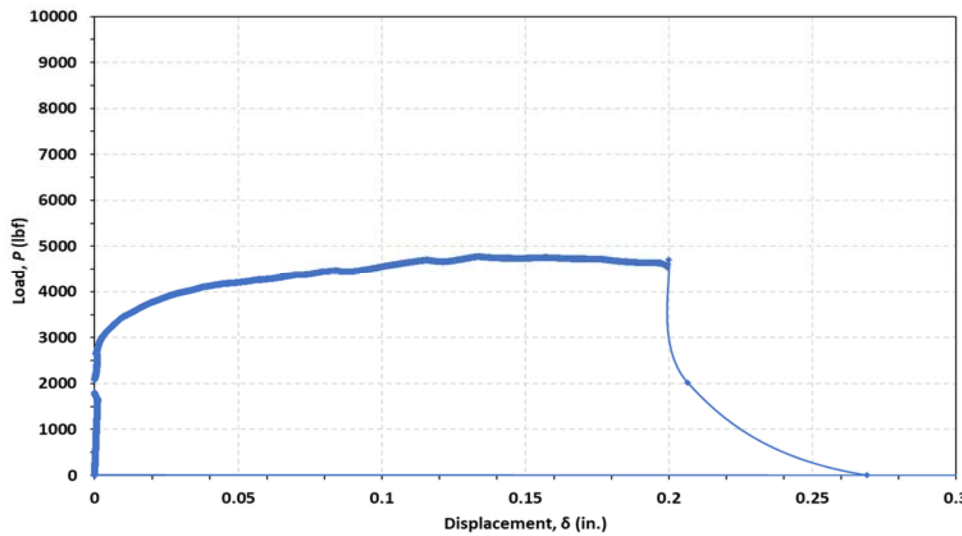
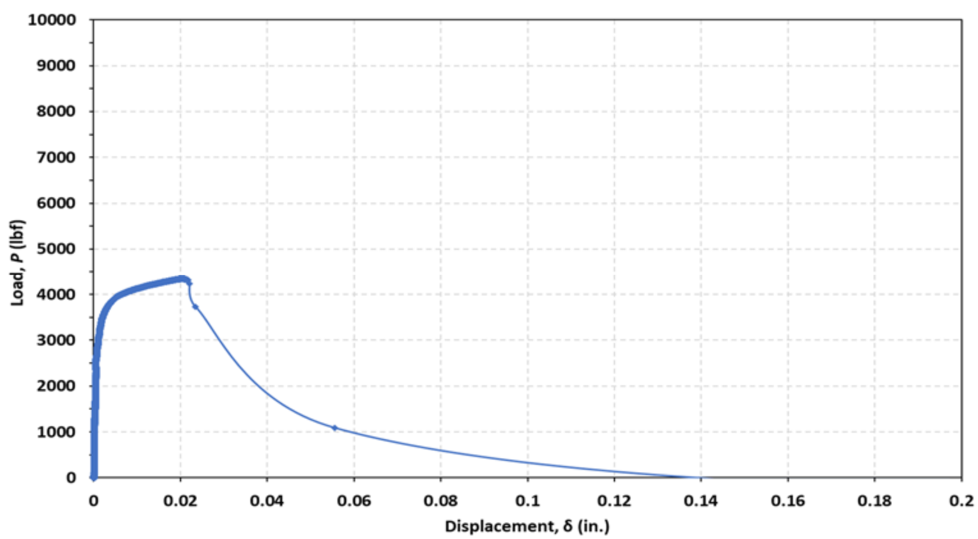
7000
6000
5000
4000
3000
2000
1000
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

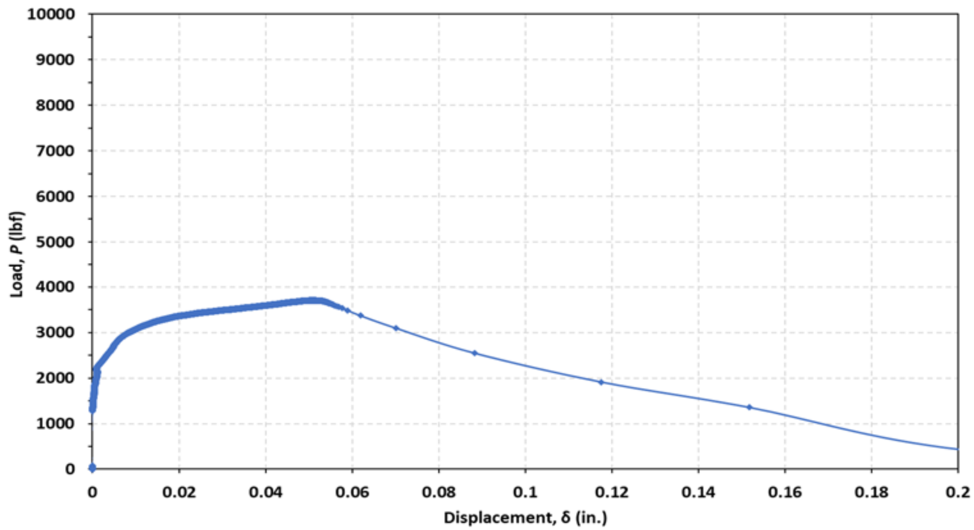
AL-CL-S-A2



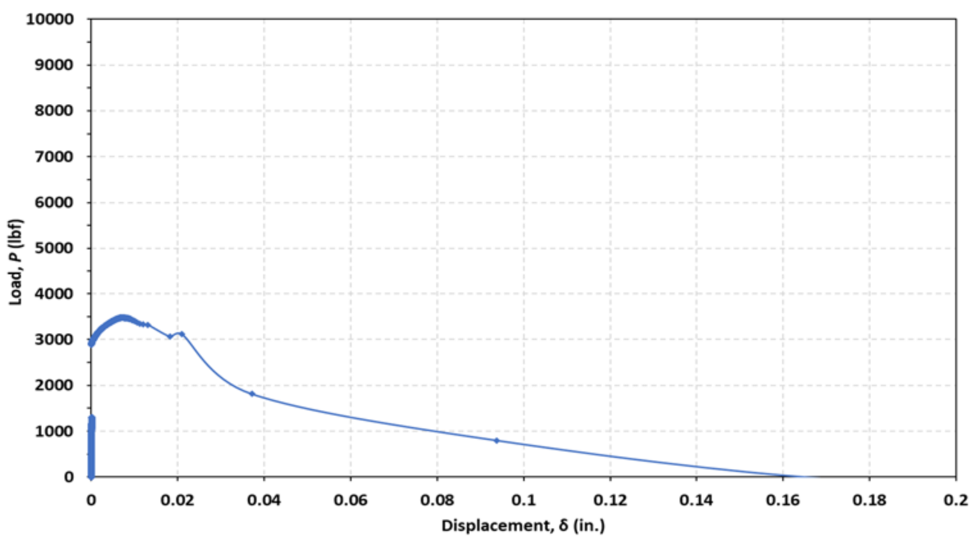
AL-SL-T-B1



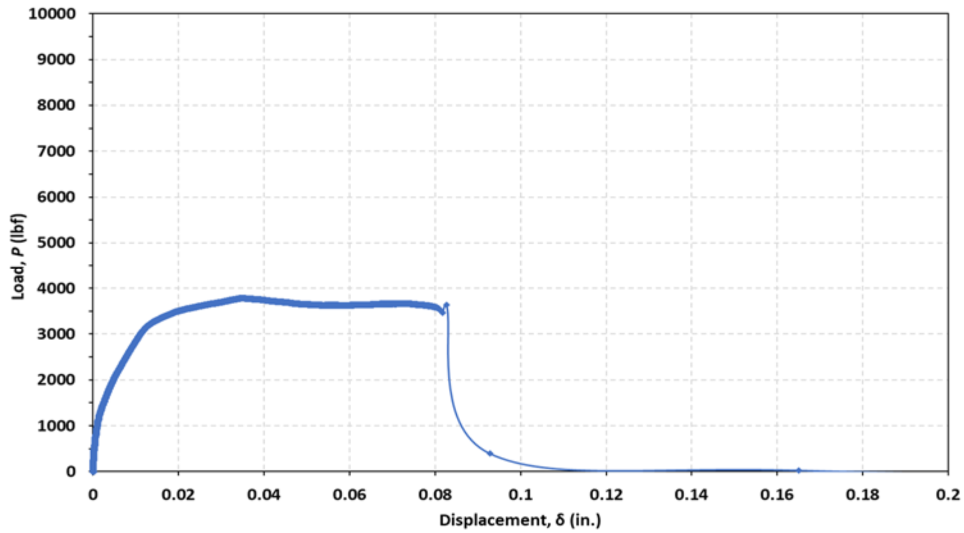
AL-SL-T-C1



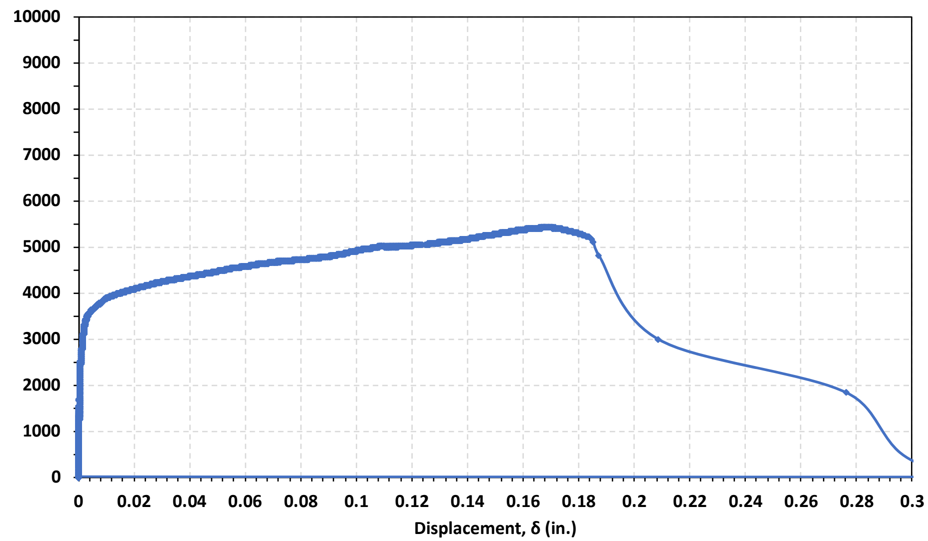
AL-SL-T-D1



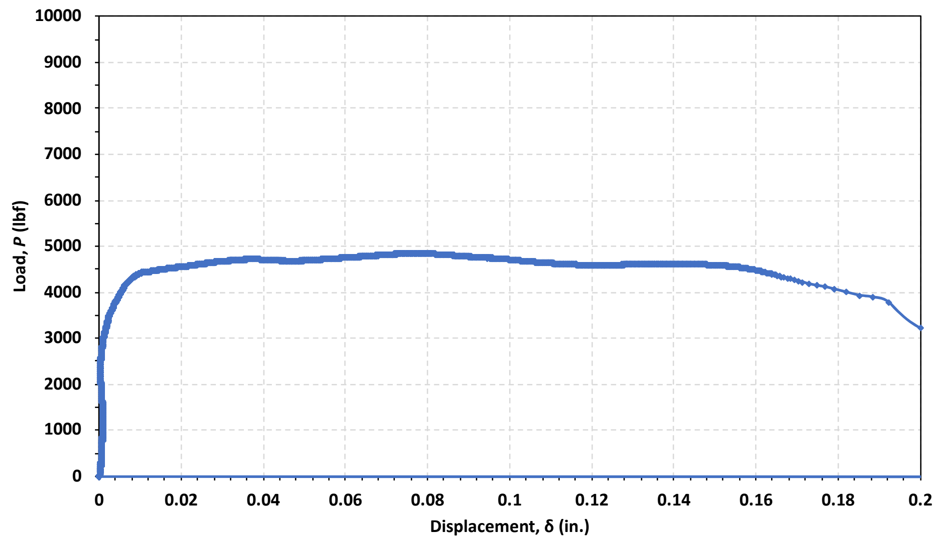
AL-SL-T-A1



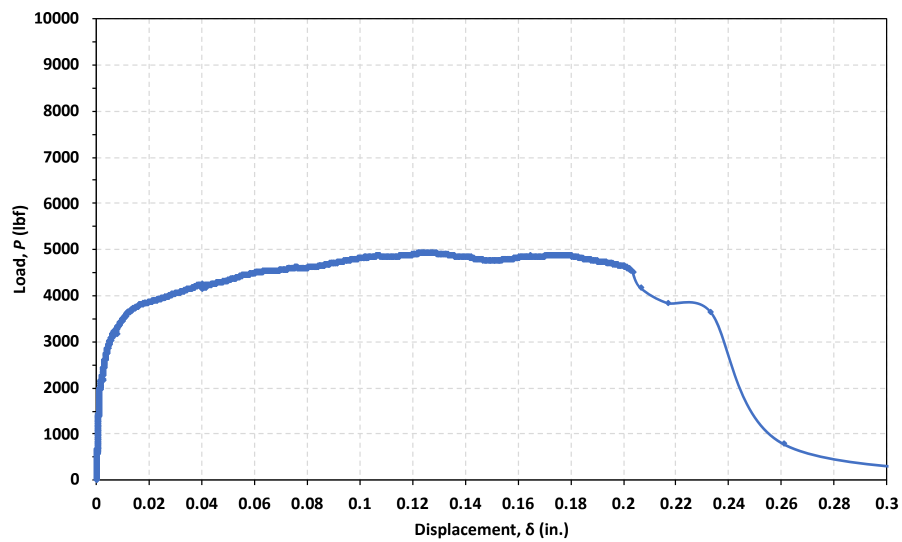
AL-SL-T-D2



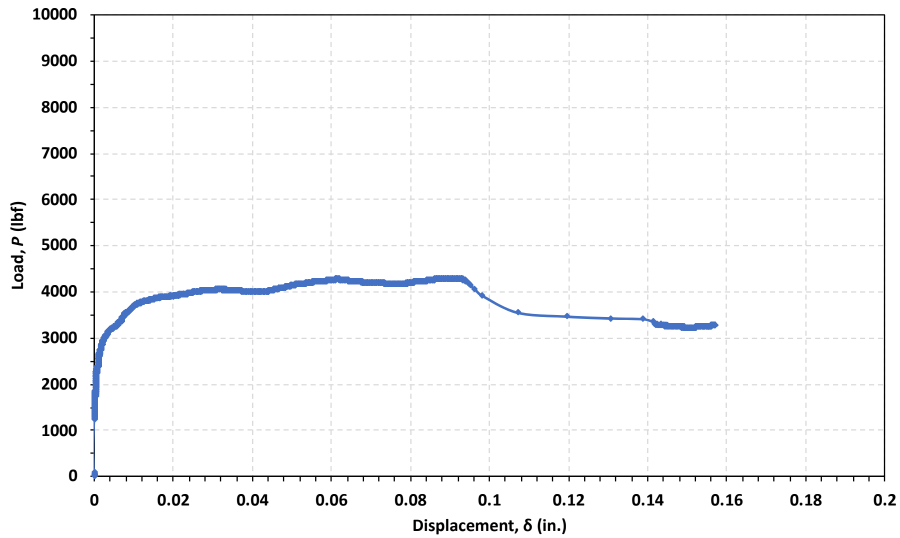
AL-SL-T-B2*



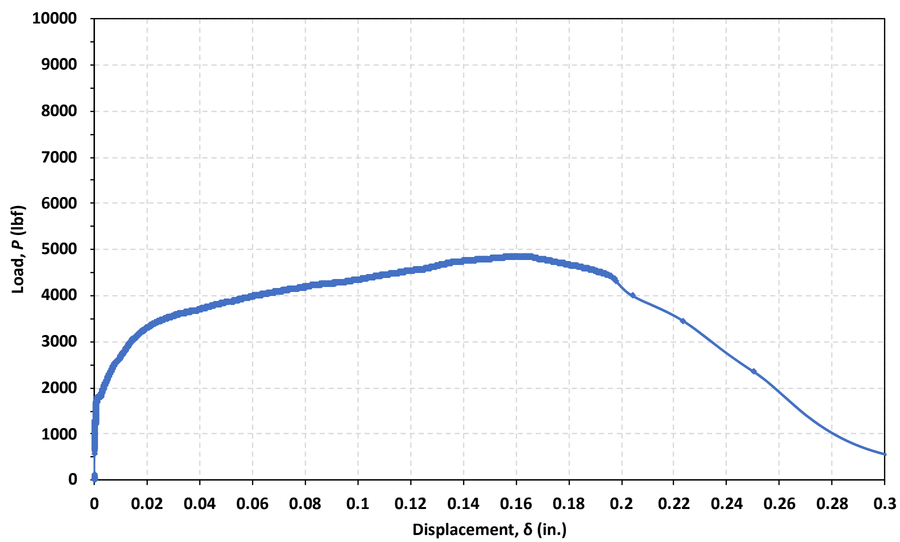
AL-SL-T-C2*



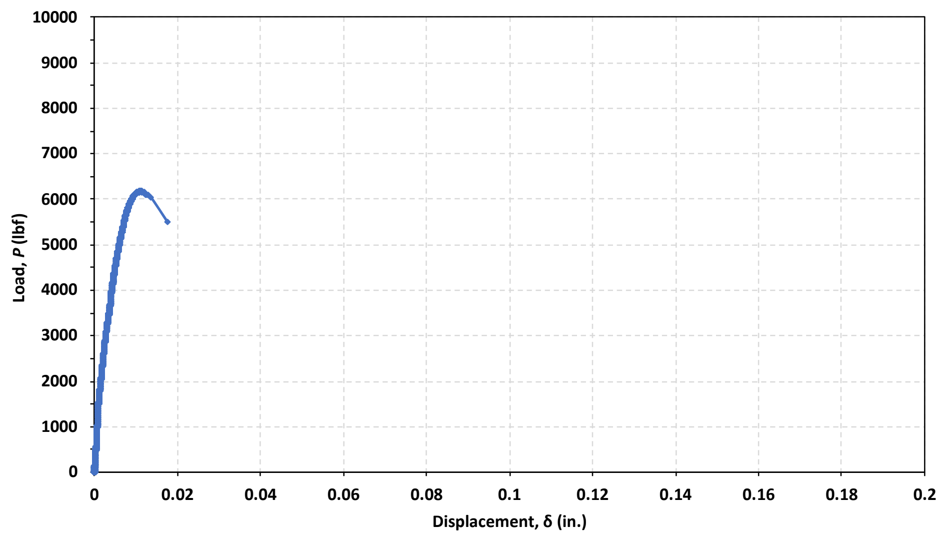
AL-SL-T-D3*



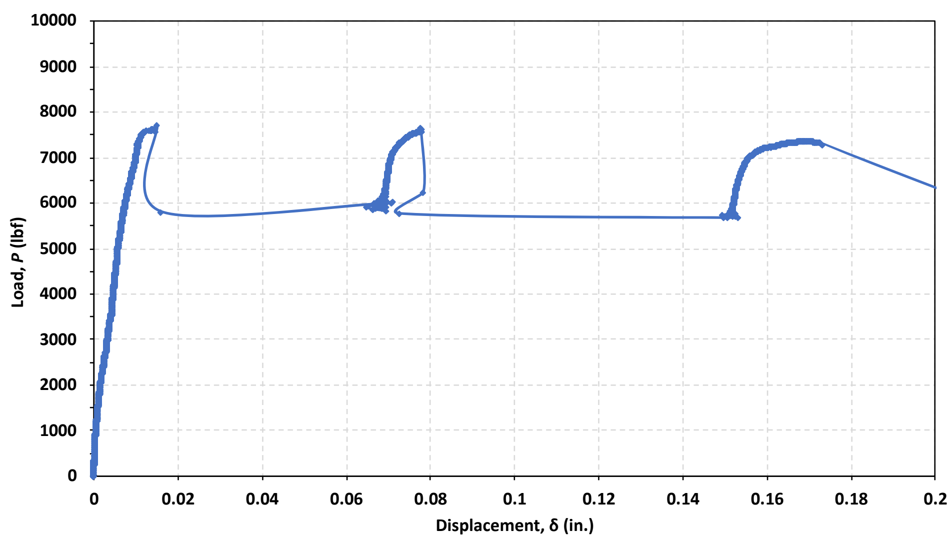
AL-SL-T-A2*



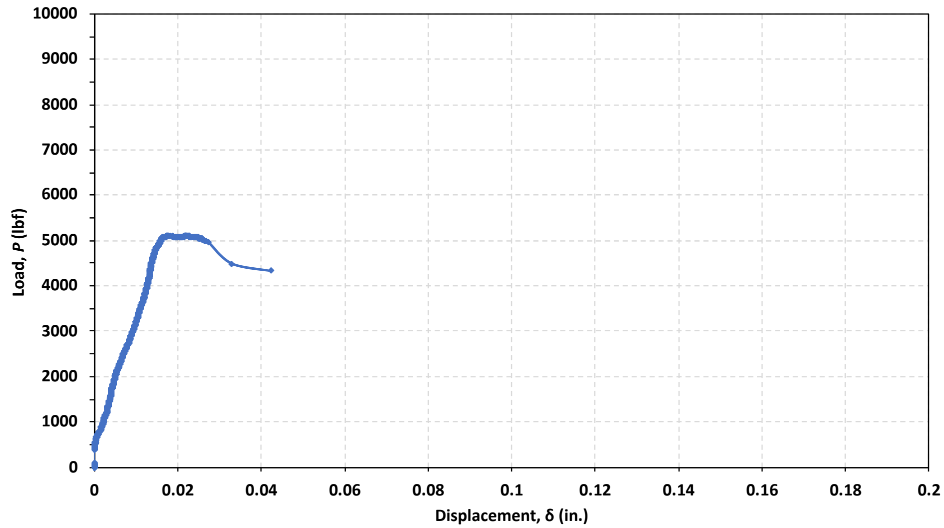
AL-SL-T-D4*



AL-SL-D-B1



AL-SL-D-C1



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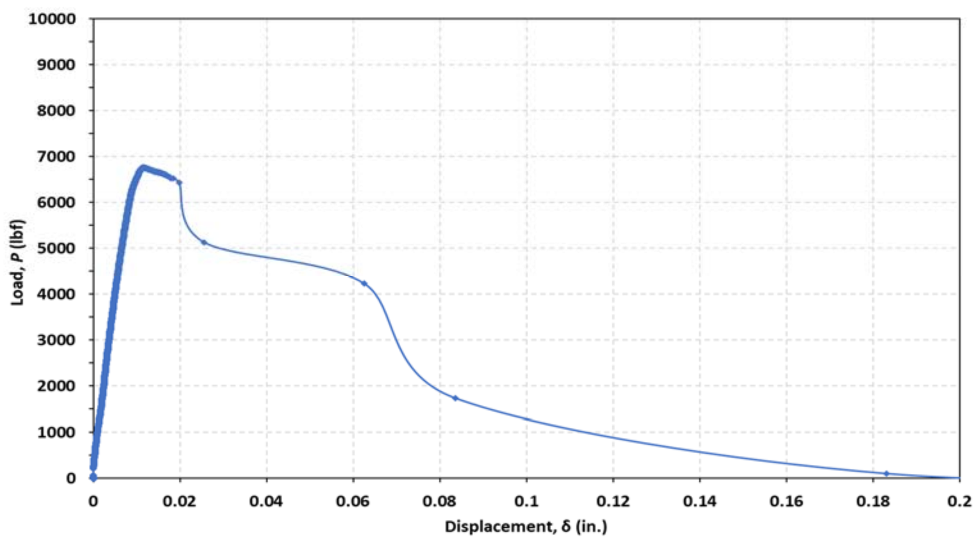
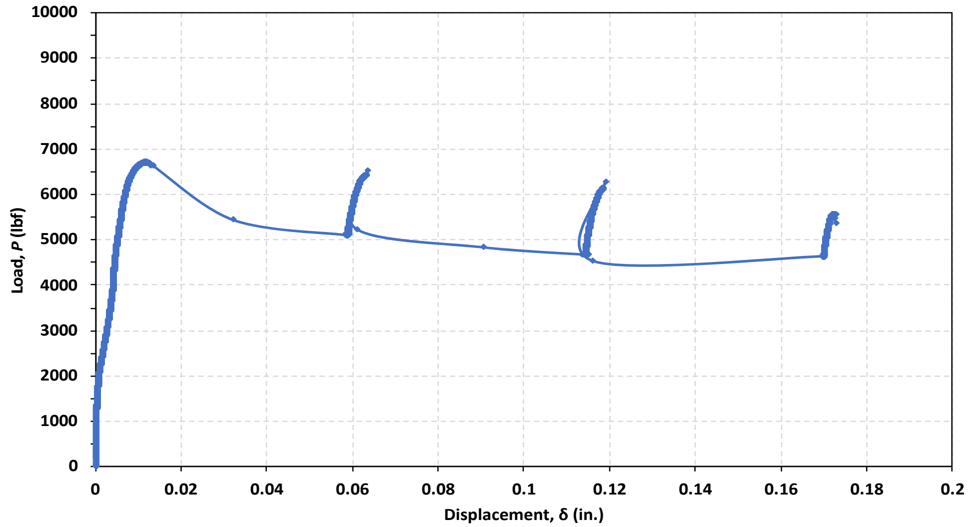
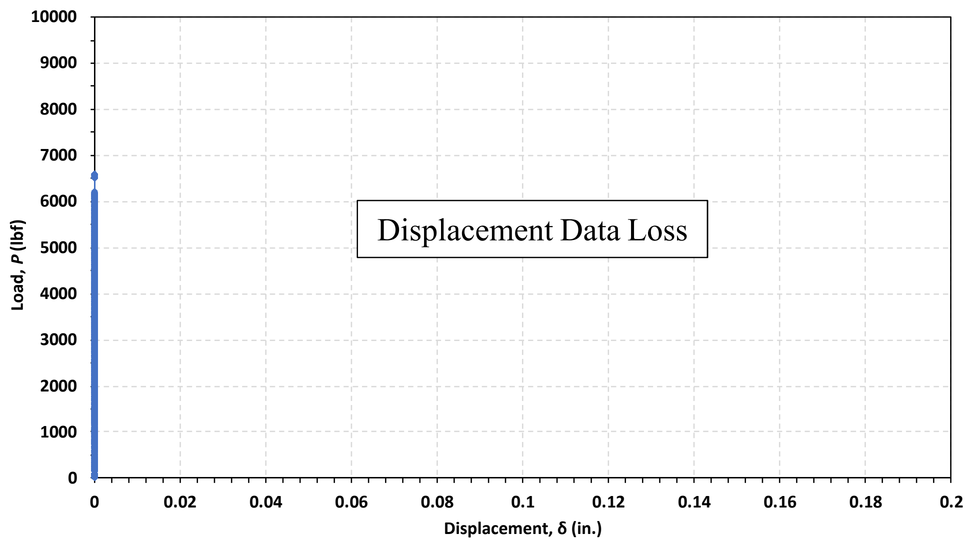


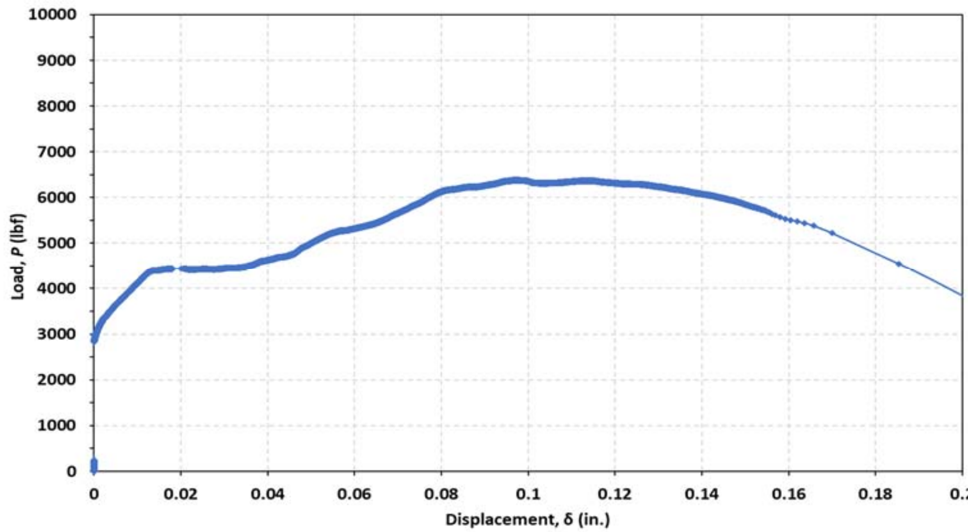
AL-SL-D-A1



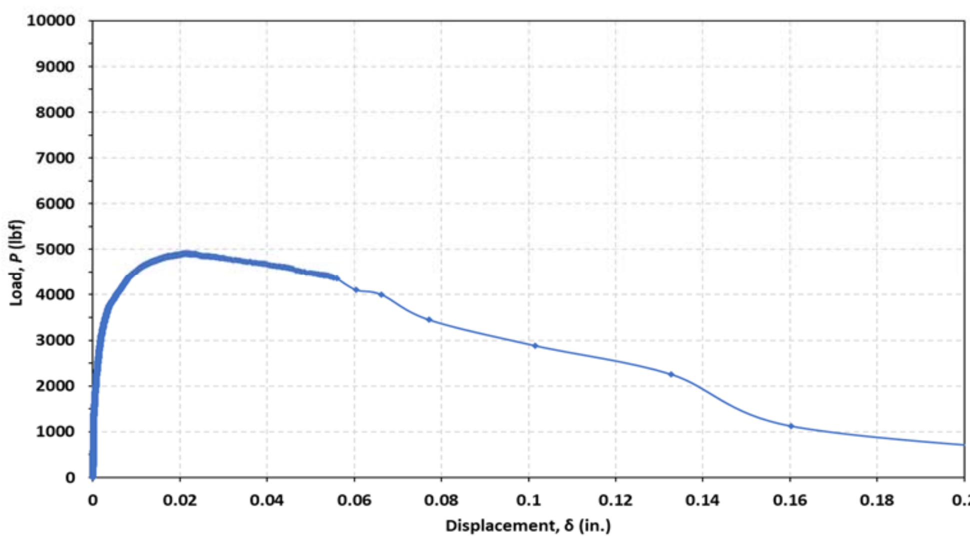
AL-SL-D-D2



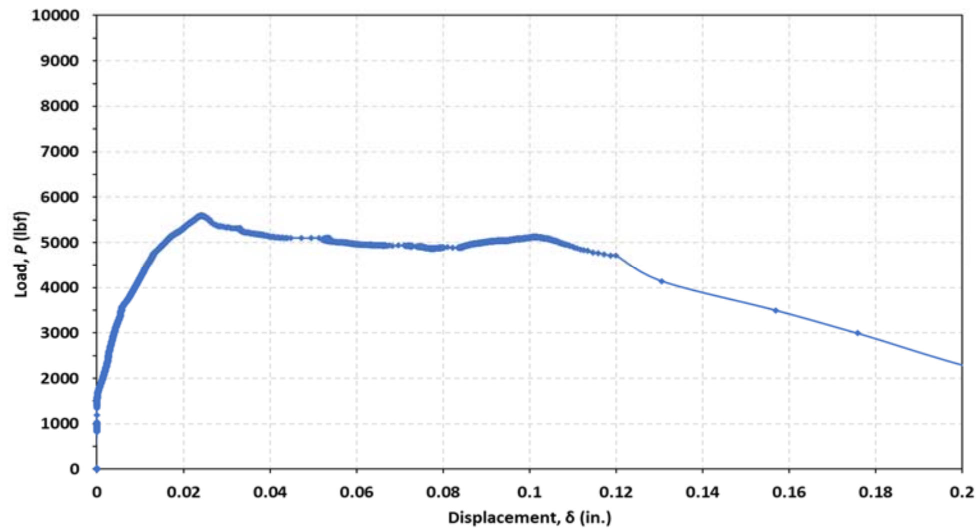
AL-SL-D-D3



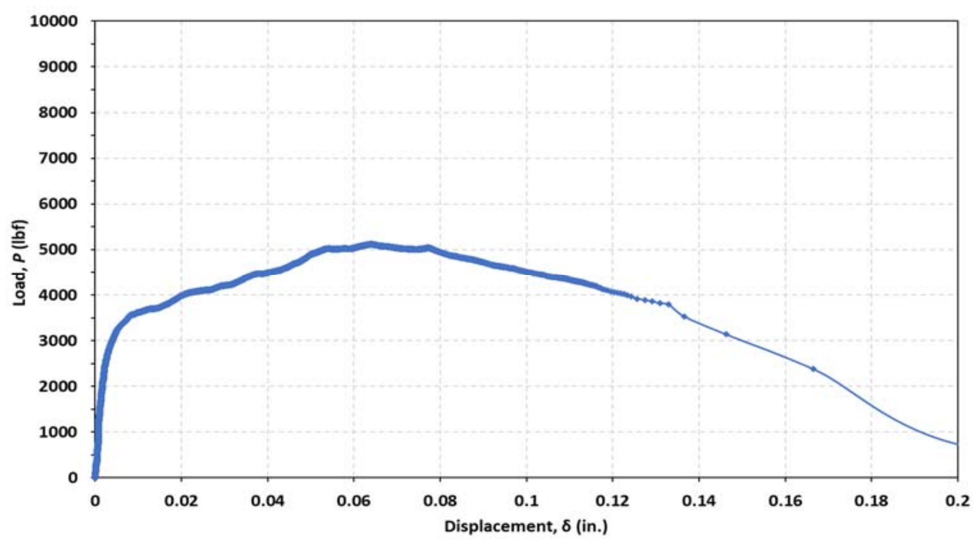
AL-SL-S-B1



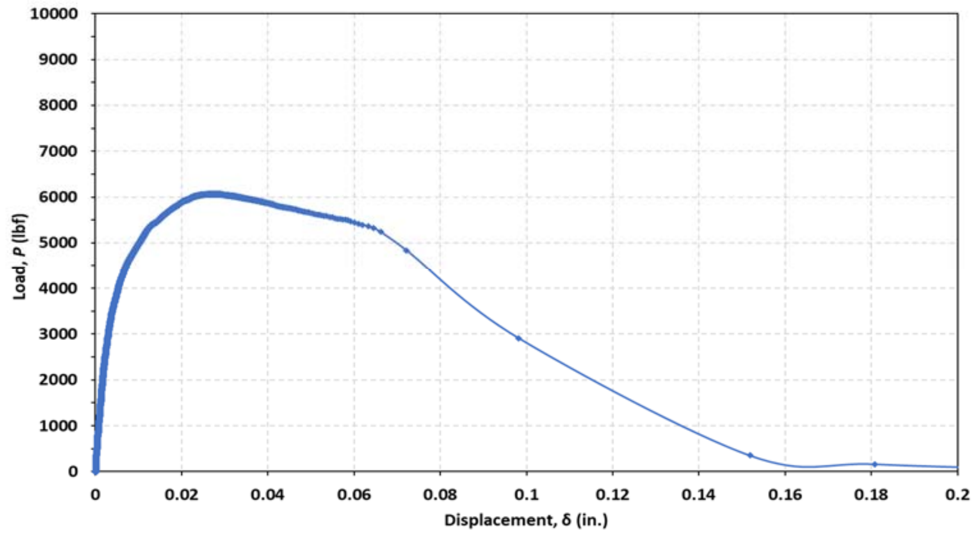
AL-SL-S-C1



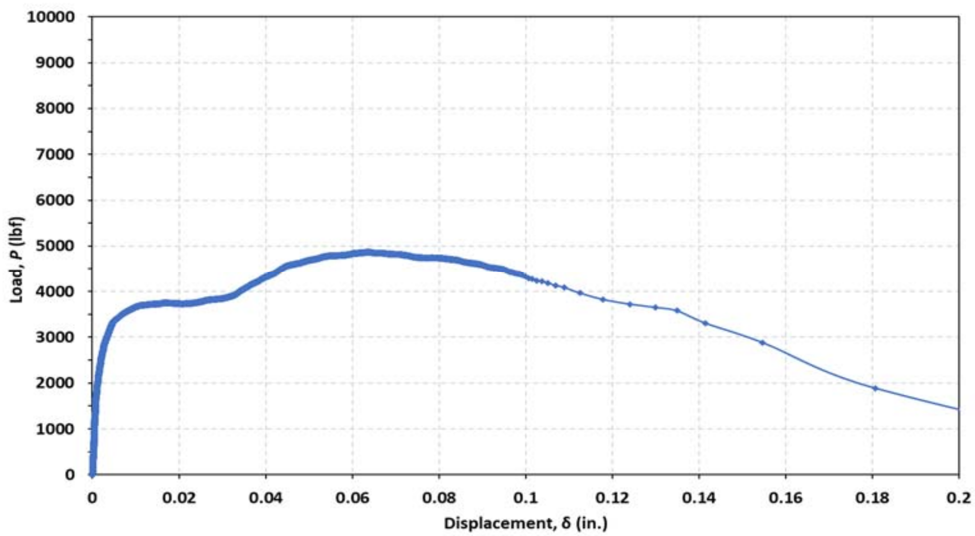
AL-SL-S-D1



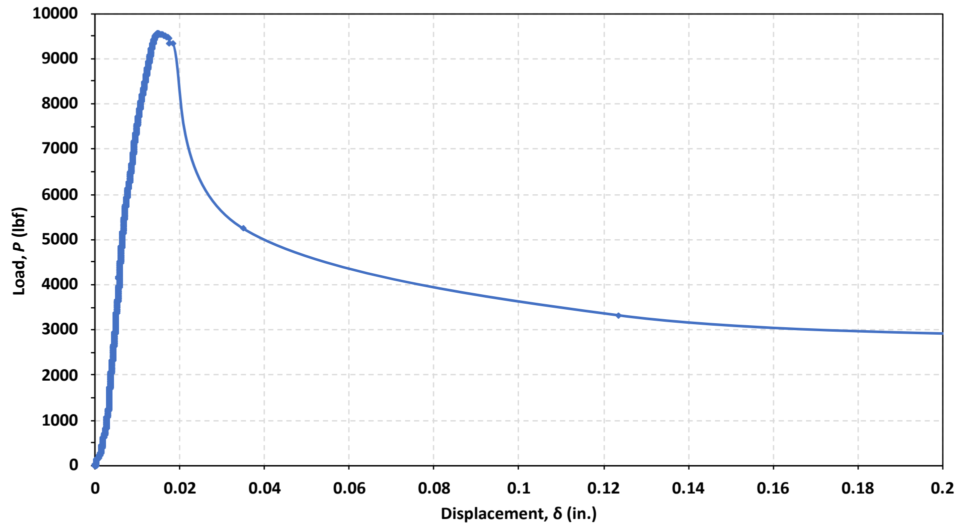
AL-SL-S-A1



AL-SL-S-D2



AL-SL-S-A2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4000
3000
2000
1000
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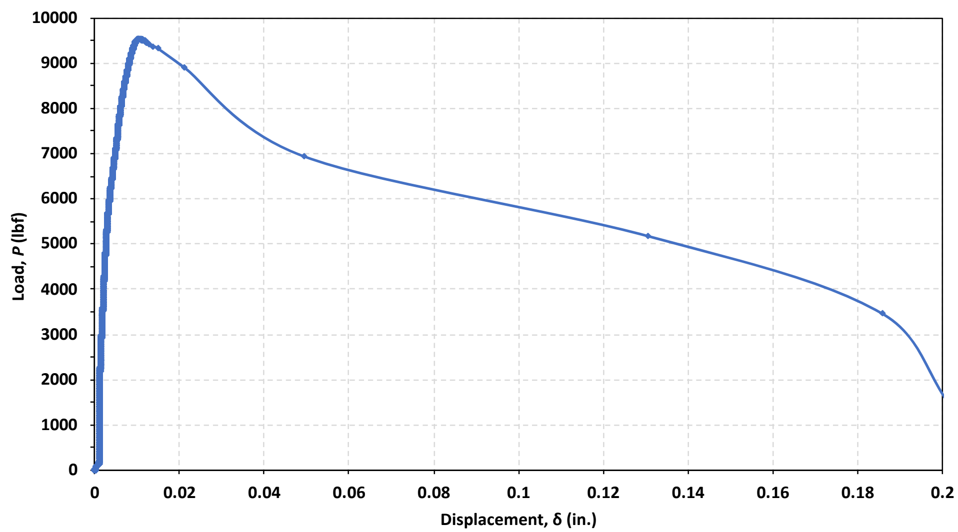
Load, P (lbf)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-C-1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1000
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Load, P (lbf)
0
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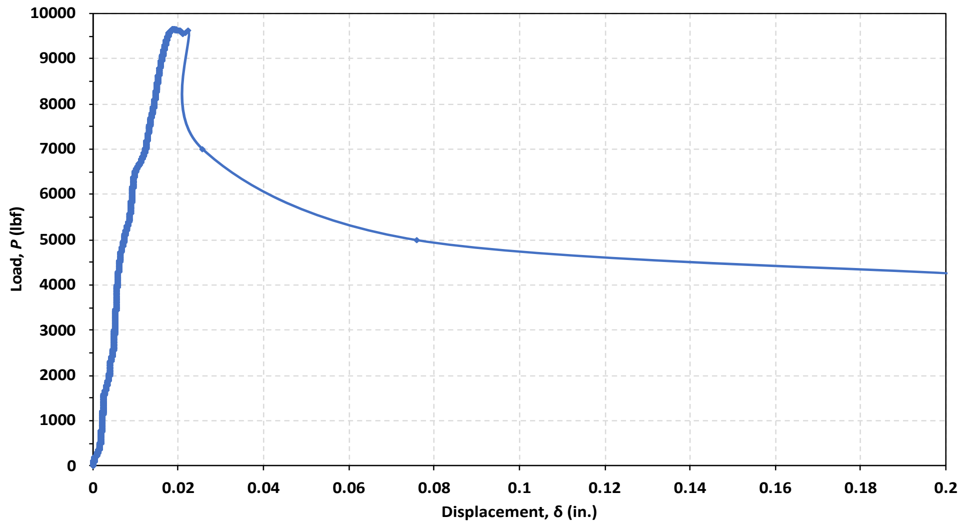
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-C-2


Load, P (lbf)
Displacement, δ (in.)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
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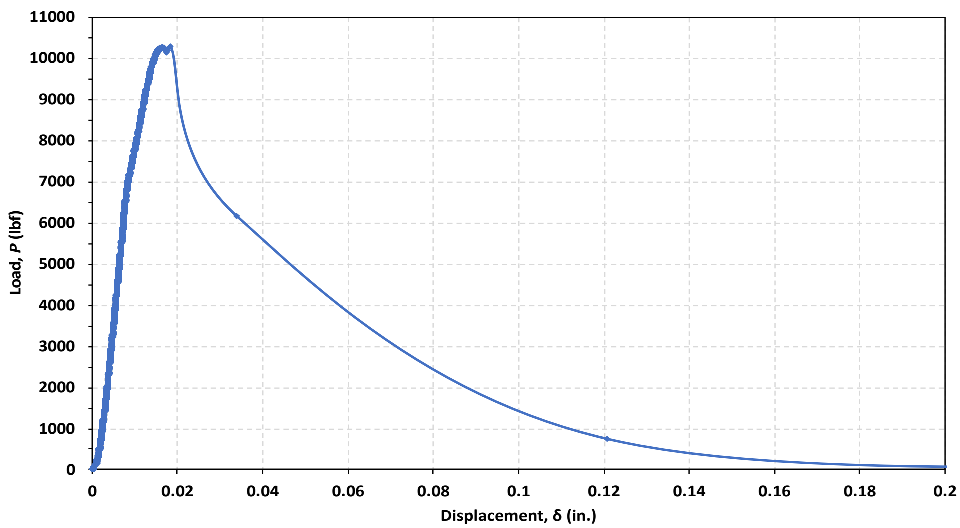
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

NW-C-3


Load, P (lbf)
Displacement, δ (in.)
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2000
3000
4000
5000
6000
7000
8000
9000
10000
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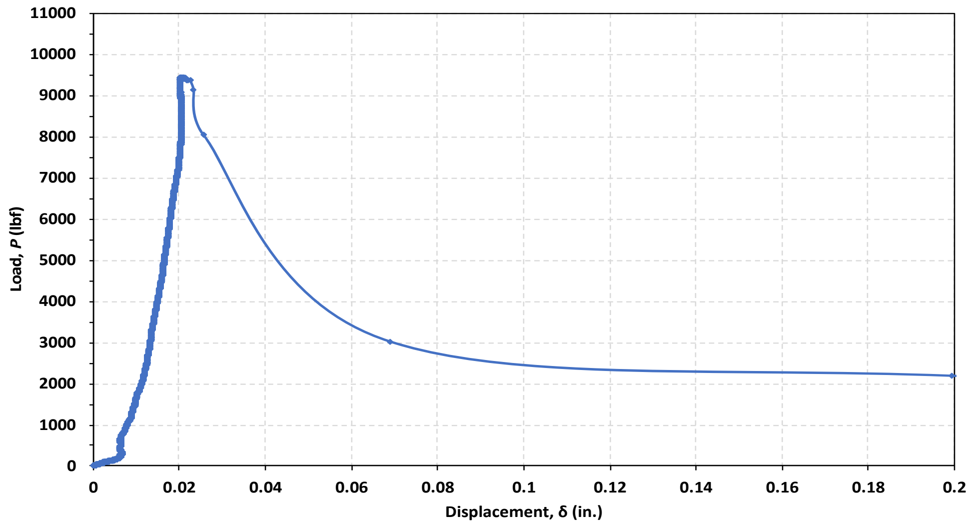
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

NW-C-4


Load, P (lbf)
Displacement, δ (in.)
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3000
4000
5000
6000
7000
8000
9000
10000
11000
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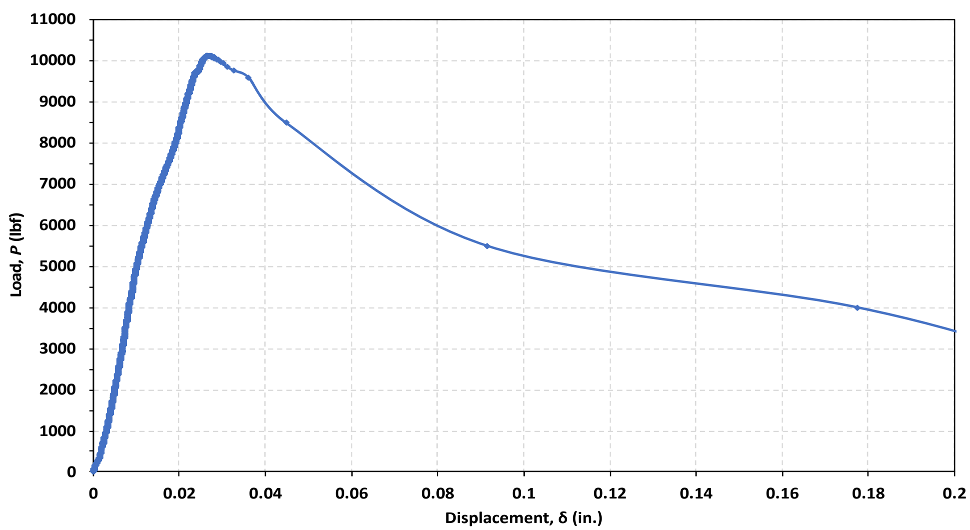
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

NW-C-5


Load, P (lbf)
Displacement, δ (in.)
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1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
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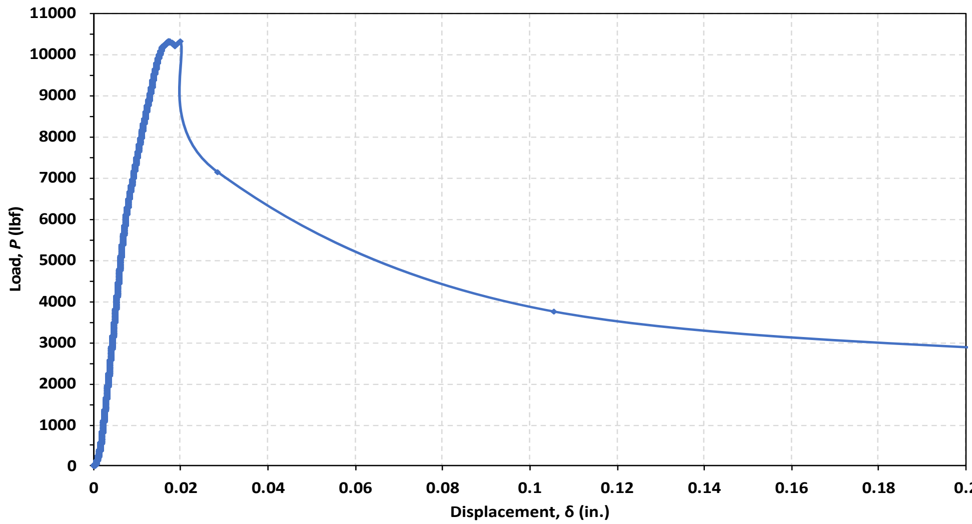
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

NW-C-6


Load, P (lbf)
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4000
3000
2000
1000
0
0
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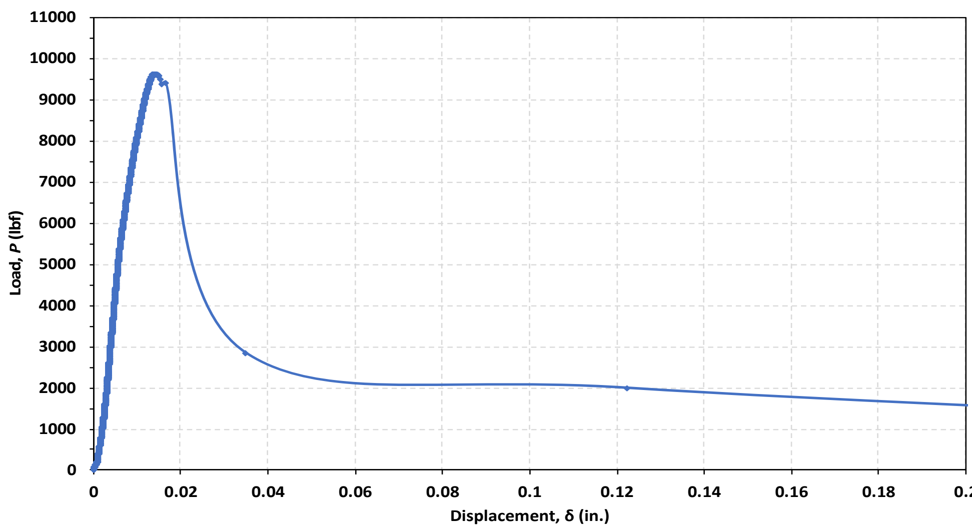
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

NW-C-7


Load, P (lbf)
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10000
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5000
4000
3000
2000
1000
0
0
0.02
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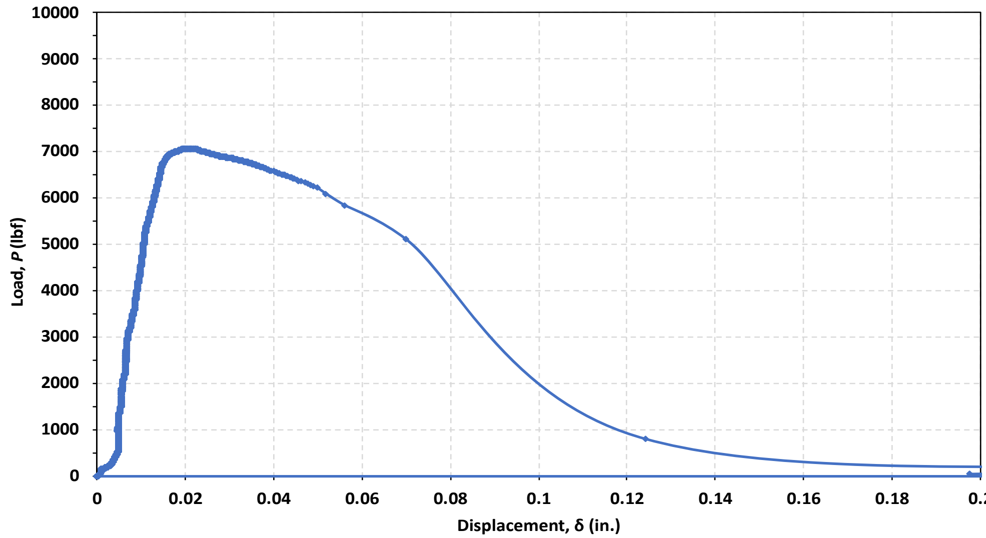
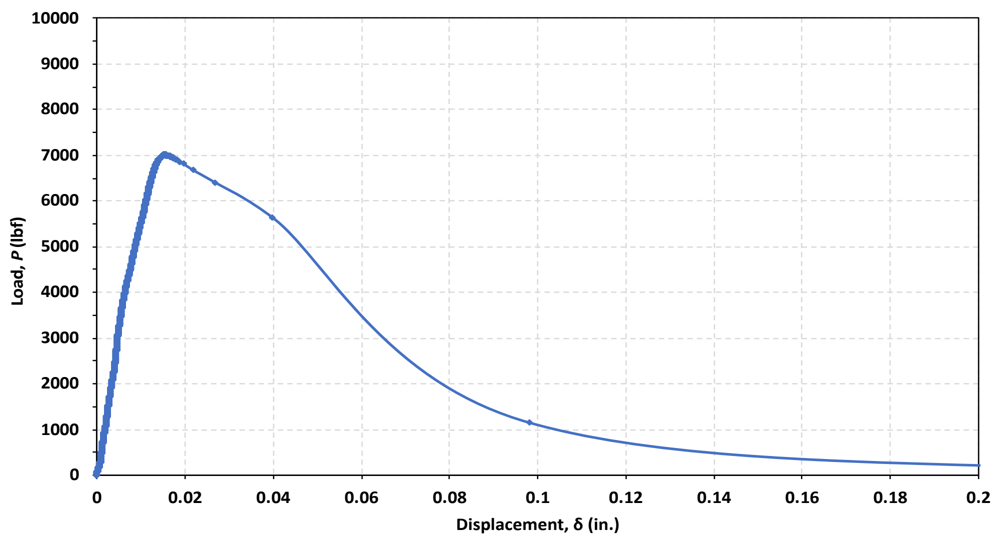
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

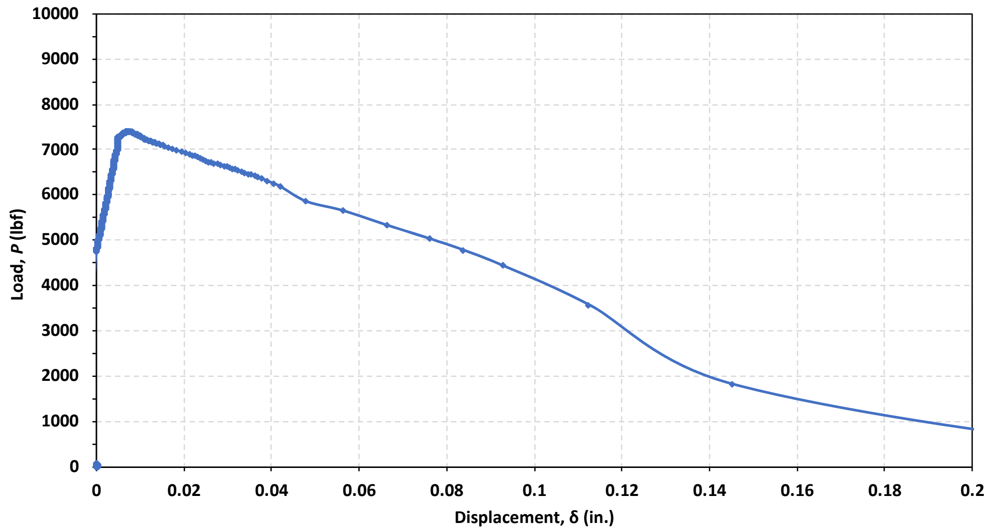
NW-C-8



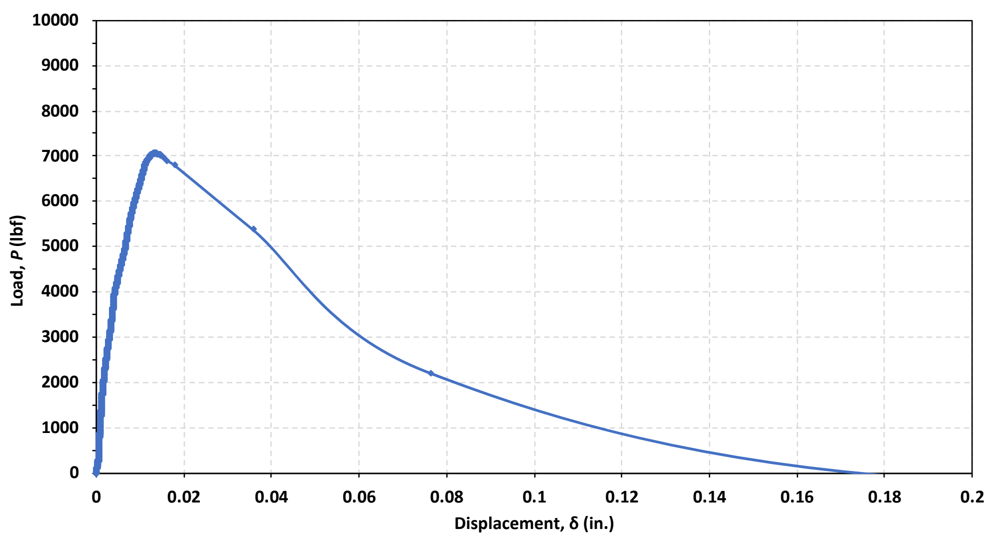
SL-SH-C-1



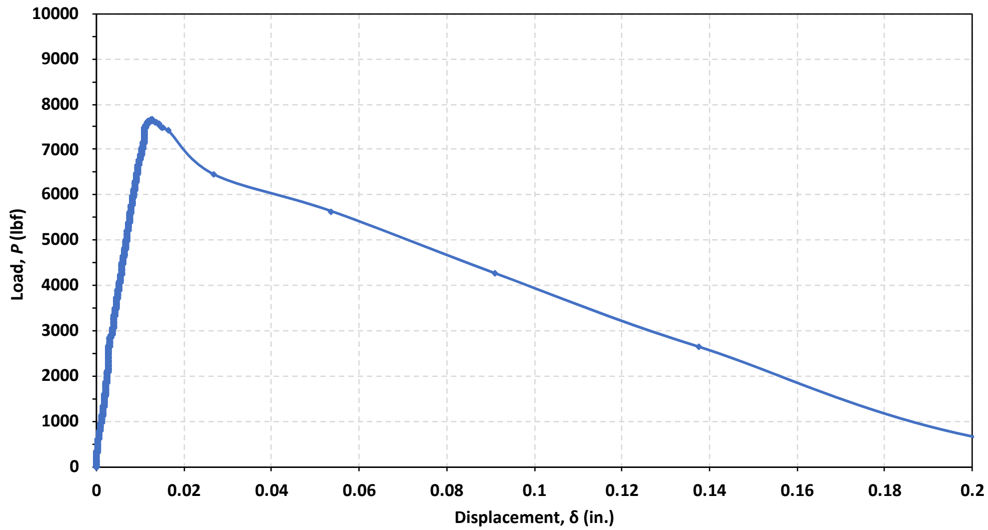
SL-SH-C-2



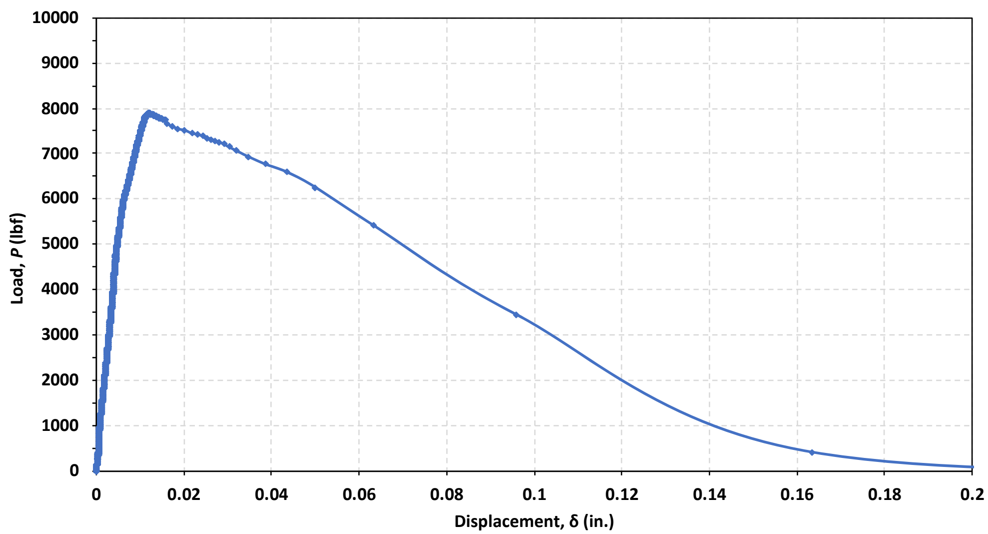
SL-SH-C-3



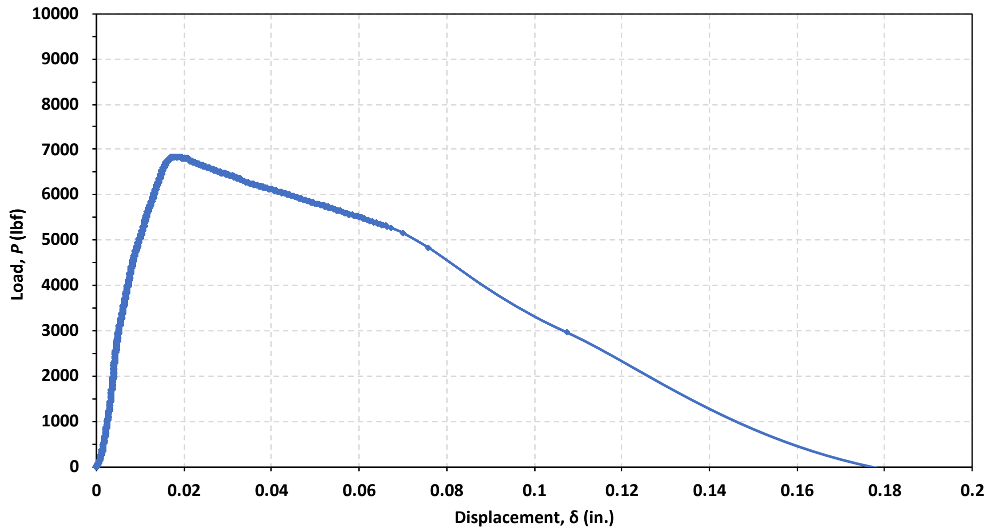
SL-SH-C-4



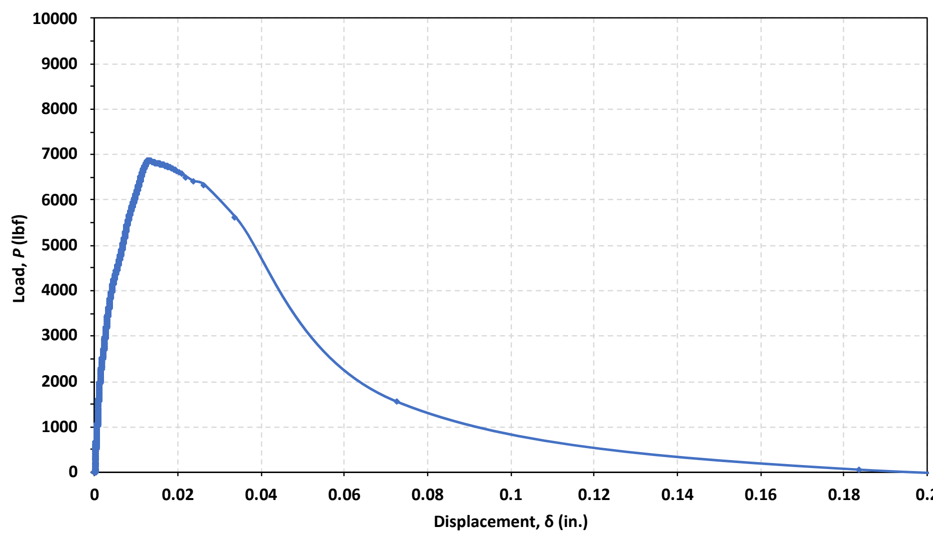
SL-SH-C-5



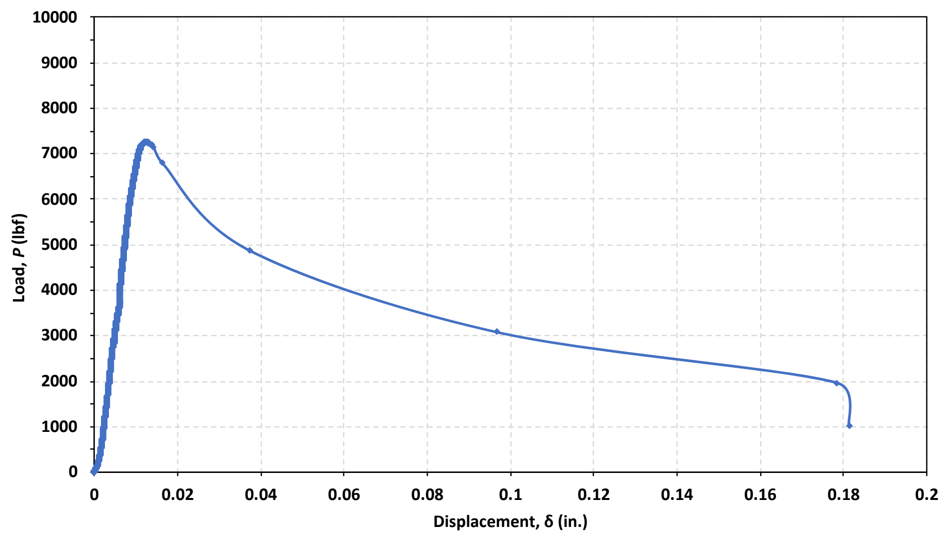
SL-SH-C-6



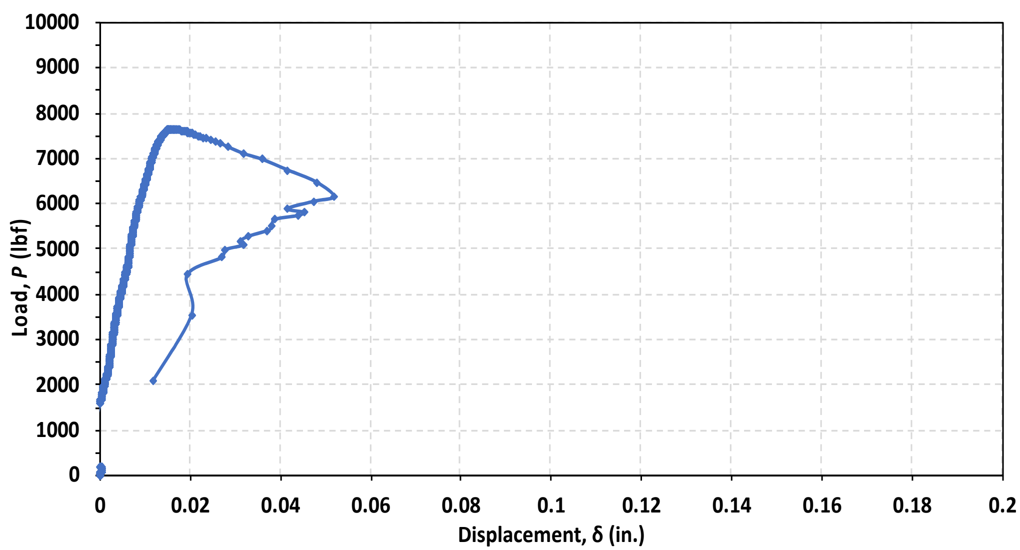
SL-SH-C-7



SL-SH-C-8



SL-CL-C-1



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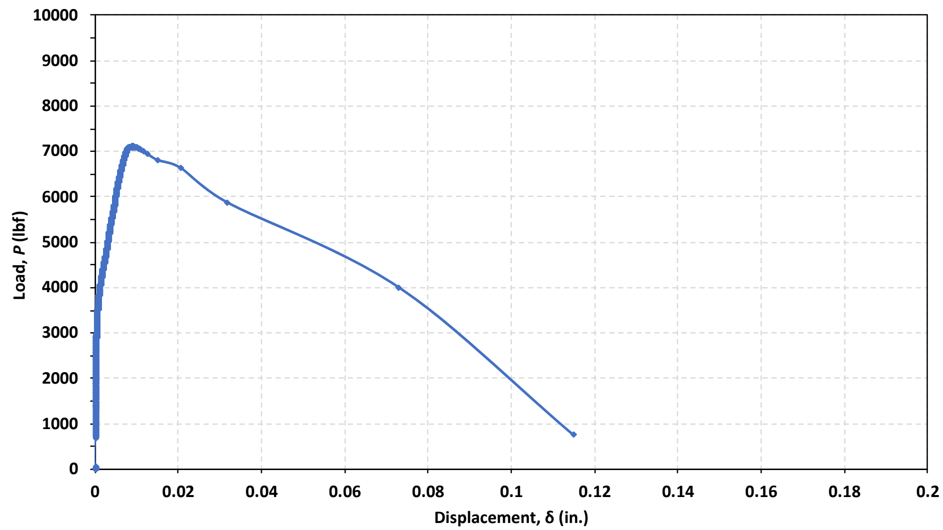

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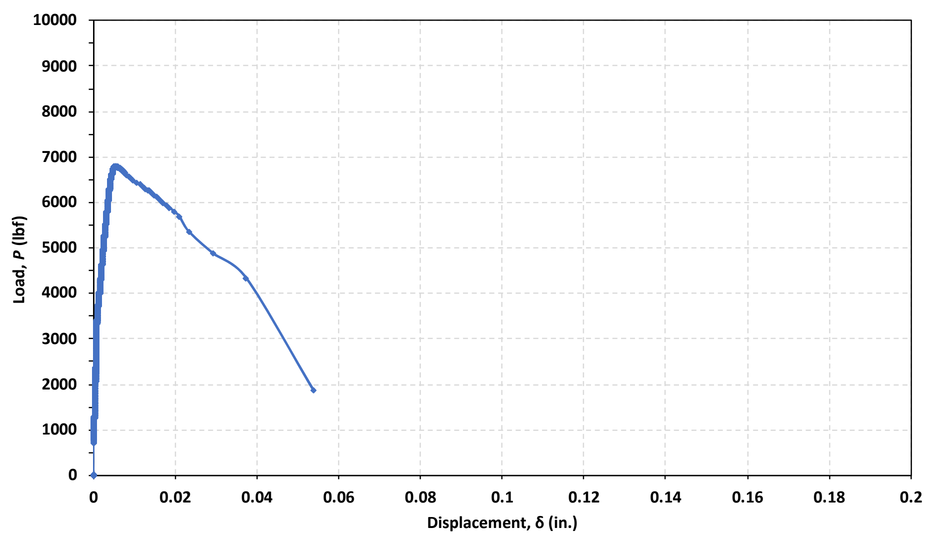

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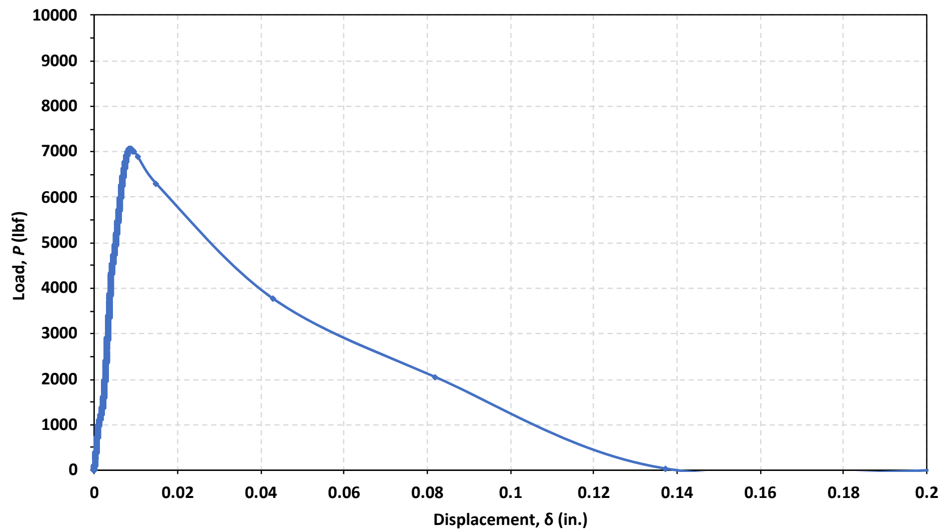

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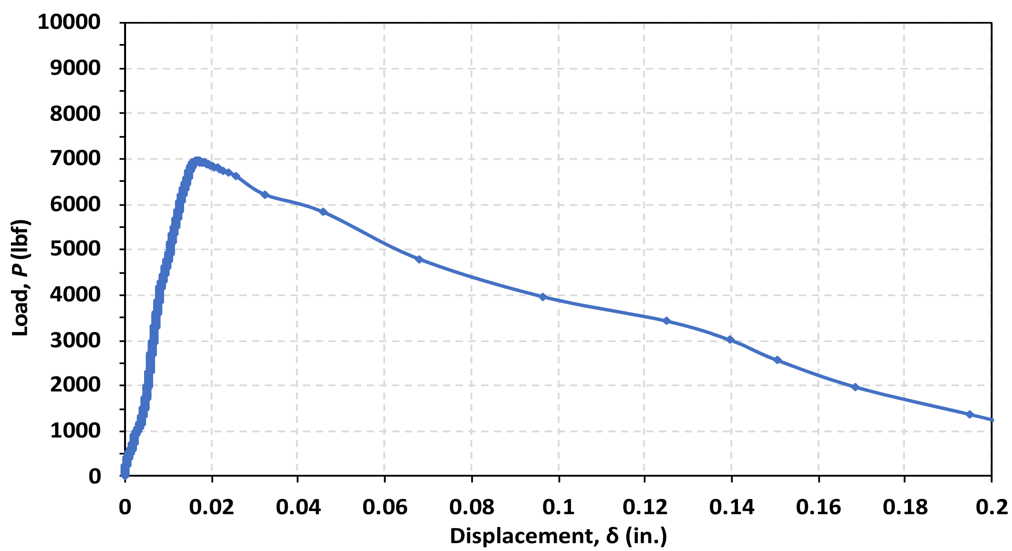

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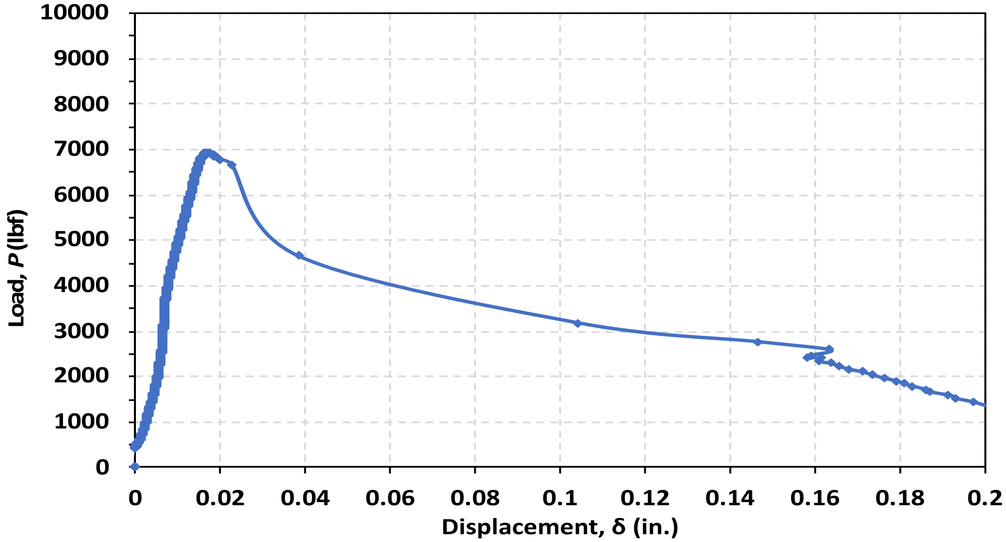

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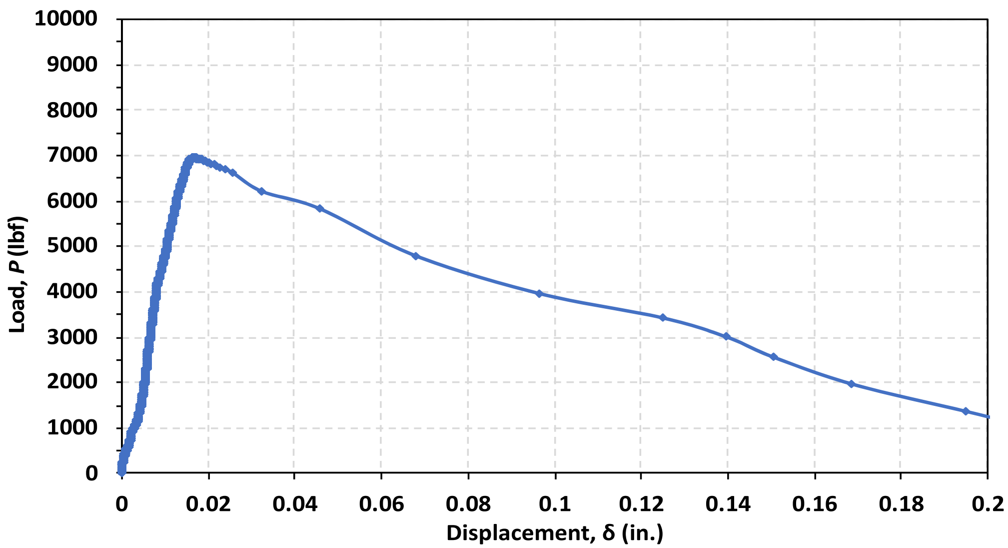

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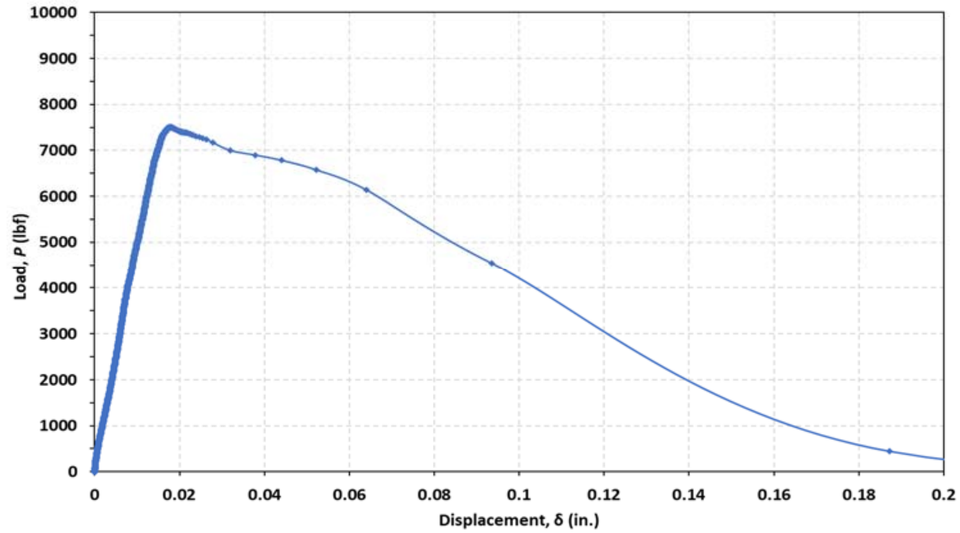

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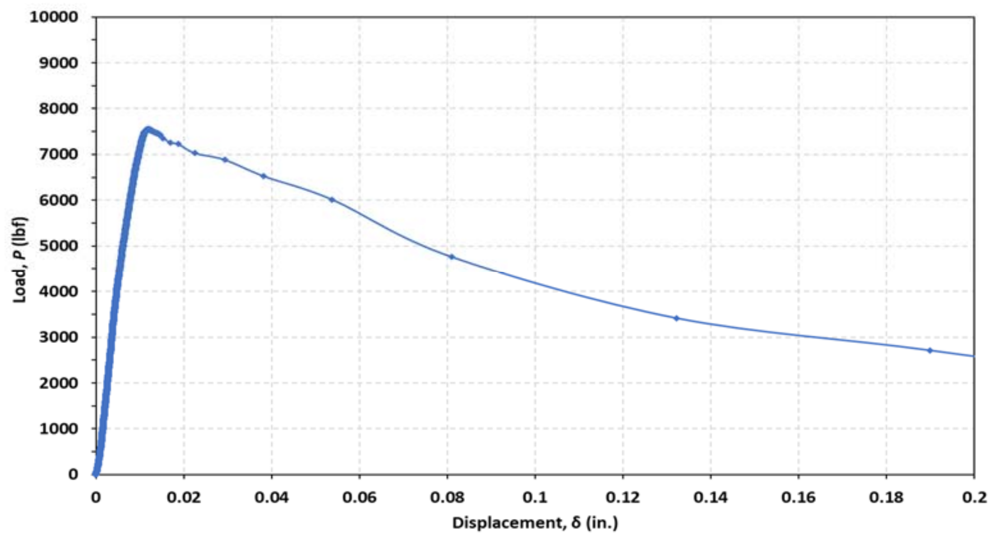

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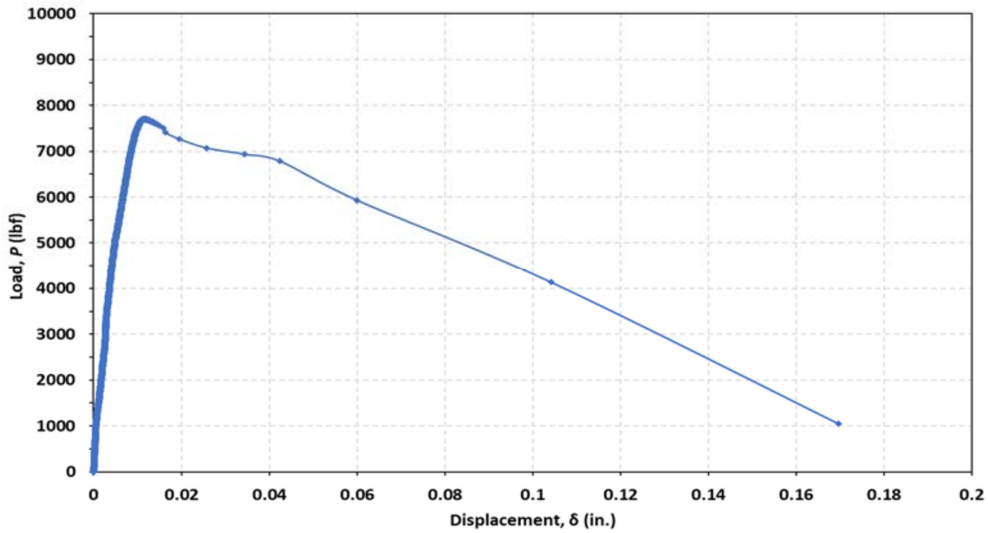

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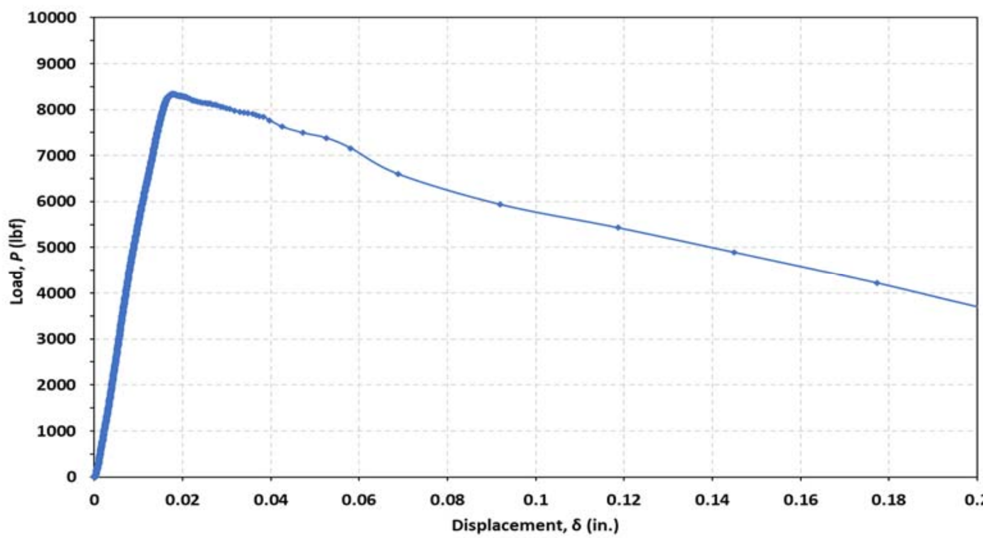

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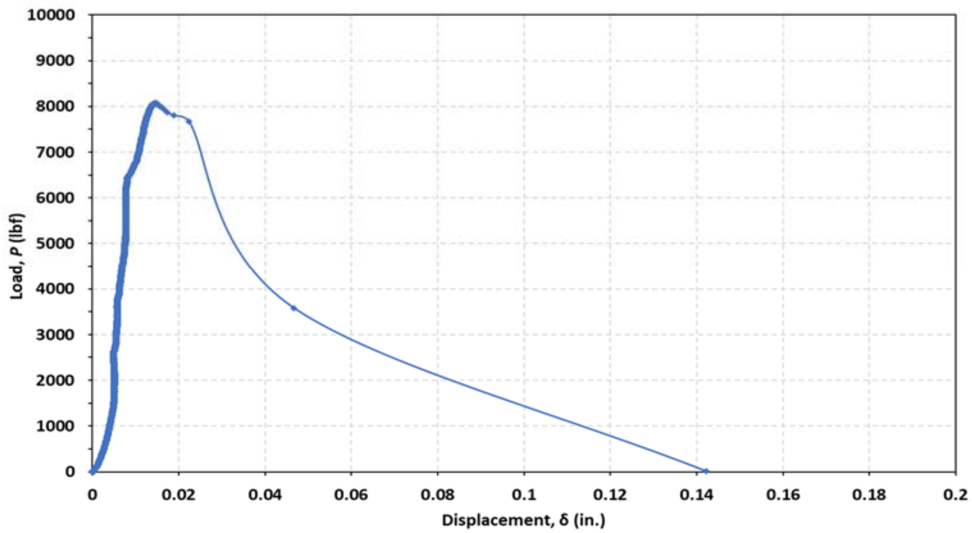

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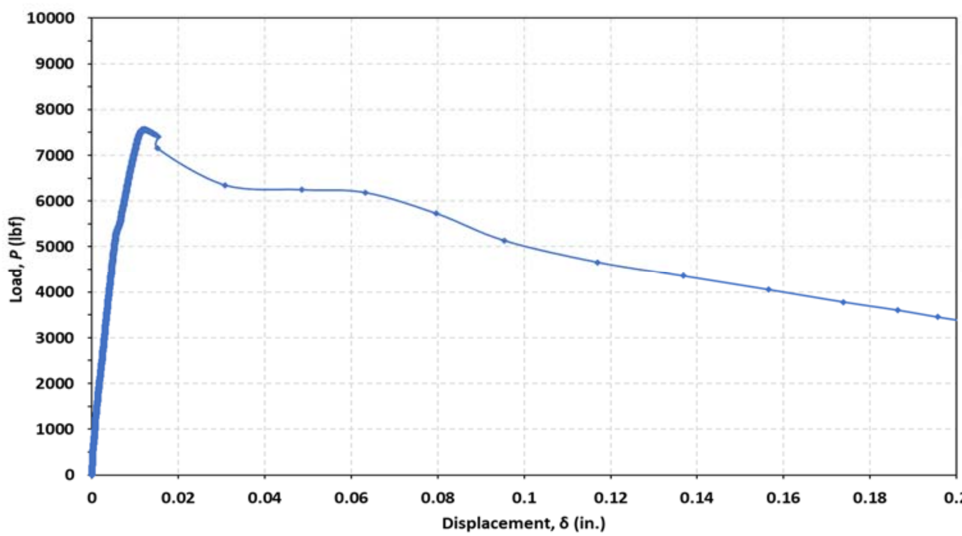

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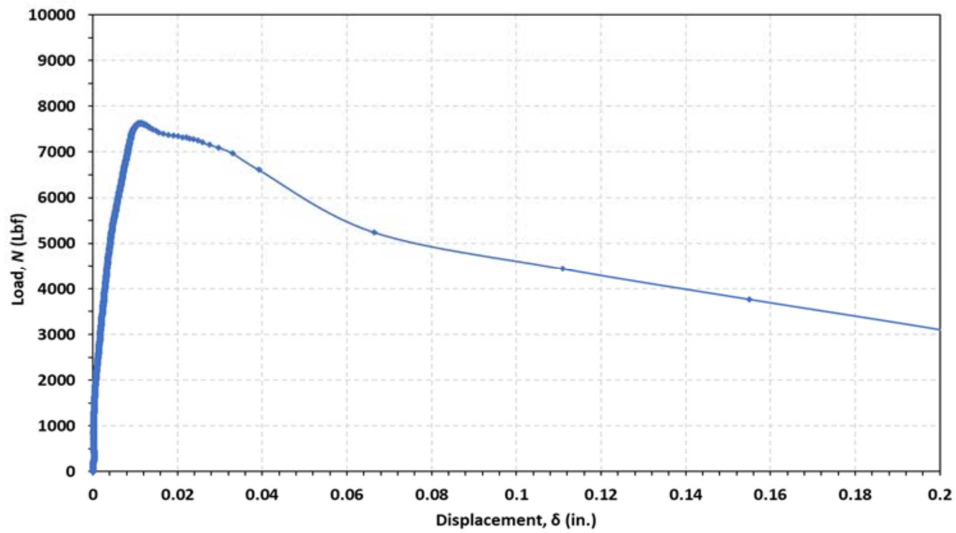
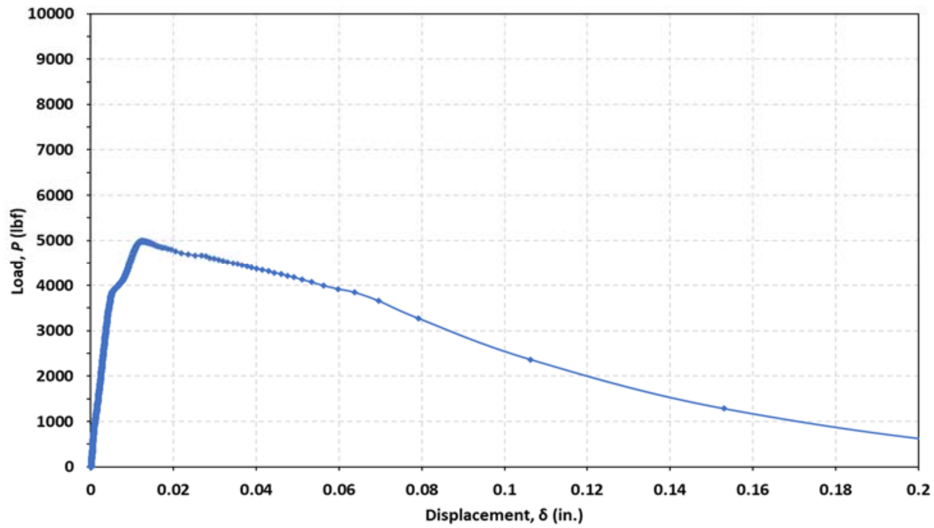
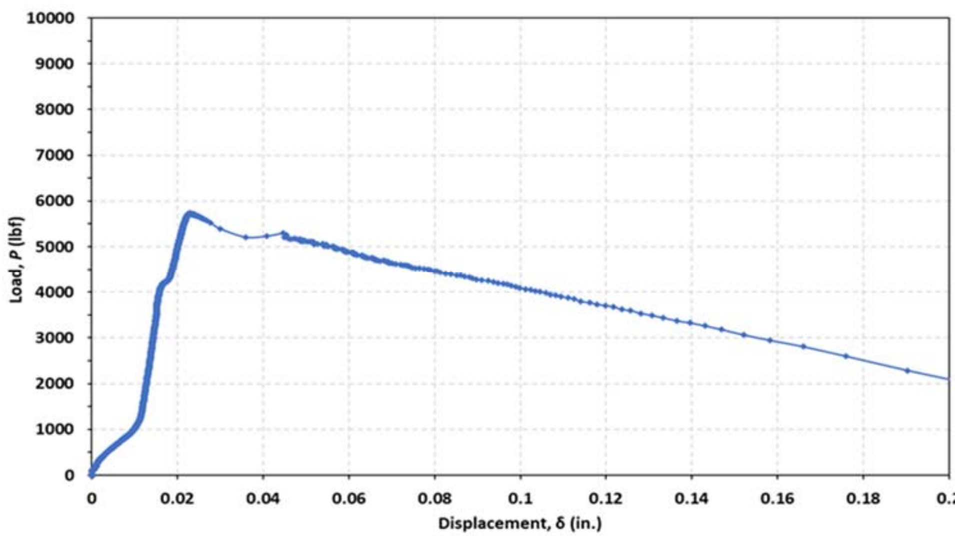


Load, N (Lbf)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

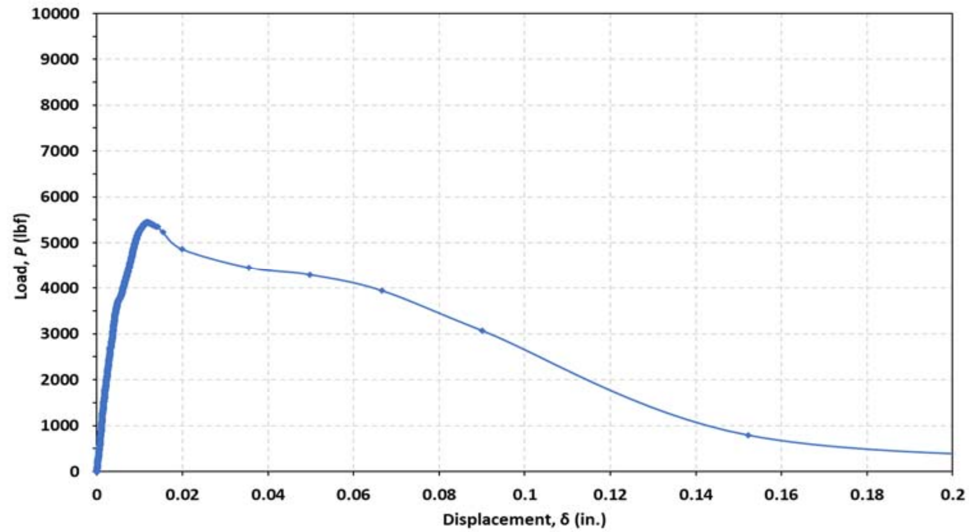
SL-SL-C-7



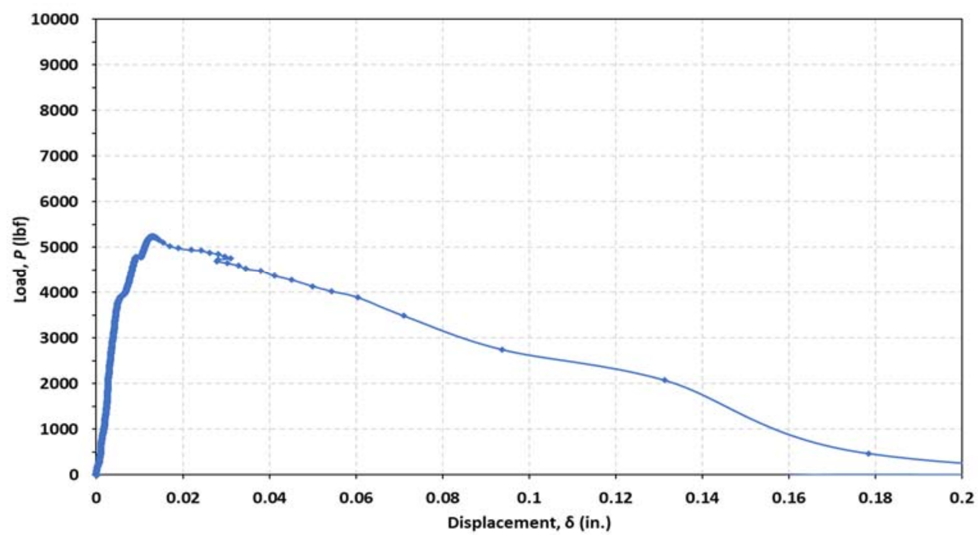
AL-SH-C-1



AL-SH-C-2



AL-SH-C-3



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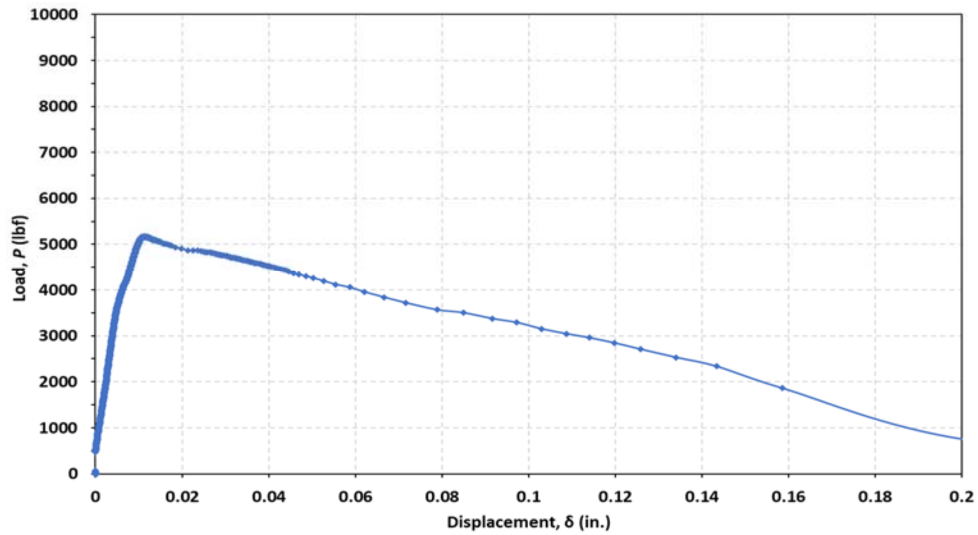

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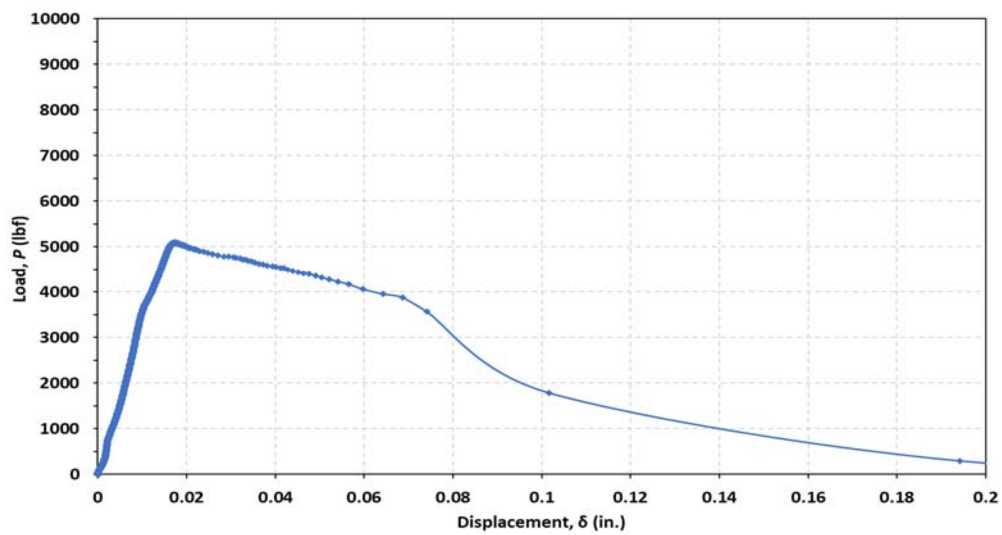
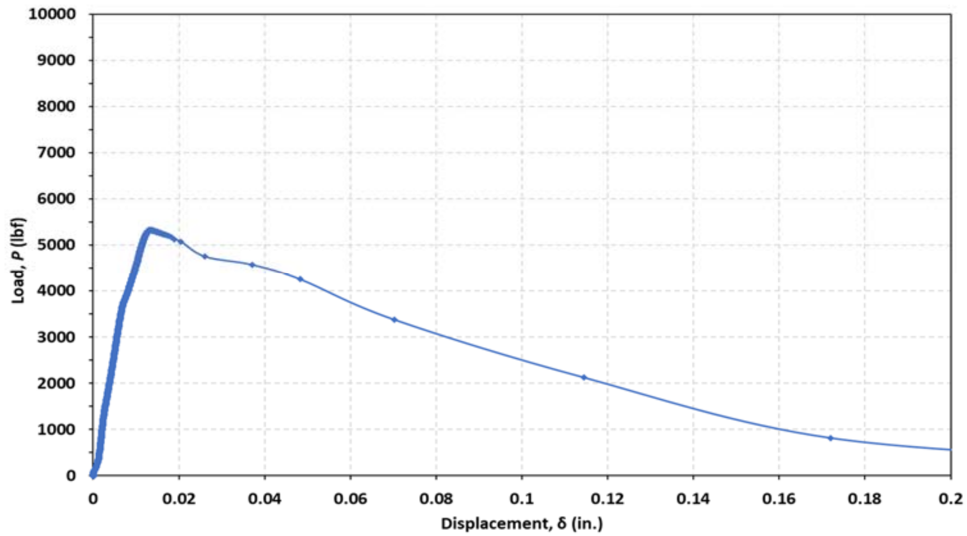
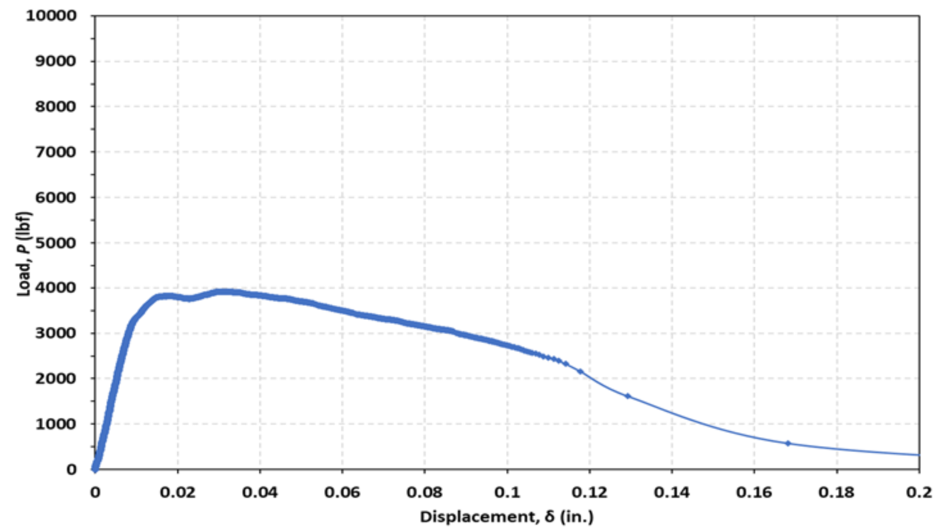


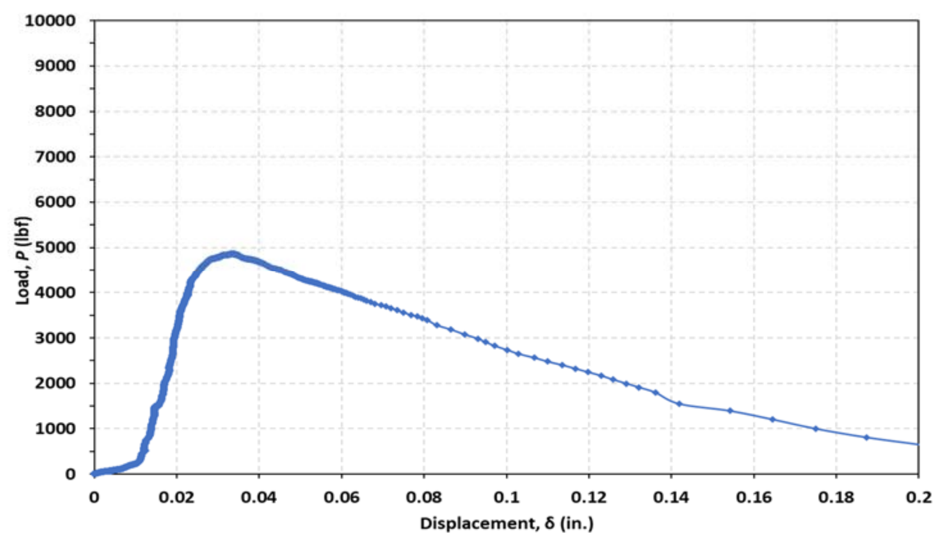
AL-SH-C-6


Load, P (lbf)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

AL-SH-C-7



AL-CL-C-1



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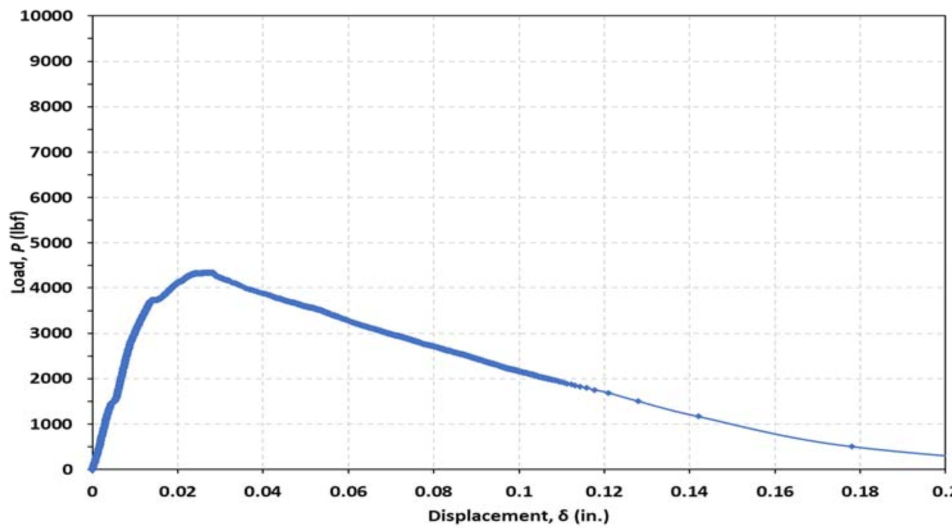

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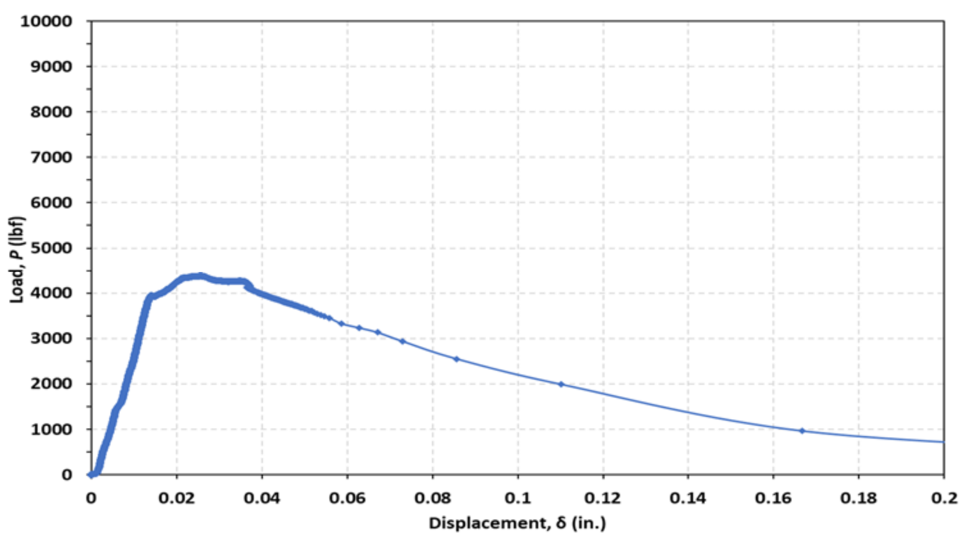

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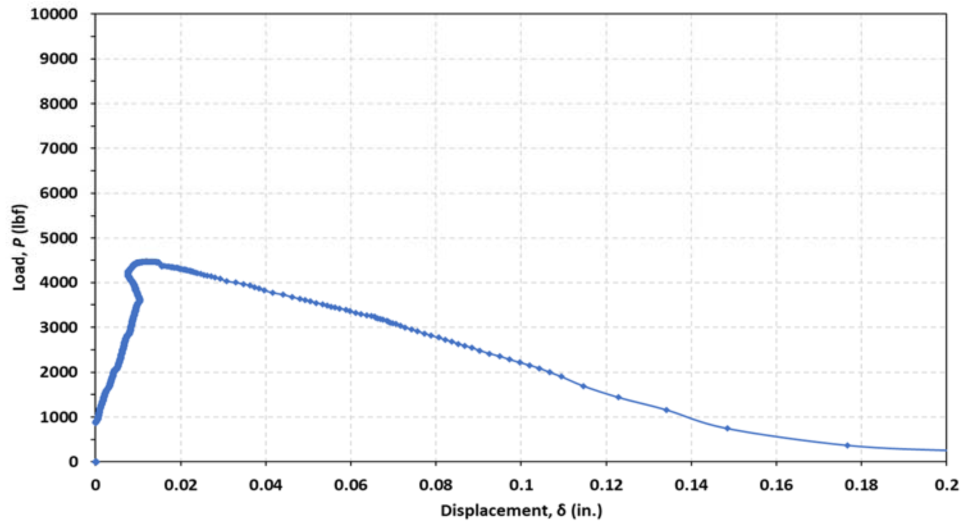

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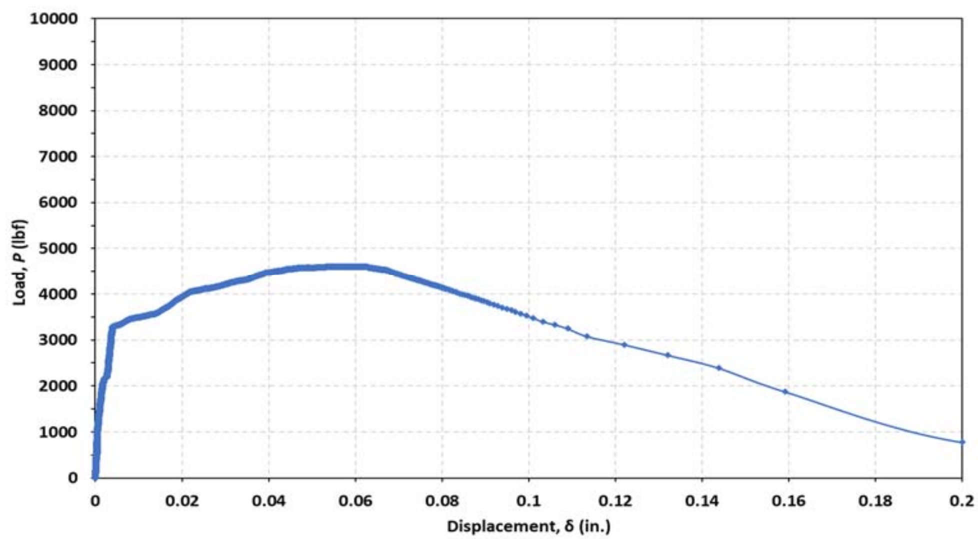

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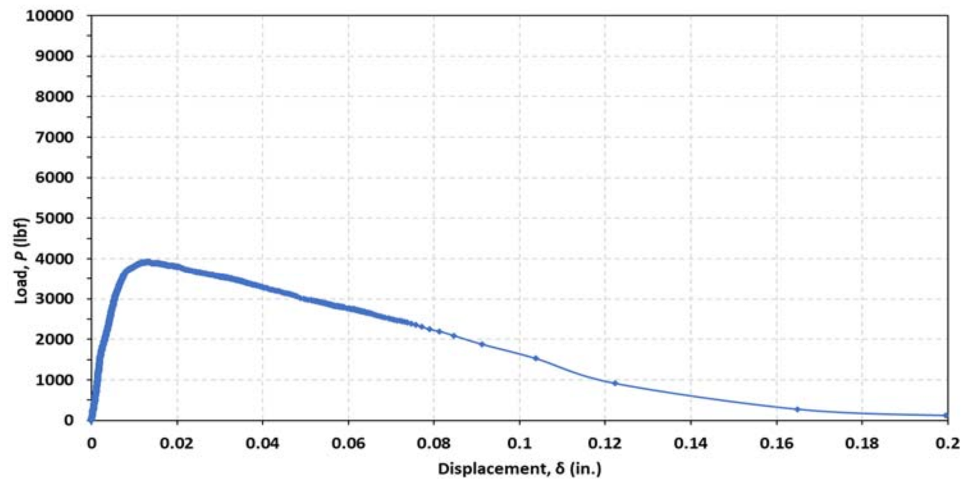

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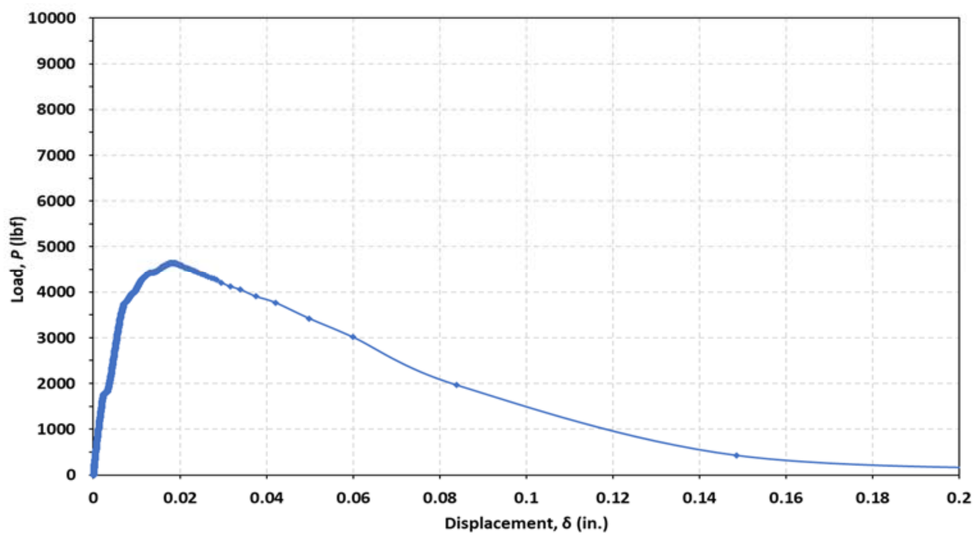
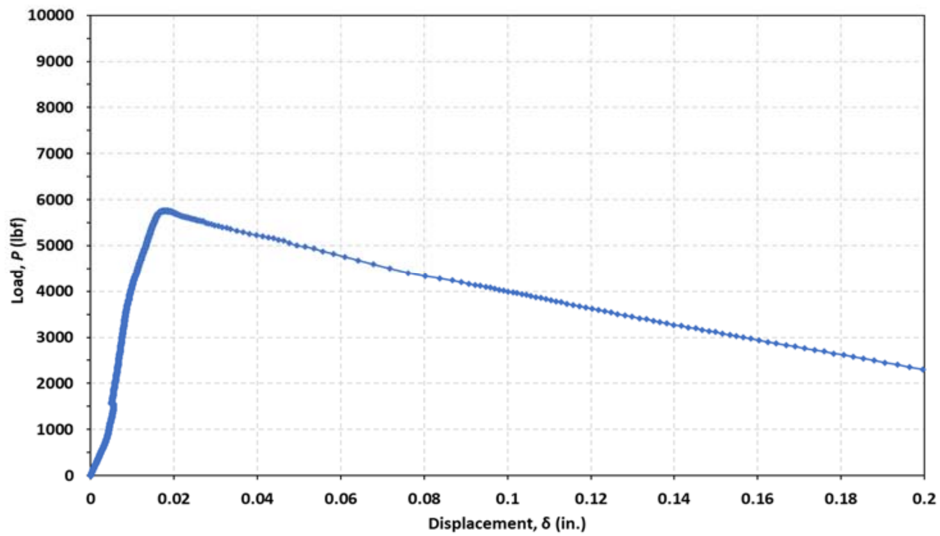
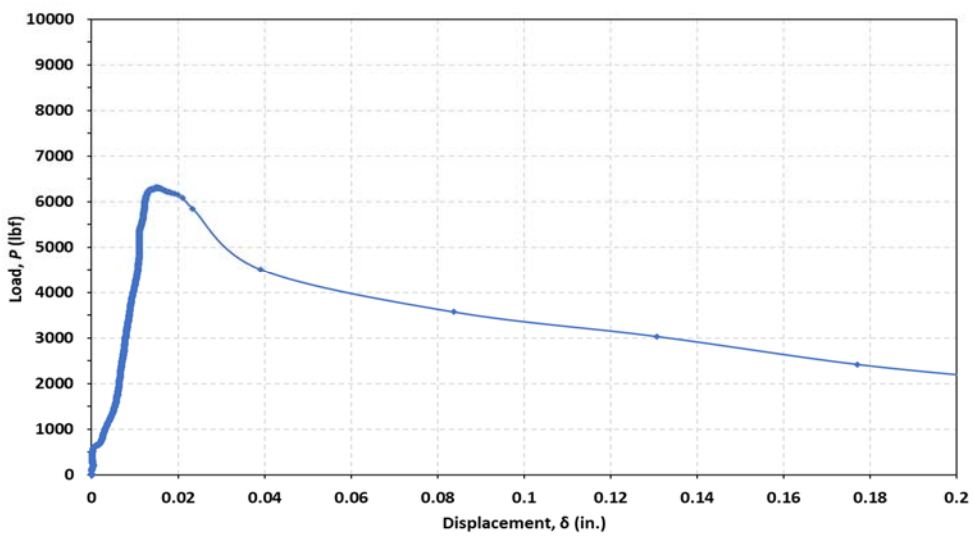


AL-CL-C-8



AL-SL-C-1



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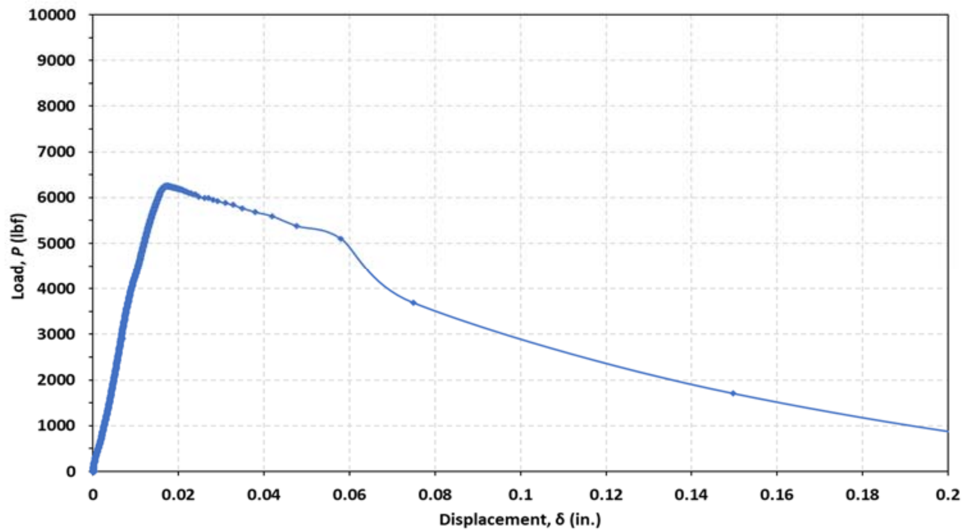

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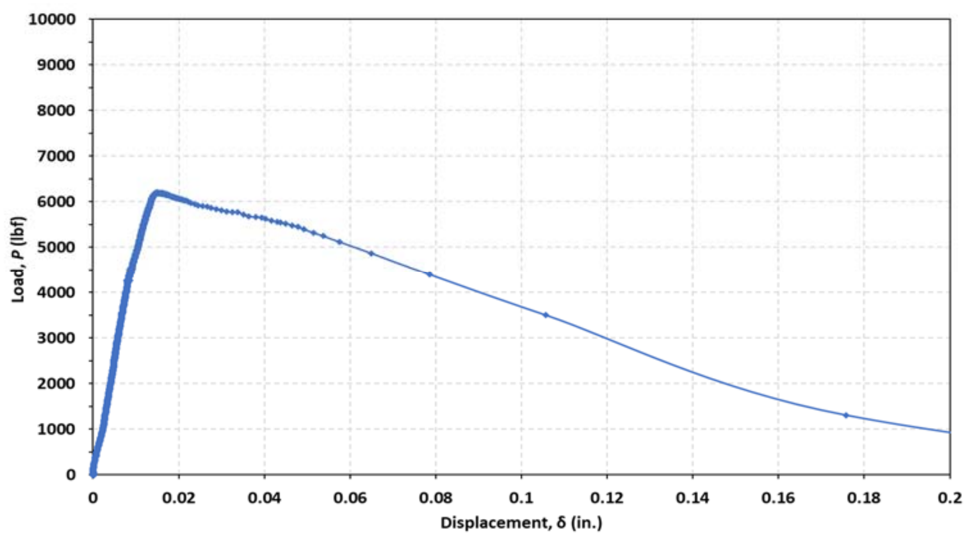

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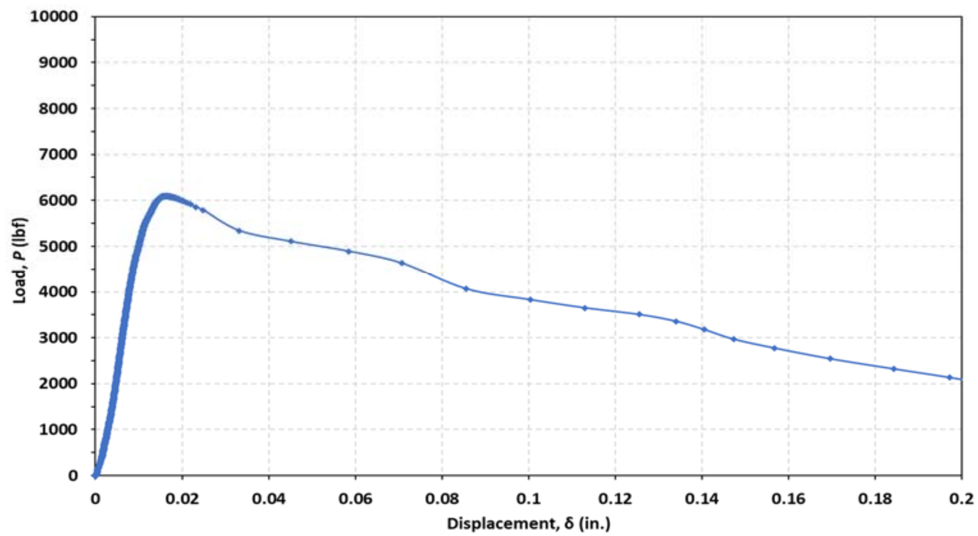

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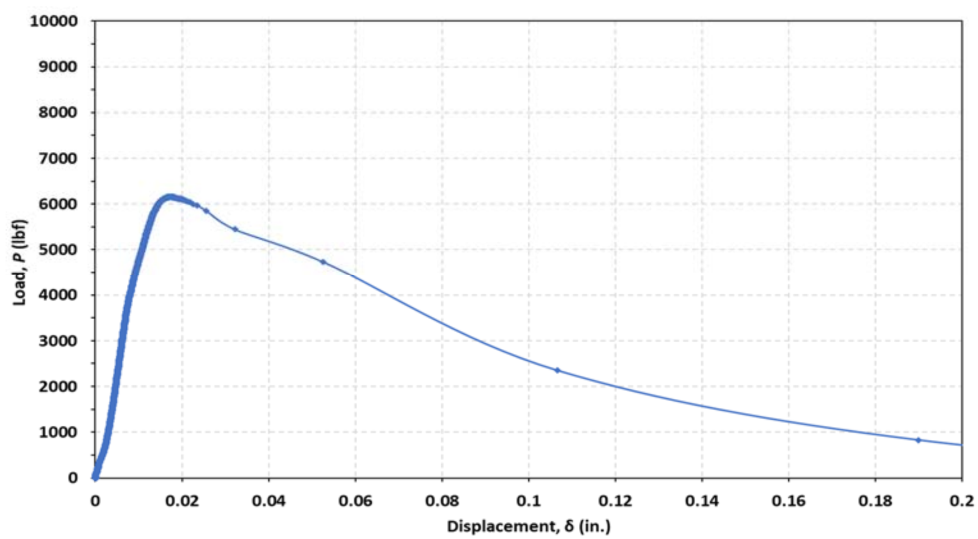
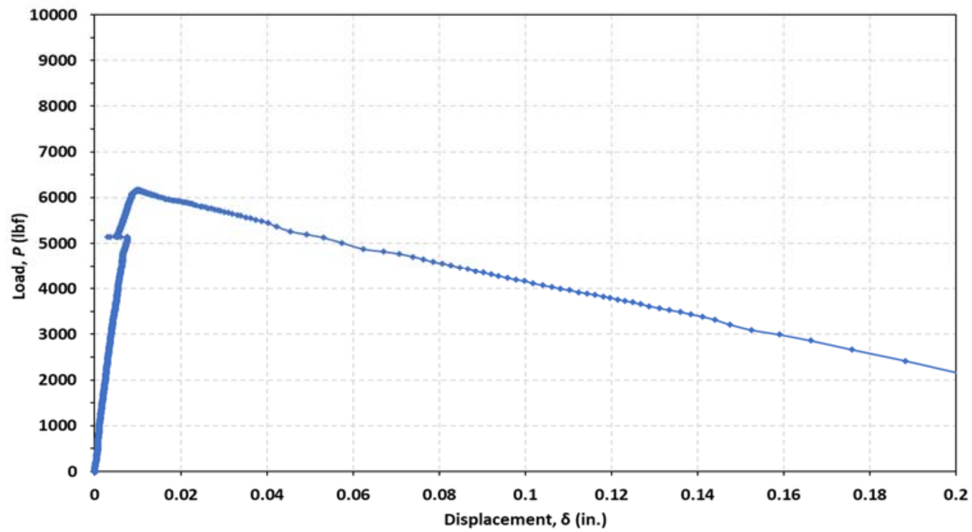


AL-SL-C-6


10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Load, P (lbf)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Displacement, δ (in.)

AL-SL-C-7

APPENDIX III: CONCRETE MIXTURE DESIGNS DEVELOPED BASED ON TRIAL BATCHES

(a) Normalweight concrete

Material	Sp.Gr.	Weight	Unit	Volume (cu. ft.)
Cement (Portland type III)	3.15	653	lb.	3.32
#9 Limestone	2.62	1738	lb.	10.63
#23 River sand	2.673	1469	lb.	8.80
Water	1	258	lb.	4.14
Glenium 7920 (HRWR)	-	20	oz.	-
MasterMatrix 362 (VMA)	-	20	oz.	-
Air (3% entrapped)	-	-	-	0.81
w/c ratio	0.40			
Design Yield (cu. ft.)	27.00			
Average 28-day f_c' (psi)	7400			
Slump (in.)	7			

(b) Shale Sand-lightweight

Material	Sp.Gr.	Weight	Unit	Volume (cu. ft.)
Cement (Portland type III)	3.15	799	lb.	4.06
3/4" Shale Lightweight	1.58	823	lb.	8.35
#23 River sand	2.673	1576	lb.	9.45
Water	1	270	lb.	4.33
Glenium 7920 (HRWR)	-	18	oz.	-
MasterMatrix 362 (VMA)	-	18	oz.	-
Master Pozzolith 80 (NRWR)	-	27	oz.	-
Air (3% entrapped)	-	-		0.81
w/c ratio	0.34			
Design Yield (cu. ft.)	27.00			
Average 28-day f_c' (psi)	7980			
Slump (in.)	7.5			

(c) Clay Sand-lightweight

Material	Sp.Gr.	Weight	Unit	Volume (cu. ft.)
Cement (Portland type III)	3.15	720	lb.	3.66
5/8" Clay Lightweight	1.36	686	lb.	8.08
#23 River sand	2.673	1783	lb.	10.69
Water	1	278	lb.	4.46
Glenium 7920 (HRWR)	-	30	oz.	-
MasterMatrix 362 (VMA)	-	30	oz.	-
Air (3 % entrapped)	-	-	-	0.81
w/c ratio	0.41			
Design Yield (cu. ft.)	27.00			
Average 28-day f_c' (psi)	7010			
Slump (in.)	8.25			

(d) Slate Sand-lightweight

Material	Sp.Gr.	Weight	Unit	Volume (cu. ft.)
Cement (Portland type III)	3.15	720	lb.	3.66
3/4" Slate Lightweight	1.52	924	lb.	9.74
#23 River sand	2.673	1389	lb.	8.33
Water	1	295	lb.	4.73
MasterMatrix 362 (VMA)	-	27	oz.	-
Master Pozzolith 80 (NRWR)	-	9	oz.	-
Air (2 % entrapped)	-	-	-	0.54
w/c ratio	0.41			
Design Yield (cu. ft.)	27.00			
Average 28-day f_c' (psi)	7040			
Slump (in.)	8			

(e) Shale All-lightweight

Material	Sp.Gr.	Weight	Unit	Volume (cu. ft.)
Cement (Portland type III)	3.15	659	lb.	3.35
3/4" Shale Lightweight	1.58	964	lb.	9.78
Shale fine aggregate	1.84	1003	lb.	8.73
Water	1	270	lb.	4.33
MasterMatrix 362 (VMA)	-	27	oz.	-
Master Pozzolith 80 (NRWR)	-	9	oz.	-
Air (3 % entrapped)	-	-	-	0.81
w/c ratio	0.41			
Design Yield (cu. ft.)	27.00			
Average 28-day f_c' (psi)	6940			
Slump (in.)	8			

(f) Clay All-lightweight

Material	Sp.Gr.	Weight	Unit	Volume (cu. ft.)
Cement (Portland type III)	3.15	744	lb.	3.79
5/8" Clay Lightweight	1.36	757	lb.	8.93
Clay fine lightweight aggregate	1.58	973	lb.	9.87
Water	1	268	lb.	4.30
Glenium 7920 (HRWR)	-	60	oz.	-
MasterMatrix 362 (VMA)	-	60	oz.	-
Master Pozzolith 80 (NRWR)	-	25	oz.	-
Air (3 % entrapped)	-	-	-	0.81
w/c ratio	0.36			
Design Yield (cu. ft.)	27.00			
Average 28-day f_c' (psi)	6500			
Slump (in.)	7.5			

(a) Slate All-lightweight

Material	Sp.Gr.	Weight	Unit	Volume (cu. ft.)
Cement(Portland type III)	3.15	741	lb.	3.77
3/4" Slate Lightweight	1.52	921	lb.	9.71
Slate fine aggregate	1.82	921	lb.	8.11
Water	1	304	lb.	4.87
MasterMatrix 362 (VMA)	-	27	oz.	-
Master Pozzolith 80 (NRWR)	-	9	oz.	-
Air (2 % entrapped)	-	-	-	0.54
w/c ratio	0.41			
Design Yield (cu. ft.)	27.00			
Average 28-day f_c' (psi)	7070			
Slump (in.)	6.5			