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Effect of Uniform Load on the Shear Strength of Slender Beams without Shear Reinforcement

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Effect of Uniform Load on the Shear Strength of Slender Beams without Shear Reinforcement

by

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Thesis

Presented to the Faculty of the Graduate School of

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Dedication

To my parents for their endless love and support

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Abstract

Effect of Uniform Load on the Shear Strength of Slender Beams without Shear Reinforcement

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The University of Texas at Austin, 2014

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Previous studies have shown that a uniform distribution of load may increase the shear strength of a slender member by as much as 40 percent (Leonhardt and Walther 1964). The increase of shear strength is potentially due to clamping stresses induced from the uniform load, although a mathematical equation to quantify the effect of clamping stress in slender uniformly loaded members has yet to be derived (Acevedo et al. 2009). Only a small percentage of all shear tests on slender specimens without shear reinforcement were completed with uniform load. Additionally, the majority of uniform load data consists of specimens with small specimen depths (d) and large longitudinal reinforcement ratios (ρ).

Six shear tests on specimens without shear reinforcement were completed at the University of Texas at Austin. Three of the six specimens were subjected to concentrated load, and the remaining three companion specimens were loaded uniformly. These specimens are among the deepest slender members without shear reinforcement that have

ever been tested under a uniform load distribution. Importantly, the ratio of maximum shear to maximum moment was maintained between concentrated and uniform load tests which ensures directly comparable tests results.

The experimental results were shown to be influenced by load distribution. Uniformly loaded specimens had an average increase in first diagonal cracking shear capacity of 17 percent with a range of increase between 10 and 23 percent when compared with specimens subjected to concentrated loads.

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CHAPTER 1

Introduction

1.1 OVERVIEW

The shear strength of slender reinforced concrete beams without shear reinforcement has been studied extensively since the unexpected and sudden collapse of an unreinforced continuous beam at Wilkins Air Force Base in 1955 (Elstner and Hognestad 1957). To better understand shear behavior, numerous tests have been conducted on shear specimens without shear reinforcement. As compiled by the ACI-DAfStb database researchers, over 1000 shear tests on slender beams without shear reinforcement have been performed to date (Reineck et al. 2013).

Despite the common use of uniform loads in design and their potential influence on shear strength, less than 10 percent of the tests compiled by the ACI-DAfStb database were completed using uniform load. This small percentage of uniform load tests is likely due to the difficultly associated with accurately applying and measuring a uniform load in the laboratory. Out of the uniform load tests reported in the literature and collected by the ACI-DAfStb database, all but nine tests were completed on specimens less than 11 in. (279 mm) in depth (d). Moreover, approximately 75 percent of the uniformly loaded specimens feature longitudinal reinforcement ratios (ρ) of 2 percent or greater. Current data and insights regarding the shear strength of slender specimens subjected to uniform loads may therefore be unrepresentative of the deeper, lightly reinforced members more commonly encountered in practice. More specifically, the effect of size on the shear strength of slender members subjected to uniform loads has yet to be defined in a meaningful way.

In order to define shear capacity for slender members with significant depth (*d*), six structural tests were completed at the University of Texas at Austin. The researchers sought to make a direct comparison between specimens subjected to concentrated and uniform loading conditions while keeping all other variables constant. These tests represent the deepest slender members (d = 21.3 in. (541 mm)) ever tested with uniform load that could be directly compared to concentrated load tests.

An increase in average normalized shear capacity at first diagonal shear cracking of approximately 17 percent was noted when comparing uniform to concentrated load specimens at location (x_r) away from the centerline of the support. Tests results were compared to shear strength estimations from several code provisions including the empirical ACI 318-11 equations 11-3 and 11-5 as well as the AASHTO LRFD 2012 shear design guidelines based upon the Modified Compression Field Theory (ACI 2011, AASHTO 2012). All three code provisions provided estimates of the concrete contribution to shear strength which exceed the appearance of the first diagonal crack in the tests. Additionally, test results were compared in conjunction with the ACI-DAfStb slender shear database. A smaller increase in shear capacity from uniform to concentrated loading was observed for the University of Texas tests than was predicted by the ACI-DAfStb database.

1.2 RESEARCH SIGNIFICANCE

In this study, three test results are presented that are among the deepest reinforced concrete beam members ever tested under uniform loading conditions. The uniform load results not only expand on the small existing ACI-DAfStb slender uniform load database, but also represent specimens of depths (*d*) and longitudinal reinforcement ratios (ρ) likely found in field structures. Furthermore, the uniform load test results were used in conjunction with concentrated load tests to directly compare the influence of load distribution on shear capacity. Comparison of the results from the six tests performed to relevant ACI 318-11 and AASHTO LRFD 2012 shear provisions showed an unconservative estimation of the concrete contribution to shear strength.

CHAPTER 2

Experimental Investigation

2.1 Beam Designation and Specimen Geometry

Five reinforced concrete specimens were fabricated to accommodate a total of six shear tests: three concentrated load tests and three uniform load tests. Two of the five specimens accommodated concentrated load tests at each end for which the results of one test (SR2-N) are not reported here. SR2-N was not reported as the test region contained post-installed shear reinforcement. The concentrated and uniform load test setups are depicted in Figure 2-1. Additionally, Figure 2-3 depicts all six test regions as well as photos for each test setup. A summary of the naming convention is as follows:

- LD1-N, LD1-S, and SR2-S: Concentrated load with shear span (*a*) equal to 53.2 in. (1.35 m).
- LD2, LD3, and LD4: Uniform load with load span of 216 in. (5.49 m).

N and S designate north and south span while 1, 2, 3, and 4 designate specimen number.

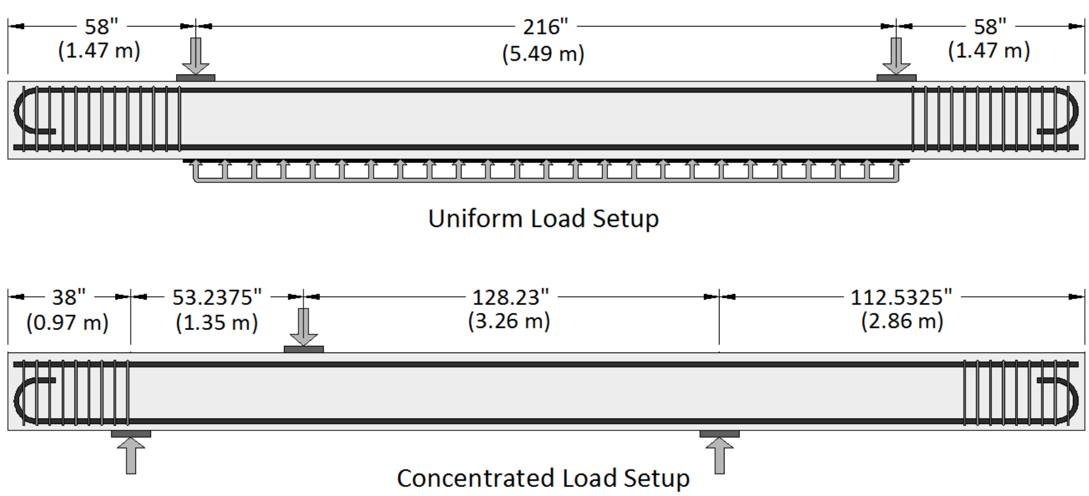


Figure 2-1: Uniform and Concentrated Load Test Setups

The overall height (h), width (b_w), and length of each specimen was 24 in. (0.61m), 36 in. (0.91 m), and 332 in. (8.43 m), respectively. Flexural reinforcement consisted of 5 No. 11 reinforcing bars at the tension face and 5 No. 11 reinforcing bars at the compression face. The average yield strength of the reinforcement is provided in Table 2-1. Note that all flexural reinforcement meets ASTM A615 standard for Grade 60 bars (ASTM 2009). Flexural reinforcement was proportioned to provide a reasonable margin against flexural failure and thus ensure each specimen failed in shear. Confining No. 5 stirrups spaced at 4 in. (102 mm) on center were provided in combination with 180 degree hooks to ensure proper anchorage of the flexural reinforcement. Concrete clear cover was 2 in. (51 mm) on the tension face and 3 in. (76 mm) on the compression face for all specimens. The effective specimen depth (d) and longitudinal reinforcement ratio (ρ) were 21.3 in. (0.54 m) and 1.02 percent, respectively. Refer to Figure 2-2 for further details regarding specimen geometry.

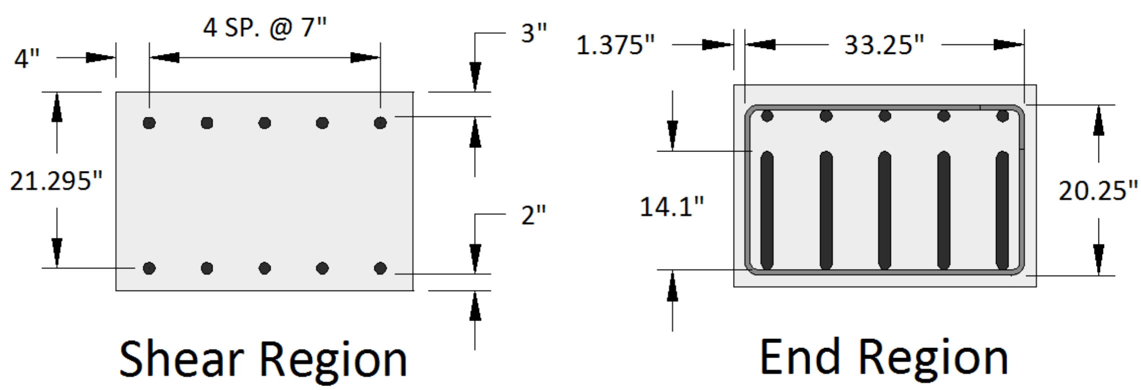


Figure 2-2: Details of Specimen Geometry

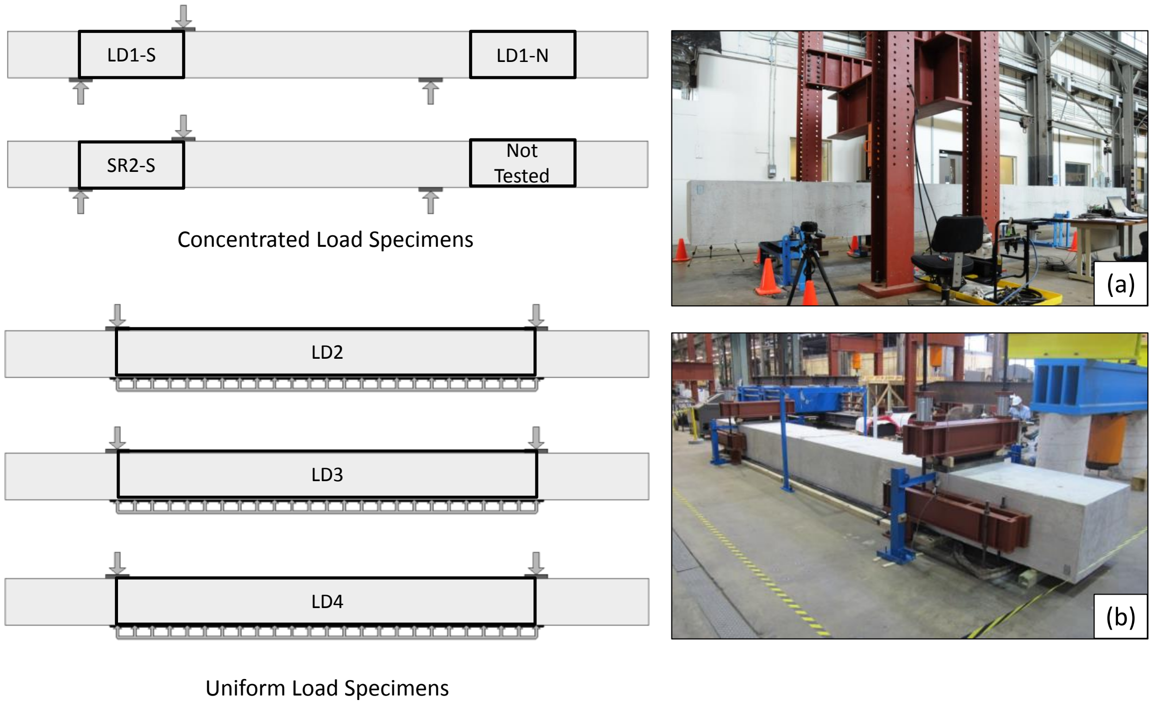


Figure 2-3: Test Regions for Each of the Five Specimens; Concentrated and Uniform Load Test Setups Shown in Photos (a) and (b)

2.2 MATERIAL PROPERTIES

Each specimen was placed with an individual batch of concrete. The concrete mix design for each specimen remained constant and consisted of the following: 28 day design strength of 4000 psi (27.6 MPa), crushed limestone coarse aggregate with a nominal maximum size (a_g) of 1 in. (25 mm), cement content of 423 lb/yd^3 (251 kg/m^3), and water to cement ratio (*w/c*) of 0.59. Cylinders with a nominal diameter of 4 in. (102 mm) and a nominal height of 8 in. (203 mm) were used to determine the concrete compressive strength. A minimum of three cylinders were tested at the time of each structural test to obtain the average concrete compressive strengths depicted in Table 2-2. Tensile testing results for flexural reinforcement are summarized in Table 2-1.

Table 2-1: Average Values for Flexural Reinforcement

Test Identification	Yield Stress, ksi (MPa)	Ultimate Stress, ksi (MPa)
LD1, LD2, LD3, SR2	69.3 (478.0)	104.0 (717.1)
LD4	67.4 (464.8)	98.8 (681.4)

Table 2-2: Age and Compressive Strength of Concrete

Test Identification	Concrete Age, days	f'_c, psi (MPa)
LD1	50	3658 (25.2)
SR2	66	4360 (30.1)
LD2	64	4071 (28.1)
LD3	59	3522 (24.3)
LD4	64	3713 (25.6)

2.3 TEST SETUP

For the concentrated load specimens, the ratio of the shear span length to the specimen depth (*a/d*) was 2.5. A shear span to depth ratio of 2.5 is noted by Macgregor and Wight (2009) to be the lower bound of slender beam behavior. Force was applied to the specimens via a hydraulic ram and measured using two load cells provided at each support. The self-weight of each specimen was measured using the calibrated load cells before load was applied by the ram. This value was reported as distributed load (ω_b). Load was applied in 10 kip (44.5 kN) increments for the purpose of marking and recording flexural cracking. After marking cracks at a total applied load of 80 kips (355.9 kN), each specimen was loaded to failure.

The uniform load test setup was designed to keep the shear span to depth ratio (*a/d*) constant between concentrated and uniform load specimens. Shear span (*a*) for a uniformly loaded specimen was taken as one-fourth of the load span in accordance with

Kani (1966). Kani defines the shear span in any loaded specimen as the ratio of maximum moment to maximum shear. Thus, by maintaining the same maximum moment to maximum shear ratio in concentrated and uniform load tests, a consistent shear span to depth ratio can be achieved. The shear span to depth ratio for the uniform load specimens was 2.53.

Force was applied to the setup via a Kevlar reinforced air bladder which exerted a uniform pressure to the underside of each specimen. As with the concentrated load setup, load was measured using two load cells provided at each support and self-weight of the specimen was recorded as (ω_b). Load was applied in 20 kip (90 kN) increments for all three specimens where cracks were marked and recorded after each step. After marking cracks at 160 kips (711.7 kN) of total applied load, specimens LD3 and LD4 were loaded to failure. Commissioning of the test setup required the unloading of specimen LD2 on two different occasions. It should be noted that diagonal cracking did not occur in specimen LD2 until the last loading attempt.

Deflections were recorded using six linear potentiometers for each test setup. Two linear potentiometers were used at each support, with two more located at the theoretical location of maximum deflection. The location of maximum deflection was taken as the point of loading from the hydraulic ram in the concentrated load setup and the midspan of the uniform load setup.

2.4 TEST RESULTS

Each specimen was loaded until a significant drop from the maximum load (minimum of 33%) was observed. Table 2-3 shows a summary of the test results. The shear force values listed in Table 2-3 include the shear force measured at the centerline of the support (V_{ns}), the shear force calculated at a distance (d) away from the edge of the support (V_d), the shear force calculated at the location where the shear crack crosses midheight of the specimen at a distance (x_r) from the centerline of the support (V_{xr}), and the shear force corresponding to the ACI-DAfStb shear databases (V_{DAfStb}) and depicted in Figure 2-5. The shear locations were chosen by the author for the following reasons: (V_{ns}) as the location of maximum shear force, (V_d) as a simplified location comparable to ACI 318-11 and AASHTO LRFD 2012 critical sections, (V_{xr}) for direct comparisons between uniform and concentrated load test results, and (V_{DAfStb}) for direct comparisons to the shear database. Actual critical shear sections for ACI 318-11 and AASHTO LRFD 2012 are described within each document. Figure 2-4 and Figure 2-5 summarize the described shear locations.

For concentrated load specimens, (V_{xr}) is equal to (V_{DAfStb}). For uniform load specimens, (V_{DAfStb}) is equal to the applied shear force at a distance (x_{ou}) from the centerline of the support plus the shear force due to the self-weight of the specimen at a distance (x_r) from the centerline of the support. As depicted in Figure 2-5, only loads on the shaded portion of the specimen are used for calculating (V_{DAfStb}). Refer to the ACI-DAfStb database document for further explanation. Shear force values account for both self-weight of specimen and setup. Additionally, shear force values at any location can be found using (V_{ns}) and self-weight (ω_b) of the specimen.

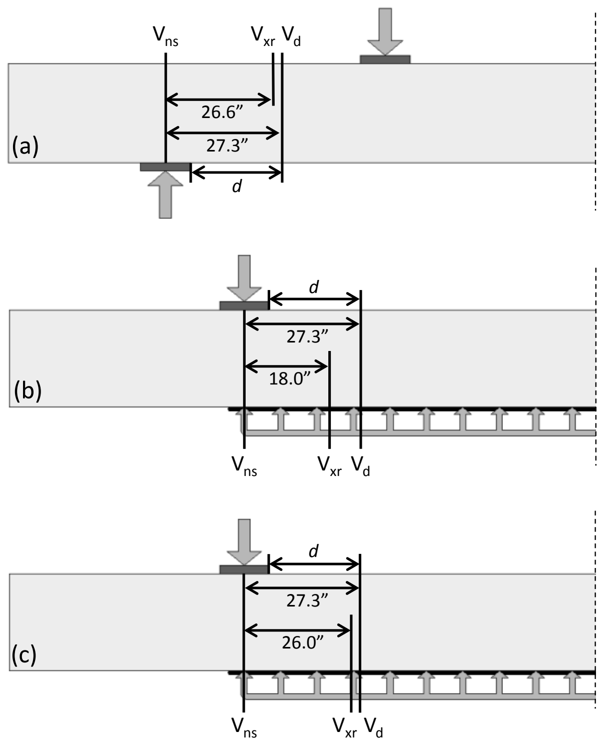


Figure 2-4: Shear Force Value Locations Showing the Following: (a) Specimens LD1-N, LD1-S, and SR2-S, (b) Specimens LD2 and LD3, (c) Specimen LD4

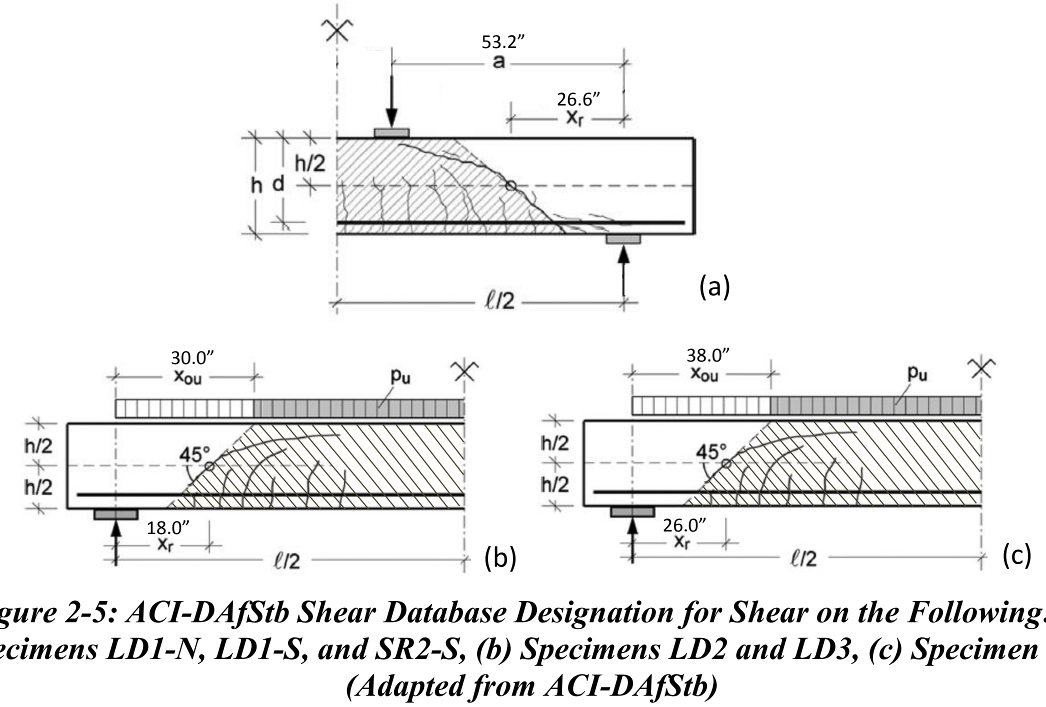


Figure 2-5: ACI-DAfStb Shear Database Designation for Shear on the Following: (a) Specimens LD1-N, LD1-S, and SR2-S, (b) Specimens LD2 and LD3, (c) Specimen LD4 (Adapted from ACI-DAfStb)

Table 2-3: Summary of Test Results

		Concentrated Load Specimens			Uniform Load Specimens		
		LD1-N	LD1-S	SR2-S	LD2	LD3	LD4
Shear at first diagonal cracking, kips (kN)	V_{ns}	92.5 (411.5)	100.7 (447.9)	90.7 (403.5)	122.0 (542.7)	122.3 (544.0)	142.8 (635.4)
	V_d	87.8 (390.7)	96.0 (427.0)	85.9 (381.9)	91.0 (405.0)	91.4 (406.7)	106.8 (475.3)
	V_{xr}	87.9 (391.0)	96.0 (427.2)	85.9 (382.1)	101.6 (451.9)	101.9 (453.3)	108.6 (482.9)
	V_{DAfStb}	87.9 (391.0)	96.0 (427.2)	85.9 (382.1)	88.9 (395.4)	89.3 (397.2)	93.6 (416.4)
Shear at maximum applied load, kips (kN)	V_{ns}	92.5 (411.5)	100.7 (447.9)	118.2 (525.8)	134.2 (597.0)	168.9 (751.3)	142.8 (635.4)
	V_d	87.8 (390.7)	96.0 (427.0)	113.4 (504.5)	100.2 (445.8)	126.3 (561.7)	106.8 (475.3)
	V_{xr}	87.9 (391.0)	96.0 (427.2)	113.5 (504.7)	111.8 (497.3)	140.8 (626.3)	108.6 (482.9)
	V_{DAfStb}	87.9 (391.0)	96.0 (427.2)	113.5 (504.7)	97.7 (434.6)	122.9 (546.7)	93.6 (416.4)
Deflection under applied load, in. (mm)	First diagonal shear cracking	0.20 (5.1)	0.21 (5.3)	0.17 (4.3)	0.54 (13.7)	0.62 (15.7)	0.71 (18.0)
	Maximum applied load	0.20 (5.1)	0.21 (5.3)	0.50 (12.7)	0.84 (21.3)	1.38 (35.1)	0.71 (18.0)

The distance between the centerline of the support and the location where the critical shear crack crossed midheight of the specimen (x_r) was consistent for the concentrated load tests. For the concentrated load setup, the critical shear crack crossed the midheight of each specimen at the midpoint of the shear span ($x_r = a/2$). In uniform load specimens LD2 and LD3, the critical shear crack crossed midheight of the specimen at approximately 18 in. (457 mm) inside the centerline of the support. While in uniform load specimen LD4, (x_r) was equal to 26 in (660 mm). Note that each of the uniform load specimen failure photos (Figure 2-6) depicts two shear cracks. The shear crack furthest from the support did not appear until failure after ultimate load had been achieved. For this reason, the shear crack closest to the support was taken as the critical shear crack for each of the uniform load test results. Diagonal shear crack patterns are depicted in Figure 2-6 for each specimen upon the completion of testing.

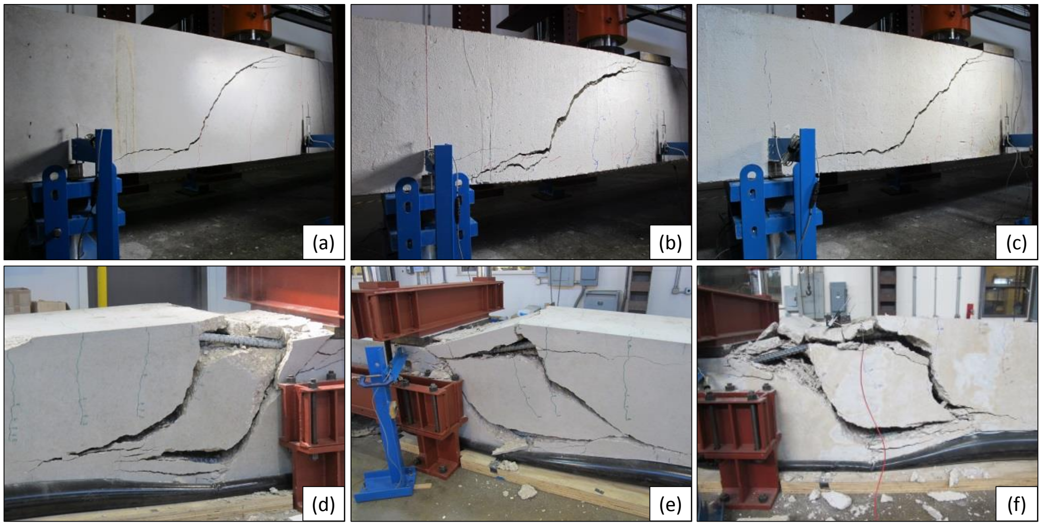


Figure 2-6: Shear Failure Cracks for the Following: (a) LD1-N, (b) LD1-S, (c) SR2-S, (d) LD2, (e) LD3, (f) LD4

The maximum applied load resistance as well as the load at first diagonal shear cracking was recorded for each of the six test results. An increase in maximum applied load from the applied load at first diagonal shear cracking was observed in tests SR2-S, LD2, and LD3. In tests LD1-N, LD1-S, and LD4, maximum applied load was achieved at first diagonal shear cracking. Because of the unpredictable post cracking behavior of the six test results, the researchers used load at first diagonal shear cracking for shear force comparisons between tests. This behavior is explicitly observed comparing the post cracking resistances of uniform test specimens LD2 and LD3. Although the specimens are nominally identical, specimen LD3 obtained a maximum applied load resistance of approximately 26 percent greater than specimen LD2. Figure 2-7 and Figure 2-8 depict the load-deflection summary for the six test results. Deflection values at first diagonal shear cracking and maximum applied load can be found in Table 2-3.

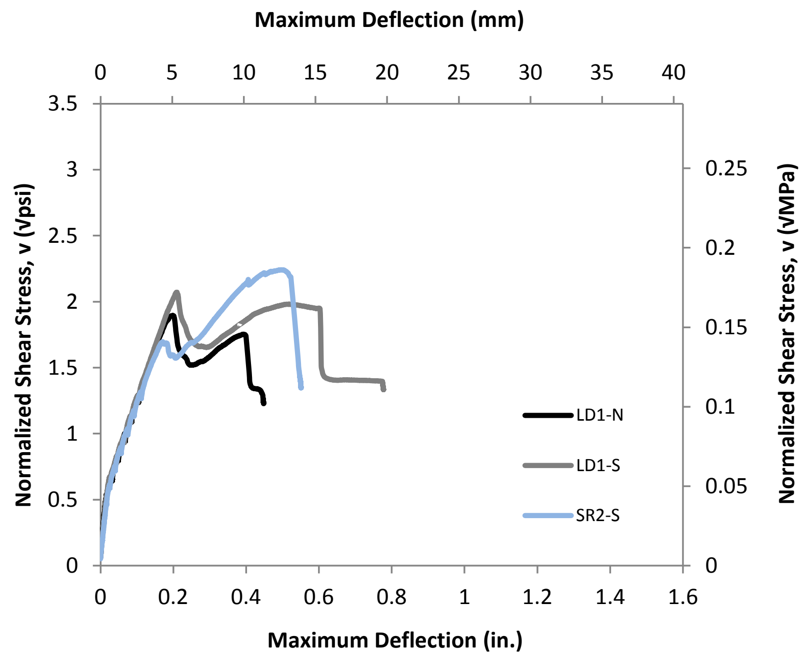


Figure 2-7: Concentrated Load Normalized Shear Stress (v_{xr}) Versus Deflection Summary

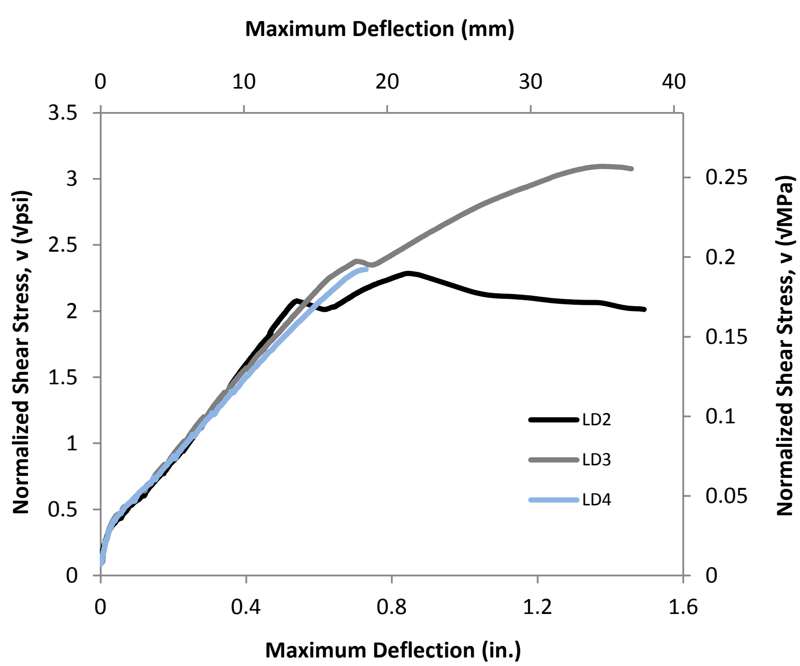


Figure 2-8: Uniform Load Normalized Shear Stress (v_{xr}) Versus Deflection Summary

Directly comparing concentrated load tests with uniform load tests, the researchers chose to use first diagonal shear cracking values located at distance (x_r) from the centerline of the support. First diagonal shear cracking was chosen as a conservative value that compares well with data used in developing empirical ACI shear equations 11-3 and 11-5. The ACI-ASCE Committee 326 report (1962) provides a more detailed description on ACI shear strength equation development. Shear force values were normalized against the square root of concrete compressive strength (f'_c) and specimen dimensions (b_w and d). Note that shear force values from all of the four locations calculated in Table 2-3 can be normalized against concrete compressive strength and specimen dimensions. Normalized shear stress at first diagonal shear cracking (v_{xr}), seen in Equation 2-1, increased in uniform load tests by an average of approximately 17 percent with a range of increase of 10 to 23 percent when compared to concentrated load tests. For comparison of tests results to the ACI-DAfStb database, (v_{DAfStb}) was used. Normalized shear stress at first diagonal cracking (v_{DAfStb}) increased in uniform load tests by an average of 2.1 percent with a range of increase of -3.8 to 6.2 percent when compared to concentrated load tests.

$$\boldsymbol{v = \frac{V}{b_w d\sqrt{f'_c}}}$$ ***Equation 2-1***

CHAPTER 3

Comparison of Test Results to the ACI-DAfStb Database[4]

Results from the six tests performed were compared to the data presented within the ACI-DAfStb shear database. The ACI-DAfStb shear database provided additional data that was used to validate the University of Texas test results. Additionally, the numerous test results found within the database were used to further compare the influence of loading condition on shear capacity. Note that all comparisons made in Chapter 3 refer to first diagonal cracking shear force and normalized shear stress values calculated per the ACI-DAfStb database (V_{DAfStb} and v_{DAfStb}).

3.1 Overview of Database

ACI code equations for the shear strength in concrete were empirically derived based upon test results completed over fifty years ago. Because the empirical code equations are still in place today, the authors of the ACI-DAfStb shear databases sought to compile additional test results. Shear test results were collected from various researchers to create a comprehensive set of data, and this new set of data was compared with current code provisions.

The concentrated load database consists of 1365 shear test results on specimens without shear reinforcement, of which 1008 are slender specimens. The slender dataset includes an abundance of tests with varying effective depths (d), longitudinal reinforcement ratios (ρ), shear span to depth ratios (a/d), and concrete compressive strengths (f'_c). The uniform load database is comprised of only 128 test results on specimens without shear reinforcement, of which 69 are slender. All but 8 of the uniform load slender specimen results have effective specimen depths of 11 in. (279 mm) or less. The 8 remaining test results all have longitudinal reinforcement ratios of 0.44% or less. As depicted in Figure 3-1 and Figure 3-2, the vast majority of the uniform load slender database is comprised of specimens with small effective depths and high longitudinal reinforcement ratios.

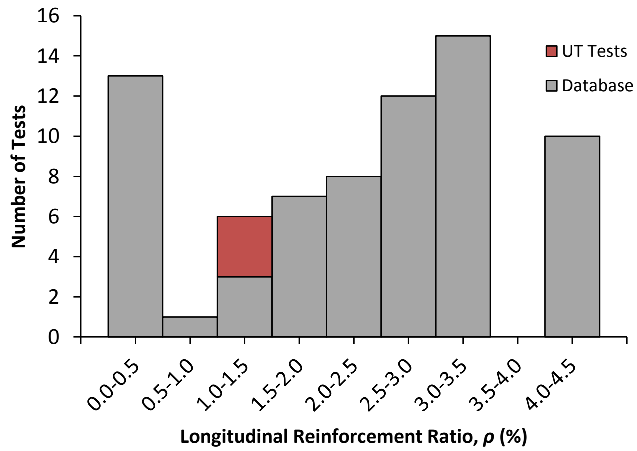


Figure 3-1: Distribution of Slender Uniform Load Tests without Shear Reinforcement with Respect to Longitudinal Reinforcement Ratio (ρ)

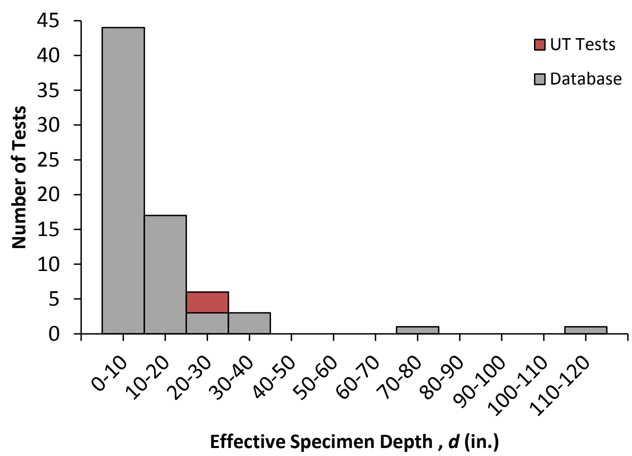


Figure 3-2: Distribution of Slender Uniform Load Tests without Shear Reinforcement with Respect to Effective Specimen Depth (d)

Parameters affecting shear strength of reinforced concrete beam specimens without stirrups were examined in order to effectively compare the University of Texas test results to the ACI-DAfStb shear database. The ACI Committee 445 report (1999) notes the following four parameters as having the largest impact on shear capacity in specimens without shear reinforcement: shear span to depth ratio (a/d), effective specimen depth (d), longitudinal reinforcement ratio (ρ), and axial load. Because axial load was not applied to test specimens within the ACI-DAfStb database, focus was directed toward the other three parameters.

Shear span to depth ratio (a/d) is important for estimating shear capacity as test specimens can exhibit either deep or slender behavior. MacGregor and Wight (2012) define the transition point from a deep to slender specimen at a shear span to depth ratio of 2.5 (originally noted as Kani's valley (1966)). ACI-DAfStb shear database authors define slender behavior in specimens with shear span to depth ratio greater than or equal to 2.4. Thus, $a/d \geq 2.4$ was taken as slender specimen behavior.

As longitudinal reinforcement ratio (ρ) increases in specimens without shear reinforcement, shear capacity also increases. Higher longitudinal reinforcement ratios are more effective in controlling crack width growth (Bentz and Collins 2006). As crack width size decreases, effects of dowel action and aggregate interlock increase, ultimately leading to an increase in overall shear capacity (MacGregor and Wight 2012).

Size effects, first studied by Kani (1967), are defined as a decrease normalized shear stress capacity for shear specimens without shear reinforcement as member depth (d) increases. Normalized shear capacity decreases in deeper members because of an increase in both crack width and spacing. Larger crack widths allow smaller shear stresses to be transferred across cracks via aggregate interlock (MacGregor and Wight 2012).

Upon examination of the slender members within the uniform load database, there is an obvious lack of full scale specimens that are more commonly encountered in practice. The majority of the test results have small effective depths (d) with high longitudinal reinforcement ratios (ρ), and the few larger test results have very low longitudinal reinforcement ratios. Based upon the preceding discussed parameters, ACI-DAfStb uniform load data is likely to vastly over or under predict shear capacity. The University of Texas test results represent specimens likely to be found in field structures with a larger specimen depth (d = 21.3 in. (541 mm)) and longitudinal reinforcement ratio of 1.02%. Thus, the test results obtained work toward addressing the visible gap within the ACI-DAfStb slender uniform database.

3.2 Test Results within Context of ACI-DAfStb Database

University of Texas test results were further validated through the use of the ACI-DAfStb database. The three concentrated load test results are plotted with results from the slender concentrated load database in Figure 3-3. Figure 3-3 depicts the extensiveness in which the ACI-DAfStb concentrated load database covers both specimen depth (d) and longitudinal reinforcement ratio (ρ). Normalized shear stress (v_{DAfStb}) is similar between University of Texas test results and concentrated load database results with analogous longitudinal reinforcement ratio.

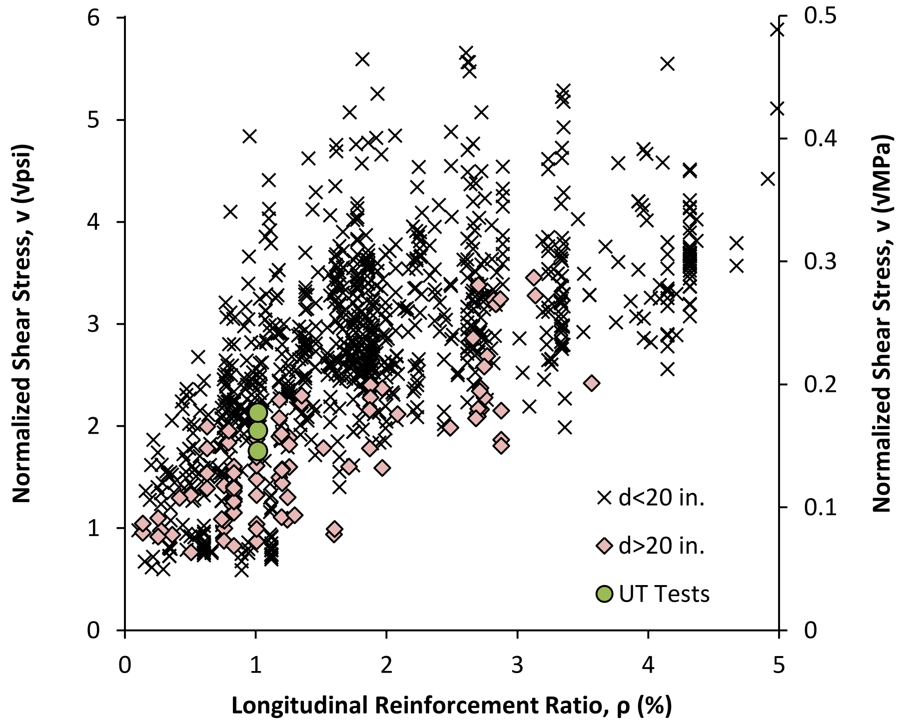


Figure 3-3: Comparison of University of Texas Test Results to the Entirety of the ACI-DAfStb Slender Concentrated Load Database

The University of Texas uniform load specimens were compared with the ACI-DAfStb slender uniform load database. Figure 3-4 depicts current uniform load database test results along with the three University of Texas test results. Unlike Figure 3-3, the slender uniform load database shows both specimen depths (*d*) and longitudinal reinforcement ratios (ρ) where little to no data has been collected. For example prior to this testing program, only four slender tests had been completed with longitudinal reinforcement ratios between 0.5% and 2%. The three University of Texas test results represent a depth and longitudinal reinforcement range not depicted within the current database.

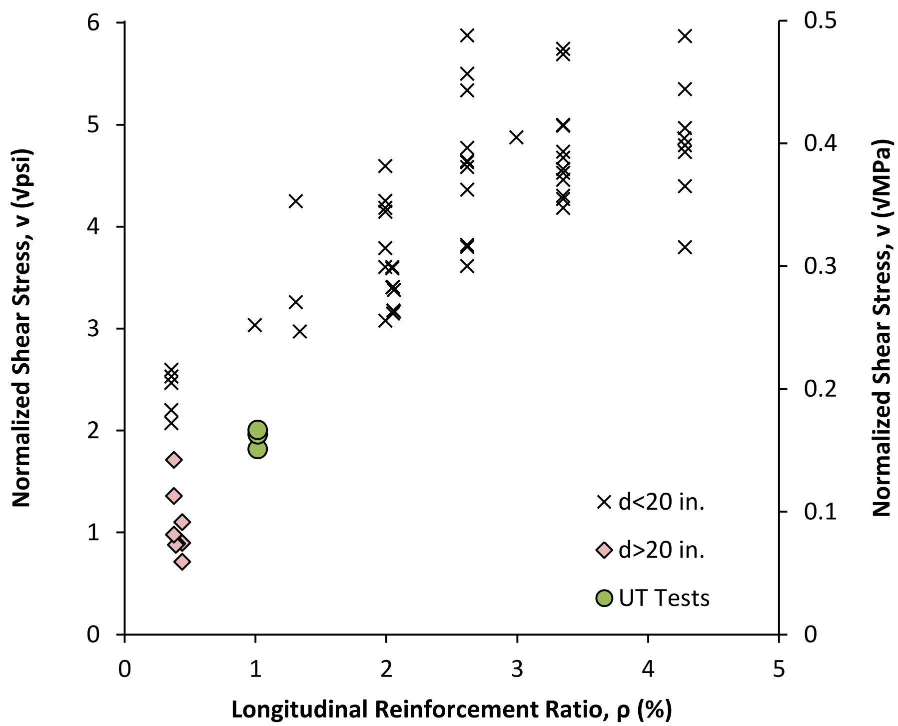


Figure 3-4: Comparison of University of Texas Test Results to the Entirety of the ACI-DAfStb Slender Uniform Load Database

3.3 INFLUENCE OF UNIFORM LOAD – GENERAL DATABASE ANALYSIS

Comparison between uniform and concentrated load was made using the entirety of the ACI-DAfStb slender database. Shear force values within the database were normalized against specimen dimensions and concrete compressive strength (Equation 2-1). The distribution of normalized shear stress (v_{DAfStb}) versus number of tests can be seen in Figure 3-5 and Figure 3-6.

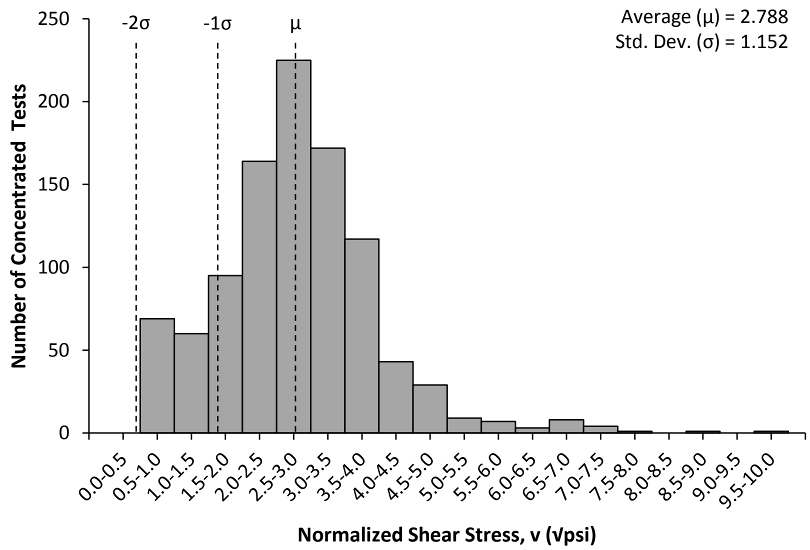


Figure 3-5: Distribution of ACI-DAfStb Slender Concentrated Load Specimens with Respect to Normalized Shear Stress (v_{DAfStb})

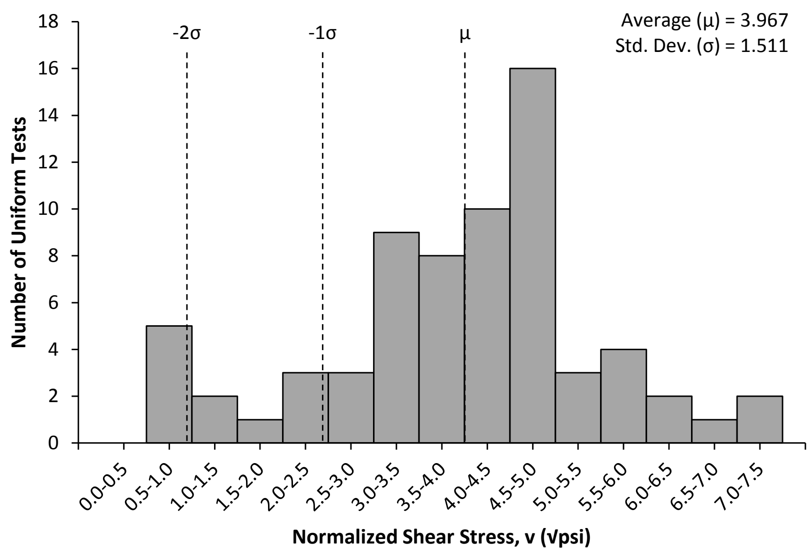


Figure 3-6: Distribution of ACI-DAfStb Slender Uniform Load Specimens with Respect to Normalized Shear Stress (v_{DAfStb})

A normal distribution of data is depicted in the slender concentrated load results, while more scatter is noticeable in the slender uniform load results. The scatter in the uniform load data is quantified mathematically with a standard deviation that is 31 percent higher than concentrated load results. On average, uniform loading increased normalized shear stress (v_{DAfStb}) by approximately 42 percent when compared to concentrated load tests. Lower bound test results are similar for both datasets with multiple specimens failing at a normalized shear stress between 0.5 and 1.0.

Comparing the complete slender uniform and concentrated load datasets has several potential limitations. Slender uniform load test results account for less than 7 percent of the total slender database. Thus, the uniform load results are not well distributed with regards to specimen depth (d) and longitudinal reinforcement ratio (ρ). Another key drawback is the small amount of directly comparable uniform and concentrated load results. In order to appropriately define increase in normalized shear stress (v_{DAfStb}), direct comparisons between datasets with identical specimen depth and longitudinal reinforcement ratio should be made.

3.4 Influence of Uniform Load Distribution – Directly Comparable Datasets

The ACI-DAfStb slender shear database was investigated to find directly comparable slender uniform and concentrated load tests. The investigation found three different series of tests in which specimens with identical specimens depths (d) and longitudinal reinforcement ratios (ρ) were tested to shear failure in both uniform and concentrated loading configurations. Shear force values were taken from the database and normalized against specimen dimensions (b_w and d) and concrete compressive strength (f'_c). Shear span to depth ratio (a/d) for each of the three comparison series ranged from 2.4 to 6.0.

Series I was derived from tests completed by Leonhardt and Walther (1964), while Series II and Series III were derived from Krefeld and Thurston (1966) test results. Note that each of the three directly comparable series were completed on specimens with small effective depths (*d*) and high longitudinal reinforcement ratios (*ρ*). Series I through Series III are shown in Figure 3-7 through Figure 3-9, respectively.

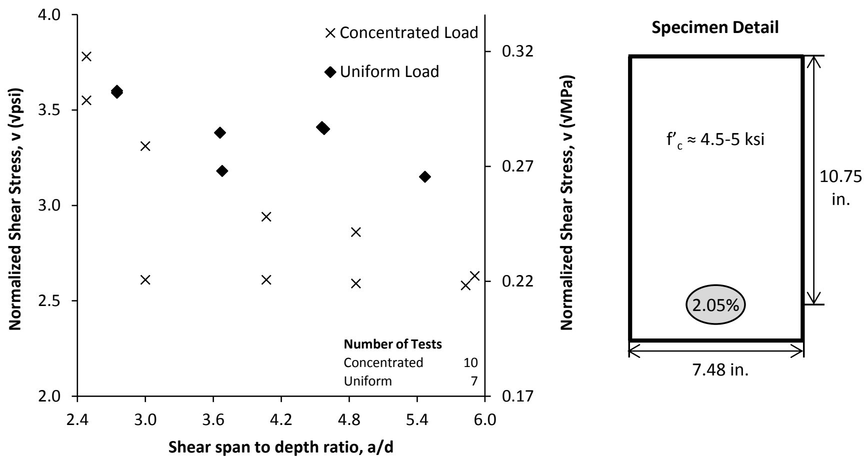


Figure 3-7: Series I: Directly Comparable Results Completed by Leonhardt and Walther

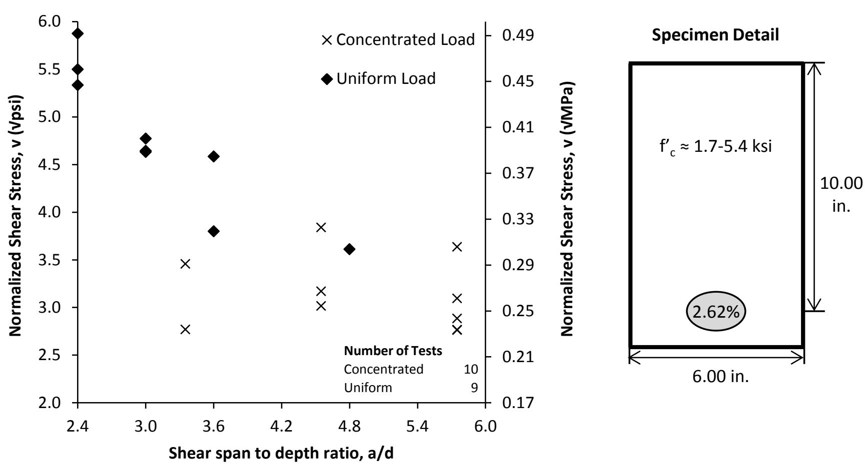


Figure 3-8: Series II: Directly Comparable Results Completed by Krefeld and Thurston

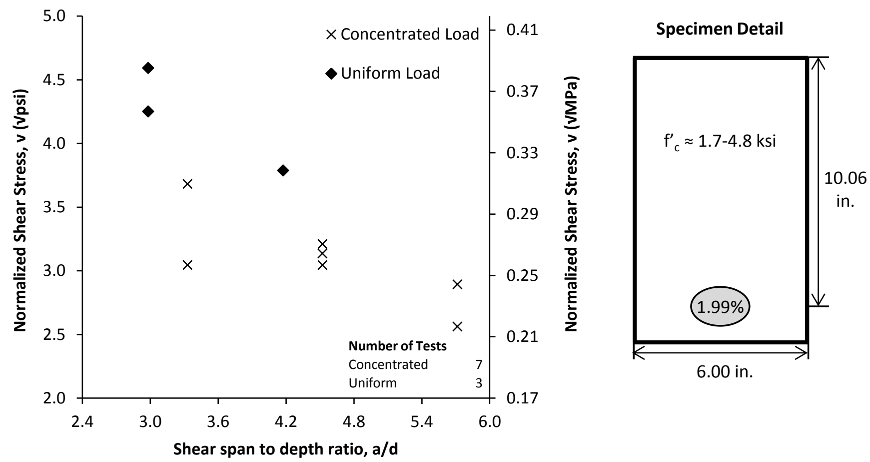


Figure 3-9: Series III: Directly Comparable Results Completed by Krefeld and Thurston

Average normalized shear stress (v_{DAfStb}) increased from concentrated to uniform load specimens by approximately 15, 54, and 37 percent for Series I, II, and III, respectively. Lower bound load distribution behavior in each series was compared by taking the lowest normalized shear stress result (v_{DAfStb}) for both concentrated and uniform load specimens. Lower bound normalized shear stress (v_{DAfStb}) increased from concentrated to uniform load specimens by approximately 22, 38, and 48 percent for Series I, II, and, III, respectively.

To quantify the effect of load distribution on normalized shear stress (v_{DAfStb}), general database comparisons, direct database comparisons, and the University of Texas test results were used. General database comparisons and direct database comparisons showed a similar increase (between 15 and 54 percent) in average normalized shear stress (v_{DAfStb}) from concentrated to uniform load specimens. The University of Texas test results were substantially different. For the six test results, average normalized shear stress (v_{DAfStb}) at first diagonal cracking increased by only 2.1 percent with a range of increase between -3.8 and 6.2 percent from concentrated to uniform load specimens. The disconnect between expected load distribution effects, based upon database results, and actual load distribution effects observed in the University of Texas specimens displays the inherent need for further study of full scale, directly comparable specimens.

CHAPTER 4

Comparison of Test Results to Relevant Code Estimates

The results from the tests conducted on six shear spans were compared to three estimations of the concrete contribution to shear strength. In order to estimate contribution of concrete to shear strength, ACI 318-11 and AASHTO LRFD 2012 provisions were used. Note that in Chapter 4 all shear force calculations were completed using the failure location at a distance (x_r) away from the center line of the support, where (x_r) is the distance from the centerline of the support to the location where the shear crack crosses midheight of the specimen. This location differs from the critical shear section presented in either ACI 318-11 or AASHTO LRFD 2012, but was used to consistently compare test results. Shear force values and normalized shear stress are presented as (V_{xr}) and (v_{xr}) respectively.

4.1 ACI EQUATION 11-5

ACI 318-11 equation 11-5 was developed as the basic equation for shear strength in members without shear reinforcement by the ACI-ASCE Committee 326 report. The report, completed in 1962, noted that the applied load causing the initial formation of a diagonal shear crack should be taken as the ultimate load for design purposes. The committee analyzed over 440 shear test results, deriving an empirical equation with the following five listed variables: longitudinal reinforcement ratio (ρ), shear times depth to moment ratio ($V_{xr}d/M_{xr}$), and concrete compressive strength (f'_c), specimen width (b_w), and specimen depth (d). Note that the ($V_{xr}d/M_{xr}$) ratio directly accounts for differences between uniform and concentrated load. ACI 318-11 equation 11-5 is listed below as Equation 4-1.

$$\boldsymbol{V_{xr} = \left(1.9\sqrt{f'_c} + 2500\rho\frac{V_{xr}d}{M_{xr}}\right)b_w d}$$ ***Equation 4-1***

The ($V_{xr}d/M_{xr}$) term is limited to a maximum value of 1.0 where (V_{xr}) and (M_{xr}) occur at the critical section. Equation 3-1 additionally limits the normalized shear stress (v_{xr}) to a maximum value of 3.5.

4.2 ACI EQUATION 11-3

ACI 318-11 equation 11-3 was derived as a simplified and conservative version of the general equation described above. ACI equation 11-3 is the most commonly used equation for estimating shear strength of concrete in United States structural engineering practice. The three variable used in equation 11-3 are concrete compressive strength (f'_c), specimen width (b_w), and specimen depth (d). Thus, equation 11-3 does not directly account for differences between concentrated and uniform load. ACI 318-11 equation 11-3 is listed below as Equation 4-2.

$$\boldsymbol{V_{xr} = 2\sqrt{f'_c}b_w d}$$ ***Equation 4-2***

4.3 AASHTO LRFD 2012

AASHTO LRFD 2012 shear design provisions are based upon the Modified Compression Field Theory (MCFT) developed by Vecchio and Collins (1986). A simplified MCFT-based sectional analysis procedure (Bentz et al. 2006) can be used to produce a non-iterative estimation of one-way shear capacity. AASHTO authors note that the following equations will give very similar results to the Canadian design code (CSA) which was also derived from MCFT. The following set of equations directly accounts for differences between uniform and concentrated load. Equation 4-3 through Equation 4-6 can be used to estimate AASHTO defined shear capacity[6].

$$s_{xe} = s_x \frac{1.38}{a_g + 0.63}$$ ***Equation 4-3***

$$\varepsilon_s = \frac{\left(\frac{|M_{xr}|}{d_v} + |V_{xr}|\right)}{E_s A_s}$$ ***Equation 4-4***

$$\beta = \frac{4.8}{(1 + 750\varepsilon_s)} \frac{51}{(39 + s_{xe})}$$ ***Equation 4-5***

$$V_{xr} = 0.0316\beta\sqrt{f'_c}\, b_w d_v$$ ***Equation 4-6***

Where:

a_g = maximum coarse aggregate size = 1 in.

A_s = area of longitudinal tension steel = 7.8 in^2

d_v = effective shear depth = 19.2 in.

E_s = modulus of elasticity of longitudinal tension steel = 29,000,000 psi

s_x = distance between layers of crack control reinforcement = 17.6 in.

s_{xe} = crack spacing parameter = 14.9 in.

β = factor relating effect of longitudinal strain on the shear capacity of concrete

ε_s = net longitudinal tensile strain in the section at the centroid of the tension reinforcement

A summary of the two ACI 318-11 shear estimation methods can be seen in Table 4-1. Table 4-1 depicts the recorded normalized shear stress at first diagonal cracking for each specimen at the chosen critical section of a distance (x_r) away from the centerline of the support. Comparative values for Equations 4-1 and 4-2 were calculated at the same critical section.

Table 4-1: Comparison of Test Results to ACI 318-11 Code Equations

	Normalized Shear Stress at First Diagonal Cracking, v_{xr} (√psi)			Actual Shear Strength/ Calculated Shear Strength	
Test Designation	Test Result	ACI Equation 11-3	ACI Equation 11-5	Test Result/ ACI Eq. 11-3	Test Result/ ACI Eq. 11-5
LD1-N	1.895	2.000	2.240	0.948	0.846
LD1-S	2.071	2.000	2.240	1.036	0.925
SR2-S	1.697	2.000	2.211	0.849	0.768
LD2	2.077	2.000	2.299	1.039	0.903
LD3	2.241	2.000	2.329	1.121	0.962
LD4	2.324	2.000	2.184	1.162	1.064
			Mean	1.025	0.911
			Standard Deviation	0.104	0.092

A summary of the AASHTO LRFD 2012 shear design provisions can be seen in Table 4-2. Table 4-2 depicts the recorded normalized shear stress at ultimate load for each specimen at the chosen critical section of a distance (x_r) away from the centerline of the support. Comparative values for Equations 4-1 and 4-2 were calculated at the same critical section.

Table 4-2: Comparison of Test Results to AASHTO LRFD 2012 Shear Design Provisions

	Normalized Shear Stress at Ultimate Load, v_{xr} (√psi)		Actual Shear Strength/ Calculated Shear Strength
Test Designation	Test Result	AASHTO LRFD 2012 Shear Design Provisions	Test Result/ AASHTO LRFD 2012
LD1-N	1.895	2.245	0.844
LD1-S	2.071	2.245	0.922
SR2-S	2.241	2.184	1.026
LD2	2.286	2.292	0.997
LD3	3.095	2.342	1.321
LD4	2.324	2.168	1.072
		Mean	1.031
		Standard Deviation	0.149

4.4 COMPARISON OF PREDICTIONS AND EXPERIMENTAL RESULTS

ACI 318-11 equation 11-3, equation 11-5, and AASHTO LRFD 2012 shear design provisions all overestimate shear strength of concrete for a minimum of two out of the six University of Texas test specimens. As expected, the simplified ACI equation 11-3 is the most conservative of all three equations predicting a normalized shear stress (v_{xr}) of 2 for all specimens tested in this study.

Interestingly, the general ACI equation 11-5 and AASHTO LRFD 2012 shear design provisions predicted similar normalized shear stress (v_{xr}) for all specimens even though each equation was developed differently. ACI equation 11-5 was developed empirically as an estimation of shear strength at first diagonal cracking while AASHTO LRFD 2012 shear design provisions were developed based upon the behavioral MCFT model to estimate ultimate shear capacity. Note that the author cautions against using additional capacity beyond first diagonal cracking due to the unpredictable shear failure observed in the six University of Texas tests. Normalized shear stress (v_{xr}) at ultimate load was used only as a direct comparison to AASHTO LRFD 2012 shear design provisions.

Although all three of the previously described equations overestimate the concrete contribution to shear strength, both ACI 318-11 and AASHTO LRFD 2012 are constructed to prevent shear failure in field structures. Both design codes require minimum shear reinforcement ($A_{s,min}$) if the applied shear (V_u) is greater than one half of the calculated shear (V_c). Thus, only test specimens with actual shear strengths of less than half of the estimated shear strength would be in danger of shear failure in field specimens. Note that the lowest ratio of (*Shear Strength of Test Result/Code Estimation of Shear Strength*) was 0.768 for the six University of Texas test results.

CHAPTER 5

Conclusions

Six shear tests were completed on specimens without shear reinforcement at the University of Texas. Based upon the results of the shear tests conducted on slender beams ($a/d > 2.5$), the following conclusions can be observed:

- A summary of the six test results can be seen on the following page in Table 5-1. Comparisons of normalized shear stress at first diagonal cracking are made between concentrated and uniform load specimens at each of the aforementioned shear locations. The range of increase in normalized shear stress (depicted in Equation 5-1) was defined as the percent increase in normalized shear stress (v_{U1}, v_{U2}, v_{U3}) for the three individual uniform test results compared to the average normalized shear stress (v_{Cavg}) of the concentrated load tests. Average increase in normalized shear stress (depicted in Equation 5-2) was defined as the percent increase in average normalized shear stress (v_{Uavg}) of the uniform load specimens compared to the average normalized shear stress (v_{Cavg}) of the concentrated load specimens. Note that as shear force is taken at locations further away from the support, load distribution has less effect on normalized shear stress carried at the formation of first diagonal cracking.

$$\textit{Range of Increase} = \frac{v_{U1,2,3} - v_{Cavg}}{v_{Cavg}} * 100 \qquad \textit{Equation 5-1}$$

$$\textit{Average Increase} = \frac{v_{Uavg} - v_{Cavg}}{v_{Cavg}} * 100 \qquad \textit{Equation 5-2}$$

Table 5-1: Summary of Increase in Normalized First Cracking Shear Capacity from Concentrated to Uniform Load Specimens

Shear Location	Range of Increase (%)	Average Increase (%)
v_{ns}	25.5 - 54.0	38.3
v_d	-1.4 - 21.2	8.8
v_{xr}	10.0 - 23.1	17.3
v_{DAfStb}	-3.8 - 6.2	2.1

- In the context of ACI 318-11, when analyzing both uniform and concentrated load test results, the use of shear force load at first diagonal cracking is appropriate. Post cracking behavior for this six test study was unpredictable, and thus counting on additional shear capacity beyond first diagonal cracking is viewed to be unconservative for specimens without shear reinforcement.
- For the six test results, average normalized shear stress (v_{DAfStb}) at first diagonal cracking increased on average by only 2.1 percent from concentrated to uniform load specimens. General ACI-DAfStb database comparisons as well as direct comparisons between concentrated and uniform load test results found within the database show a much larger increase (15 to 54 percent) in average normalized shear stress (v_{DAfStb}) from concentrated to uniform load specimens.
- Although code equations (ACI 318-11 equation 11-3, ACI 318-11 equation 11-5, and AASHTO LRFD 2012 shear design provisions) all overestimate the shear contribution of concrete in comparison to test results, the equations are inherently conservative against shear failure for

field specimens. This conservatism is derived from both ACI318-11 and AASHTO 2012 requiring minimum shear reinforcement ($A_{s,min}$) if the applied shear (V_u) is greater than one half of the calculated shear (V_c).

The subject of load distribution in deeper slender specimens without shear reinforcement has only begun to be investigated. Further testing is needed to develop a broader understanding of the behavior of both specimens tested under concentrated and uniform load. The additional testing could be used to create a larger ACI-DAfStb shear database for uniform loads and to accurately quantify load distribution effects on shear capacity.

APPENDIX A

Shear Database Filtering

Appendix A includes a detailed explanation of the filtering process of the ACI-DAfStb shear database. Results are presented in the following manner:

- *Summary of Filtering Parameters*
- *Comparison of Test Results to the Database:* Table A-1 through Table A-2 and Figure A-1 through Figure A-2

A.1 SUMMARY OF FILTERING PARAMETERS

The concentrated load database is comprised of a total of 1365 data points. Data was filtered by the following three parameters as outlined within the main document:

- Shear span to depth ratio (*a/d*) greater than 2.4
- Longitudinal reinforcement ratio (ρ) between 0.75% and 1.25%
- Specimen depth (*d*) between 17 inches and 25 inches

Filtering produced 14 remaining data points which can be seen along with the University of Texas test results in Table A-1 and Figure A-1.

The uniform load database consisted of only 128 data points. Unfortunately, the majority of the tests were completed on small specimens with a depth of less than 12 inches. Thus, no direct comparison could be made between the database and test results. The specimen depth filter was removed in order to preserve useful data on smaller specimens. Additionally, the range on longitudinal reinforcement ratio was increased. Note that the database values for normalized shear stress (v_{DAfStb}) would be expected to be larger than the University of Texas values for normalized shear stress (v_{DAfStb}) due to size effects. Data was filtered by the following two parameters:

- Shear span to depth ratio (*a/d*) greater than 2.4
- Longitudinal reinforcement ratio (ρ) between 0.75% and 1.35%

Filtering produced 4 remaining data points. Results can be seen in Table A-2 and Figure A-2.

Table A-1: ACI-DAfStb Concentrated Load Filtered Database

Test Identification	Specimen Width, b_w (in.)	Specimen Height, *h* (in.)	Specimen Depth, *d* (in.)	Shear Span to Depth Ratio, *a/d*	Longitudinal Reinforcement Ratio, *ρ (%)*	Normalized Shear Stress, v_{DAfStb} ($\sqrt{f'_c}$)
163	9.84	18.46	17.20	2.89	0.9153	2.15
164	9.92	18.54	17.28	2.87	0.9039	2.05
165	39.45	18.54	17.28	2.87	0.9093	2.16
166	39.45	18.50	17.24	2.88	0.9114	2.05
167	118.31	18.58	17.28	2.87	0.9096	1.92
406	15.75	19.09	17.32	2.50	1.1932	2.30
418	15.75	19.09	17.32	2.50	1.1932	1.86
1029	11.81	19.69	17.72	2.92	0.8119	1.99
1030	11.81	19.69	17.72	2.92	0.8119	1.21
1234	46.06	23.23	21.18	3.30	0.7943	1.95
1272	8.86	19.49	17.72	3.93	1.2039	1.92
1273	11.81	25.47	23.62	3.94	1.1990	1.92
1359	12.06	24.06	20.94	2.89	1.2443	1.30
1363	16.06	23.94	20.75	2.92	1.1995	1.11
LD1-N	36.00	24.00	21.30	2.50	1.0175	1.90
LD1-S	36.00	24.00	21.30	2.50	1.0175	2.07
SR2-S	36.00	24.00	21.30	2.50	1.0175	1.70

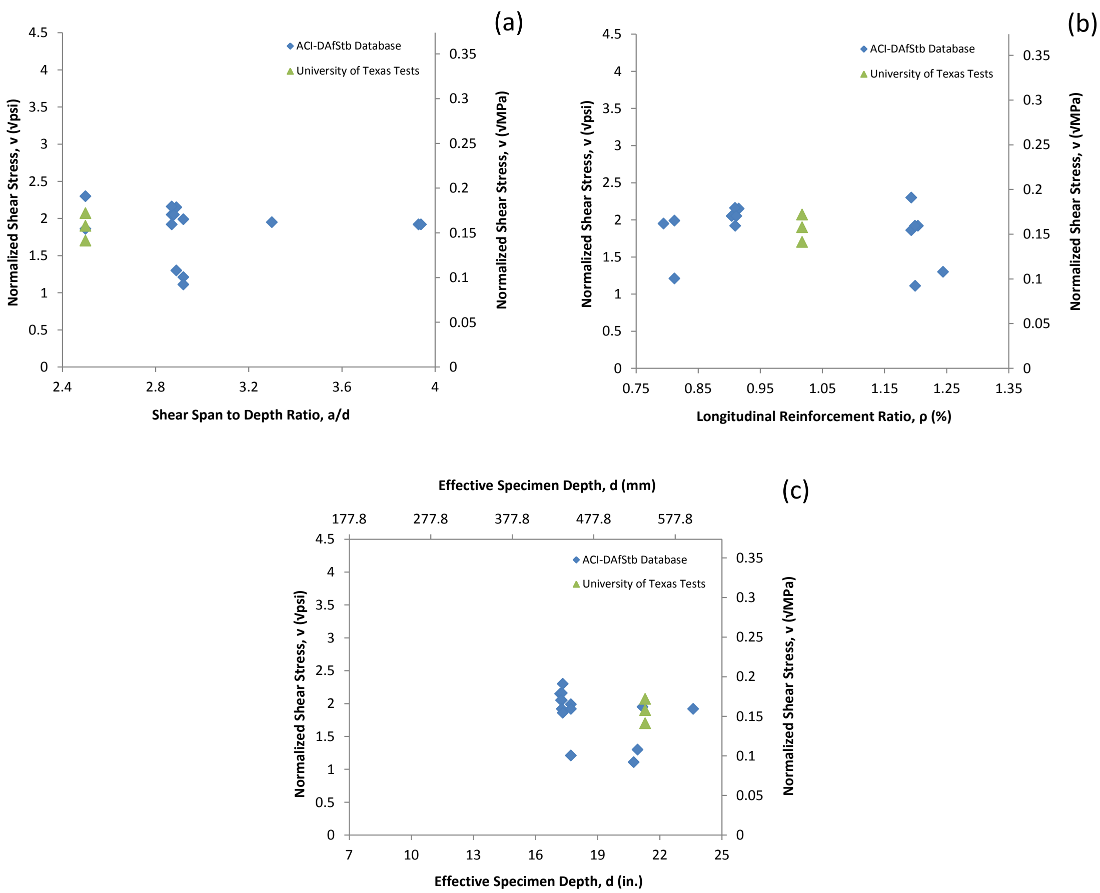


Figure A-1: ACI-DAfStb Database and University of Texas Concentrated Load Tests Showing the Following: (a) Shear Span to Depth Ratio, (b) Longitudinal Reinforcement Ratio, (c) Effective Specimen Depth

Table A-2: ACI-DAfStb Uniform Load Filtered Database

Test Identification	Specimen Width, b_w (in.)	Specimen Height, *h* (in.)	Specimen Depth, *d* (in.)	Shear Span to Depth Ratio, *a/d*	Longitudinal Reinforcement Ratio, *ρ (%)*	Normalized Shear Stress, v_{DafStb} ($\sqrt{f'_c}$)
26	6.00	12.00	10.00	2.40	1.3090	4.25
31	6.00	12.00	10.06	2.98	0.9960	3.03
32	6.00	12.00	10.00	3.00	1.3090	3.26
115	11.81	9.45	7.87	2.50	1.3400	2.97
LD2	36.00	24.00	21.30	2.53	1.0175	1.82
LD3	36.00	24.00	21.30	2.53	1.0175	1.96
LD4	36.00	24.00	21.30	2.53	1.0175	2.00

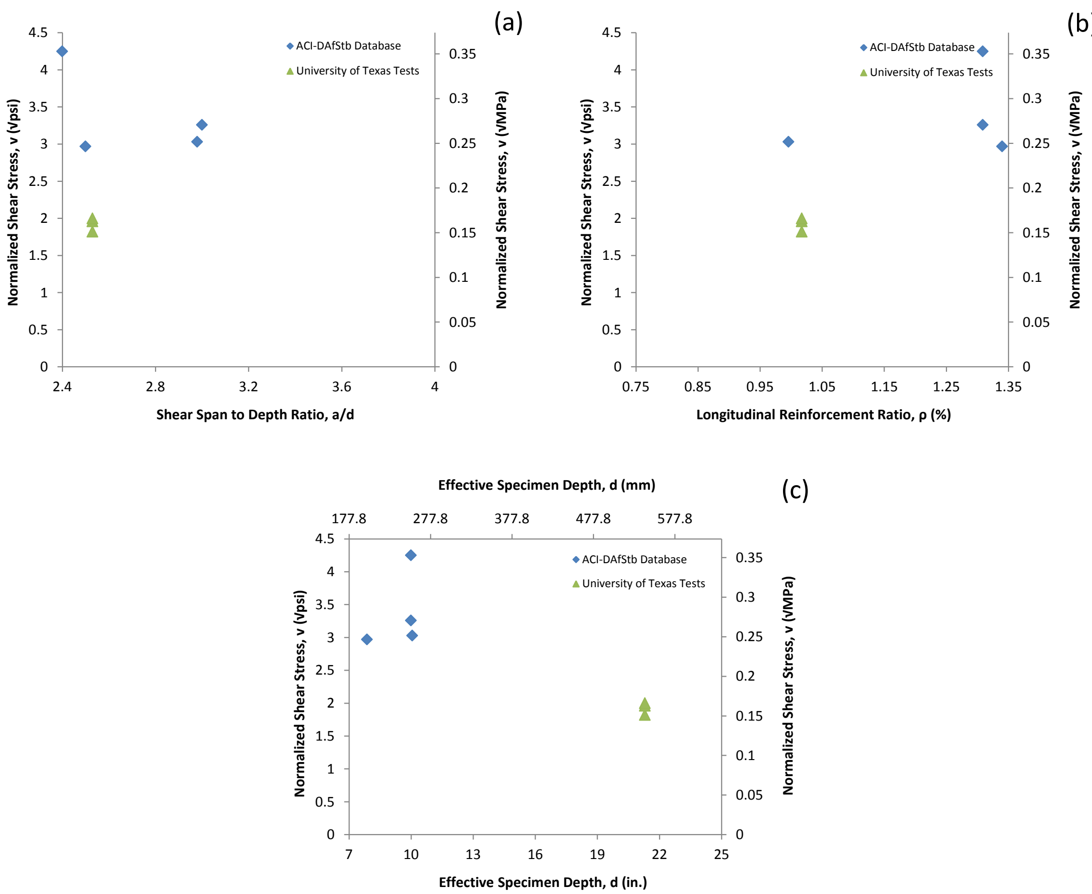


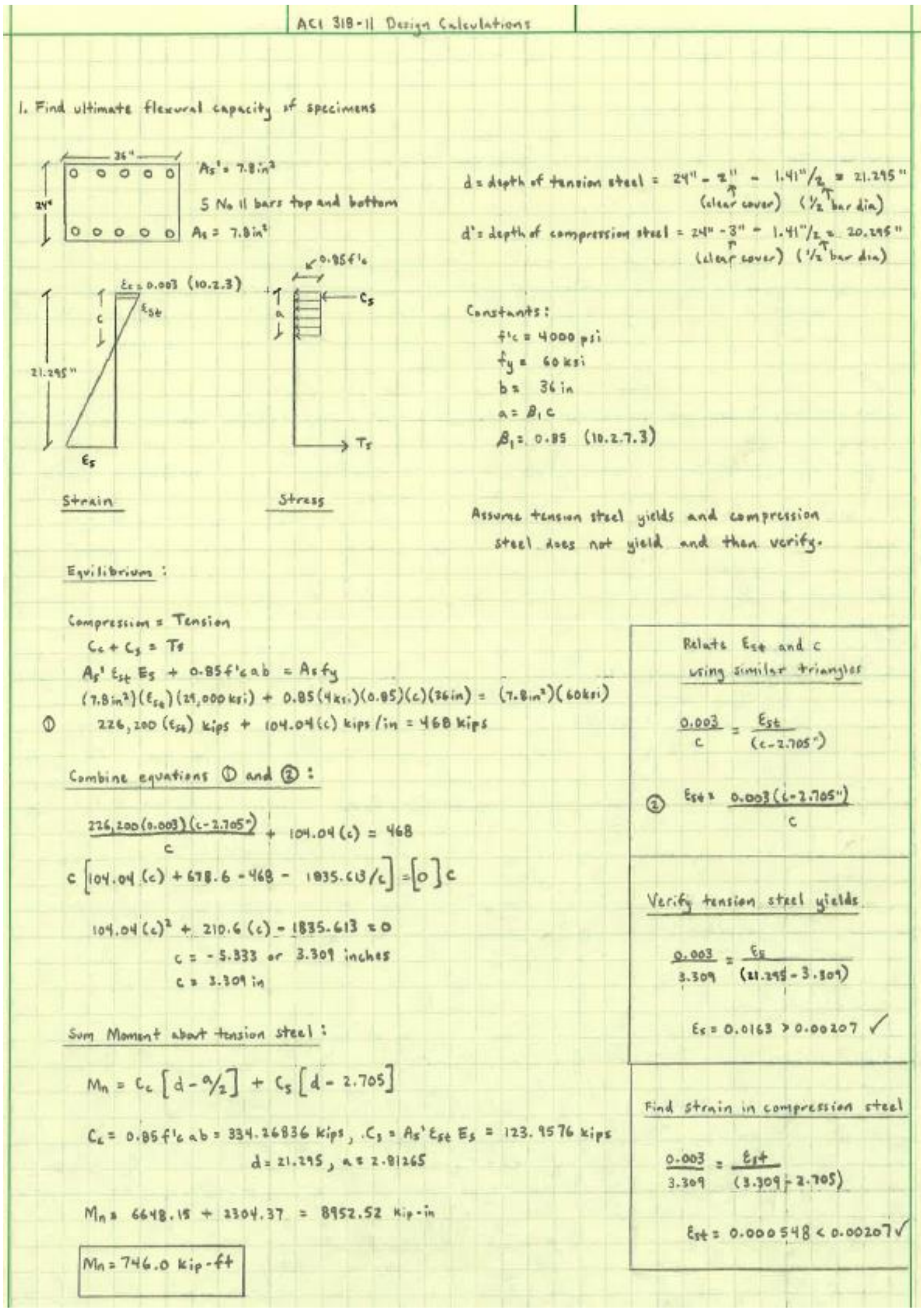
Figure A-2: ACI-DAfStb Database and University of Texas Uniform Load Tests Showing the Following: (a) Shear Span to Depth Ratio, (b) Longitudinal Reinforcement Ratio, (c) Effective Specimen Depth

APPENDIX B

Specimen Design and Construction

Appendix B includes detailed results pertaining to the design and construction of the six shear specimens: Results are presented in the following manner:

- *Design Calculations Based Upon ACI 318-11:* Figure B-1 through Figure B-2
- *Reinforcing Cage Construction:* Figure B-3
- *Concrete Placement:* Figure B-4
- *Concentrated Load Setup and Instrumentation:* Figure B-5
- *Uniform Load Setup and Instrumentation:* Figure B-6
- *Location of Form Brackets:* Figure B-7
- *Test Setup Photos:* Figure B-8



ACI 318-11 Design Calculations

1. Find ultimate flexural capacity of specimens

$A_s' = 7.8 in^2$

5 No 11 bars top and bottom

$A_s = 7.8 in^2$

d = depth of tension steel = 24" − 2" (clear cover) − 1.41"/2 (½ bar dia) = 21.295"

d' = depth of compression steel = 24" − 3" (clear cover) − 1.41"/2 (½ bar dia) = 20.295"

Constants:

$f'_c = 4000$ psi

$f_y = 60$ ksi

b = 36 in

$a = \beta_1 c$

$\beta_1 = 0.85$ (10.2.7.3)

Assume tension steel yields and compression steel does not yield and then verify.

Equilibrium:

Compression = Tension

$C_c + C_s = T_s$

$A_s' \varepsilon_{st} E_s + 0.85 f'_c a b = A_s f_y$

$(7.8 in^2)(\varepsilon_{st})(29{,}000 ksi) + 0.85(4 ksi)(0.85)(c)(36 in) = (7.8 in^2)(60 ksi)$

① $226{,}200 (\varepsilon_{st})$ kips $+ 104.04(c)$ kips/in $= 468$ kips

Relate ε_{st} and c using similar triangles

$\frac{0.003}{c} = \frac{\varepsilon_{st}}{(c - 2.705")}$

② $\varepsilon_{st} = \frac{0.003(c - 2.705")}{c}$

Combine equations ① and ②:

$\frac{226{,}200(0.003)(c - 2.705")}{c} + 104.04(c) = 468$

$c\left[104.04(c) + 678.6 - 468 - 1835.613/c\right] = [0]\,c$

$104.04(c)^2 + 210.6(c) - 1835.613 = 0$

c = −5.333 or 3.309 inches

c = 3.309 in

Verify tension steel yields

$\frac{0.003}{3.309} = \frac{\varepsilon_s}{(21.295 - 3.309)}$

$\varepsilon_s = 0.0163 > 0.00207$ ✓

Sum Moment about tension steel:

$M_n = C_c\left[d - a/2\right] + C_s\left[d - 2.705\right]$

$C_c = 0.85 f'_c a b = 334.26836$ kips, $C_s = A_s' \varepsilon_{st} E_s = 123.9576$ kips

d = 21.295, a = 2.81265

$M_n = 6648.15 + 2304.37 = 8952.52$ kip-in

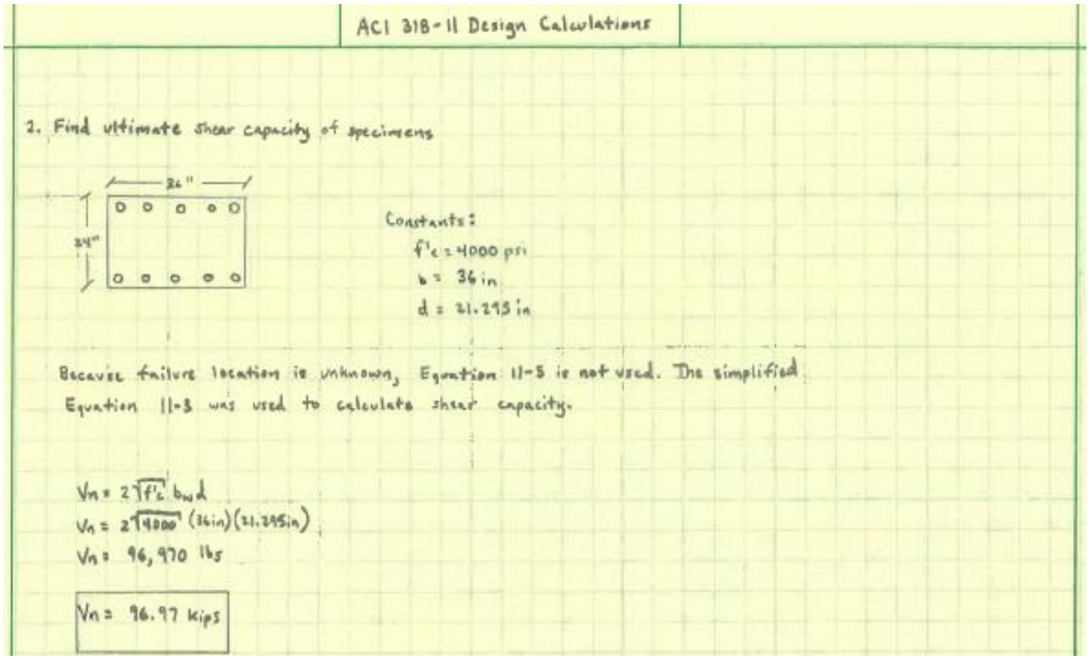
$M_n = 746.0$ kip-ft

Find strain in compression steel

$\frac{0.003}{3.309} = \frac{\varepsilon_{st}}{(3.309 - 2.705)}$

$\varepsilon_{st} = 0.000548 < 0.00207$ ✓

Figure B-1: ACI 318-11 Flexural Design Calculations



ACI 318-11 Design Calculations

2. Find ultimate shear capacity of specimens

36"

24"

Constants:

$f'_c = 4000$ psi

$b = 36$ in

$d = 21.295$ in

Because failure location is unknown, Equation 11-5 is not used. The simplified Equation 11-3 was used to calculate shear capacity.

$V_n = 2\sqrt{f'_c}\, b_w d$

$V_n = 2\sqrt{4000}\,(36in)(21.295in)$

$V_n = 96,970$ lbs

$V_n = 96.97$ kips

Figure B-2: ACI 318-11 Shear Design Calculations

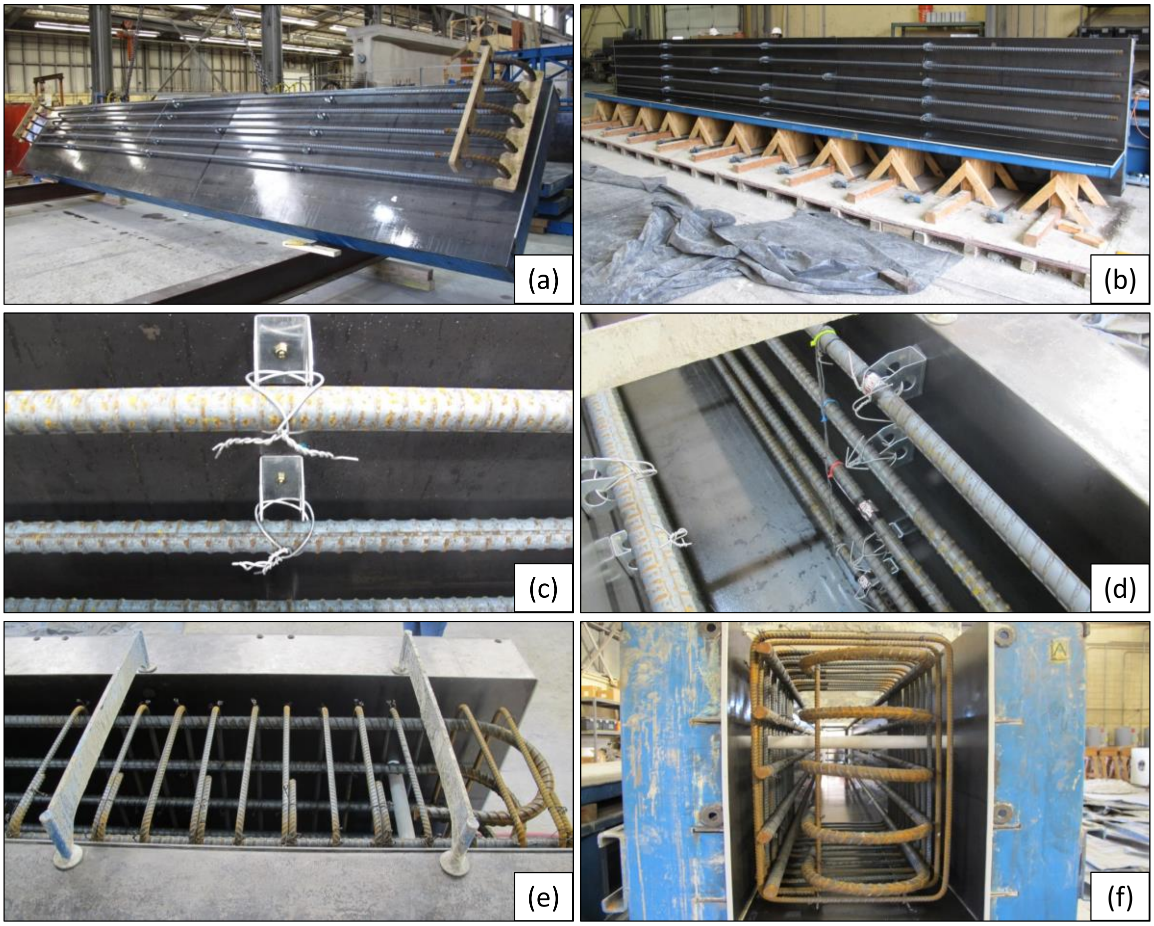
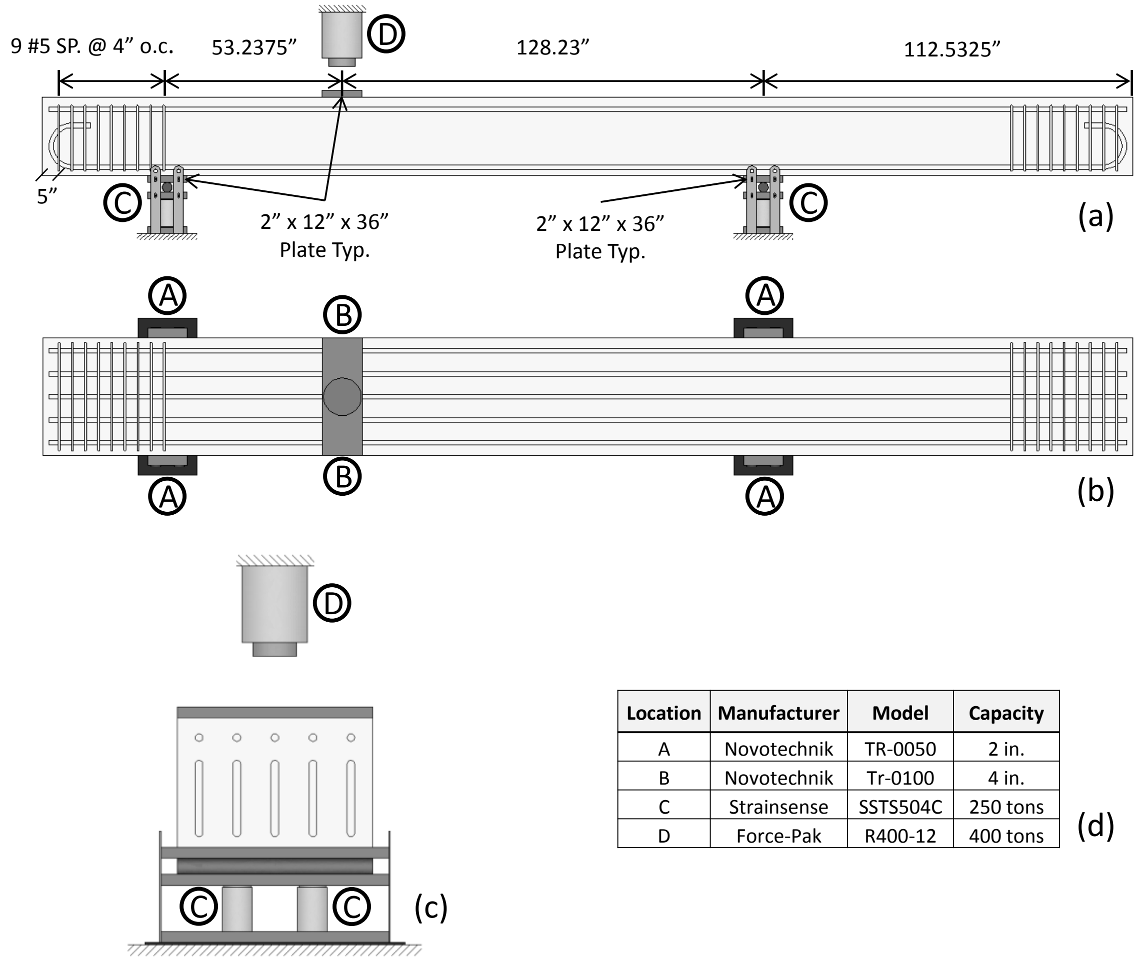


Figure B-3: Reinforcing Cage Construction Showing the Following: (a) Placement of Tension Steel, (b) Placement of Compression Steel, (c) and (d) Form Bracket Detail, (e) Stirrup Placement, (f) Completed Cage

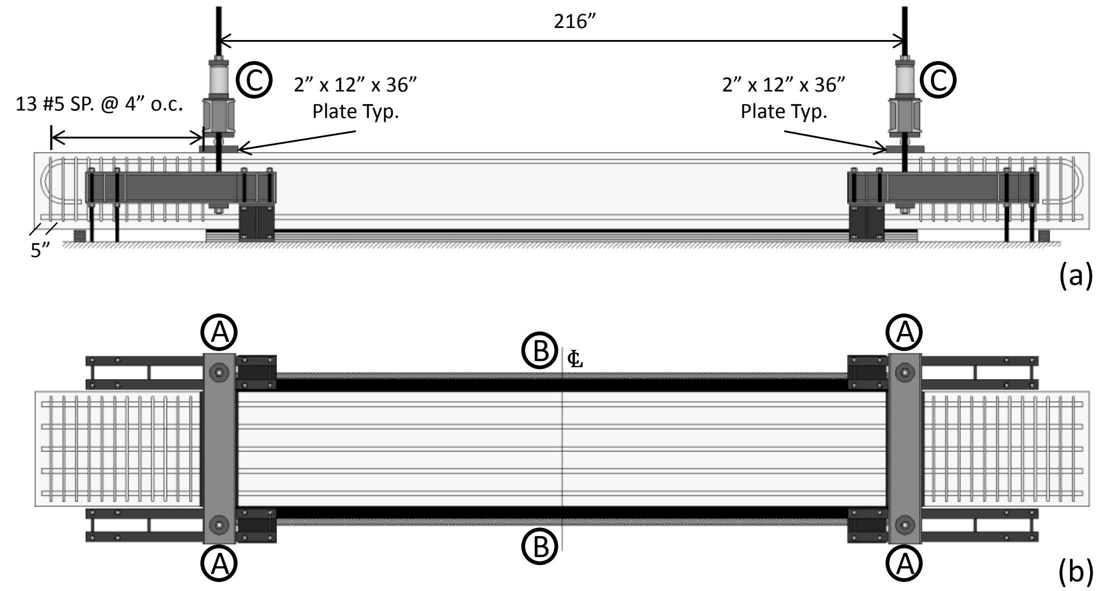
Figure B-4: Concrete Placement Showing the Following: (a) Slump Test, (b) Cylinder Finishing, (c) Main Specimen Placement, (d) Internal Vibration, (e) Finishing of Main Specimen, (f) Completed Specimen

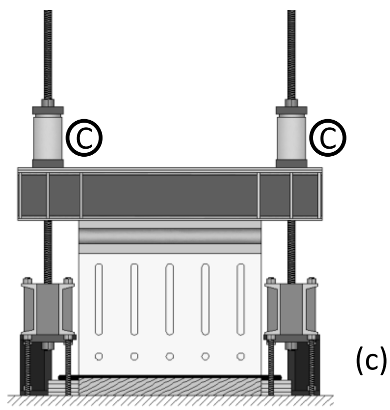


Location	Manufacturer	Model	Capacity
A	Novotechnik	TR-0050	2 in.
B	Novotechnik	Tr-0100	4 in.
C	Strainsense	SSTS504C	250 tons
D	Force-Pak	R400-12	400 tons

(d)

Figure B-5: Concentrated Load Setup Showing the Following: (a) Elevation View, (b) Plan View, (c) End View, (d) Instrumentation Designation





Location	Manufacturer	Model	Capacity
A	Novotechnik	TR-0050	2 in.
B	Novotechnik	Tr-0100	4 in.
C	Strainsense	SSTS504C	250 tons
n/a	Aero Tech	Kevlar Reinforced Bladder	50 psi

(d)

Figure B-6: Uniform Load Setup Showing the Following: (a) Elevation View, (b) Plan View, (c) End View, (d) Instrumentation Designation

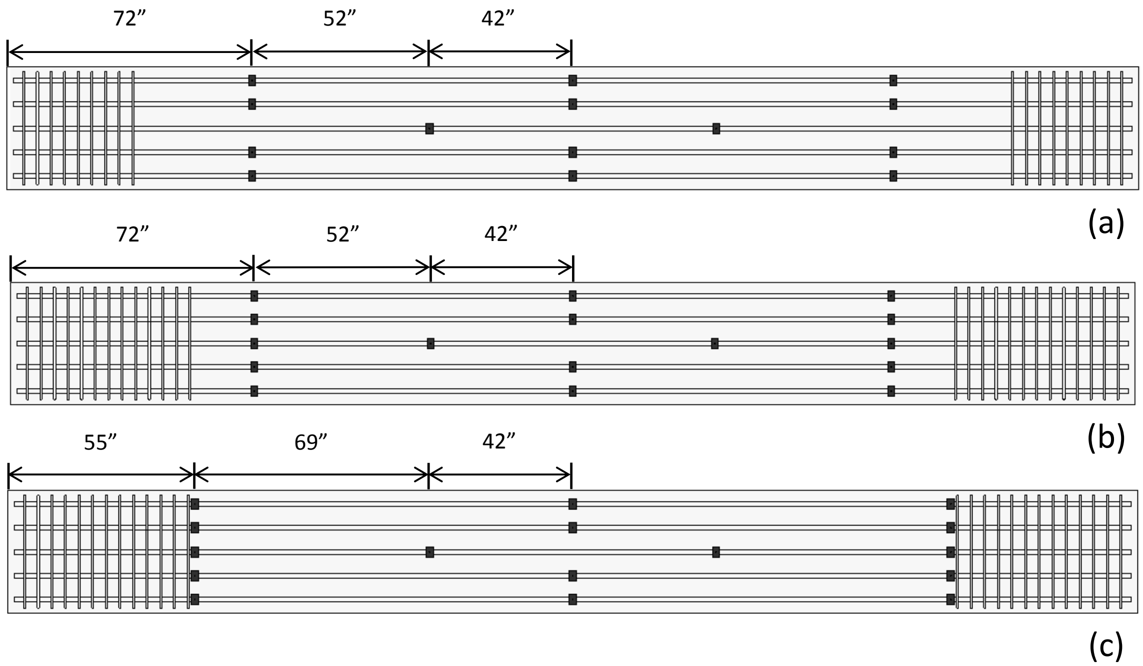


Figure B-7: Location of Form Brackets Showing the Following: (a) Specimen LD1, (b) Specimens LD2 and LD3, (c) Specimen LD4

Figure B-8: Test Setup Photos Showing the Following: (a), (b), and (c) Concentrated Load Setup, (d), (e), and (f) Uniform Load Setup

APPENDIX C

Material Testing Results

Appendix C includes detailed results of both concrete and steel material tests. The results are presented as follows:

- *Gradation Report for 1" Limestone Coarse Aggregate Found within Concrete Mix Design:* Figure C-1
- *Concrete Mix Design Properties:* Figure C-2
- *Individual Concrete Batch Tickets:* Figure C-3 through Figure C-7
- *Concrete Compressive Strength Data:* Table C-1 through Table C-5
- *Concrete Compressive Strength Development:* Figure C-8 through C-12
    - *Note cylinders were constructed and field cured in accordance with ASTM C31 (2010). Loss of strength after 28 days may be attributed to field curing conditions and/or concrete mixture design characteristics.*
- *Steel Mill Certification Details:* Figure C-13
- *Steel LTI Tensile Testing Data:* Table C-6

Report Date : 3/6/2013

Aggregate Properties Report

TEXAS CONCRETE MATERIALS
apac Safety First Always
a division of the Southeast Group of Oldcastle Materials

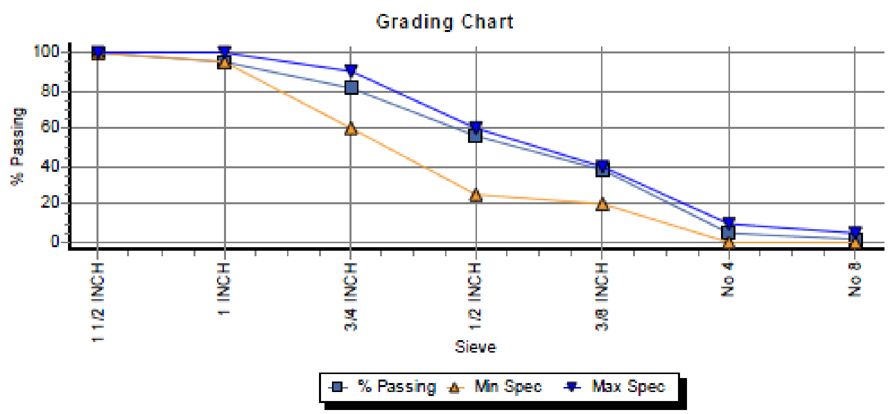
57CLS

Sample ID :	03042013	Plant :	973 PLANT
Sample Date :	3/6/2013	Customer :	
Sample By :	Corben Thomas	Attention :	
Supplier :	COLORADO	Project:	
Supplier Source :	SAN MARCOS	Specification :	ASTM C 33 #57
Sample Location :	PIT SAMPLE		

Grading

Sieve (mm)	Mass Retained	Cumulative Mass	% Retained	% Passing	Specification Min	% Pass Max
1 1/2 INCH	0	0	0	100	100	100
1 INCH	1.4	1.4	5	95	95	100
3/4 INCH	4.4	5.8	19	81	60	90
1/2 INCH	7.7	13.5	44	56	25	60
3/8 INCH	5.7	19.2	62	38	20	40
No 4	10.2	29.4	95	5	0	10
No 8	0.9	30.3	98	2	0	5

Decant	1.00 %	**Fineness Modulus**	6.75
Absorption	2.50%	**Specific Gravity**	2.57



Tested By :	Corben Thomas	**Approved By :**	Corben Thomas
Date :	3/4/2013	**Date :**	3/6/2013
		Certification Number :	ACI Aggregate Testing Technician: 36569

Figure C-1: Coarse Aggregate (1" Limestone) Gradation Report

TEXAS CONCRETE MATERIALS
apac Safety First Always

UT RESEARCH PROJECT

Date : **2/14/2014**
Mix Code : **4500727** Description : **4.5 SK NO FA, 3/4"LS, MRWR**

Revision Number : 4 Creation Date : 14 Feb 2014 Customer :
Plant : 973 PLANT Created By : cthomas2 Project :

Specifications

Consistence Class : 4.00 Air, % : 1.5
Strength Class : 3000 Max W/C : Max Agg Size : 1

Material Type	Material Code	Description	Supplier Source	Design Quantity	Specific Gravity	Volume ft3
Cement	CEMENT	CEMENT	ALAMO CEMENT CO-SANANTON	423 lb	3.15	2.15
Fine Aggregate	SAND	SAND	AUSTIN AGGREGATES-AUSTIN	1505 lb	2.62	9.20
Coarse Aggregate	57CLS	1" Limestone	COLORADO MATERIALS-SAN MA	1795 lb	2.57	11.19
Water	WATER	WATER	CITY-WATER	30.0 gal	1.00	4.01
Admixture	WREDUCER	WATER REDUCER	SIKA ADMIXTURES-DALLAS	7.0 /cwt	1.10	0.03
Admixture	WRRETARD	RETARDER/WATER REDUCER	SIKA ADMIXTURES-DALLAS	1.0 /cwt	1.20	0.00
			Yield	**3975 lb**		**27.00**

Design Properties

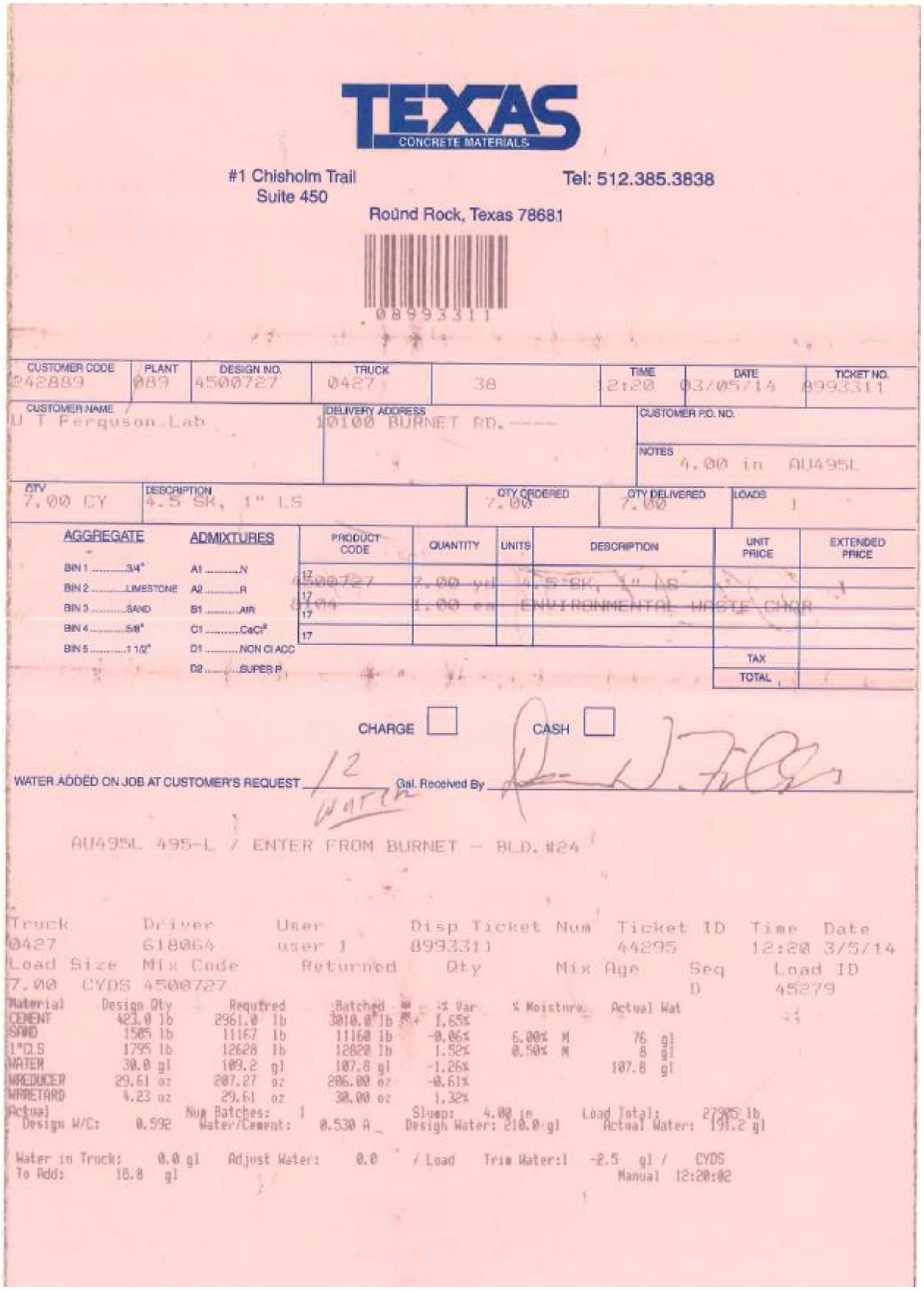
Density : 147.2 lb/ft3 Grading Specification :
Cement Content : 423 lb Actual Dmax : 1 mm

Prepared By :

Corben Thomas

Page 1

Figure C-2: Concrete Mix Design



TEXAS CONCRETE MATERIALS

#1 Chisholm Trail
Suite 450

Tel: 512.385.3838

Round Rock, Texas 78681

08993311

CUSTOMER CODE	PLANT	DESIGN NO.	TRUCK		TIME	DATE	TICKET NO.
242889	089	4500727	0427	38	2:20	03/05/14	8993311

CUSTOMER NAME: U T Ferguson Lab
DELIVERY ADDRESS: 10100 BURNET RD. -----
CUSTOMER P.O. NO.:
NOTES: 4.00 in AU495L

QTY	DESCRIPTION	QTY ORDERED	QTY DELIVERED	LOADS
7.00 CY	4.5 SK, 1" LS	7.00	7.00	1

AGGREGATE	ADMIXTURES
BIN 1 .... 3/4"	A1 .... N
BIN 2 .... LIMESTONE	A2 .... R
BIN 3 .... SAND	B1 .... AIR
BIN 4 .... 5/8"	C1 .... CaCl²
BIN 5 .... 1 1/2"	D1 .... NON Cl ACC
	D2 .... SUPER P

PRODUCT CODE	QUANTITY	UNITS	DESCRIPTION	UNIT PRICE	EXTENDED PRICE
4500727	7.00	yd	4.5 SK, 1" LS		
8104	1.00	ea	ENVIRONMENTAL WASTE CHGR		
				TAX	
				TOTAL	

CHARGE ☐ CASH ☐

WATER ADDED ON JOB AT CUSTOMER'S REQUEST 12 water Gal. Received By [signature]

AU495L 495-L / ENTER FROM BURNET - BLD.#24

Truck	Driver	User	Disp Ticket Num	Ticket ID	Time	Date
0427	618064	user 1	8993311	44295	12:20	3/5/14

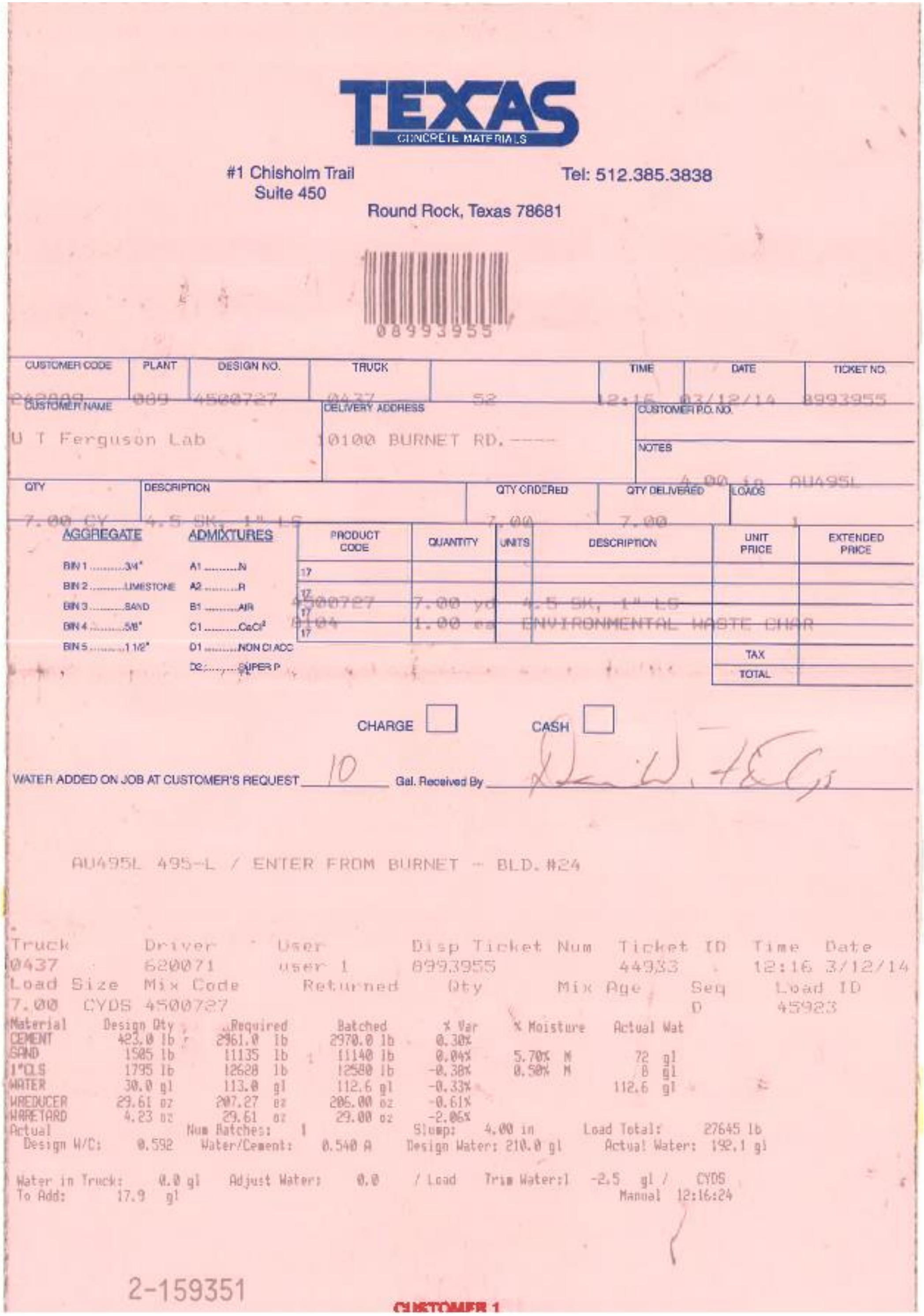
Load Size	Mix Code	Returned	Qty	Mix Age	Seq	Load ID
7.00 CYDS	4500727				0	45279

Material	Design Qty	Required	Batched	% Var	% Moisture	Actual Wat
CEMENT	423.0 lb	2961.0 lb	3010.0 lb	1.65%		
SAND	1505 lb	11167 lb	11160 lb	-0.06%	6.00% M	76 gl
1"CLS	1795 lb	12628 lb	12820 lb	1.52%	0.50% M	8 gl
WATER	30.0 gl	109.2 gl	107.8 gl	-1.26%		107.8 gl
WREDUCER	29.61 oz	207.27 oz	206.00 oz	-0.61%		
WRRETARD	4.23 oz	29.61 oz	30.00 oz	1.32%		

Actual Num Batches: 1 Slump: 4.00 in Load Total: 27905 lb
Design W/C: 0.592 Water/Cement: 0.530 A Design Water: 210.0 gl Actual Water: 191.2 gl

Water in Truck: 0.0 gl Adjust Water: 0.0 / Load Trim Water:1 -2.5 gl / CYDS
To Add: 18.8 gl Manual 12:20:02

Figure C-3: Specimen LD1 Concrete Batch Ticket



TEXAS CONCRETE MATERIALS

#1 Chisholm Trail
Suite 450
Round Rock, Texas 78681
Tel: 512.385.3838

08993955

CUSTOMER CODE	PLANT	DESIGN NO.	TRUCK		TIME	DATE	TICKET NO.
[illegible]	009	4500727	0437	52	12:16	03/12/14	8993955

CUSTOMER NAME	DELIVERY ADDRESS	CUSTOMER P.O. NO. / NOTES
U T Ferguson Lab	10100 BURNET RD.-----	4.00 in AU495L

QTY	DESCRIPTION	QTY ORDERED	QTY DELIVERED	LOADS
7.00 CY	4.5 SK, 1" LS	7.00	7.00	1

AGGREGATE	ADMIXTURES
BIN 1 ....3/4"	A1 ....N
BIN 2 ....LIMESTONE	A2 ....R
BIN 3 ....SAND	B1 ....AIR
BIN 4 ....5/8"	C1 ....CaCl²
BIN 5 ....1 1/2"	D1 ....NON Cl ACC
	D2 ....SUPER P

PRODUCT CODE	QUANTITY	UNITS	DESCRIPTION	UNIT PRICE	EXTENDED PRICE
4500727	7.00	yd	4.5 SK, 1" LS		
0104	1.00	ea	ENVIRONMENTAL WASTE CHAR		
				TAX	
				TOTAL	

CHARGE ☐ CASH ☐

WATER ADDED ON JOB AT CUSTOMER'S REQUEST 10 Gal. Received By [signature]

AU495L 495-L / ENTER FROM BURNET - BLD. #24

Truck	Driver	User	Disp Ticket Num	Ticket ID	Time	Date
0437	620071	user 1	8993955	44933	12:16	3/12/14

Load Size	Mix Code	Returned	Qty	Mix Age	Seq	Load ID
7.00 CYDS	4500727				D	45923

Material	Design Qty	Required	Batched	% Var	% Moisture	Actual Wat
CEMENT	423.0 lb	2961.0 lb	2970.0 lb	0.30%		
SAND	1505 lb	11135 lb	11140 lb	0.04%	5.70% M	72 gl
1"CLS	1795 lb	12628 lb	12580 lb	-0.38%	0.50% M	8 gl
WATER	30.0 gl	113.0 gl	112.6 gl	-0.33%		112.6 gl
WREDUCER	29.61 oz	207.27 oz	206.00 oz	-0.61%		
WRETARD	4.23 oz	29.61 oz	29.00 oz	-2.06%		

Actual Num Batches: 1 Slump: 4.00 in Load Total: 27645 lb
Design W/C: 0.592 Water/Cement: 0.540 A Design Water: 210.0 gl Actual Water: 192.1 gl

Water in Truck: 0.0 gl Adjust Water: 0.0 / Load Trim Water:1 -2.5 gl / CYDS
To Add: 17.9 gl Manual 12:16:24

2-159351

CUSTOMER 1

Figure C-4: Specimen LD2 Concrete Batch Ticket

TEXAS CONCRETE MATERIALS

#1 Chisholm Trail
Suite 450
Round Rock, Texas 78681
Tel: 512.385.3838

08994433

CUSTOMER CODE	PLANT	DESIGN NO.	TRUCK		TIME	DATE	TICKET NO.
242889	089	4500727	0456	49	13:10	03/18/14	8994433

CUSTOMER NAME	DELIVERY ADDRESS	CUSTOMER P.O. NO.
U T Ferguson Lab	10100 BURNET RD.	
		NOTES: 4.00 in AU495L

QTY	DESCRIPTION	QTY ORDERED	QTY DELIVERED	LOADS
7.50 CY	4.5 SK, 1" LS	7.50	7.50	1

AGGREGATE	ADMIXTURES
BIN 1 ....3/4"	A1 ....N
BIN 2 ....LIMESTONE	A2 ....R
BIN 3 ....SAND	B1 ....AIR
BIN 4 ....5/8"	C1 ....CaCl²
BIN 5 ....1 1/2"	D1 ....NON Cl ACC
	D2 ....SUPER P

PRODUCT CODE	QUANTITY	UNITS	DESCRIPTION	UNIT PRICE	EXTENDED PRICE
4500727	7.50	yd	4.5 SK, 1" LS		
8104	1.00	ea	ENVIRONMENTAL WASTE CHAR		
				TAX	
				TOTAL	

CHARGE ☐ CASH ☐

WATER ADDED ON JOB AT CUSTOMER'S REQUEST 20 Gal. Received By [signature]

AU495L 495-L / ENTER FROM BURNET - BLD. #24

Truck	Driver	User	Disp Ticket Num	Ticket ID	Time	Date
0456	619219	user 1	8994433	45406	13:10	3/18/14

Load Size	Mix Code	Returned	Qty	Mix Age	Seq	Load ID
7.50 CYDS	4500727				D	46400

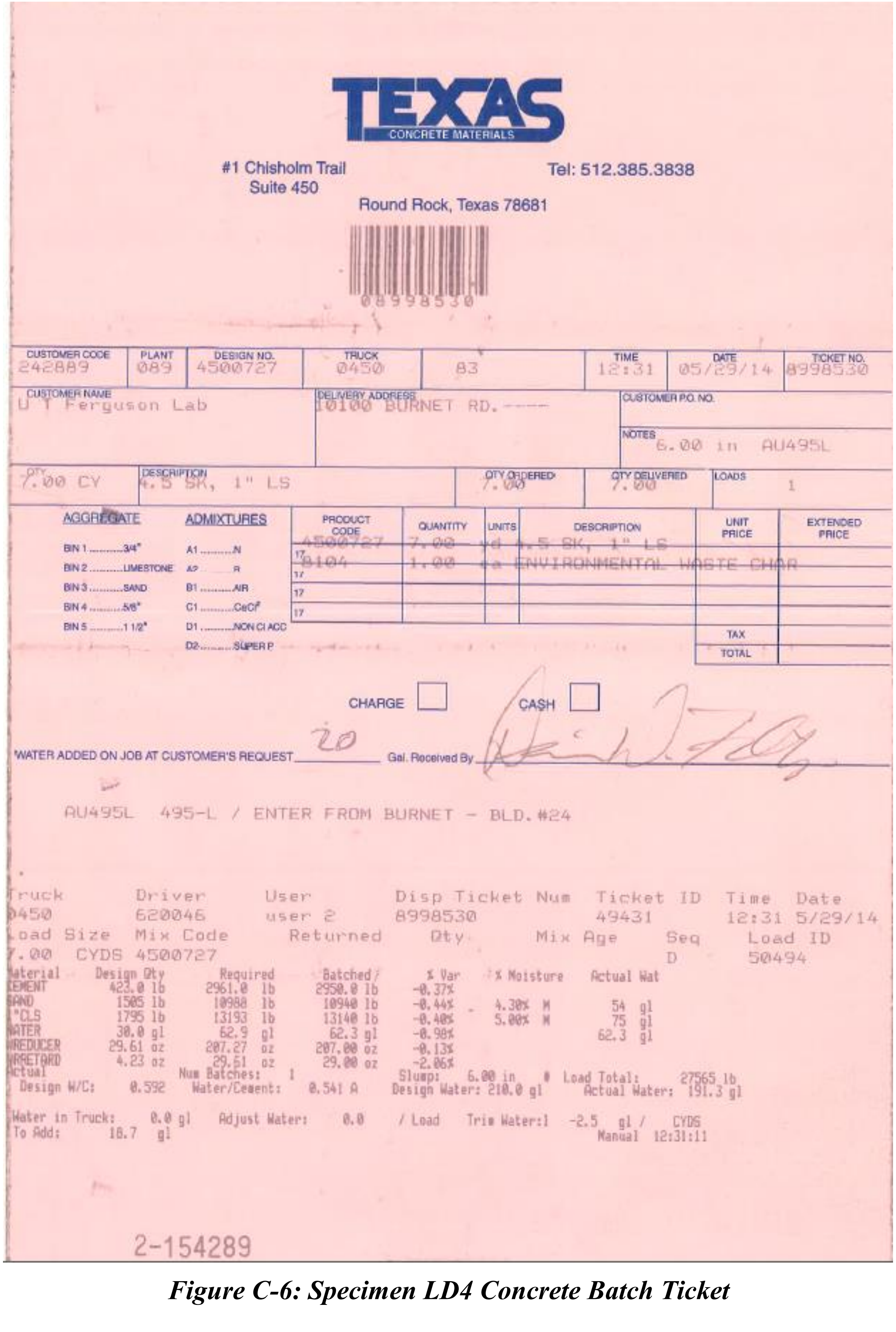
Material	Design Qty	Required	Batched	% Var	% Moisture	Actual Wat
CEMENT	423.0 lb	3172.5 lb	3150.0 lb	-0.71%		
SAND	1505 lb	11908 lb	11880 lb	-0.24%	5.50% M	74 gl
1"CLS	1795 lb	13530 lb	13500 lb	-0.22%	0.50% M	8 gl
WATER	30.0 gl	123.8 gl	122.8 gl	-0.78%		122.8 gl
WREDUCER	29.61 oz	222.08 oz	220.00 oz	-0.93%		
WRRETARD	4.23 oz	31.73 oz	31.00 oz	-2.29%		

Actual Num Batches: 1 Slump: 4.00 in Load Total: 29571 lb
Design W/C: 0.592 Water/Cement: 0.543 A Design Water: 225.0 gl Actual Water: 205.1 gl

Water in Truck: 0.0 gl Adjust Water: 0.0 / Load Trim Water:1 -2.5 gl / CYDS
To Add: 19.9 gl Manual 13:10:09

2-152868

Figure C-5: Specimen LD3 Concrete Batch Ticket



TEXAS CONCRETE MATERIALS

#1 Chisholm Trail
Suite 450

Round Rock, Texas 78681

Tel: 512.385.3838

08998530

CUSTOMER CODE	PLANT	DESIGN NO.	TRUCK		TIME	DATE	TICKET NO.
242889	089	4500727	0450	83	12:31	05/29/14	8998530

CUSTOMER NAME: U T Ferguson Lab

DELIVERY ADDRESS: 10100 BURNET RD. -----

CUSTOMER P.O. NO.

NOTES: 6.00 in AU495L

QTY: 7.00 CY | DESCRIPTION: 4.5 SK, 1" LS | QTY ORDERED: 7.00 | QTY DELIVERED: 7.00 | LOADS: 1

PRODUCT CODE	QUANTITY	UNITS	DESCRIPTION	UNIT PRICE	EXTENDED PRICE
4500727	7.00	yd	4.5 SK, 1" LS		
8104	1.00	ea	ENVIRONMENTAL WASTE CHAR		

AGGREGATE: BIN 1 ....3/4"; BIN 2 ....LIMESTONE; BIN 3 ....SAND; BIN 4 ....5/8"; BIN 5 ....1 1/2"

ADMIXTURES: A1 ....N; A2 ....R; B1 ....AIR; C1 ....CaCl²; D1 ....NON Cl ACC; D2 ....SUPER P

TAX

TOTAL

CHARGE ☐ CASH ☐

WATER ADDED ON JOB AT CUSTOMER'S REQUEST 20 Gal. Received By

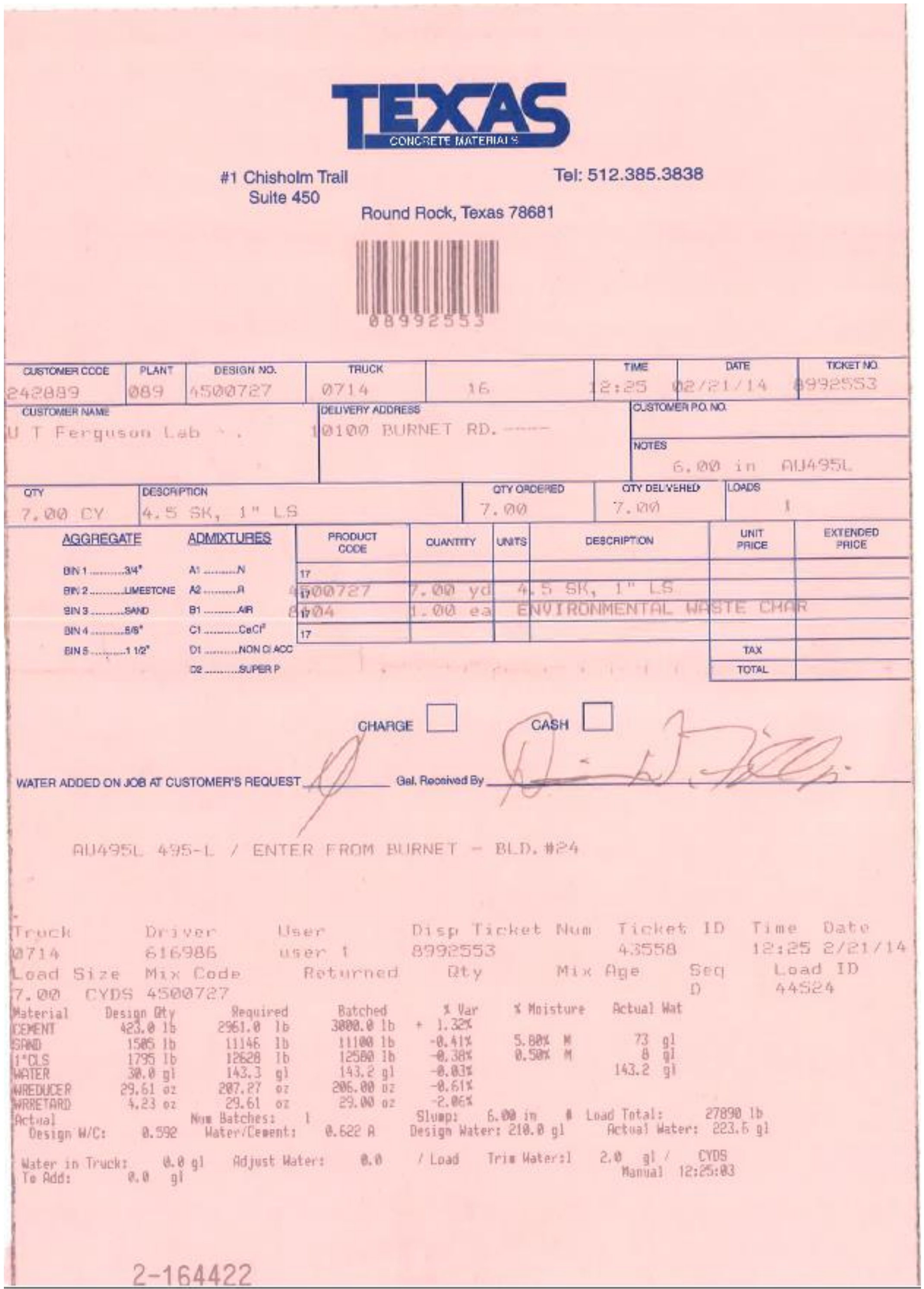
AU495L 495-L / ENTER FROM BURNET - BLD.#24

```
Truck      Driver     User       Disp Ticket Num   Ticket ID   Time   Date
0450       620046     user 2     8998530           49431       12:31 5/29/14
Load Size  Mix Code   Returned   Qty        Mix Age      Seq    Load ID
7.00  CYDS 4500727                                       D      50494
Material   Design Qty   Required     Batched/     % Var    % Moisture   Actual Wat
CEMENT     423.0 lb     2961.0 lb    2950.0 lb    -0.37%
SAND       1505 lb      10988 lb     10940 lb     -0.44%   4.30% M      54 gl
1"CLS      1795 lb      13193 lb     13140 lb     -0.40%   5.00% M      75 gl
WATER      30.0 gl      62.9 gl      62.3 gl      -0.98%                62.3 gl
WREDUCER   29.61 oz     207.27 oz    207.00 oz    -0.13%
WRRETARD   4.23 oz      29.61 oz     29.00 oz     -2.06%
Actual                  Num Batches: 1            Slump: 6.00 in  # Load Total: 27565 lb
 Design W/C: 0.592      Water/Cement: 0.541 A     Design Water: 210.0 gl   Actual Water: 191.3 gl

Water in Truck: 0.0 gl   Adjust Water: 0.0   / Load   Trim Water:1  -2.5 gl /  CYDS
To Add: 18.7 gl                                                  Manual 12:31:11
```

2-154289

Figure C-6: Specimen LD4 Concrete Batch Ticket


TEXAS CONCRETE MATERIALS

#1 Chisholm Trail
Suite 450
Round Rock, Texas 78681
Tel: 512.385.3838

08992553

CUSTOMER CODE	PLANT	DESIGN NO.	TRUCK		TIME	DATE	TICKET NO.
242889	089	4500727	0714	16	12:25	02/21/14	8992553

CUSTOMER NAME: U T Ferguson Lab

DELIVERY ADDRESS: 10100 BURNET RD.

CUSTOMER P.O. NO.:

NOTES: 6.00 in AU495L

QTY	DESCRIPTION	QTY ORDERED	QTY DELIVERED	LOADS
7.00 CY	4.5 SK, 1" LS	7.00	7.00	1

AGGREGATE: BIN 1 ....3/4"; BIN 2 ....LIMESTONE; BIN 3 ....SAND; BIN 4 ....5/8"; BIN 5 ....1 1/2"

ADMIXTURES: A1 ....N; A2 ....R; B1 ....AIR; C1 ....CaCl²; D1 ....NON Cl ACC; D2 ....SUPER P

PRODUCT CODE	QUANTITY	UNITS	DESCRIPTION	UNIT PRICE	EXTENDED PRICE
17					
4500727	7.00	yd	4.5 SK, 1" LS		
8404	1.00	ea	ENVIRONMENTAL WASTE CHAR		
17					
				TAX	
				TOTAL	

CHARGE ☐ CASH ☐

WATER ADDED ON JOB AT CUSTOMER'S REQUEST ____ Gal. Received By ____

AU495L 495-L / ENTER FROM BURNET - BLD.#24

Truck	Driver	User	Disp Ticket Num	Ticket ID	Time	Date
0714	616986	user 1	8992553	43558	12:25	2/21/14

Load Size	Mix Code	Returned	Qty	Mix Age	Seq	Load ID
7.00 CYDS	4500727				D	44524

Material	Design Qty	Required	Batched	% Var	% Moisture	Actual Wat
CEMENT	423.0 lb	2961.0 lb	3000.0 lb	+ 1.32%		
SAND	1505 lb	11146 lb	11100 lb	-0.41%	5.80% M	73 gl
1"CLS	1795 lb	12628 lb	12580 lb	-0.38%	0.50% M	8 gl
WATER	30.0 gl	143.3 gl	143.2 gl	-0.03%		143.2 gl
WREDUCER	29.61 oz	207.27 oz	206.00 oz	-0.61%		
WRRETARD	4.23 oz	29.61 oz	29.00 oz	-2.06%		

Actual Num Batches: 1 Slump: 6.00 in # Load Total: 27890 lb

Design W/C: 0.592 Water/Cement: 0.622 A Design Water: 210.0 gl Actual Water: 223.6 gl

Water in Truck: 0.0 gl Adjust Water: 0.0 / Load Trim Water:1 2.0 gl / CYDS

To Add: 0.0 gl Manual 12:25:03

2-164422

Figure C-7: Specimen SR2 Concrete Batch Ticket

Table C-1: Specimen LD1 Concrete Compressive Strength Data

Cylinder ID	Date	Time	Test (days)	Diameter (in)	$Length_1$ (in)	$Length_2$ (in)	$Length_3$ (in)	$Length_4$ (in)	$Length_{AVG}$ (in)	L/D ratio	Maximum Load (lbs)	Failure Type	Maximum Stress (psi)
LD1_1	3/7/2014	3:37 PM	2	4.006	7.7775	7.7765	7.7830	7.7750	7.7780	1.94	22,424	III	1779.10
LD1_2	3/8/2014	5:45 PM	3	4.006	7.7840	7.7900	7.7900	7.7875	7.7879	1.94	31,438	III	2494.27
LD1_3	3/8/2014	5:55 PM	3	4.007	7.8490	7.8505	7.8545	7.8500	7.8510	1.96	30,733	III	2437.12
LD1_4	3/8/2014	6:03 PM	3	4.006	7.8585	7.8570	7.8750	7.8600	7.8626	1.96	31,112	III	2468.40
LD1_5	3/12/2014	10:40 AM	7	4.006	7.7635	7.7640	7.7710	7.7660	7.7661	1.94	41,451	III	3288.69
LD1_6	3/13/2014	10:44 AM	7	4.006	7.7575	7.7595	7.7640	7.7620	7.7608	1.94	40,952	III	3249.10
LD1_7	3/14/2014	10:48 PM	7	4.007	7.7880	7.7880	7.7990	7.7935	7.7921	1.94	41,003	III	3251.52
LD1_8	3/19/2014	2:20 PM	14	4.007	7.8350	7.8290	7.8360	7.8360	7.8340	1.96	47,798	III	3790.37
LD1_9	3/19/2014	2:26 PM	14	4.005	7.7730	7.7785	7.7675	7.7755	7.7736	1.94	46,766	III	3712.23
LD1_10	4/2/2014	1:49 PM	28	4.008	7.7700	7.7730	7.7800	7.7770	7.7750	1.94	48,074	III	3810.35
LD1_11	4/2/2014	1:51 PM	28	4.005	7.7930	7.7915	7.7900	7.7905	7.7913	1.95	46,156	III	3663.81
LD1_12	4/2/2014	1:54 PM	28	4.006	7.7740	7.7790	7.7760	7.7785	7.7769	1.94	46,216	III	3666.74
LD1_13	4/24/2014	11:23 AM	50	4.005	7.7445	7.7450	7.7590	7.7640	7.7531	1.94	46,061	III	3656.27
LD1_14	4/24/2014	11:26 AM	50	4.006	7.7700	7.7725	7.7890	7.7825	7.7785	1.94	47,506	III	3769.09
LD1_15	4/24/2014	11:29 AM	50	4.006	7.7790	7.7860	7.7825	7.7840	7.7829	1.94	44,710	III	3547.26

Table C-2: Specimen LD2 Concrete Compressive Strength Data

Cylinder ID	Date	Time	Test (days)	Diameter (in)	$Length_1$ (in)	$Length_2$ (in)	$Length_3$ (in)	$Length_4$ (in)	$Length_{AVG}$ (in)	L/D ratio	Maximum Load (lbs)	Failure Type	Maximum Stress (psi)
LD2_1	3/15/2014	1:38 PM	3	4.010	7.7880	7.7775	7.7770	7.7825	7.7813	1.94	29,555	III	2340.20
LD2_2	3/15/2014	1:42 PM	3	4.011	7.7770	7.7790	7.7915	7.7860	7.7834	1.94	29,254	III	2315.21
LD2_3	3/15/2014	1:46 PM	3	4.011	7.6830	7.6855	7.6845	7.6815	7.6836	1.92	29,262	III	2315.84
LD2_4	3/19/2014	2:30 PM	7	4.012	7.7740	7.7660	7.7640	7.7695	7.7684	1.94	43,154	III	3413.57
LD2_5	3/19/2014	2:34 PM	7	4.011	7.7825	7.7835	7.7785	7.7825	7.7818	1.94	43,945	III	3477.88
LD2_6	3/19/2014	2:37 PM	7	4.008	7.8280	7.8215	7.8345	7.8330	7.8293	1.95	42,801	III	3392.41
LD2_7	3/26/2014	10:52 AM	14	4.008	7.7200	7.7065	7.7085	7.7125	7.7119	1.92	52,911	III	4193.73
LD2_8	3/26/2014	10:56 AM	14	4.008	7.8080	7.8080	7.8085	7.8100	7.8086	1.95	51,866	III	4110.91
LD2_9	4/9/2014	10:38 AM	28	4.009	7.8260	7.8340	7.8230	7.8260	7.8273	1.95	56,106	III	4444.75
LD2_10	4/9/2014	10:41 AM	28	4.008	7.8120	7.8140	7.8160	7.8110	7.8133	1.95	54,430	III	4314.13
LD2_11	4/9/2014	10:45 AM	28	4.005	7.7270	7.7330	7.7245	7.7280	7.7281	1.93	56,581	III	4491.34
LD2_12	5/15/2014	4:38 PM	64	4.006	7.8005	7.8105	7.7920	7.7860	7.7973	1.95	50,874	III	4036.31
LD2_13	5/15/2014	4:41 PM	64	4.006	7.7780	7.7790	7.7835	7.7815	7.7805	1.94	51,003	III	4046.54
LD2_14	5/15/2014	4:44 PM	64	4.005	7.7205	7.7175	7.7230	7.7190	7.7200	1.93	51,582	III	4094.52
LD2_15	5/15/2014	4:47 PM	64	4.005	7.7230	7.7225	7.7255	7.7270	7.7245	1.93	51,720	III	4105.48

Table C-3: Specimen LD3 Concrete Compressive Strength Data

Cylinder ID	Date	Time	Test (days)	Diameter (in)	$Length_1$ (in)	$Length_2$ (in)	$Length_3$ (in)	$Length_4$ (in)	$Length_{AVG}$ (in)	L/D ratio	Maximum Load (lbs)	Failure Type	Maximum Stress (psi)
LD3_1	3/20/2014	10:54 AM	2								24,256	III	
LD3_2	3/21/2014	1:14 PM	3	4.010	7.8185	7.8195	7.8395	7.8220	7.8249	1.95	30,845	III	2442.34
LD3_3	3/21/2014	1:16 PM	3	4.009	7.7845	7.7860	7.7915	7.7845	7.7866	1.94	32,247	III	2554.63
LD3_4	3/21/2014	1:18 PM	3	4.010	7.8230	7.8280	7.8375	7.8270	7.8289	1.95	31,843	III	2521.36
LD3_5	3/25/2014	4:16 PM	7	4.012	7.8390	7.8395	7.8465	7.8390	7.8410	1.95	41,322	III	3268.66
LD3_6	3/25/2014	4:20 PM	7	4.011	7.7690	7.7730	7.7785	7.7760	7.7741	1.94	40,281	III	3187.90
LD3_7	3/25/2014	4:24 PM	7	4.012	7.7930	7.7890	7.7895	7.7900	7.7904	1.94	40,212	III	3180.86
LD3_8	4/1/2014	3:18 PM	14	4.012	7.8220	7.8225	7.8255	7.8235	7.8234	1.95	44,513	III	3521.07
LD3_9	4/1/2014	3:20 PM	14	4.012	7.8040	7.8020	7.8015	7.7935	7.8003	1.94	44,762	III	3540.77
LD3_10	4/15/2014	4:42 PM	28	4.010	7.8355	7.8430	7.8550	7.8355	7.8423	1.96	47,119	III	3730.93
LD3_11	4/15/2014	4:45 PM	28	4.006	7.8010	7.7955	7.8000	7.7955	7.7980	1.95	47,007	III	3729.50
LD3_12	4/15/2014	4:47 PM	28	4.008	7.7905	7.8085	7.7970	7.7920	7.7970	1.95	47,454	III	3761.21
LD3_13	5/16/2014	6:21 PM	59	4.007	7.7430	7.7440	7.7540	7.7495	7.7476	1.93	45,287	III	3591.24
LD3_14	5/16/2014	6:27 PM	59	4.006	7.7710	7.7820	7.7855	7.7695	7.7770	1.94	43,283	III	3434.04
LD3_15	5/16/2014	6:32 PM	59	4.007	7.7860	7.7830	7.7890	7.7810	7.7848	1.94	44,633	III	3539.38

Table C-4: Specimen LD4 Concrete Compressive Strength Data

Cylinder ID	Date	Time	Test (days)	Diameter (in)	$Length_1$ (in)	$Length_2$ (in)	$Length_3$ (in)	$Length_4$ (in)	$Length_{AVG}$ (in)	L/D ratio	Maximum Load (lbs)	Failure Type	Maximum Stress (psi)
LD4_1	6/5/2014	3:23 PM	7	4.012	7.7910	7.7890	7.8025	7.7980	7.7951	1.94	41,149	III	3254.97
LD4_2	6/5/2014	3:26 PM	7	4.012	7.8425	7.8430	7.8385	7.8490	7.8433	1.95	41,949	III	3318.26
LD4_3	6/5/2014	3:29 PM	7	4.013	7.8360	7.8455	7.8400	7.8360	7.8394	1.95	41,949	III	3316.60
LD4_4	6/12/2014	10:02 AM	14	4.020	7.8905	7.8855	7.8895	7.8930	7.8896	1.96	47,833	III	3768.65
LD4_5	6/12/2014	10:05 AM	14	4.022	7.8670	7.8585	7.8715	7.8680	7.8663	1.96	45,915	III	3613.94
LD4_6	6/12/2014	10:09 AM	14	4.019	7.8525	7.8465	7.8560	7.8510	7.8515	1.95	46,181	III	3640.30
LD4_7	6/26/2014	2:48 PM	28	4.019	7.8765	7.8775	7.8730	7.8730	7.8750	1.96	48,702	III	3839.02
LD4_8	6/26/2014	2:52 PM	28	4.019	7.9040	7.9075	7.9070	7.9020	7.9051	1.97	48,856	III	3851.16
LD4_9	6/26/2014	2:56 PM	28	4.020	7.8615	7.8745	7.8560	7.8555	7.8619	1.96	48,693	III	3836.41
LD4_10	8/1/2014	5:40 PM	64	4.024	7.8955	7.8995	7.9005	7.8915	7.8968	1.96	47,764	III	3755.73
LD4_11	8/1/2014	5:44 PM	64	4.020	7.9175	7.9190	7.9260	7.9210	7.9209	1.97	46,543	III	3667.01
LD4_12	8/1/2014	5:48 PM	64	4.018	7.9040	7.9045	7.9160	7.9125	7.9093	1.97	47,102	III	3714.75

Table C-5: Specimen SR2 Concrete Compressive Strength Data

Cylinder ID	Date	Time	Test (days)	Diameter (in)	$Length_1$ (in)	$Length_2$ (in)	$Length_3$ (in)	$Length_4$ (in)	$Length_{AVG}$ (in)	L/D ratio	Maximum Load (lbs)	Failure Type	Maximum Stress (psi)
SR2_1	2/24/2014	9:30 AM	3	4.010	7.8305	7.8295	7.8290	7.8275	7.8291	1.95	36,083	III	2857.09
SR2_2	2/24/2014	9:35 AM	3	4.011	7.8800	7.8765	7.8780	7.8775	7.8780	1.96	36,487	III	2887.64
SR2_3	2/24/2014	9:40 AM	3	4.009	7.7880	7.7805	7.7815	7.7845	7.7836	1.94	36,969	III	2928.71
SR2_4	2/28/2014	10:45 AM	7	4.012	7.8930	7.8885	7.8870	7.8925	7.8903	1.97	49,493	III	3915.00
SR2_5	2/28/2014	10:45 AM	7	4.013	7.9095	7.9090	7.9110	7.9100	7.9099	1.97	48,865	III	3863.40
SR2_6	2/28/2014	10:45 AM	7	4.011	7.8475	7.8475	7.8480	7.8460	7.8473	1.96	48,968	III	3875.41
SR2_7	3/21/2014	11:00 AM	28	4.011	7.8460	7.8475	7.8460	7.8485	7.8470	1.96	57,911	III	4583.17
SR2_8	3/21/2014	11:00 AM	28	4.009	7.9455	7.9500	7.9455	7.9430	7.9460	1.98	58,049	III	4598.68
SR2_9	3/21/2014	11:00 AM	28	4.010	7.9130	7.9205	7.9120	7.9115	7.9143	1.97	58,135	III	4603.19
SR2_10	4/28/2104	2:28 PM	66	4.005	7.8580	7.8595	7.8530	7.8530	7.8559	1.96	54,586	III	4332.98
SR2_11	4/28/2014	2:33 PM	66	4.012	7.8430	7.8380	7.8430	7.8440	7.8420	1.95	54,189	III	4286.47
SR2_12	4/28/2014	2:41 PM	66	4.011	7.8710	7.8770	7.8790	7.8705	7.8744	1.96	56,365	III	4460.82

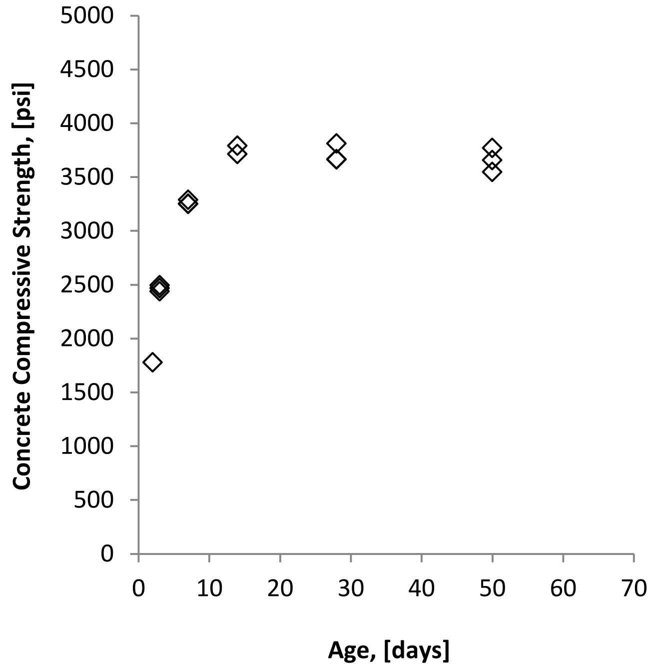


Figure C-8: Specimen LD1 Concrete Compressive Strength Development

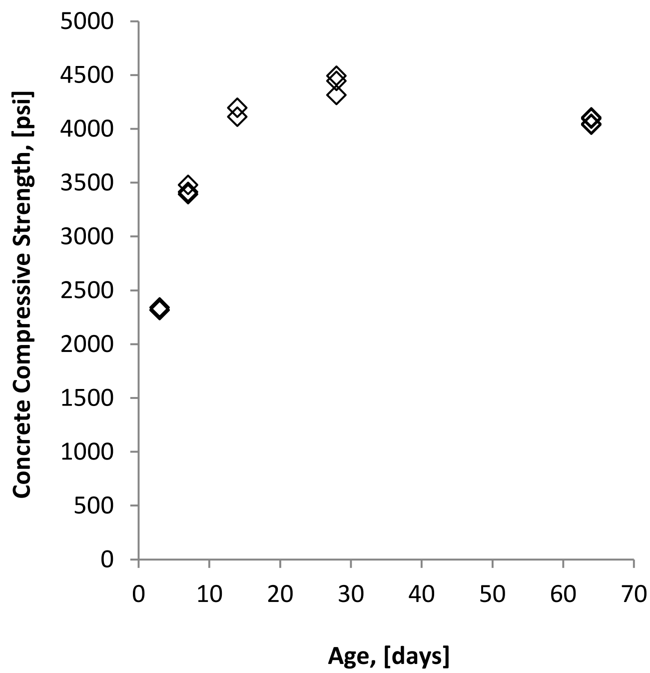


Figure C-9: Specimen LD2 Concrete Compressive Strength Development

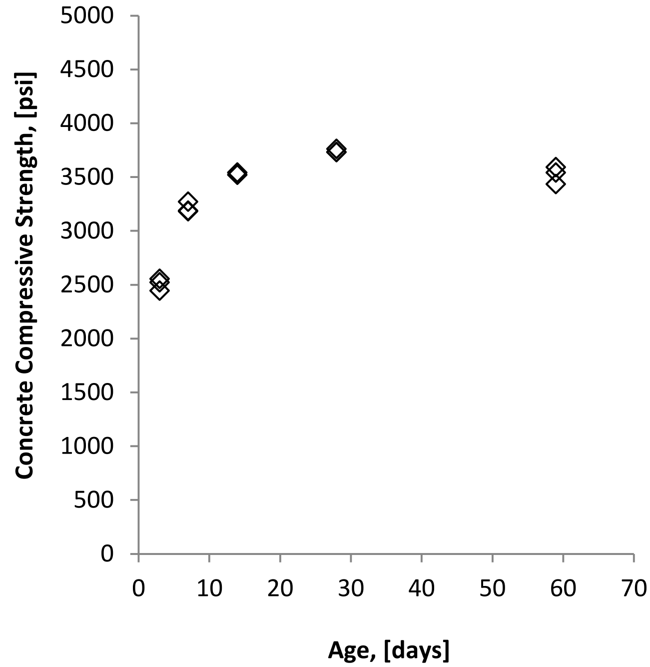


Figure C-10: Specimen LD3 Concrete Compressive Strength Development

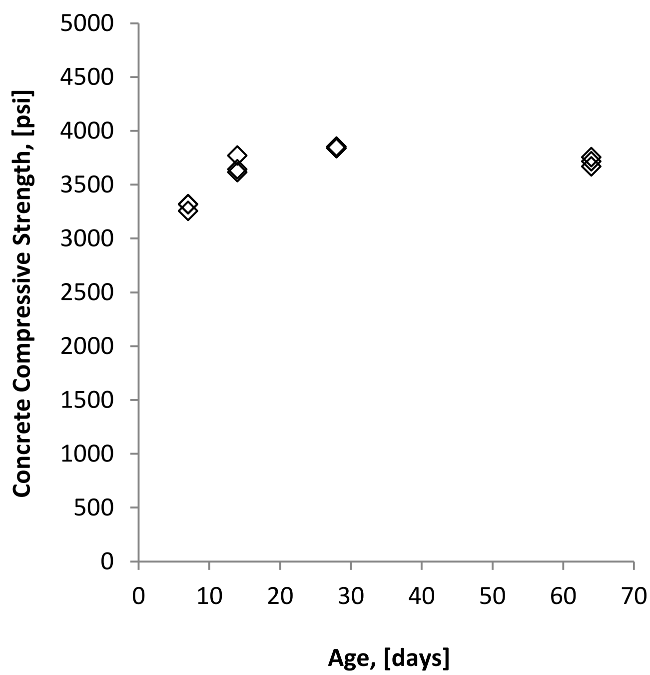


Figure C-11: Specimen LD4 Concrete Compressive Strength Development

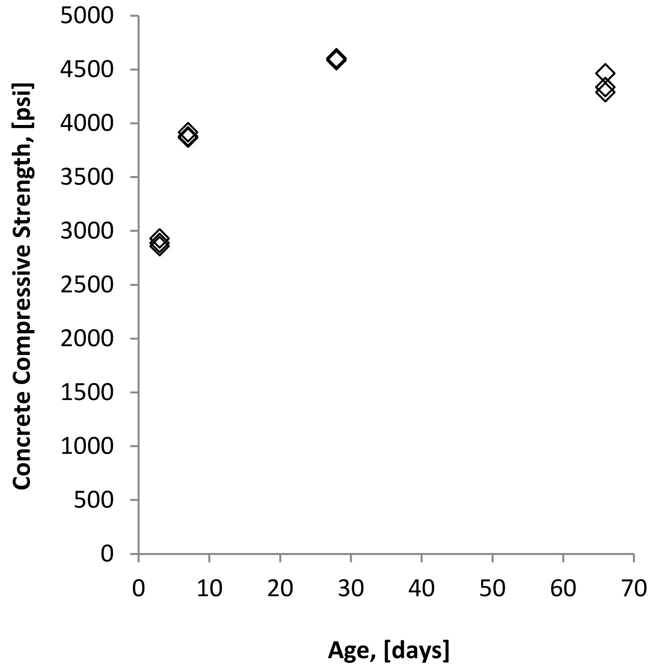


Figure C-12: Specimen SR2 Concrete Compressive Strength Development

Mill Certification Details

Customer: Ambassador Steel Corporation
Bill of Lading #: 401944-NUJ
Chief Metallurgist:
Heat #: JK13103220
Product: Rebar ASTM A615/A615M-12 GR 60[420] AASHTO M31-07 36/#11 Rebar
Grade: A61560
Comments:

Date: 7/9/2013
Tag #: JK1311064963
Mill: Nucor Jackson
Size: 36/#11 Rebar
Division: San Antonio, TX

Chemical Properties - Wt.%

Mn	C	Cu	Si	Ni	Cr	S	V	Mo	P	Nb	Pb	Sn	Ti	N	Ca	Al	B	Ceq
1.170	.410	.310	.230	.140	.110	.057	.035	.035	.012	.003	.000	.000	.000	.000	.000	.000	.000	.630

Carbon Equivalent= 0.63

Physical Properties

	Imperial = psi
Tensile:	110,360
Yield:	74,400
Elongation (in 8 inches):	11.30
Elongation (in 2 inches):	
Bend Test:	OK

The testing was conducted in accordance with the requirements of this specification. All melting and manufacturing processes were performed in the United States of America.

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Figure C-13: Steel Mill Certification Details

Table C-6: Steel LTI Tensile Testing Data

Test Identification	Bar Number	Diameter of bar, in.	Yield Stress f_y, (ksi)	Ultimate Stress f_u, (ksi)	f_u/f_y
LD1, LD2, LD3, SR2	#1	1.41	69.5	104.0	1.50
	#2	1.41	69.5	104.0	1.50
	#3	1.41	69.0	104.0	1.51
LD4	#4	1.41	67.5	99.0	1.47
	#5	1.41	67.5	99.0	1.47
	#6	1.41	67.25	98.5	1.46

APPENDIX D

Experimental Methods

Appendix D outlines the shear testing process for both uniform and concentrated load specimens. Results are presented in the following manner:

- *Test Matrix Showing Investigated and Constant Parameters:* Table D-1 through Table D-2
- *Detailed Description of Shear Testing Process*

Table D-1: Test Matrix Showing Investigated Parameters

Test Identification	Type of Loading	Concrete Compressive Strength, f'_c (psi)	Shear Span, *a* (in.)	Shear Span to Depth Ratio, *a/d*
LD1-N	Concentrated	3658	53.2375	2.5
LD1-S	Concentrated	3658	53.2375	2.5
SR2-S	Concentrated	4360	53.2375	2.5
LD2	Uniform	4071	54	2.54
LD3	Uniform	3522	54	2.54
LD4	Uniform	3713	54	2.54

Table D-2: Test Matrix Showing Constant Parameters

Specimen Width, b_w (in.)	Specimen Height, *h* (in.)	Specimen Depth, *d* (in.)	Area of Steel, A_s (in^2)	Longitudinal Reinforcement Ratio, ρ
36	24	21.295	7.8	0.0102

D.1 Shear Testing Process

Specific shear testing procedures were followed for both uniform and concentrated load testing. Specimen capacity was estimated using nominal concrete strength as seen in Appendix B. All specimens were loaded in a similar manner until a well-defined shear failure had occurred.

Concentrated load specimens were loaded in 10 kip increments. Upon the completion of each load step, flexural cracks were marked and photographs were taken. Specimens LD1-N and LD1-S were loaded in this manner until 80 kips of total load had been applied, while specimen SR2-S was loaded up to 90 kips. At this point, specimens were loaded until shear failure occurred as defined by the applied load dropping to 67% of the ultimate applied load. For all three specimens, load was applied at a consistent rate between 150 and 200 pounds per second.

The uniform load specimens were loaded using a custom made Kevlar reinforced air bladder. Air pressure within the bladder was closely controlled using a pressure regulator. The loading process began by slowly increasing the air pressure inside the bladder until the specimen was in contact with the supports. At this point, the load cells began reading load. Then, each specimen was loaded in 20 kip increments. Upon the completion of each load step, flexural cracks were marked and photographs were taken. Each specimen was loaded in this manner up to a total applied load of 160 kips. Specimens LD3 and LD4 were then loaded to failure. Commissioning of the test setup required the unloading of specimen LD2 on two different occasions. It should be noted that diagonal cracking did not occur in specimen LD2 until the last loading attempt. Shear failure was easily noticeable and defined as the applied load dropping to 67% of the ultimate applied load. For all three specimens, load was consistently applied at a rate between 30 and 70 pounds per second.

APPENDIX E

Experimental Results

Appendix E includes detailed results pertaining to the testing of specimens to failure. Results are presented in the following manner:

- *Load-Deflection Summary:* Figure E-1 through Figure E-6
- *Shortened Dataset:* Table E-1 through Table E-7
  - *Summary of Dataset and Equations for Converting Shear*
- *Photo Sequence Showing Testing Process for Each Specimen:* Figure E-7 through Figure E-12
  - *Failure Photos of Uniform Load Tests:* Figure E-13 through Figure E-15
- *Observation Records:* Table E-8 through Table E-13
- *Strain Gauge Summary at Location of Maximum Moment:* Figure E-16 through Figure E-21

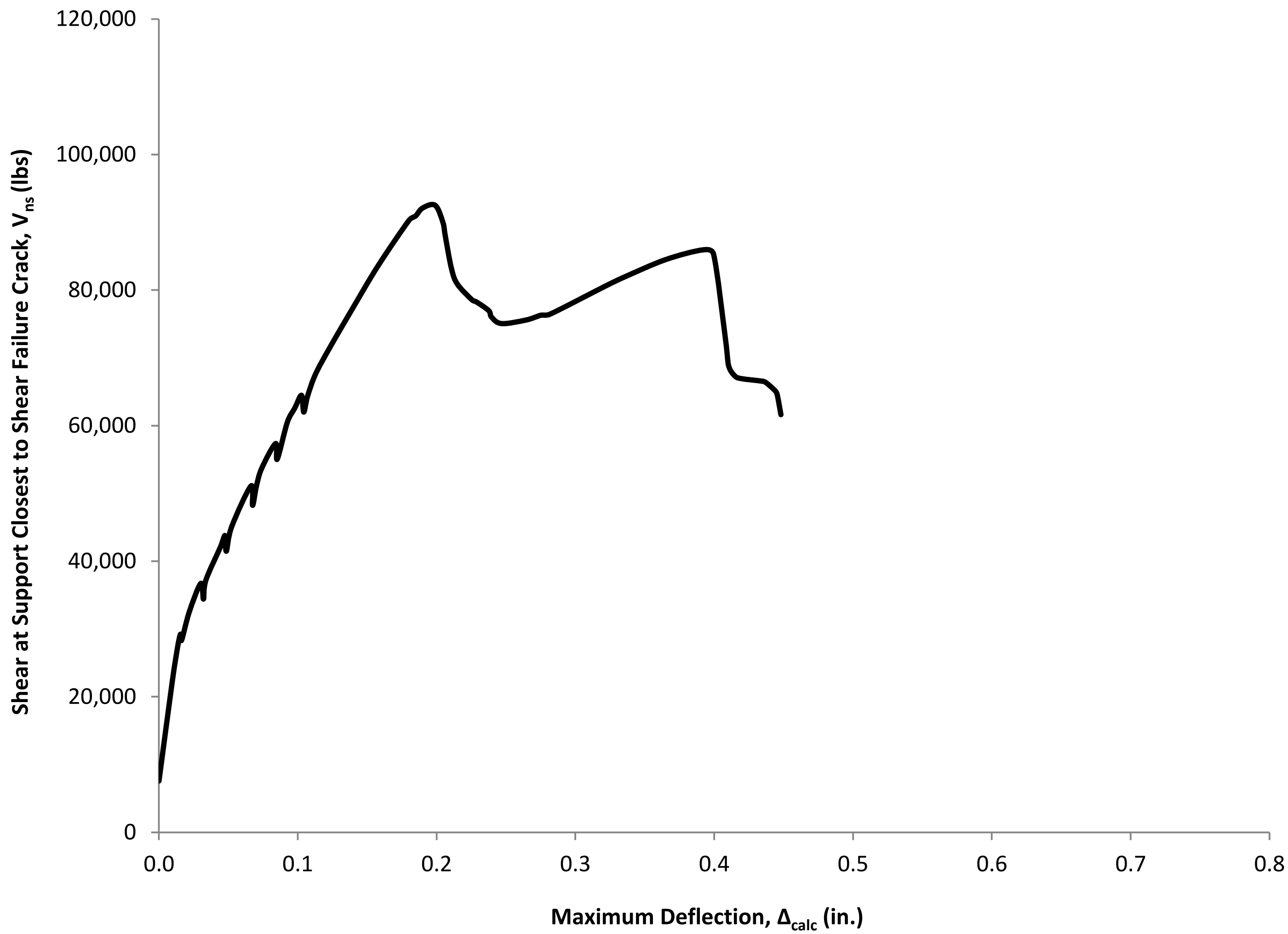


Figure E-1: Specimen LD1-N Load-Deflection Summary

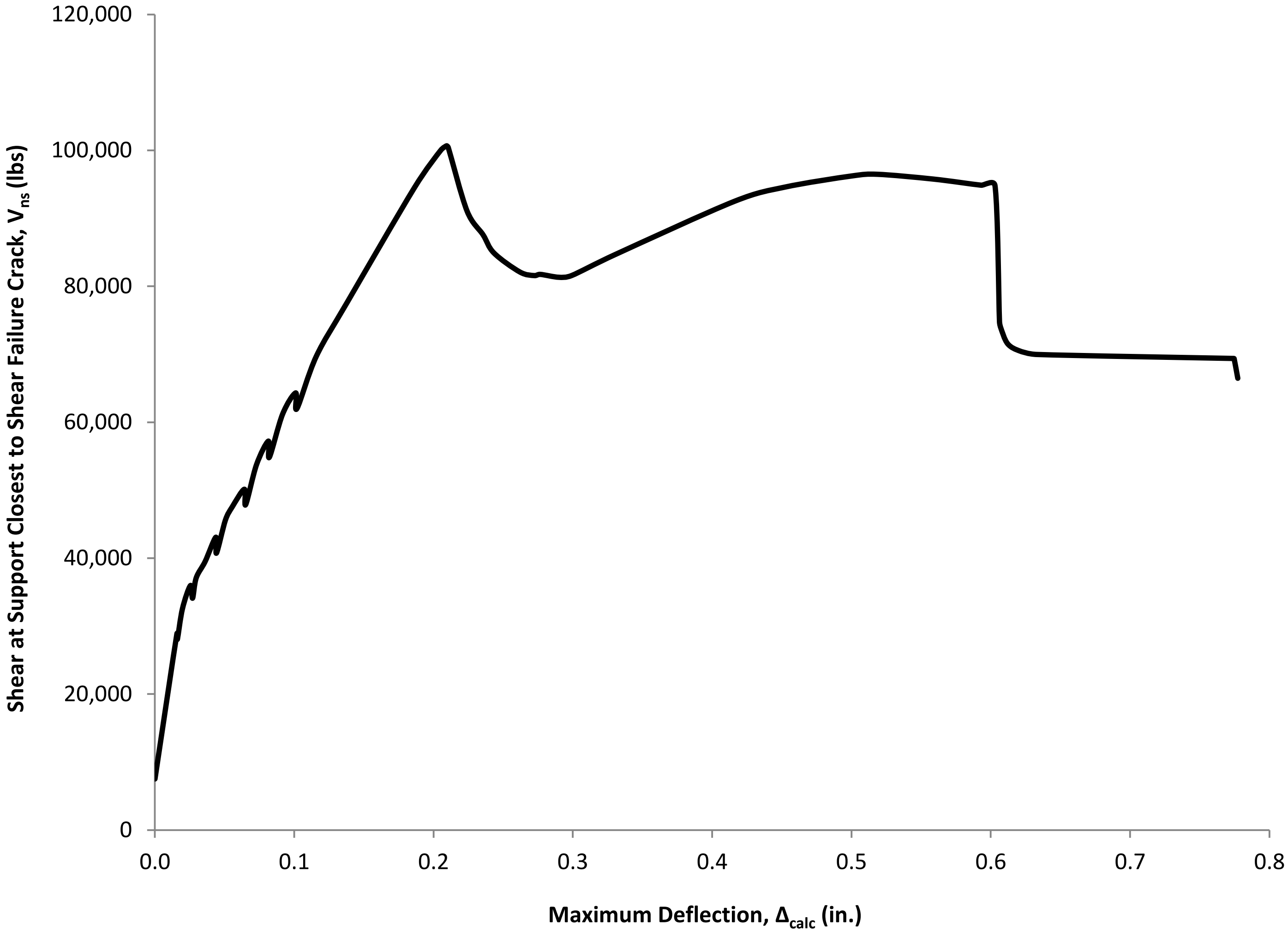


Figure E-2: Specimen LD1-S Load-Deflection Summary

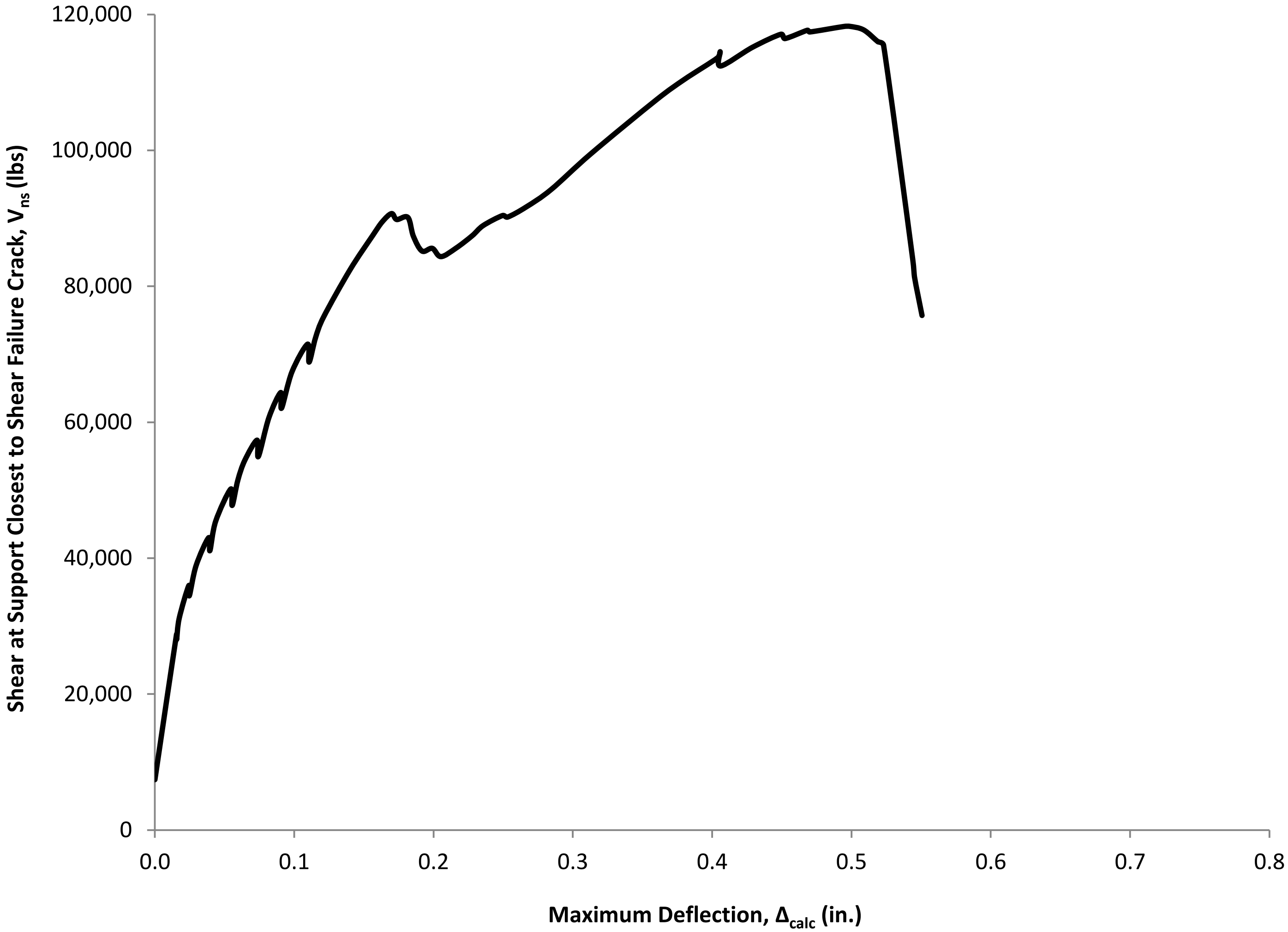


Figure E-3: Specimen SR2-S Load-Deflection Summary

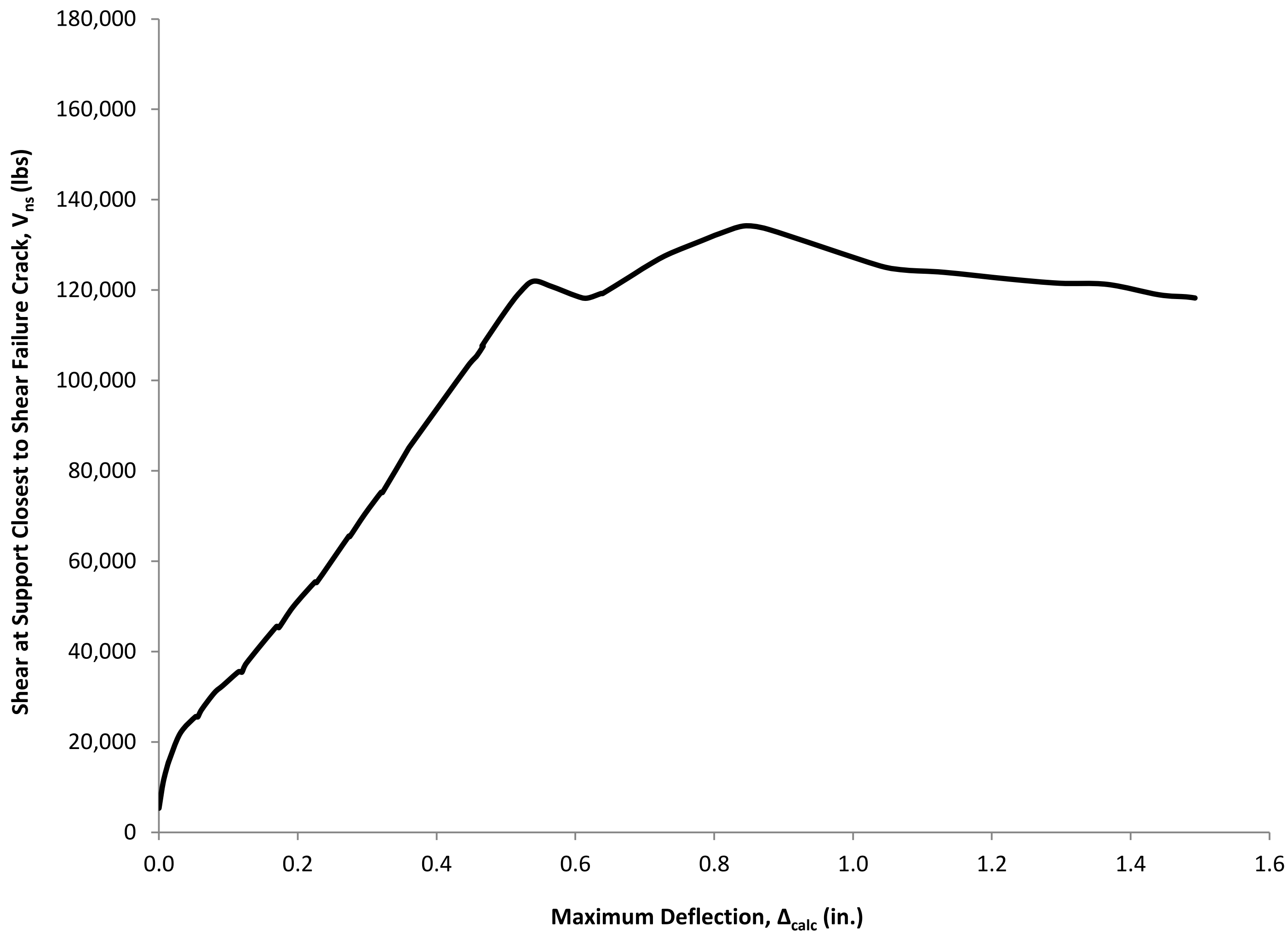


Figure E-4: Specimen LD2 Load-Deflection Summary

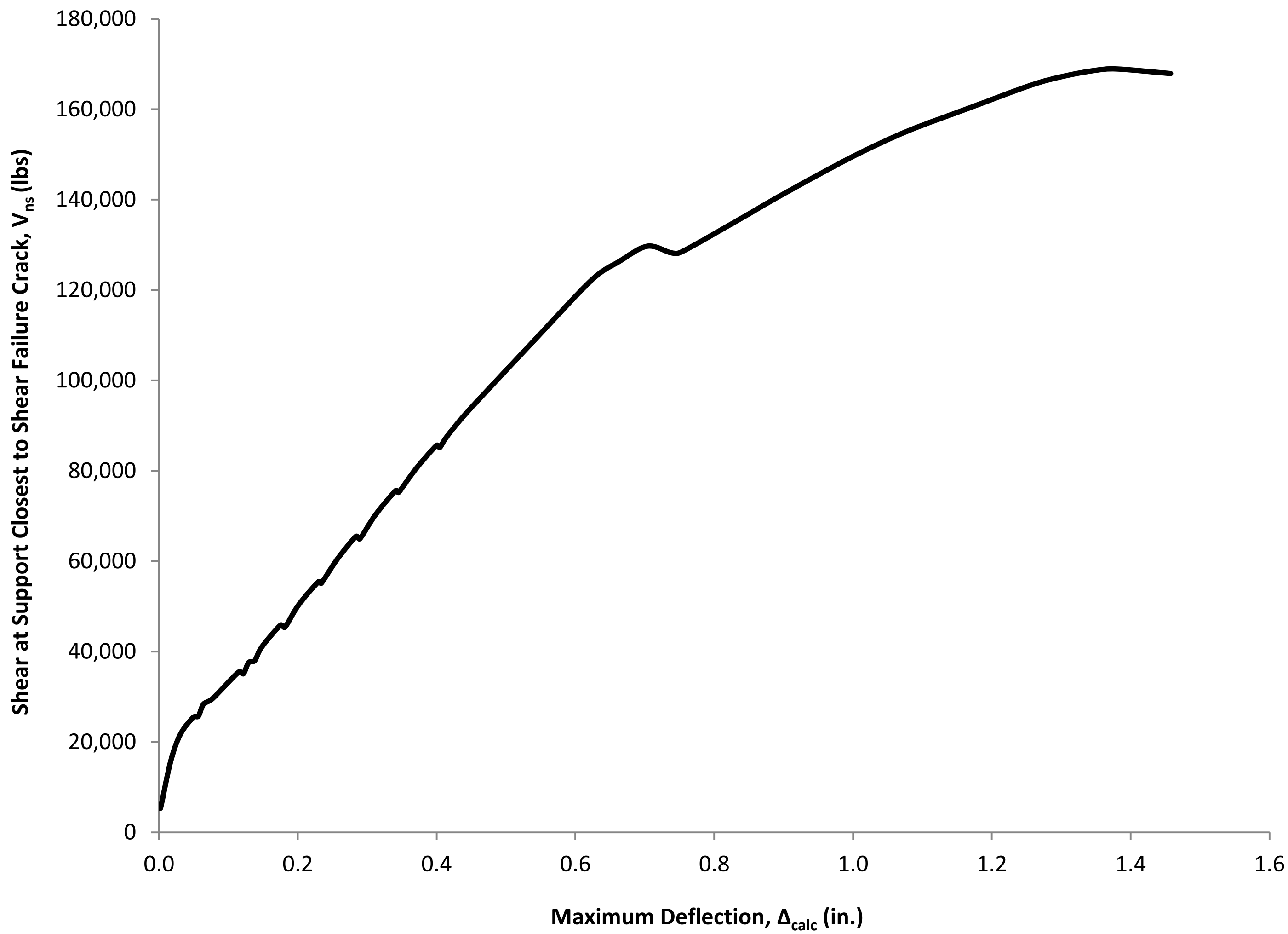


Figure E-5: Specimen LD3 Load-Deflection Summary

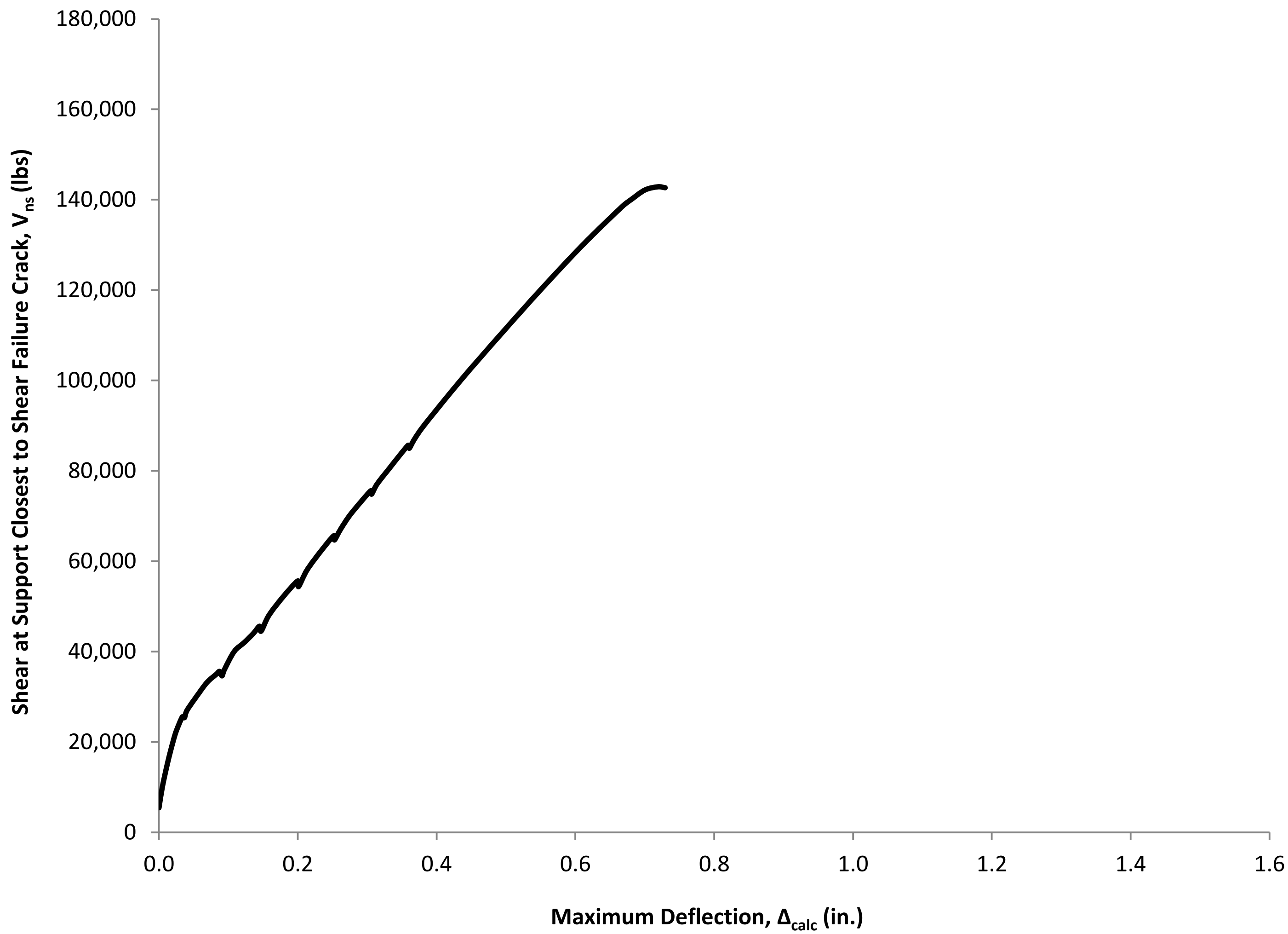


Figure E-6: Specimen LD4 Load-Deflection Summary

E.1 DATASET SUMMARY

The dataset for each test result was comprised of roughly 10,000 data points. In order to shorten each set for reporting within this document, approximately 50-60 points were strategically chosen. The chosen data can be plotted to show a nearly equivalent load-deflection graph when compared to the full dataset. These results can be found in Table E-2 through Table E-7.

Reported data shows shear at the centerline of the support closest to the shear crack (V_{ns}). Using this value, shear at the following three locations can be found: at a distance d away from the edge of the support (V_d), at a distance x_r away from the centerline of the support (V_{xr}), and shear in accordance to the ACI-DAfStb databases (V_{DAfStb}). Equations E-1 through E-8 can be used to calculate shear at the three locations are listed below.

For specimens subjected to concentrated loading (LD1-N, LD1-S, and SR2-S):

$$\boldsymbol{V_d = V_{ns} - \omega_b(65.295)}$$ ***Equation E-1***

$$\boldsymbol{V_{xr} = V_{ns} - \omega_b(64.61875)}$$ ***Equation E-2***

$$\boldsymbol{V_{DAfStb} = V_{ns} - \omega_b(64.61875)}$$ ***Equation E-3***

For specimens subjected to uniform loading (LD2 and LD3):

$$\boldsymbol{V_d = V_{ns} - (R_n + R_f + \omega_b(116) + 2{,}052)\frac{27.295}{216}}$$ ***Equation E-4***

$$\boldsymbol{V_{xr} = V_{ns} - (R_n + R_f + \omega_b(116) + 2{,}052)\frac{18}{216}}$$ ***Equation E-5***

$$\boldsymbol{V_{DAfStb} = V_{ns} + \omega_b(12) - (R_n + R_f + \omega_b(116) + 2{,}052)\frac{30}{216}}$$ ***Equation E-6***

For specimens subjected to uniform loading (LD4):

$$V_d = V_{ns} - (R_n + R_f + \omega_b(116) + 2,052)\frac{27.295}{216}$$ *Equation E-4*

$$V_{xr} = V_{ns} - (R_n + R_f + \omega_b(116) + 2,052)\frac{26}{216}$$ *Equation E-7*

$$V_{DAfStb} = V_{ns} + \omega_b(12) - (R_n + R_f + \omega_b(116) + 2,052)\frac{38}{216}$$ *Equation E-8*

Where:

P Total applied load recorded by all four load cells

R_n Total applied load recorded by the two load cells at support closest to shear failure crack

R_f Total applied load recorded by the two load cells at support furthest from shear failure crack

δ_n Average displacement at support closest to shear failure crack

δ_f Average displacement at support furthest from shear failure crack

δ_m Average displacement at theoretical location of maximum deflection (location of point load for concentrated load specimens or midspan for uniform load specimens)

Δ_{calc} Calculated deflection at theoretical location of maximum deflection

V_{ns} Shear at the support closest to the shear failure crack

ω_b Distributed self-weight of specimen (values for each specimen given below in Table E-1)

Table E-1: Distributed Self-Weight of Each Specimen

Specimen Identification	Distributed self-weight, ω_b (lbs/in.)
LD1	71.691
LD2	74.229
LD3	73.399
LD4	73.767
SR2	74.048

Table E-2: Specimen LD1-N Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
7.1	29.3	-22.2	0.0000	0.0000	0.0000	0.0000	7570.4
20437.9	15005.5	5432.3	0.0042	0.0013	0.0131	0.0098	22546.6
27260.9	20000.2	7260.7	0.0049	0.0018	0.0176	0.0136	27541.3
29601.5	21677.4	7924.1	0.0052	0.0020	0.0197	0.0154	29218.5
28490.2	20809.5	7680.7	0.0052	0.0021	0.0206	0.0163	28350.6
34224.0	24980.2	9243.8	0.0055	0.0022	0.0264	0.0218	32521.3
40068.2	29173.1	10895.1	0.0060	0.0026	0.0351	0.0301	36714.2
36991.8	26863.6	10128.2	0.0060	0.0026	0.0371	0.0320	34404.7
40745.2	29629.1	11116.1	0.0065	0.0028	0.0391	0.0337	37170.2
47626.8	34593.8	13032.9	0.0070	0.0029	0.0501	0.0444	42134.9
49900.8	36241.2	13659.6	0.0071	0.0028	0.0533	0.0475	43782.3
46831.7	33939.0	12892.7	0.0070	0.0029	0.0543	0.0485	41480.1
51777.1	37557.3	14219.8	0.0073	0.0030	0.0584	0.0524	45098.4
60144.4	43550.8	16593.6	0.0079	0.0034	0.0728	0.0663	51091.9
57281.0	40696.0	16585.0	0.0074	0.0034	0.0737	0.0674	48237.1
61284.4	43527.2	17757.2	0.0077	0.0035	0.0767	0.0702	51068.3
65037.8	46197.0	18840.9	0.0080	0.0034	0.0807	0.0741	53738.1
70086.4	49808.1	20278.3	0.0081	0.0037	0.0908	0.0840	57349.2
66847.0	47520.3	19326.7	0.0082	0.0038	0.0921	0.0852	55061.4
74530.1	52977.0	21553.1	0.0086	0.0040	0.0997	0.0925	60518.1
77400.2	55028.8	22371.4	0.0088	0.0042	0.1052	0.0978	62569.9
80056.5	56933.3	23123.2	0.0089	0.0043	0.1102	0.1027	64474.4
76560.9	54454.9	22105.9	0.0088	0.0044	0.1118	0.1043	61996.0
79857.4	56778.5	23079.0	0.0090	0.0044	0.1147	0.1070	64319.6
84471.6	60065.7	24406.0	0.0091	0.0045	0.1206	0.1128	67606.8
90093.8	64073.3	26020.5	0.0096	0.0049	0.1316	0.1233	71614.4
98505.5	70059.6	28445.9	0.0100	0.0052	0.1490	0.1404	77600.7
106932.5	76068.9	30863.6	0.0105	0.0056	0.1670	0.1579	83610.0
116278.5	82731.8	33546.8	0.0107	0.0060	0.1894	0.1801	90272.9
117226.0	83376.4	33849.6	0.0106	0.0061	0.1941	0.1848	90917.5

Table E-2: Specimen LD1-N Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
118917.7	84566.6	34351.1	0.0106	0.0062	0.1993	0.1899	92107.7
119490.8	84962.5	34528.3	0.0106	0.0063	0.2083	0.1990	92503.6
115868.0	82400.6	33467.3	0.0104	0.0062	0.2138	0.2046	89941.7
113211.6	80489.0	32722.6	0.0104	0.0062	0.2154	0.2062	88030.1
106558.3	75663.8	30894.5	0.0099	0.0060	0.2194	0.2107	83204.9
103350.4	73326.0	30024.4	0.0099	0.0060	0.2238	0.2150	80867.1
100133.9	71023.8	29110.1	0.0096	0.0059	0.2340	0.2255	78564.9
99684.9	70707.5	28977.4	0.0095	0.0059	0.2371	0.2287	78248.6
97816.8	69429.9	28386.9	0.0094	0.0058	0.2459	0.2375	76971.0
96427.0	68461.0	27966.0	0.0093	0.0057	0.2479	0.2396	76002.1
95074.3	67514.6	27559.8	0.0092	0.0058	0.2551	0.2469	75055.7
95752.3	68038.7	27713.6	0.0088	0.0057	0.2724	0.2645	75579.8
96702.5	68753.6	27948.9	0.0086	0.0057	0.2830	0.2752	76294.7
96872.6	68909.4	27963.1	0.0086	0.0058	0.2896	0.2818	76450.5
102642.4	73088.4	29554.0	0.0084	0.0059	0.3297	0.3220	80629.5
104453.2	74435.4	30017.8	0.0086	0.0060	0.3437	0.3359	81976.5
107838.2	76950.8	30887.5	0.0086	0.0060	0.3728	0.3650	84491.9
109817.2	78391.6	31425.6	0.0083	0.0061	0.3996	0.3919	85932.7
108778.4	77766.1	31012.3	0.0079	0.0062	0.4069	0.3995	85307.2
90764.9	64860.3	25904.6	0.0046	0.0059	0.4134	0.4083	72401.4
86503.5	61328.7	25174.8	0.0041	0.0058	0.4149	0.4103	68869.8
84369.3	59747.3	24622.0	0.0036	0.0060	0.4194	0.4151	67288.4
83876.1	59379.3	24496.8	0.0034	0.0060	0.4242	0.4201	66920.4
83470.9	59062.4	24408.5	0.0027	0.0061	0.4363	0.4327	66603.5
83235.2	58878.2	24357.0	0.0019	0.0060	0.4398	0.4367	66419.3
81696.1	57780.8	23915.4	0.0014	0.0060	0.4457	0.4430	65321.9
80768.9	57104.0	23664.9	0.0010	0.0059	0.4477	0.4453	64645.1
76560.2	54075.0	22485.2	-0.0005	0.0058	0.4494	0.4481	61616.1

Table E-3: Specimen LD1-S Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
29.1	7.2	21.9	0.0002	0.0001	0.0002	0.0000	7510.5
30122.0	21373.6	8748.4	0.0066	0.0024	0.0212	0.0158	28876.8
28951.2	20542.1	8409.1	0.0067	0.0024	0.0215	0.0161	28045.4
35362.3	25073.7	10288.6	0.0074	0.0027	0.0258	0.0198	32576.9
40146.7	28465.2	11681.6	0.0078	0.0031	0.0319	0.0255	35968.4
37503.8	26603.8	10900.0	0.0077	0.0031	0.0333	0.0270	34107.0
41750.8	29590.3	12160.5	0.0082	0.0032	0.0364	0.0296	37093.6
45136.5	32010.6	13125.9	0.0087	0.0034	0.0432	0.0361	39513.9
50156.3	35563.6	14592.6	0.0094	0.0036	0.0514	0.0437	43066.8
46888.5	33246.5	13641.9	0.0094	0.0036	0.0519	0.0442	40749.8
53726.2	38086.7	15639.6	0.0102	0.0039	0.0589	0.0506	45589.9
56442.3	40013.9	16428.4	0.0104	0.0040	0.0640	0.0554	47517.1
60100.3	42632.5	17467.8	0.0106	0.0044	0.0730	0.0642	50135.7
56927.2	40381.0	16546.2	0.0106	0.0043	0.0739	0.0652	47884.2
65236.8	46257.9	18978.9	0.0114	0.0047	0.0824	0.0729	53761.1
70086.9	49707.3	20379.6	0.0122	0.0049	0.0914	0.0814	57210.5
66775.3	47361.2	19414.1	0.0122	0.0049	0.0922	0.0822	54864.4
75731.6	53700.8	22030.8	0.0131	0.0053	0.1025	0.0917	61204.0
80088.4	56804.3	23284.0	0.0134	0.0054	0.1121	0.1010	64307.5
76894.6	54531.8	22362.9	0.0134	0.0055	0.1131	0.1020	62035.0
87750.3	62217.4	25532.9	0.0139	0.0057	0.1274	0.1159	69720.7
98803.4	70056.3	28747.1	0.0146	0.0063	0.1500	0.1378	77559.6
122725.8	87040.4	35685.4	0.0167	0.0080	0.2005	0.1864	94543.6
130428.6	92486.5	37942.2	0.0176	0.0084	0.2201	0.2051	99989.7
131399.1	93169.1	38230.0	0.0180	0.0084	0.2246	0.2095	100672.3
131059.7	92895.7	38164.0	0.0182	0.0084	0.2260	0.2106	100398.9
118069.7	83559.3	34510.4	0.0190	0.0080	0.2399	0.2241	91062.6
113138.0	80072.3	33065.7	0.0187	0.0079	0.2511	0.2355	87575.5
109429.5	77388.9	32040.7	0.0181	0.0077	0.2585	0.2434	84892.1
105405.0	74595.8	30809.2	0.0172	0.0077	0.2764	0.2620	82099.0

Table E-3: Specimen LD1-S Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
104596.2	74067.4	30528.8	0.0168	0.0076	0.2865	0.2723	81570.6
104794.5	74243.8	30550.8	0.0167	0.0075	0.2907	0.2767	81747.0
104117.8	73817.7	30300.1	0.0163	0.0076	0.3037	0.2899	81320.9
104405.2	74083.0	30322.1	0.0159	0.0075	0.3128	0.2993	81586.3
108577.9	77232.1	31345.9	0.0151	0.0078	0.3441	0.3311	84735.3
119068.5	85011.4	34057.1	0.0135	0.0078	0.4281	0.4162	92514.7
121850.5	87078.4	34772.2	0.0131	0.0080	0.4637	0.4520	94581.6
124058.5	88733.8	35324.7	0.0116	0.0083	0.5111	0.5005	96237.0
124375.2	88969.5	35405.7	0.0112	0.0084	0.5290	0.5187	96472.7
123352.3	88264.1	35088.2	0.0104	0.0084	0.5686	0.5588	95767.3
122093.4	87367.0	34726.4	0.0092	0.0084	0.6021	0.5931	94870.2
117482.4	87300.9	30181.4	0.0061	0.0074	0.6095	0.6030	94804.2
94516.5	67295.8	27220.7	0.0048	0.0076	0.6119	0.6063	74799.1
93390.2	66420.1	26970.1	0.0048	0.0078	0.6128	0.6071	73923.3
90203.4	64036.0	26167.3	0.0035	0.0076	0.6168	0.6122	71539.3
88753.6	62954.6	25798.9	0.0026	0.0075	0.6252	0.6211	70457.9
88113.4	62461.8	25651.6	0.0021	0.0075	0.6368	0.6331	69965.1
87628.0	61874.1	25753.9	-0.0027	0.0074	0.7746	0.7744	69377.4
87606.0	61859.5	25746.5	-0.0027	0.0075	0.7750	0.7747	69362.7
83543.9	58962.1	24581.8	-0.0033	0.0073	0.7771	0.7774	66465.4

Table E-4: Specimen SR2-S Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
-0.1	0.0	-0.1	0.0000	0.0000	0.0000	0.0000	7407.0
29991.4	21330.2	8661.2	0.0045	0.0012	0.0190	0.0154	28737.2
28974.6	20608.7	8365.8	0.0044	0.0012	0.0191	0.0156	28015.8
33420.3	23757.2	9663.1	0.0049	0.0013	0.0213	0.0174	31164.2
40110.2	28509.0	11601.1	0.0054	0.0017	0.0285	0.0242	35916.1
38122.8	27096.7	11026.1	0.0053	0.0017	0.0290	0.0248	34503.7
44320.0	31502.9	12817.1	0.0055	0.0018	0.0340	0.0295	38909.9
50030.9	35585.4	14445.5	0.0058	0.0023	0.0433	0.0385	42992.4
47432.5	33709.5	13723.0	0.0057	0.0023	0.0442	0.0395	41116.5
53511.5	38034.4	15477.1	0.0062	0.0025	0.0487	0.0436	45441.4
60120.6	42749.5	17371.1	0.0067	0.0029	0.0600	0.0544	50156.5
56764.2	40351.5	16412.7	0.0067	0.0029	0.0610	0.0555	47758.5
61974.3	44065.5	17908.8	0.0069	0.0031	0.0653	0.0595	51472.5
66110.4	47000.3	19110.1	0.0069	0.0031	0.0704	0.0645	54407.3
70230.9	49949.2	20281.7	0.0068	0.0033	0.0790	0.0732	57356.2
66911.8	47566.2	19345.6	0.0067	0.0033	0.0800	0.0743	54973.3
74933.0	53288.0	21645.1	0.0069	0.0035	0.0878	0.0818	60695.0
80076.9	56950.4	23126.5	0.0074	0.0036	0.0965	0.0902	64357.4
76911.2	54677.0	22234.2	0.0073	0.0037	0.0972	0.0909	62084.0
84358.2	60001.3	24356.9	0.0077	0.0039	0.1050	0.0984	67408.3
90061.6	64068.1	25993.5	0.0078	0.0041	0.1163	0.1095	71475.1
86402.7	61434.2	24968.5	0.0078	0.0040	0.1174	0.1107	68841.3
91428.5	65030.1	26398.4	0.0078	0.0040	0.1220	0.1153	72437.2
95674.3	68052.5	27621.9	0.0080	0.0041	0.1279	0.1210	75459.5
105438.5	75008.1	30430.5	0.0084	0.0045	0.1473	0.1400	82415.1
112545.1	80064.9	32480.2	0.0085	0.0048	0.1638	0.1563	87471.9
115384.1	82055.8	33328.3	0.0086	0.0048	0.1706	0.1631	89462.9
117176.2	83286.6	33889.6	0.0086	0.0049	0.1774	0.1699	90693.6
115993.2	82411.1	33582.1	0.0086	0.0049	0.1811	0.1735	89818.2
116481.5	82728.7	33752.8	0.0086	0.0051	0.1892	0.1816	90135.7

Table E-4: Specimen SR2-S Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
112567.9	79957.7	32610.2	0.0084	0.0049	0.1929	0.1855	87364.7
109573.3	77773.7	31799.7	0.0082	0.0049	0.1989	0.1917	85180.7
110096.8	78172.0	31924.8	0.0080	0.0049	0.2062	0.1991	85579.0
108362.9	76954.7	31408.2	0.0080	0.0049	0.2124	0.2053	84361.7
110063.0	78197.8	31865.2	0.0079	0.0049	0.2231	0.2161	85604.9
112603.2	80023.1	32580.1	0.0079	0.0051	0.2348	0.2277	87430.2
114657.0	81516.9	33140.1	0.0080	0.0051	0.2427	0.2356	88923.9
116653.7	82990.6	33663.1	0.0076	0.0051	0.2563	0.2494	90397.6
116352.3	82777.6	33574.8	0.0075	0.0051	0.2601	0.2533	90184.6
118317.8	84256.5	34061.3	0.0073	0.0052	0.2732	0.2665	91663.5
121732.7	86816.2	34916.5	0.0072	0.0054	0.2910	0.2844	94223.2
128965.9	92074.3	36891.6	0.0073	0.0058	0.3197	0.3129	99481.3
139931.2	100024.9	39906.3	0.0075	0.0061	0.3670	0.3600	107431.9
144022.7	103003.9	41018.8	0.0077	0.0060	0.3871	0.3799	110410.9
148474.7	106210.7	42264.1	0.0073	0.0063	0.4109	0.4039	113617.7
149669.7	107108.4	42561.4	0.0078	0.0069	0.4133	0.4057	114515.4
147430.9	105002.1	42428.8	0.0079	0.0070	0.4138	0.4062	112409.1
150990.0	107757.7	43232.4	0.0077	0.0071	0.4365	0.4290	115164.7
153574.1	109671.5	43902.7	0.0073	0.0071	0.4566	0.4494	117078.5
153083.0	109035.2	44047.8	0.0071	0.0071	0.4594	0.4523	116442.2
154571.5	110266.0	44305.5	0.0074	0.0071	0.4757	0.4684	117673.0
154459.4	110007.3	44452.2	0.0073	0.0071	0.4773	0.4701	117414.3
155564.0	110810.5	44753.4	0.0072	0.0070	0.5014	0.4943	118217.5
155593.5	110832.9	44760.6	0.0071	0.0070	0.5059	0.4988	118239.9
154864.9	110311.0	44553.9	0.0069	0.0070	0.5157	0.5088	117718.0
152422.2	108553.8	43868.4	0.0066	0.0069	0.5258	0.5191	115960.8
150668.7	108046.5	42622.2	0.0057	0.0068	0.5291	0.5231	115453.5
107694.7	76547.9	31146.8	-0.0004	0.0053	0.5453	0.5440	83955.0
104493.3	73994.8	30498.6	-0.0009	0.0054	0.5461	0.5452	81401.8
96884.9	68383.4	28501.5	-0.0024	0.0052	0.5504	0.5506	75790.4
96745.1	68295.1	28450.0	-0.0025	0.0052	0.5505	0.5507	75702.1

Table E-5: Specimen LD2 Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
88.1	-7.4	95.5	0.5100	0.5136	0.5118	0.0000	5323.9
11688.4	5801.0	5887.4	0.5942	0.5565	0.5815	0.0061	11132.3
20234.3	10112.6	10121.7	0.6056	0.5726	0.6026	0.0134	15443.9
20212.4	10112.7	10099.7	0.6058	0.5729	0.6029	0.0135	15444.0
32888.0	16502.6	16385.4	0.6169	0.5910	0.6343	0.0303	21833.8
40264.1	20231.8	20032.3	0.6246	0.5995	0.6647	0.0526	25563.1
40198.1	20187.7	20010.4	0.6264	0.6005	0.6694	0.0559	25519.0
43466.4	21853.3	21613.2	0.6290	0.6036	0.6779	0.0616	27184.5
50987.9	25522.8	25465.0	0.6336	0.6105	0.7019	0.0798	30854.1
54212.2	27136.9	27075.3	0.6361	0.6131	0.7167	0.0920	32468.2
60307.6	30180.7	30127.0	0.6414	0.6182	0.7445	0.1146	35511.9
60123.6	30099.5	30024.1	0.6423	0.6192	0.7503	0.1196	35430.8
64201.8	32118.9	32082.9	0.6448	0.6224	0.7597	0.1261	37450.2
80381.5	40203.2	40178.3	0.6580	0.6340	0.8153	0.1693	45534.5
79903.0	39952.6	39950.4	0.6591	0.6349	0.8197	0.1728	45283.9
89251.6	44588.0	44663.6	0.6653	0.6392	0.8457	0.1934	49919.3
100147.3	50078.6	50068.7	0.6764	0.6450	0.8856	0.2249	55409.9
99853.0	49953.3	49899.7	0.6783	0.6453	0.8890	0.2272	55284.5
120251.1	60218.8	60032.3	0.7021	0.6554	0.9524	0.2736	65550.1
119947.7	60085.4	59862.4	0.7063	0.6564	0.9561	0.2748	65416.7
130091.3	65008.4	65082.9	0.7171	0.6641	0.9869	0.2963	70339.7
140213.3	69924.4	70288.9	0.7278	0.6733	1.0207	0.3202	75255.7
139841.3	69874.5	69966.8	0.7319	0.6785	1.0273	0.3221	75205.7
160040.0	79772.6	80267.5	0.7582	0.7067	1.0926	0.3602	85103.8
159373.8	79792.0	79581.8	0.7582	0.7067	1.0926	0.3602	85123.2
196021.7	98008.6	98013.2	0.7840	0.7402	1.2078	0.4458	103339.8
200039.8	99990.7	100049.1	0.7887	0.7451	1.2244	0.4575	105322.0
200782.6	100005.9	100776.7	0.7887	0.7451	1.2244	0.4575	105337.2
205273.1	102253.8	103019.3	0.7916	0.7489	1.2374	0.4672	107585.1
205427.7	102327.6	103100.2	0.7916	0.7526	1.2376	0.4654	107658.9

Table E-5: Specimen LD2 Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
220803.4	110013.4	110790.0	0.8023	0.7672	1.2840	0.4993	115344.7
229204.2	114200.4	115003.8	0.8081	0.7737	1.3112	0.5203	119531.7
234010.3	116624.8	117385.4	0.8115	0.7768	1.3338	0.5396	121956.1
232015.1	115482.4	116532.7	0.8088	0.7756	1.3576	0.5654	120813.7
227730.0	113405.0	114325.0	0.8015	0.7736	1.3880	0.6005	118736.3
226500.1	112867.5	113632.7	0.7972	0.7730	1.4014	0.6163	118198.8
228450.4	113913.9	114536.5	0.7947	0.7743	1.4218	0.6373	119245.2
228457.7	113906.5	114551.2	0.7945	0.7743	1.4237	0.6393	119237.8
235530.6	117502.0	118028.6	0.7944	0.7795	1.4643	0.6774	122833.3
240558.2	120000.1	120558.2	0.7946	0.7829	1.4920	0.7032	125331.4
245651.0	122549.4	123101.6	0.7949	0.7863	1.5239	0.7333	127880.7
251841.8	125629.9	126211.9	0.7932	0.7906	1.5745	0.7825	130961.2
254860.0	127148.0	127712.0	0.7928	0.7931	1.6005	0.8076	132479.3
258319.8	128872.7	129447.1	0.7920	0.7956	1.6375	0.8438	134204.0
257310.8	128121.6	129189.2	0.7899	0.7946	1.6699	0.8777	133452.9
241181.1	120111.3	121069.8	0.7717	0.7865	1.8160	1.0369	125442.6
239031.9	119086.9	119945.0	0.7682	0.7855	1.8524	1.0756	124418.2
238052.8	118593.1	119459.8	0.7650	0.7853	1.9067	1.1316	123924.4
235108.1	117090.0	118018.2	0.7580	0.7837	1.9966	1.2257	122421.3
233304.4	116183.7	117120.8	0.7518	0.7830	2.0644	1.2970	121515.0
232766.9	115918.5	116848.4	0.7462	0.7828	2.1311	1.3666	121249.8
228276.3	113634.2	114642.1	0.7342	0.7801	2.1976	1.4405	118965.5
227260.7	113162.4	114098.3	0.7288	0.7797	2.2346	1.4804	118493.7
226797.3	112911.6	113885.6	0.7277	0.7796	2.2465	1.4928	118242.9

Table E-6: Specimen LD3 Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
7.3	7.3	0.0	0.4967	0.1466	0.3216	0.0000	5290.5
95.7	73.5	22.1	0.5053	0.1530	0.3314	0.0022	5356.7
20323.9	10205.3	10118.6	0.5688	0.5448	0.5732	0.0164	15488.4
32602.2	16330.4	16271.8	0.5860	0.5604	0.6038	0.0306	21613.6
40206.4	20146.7	20059.7	0.5944	0.5685	0.6308	0.0493	25429.9
40713.8	20381.7	20332.1	0.5959	0.5687	0.6389	0.0566	25664.8
46153.4	23102.2	23051.2	0.6007	0.5731	0.6512	0.0642	28385.3
48575.2	24308.1	24267.2	0.6025	0.5754	0.6662	0.0772	29591.2
60271.9	30182.9	30089.0	0.6116	0.5845	0.7129	0.1149	35466.0
59476.6	29778.3	29698.3	0.6123	0.5846	0.7200	0.1216	35061.5
64438.4	32271.2	32167.2	0.6155	0.5880	0.7309	0.1291	37554.3
65336.7	32727.1	32609.6	0.6165	0.5886	0.7406	0.1380	38010.3
71335.4	35726.7	35608.7	0.6200	0.5930	0.7546	0.1481	41009.8
80918.6	40542.0	40376.5	0.6260	0.5999	0.7880	0.1750	45825.2
80094.7	40108.4	39986.3	0.6260	0.6001	0.7946	0.1816	45391.6
89789.2	45005.2	44784.0	0.6317	0.6060	0.8199	0.2010	50288.3
100152.4	50187.8	49964.6	0.6385	0.6125	0.8554	0.2299	55471.0
99518.7	49849.2	49669.6	0.6393	0.6132	0.8602	0.2339	55132.3
109794.4	55010.3	54784.1	0.6450	0.6196	0.8885	0.2562	60293.5
120090.7	60185.3	59905.4	0.6510	0.6272	0.9228	0.2837	65468.4
119205.8	59699.0	59506.8	0.6513	0.6275	0.9289	0.2895	64982.2
129732.5	65007.6	64725.0	0.6569	0.6342	0.9576	0.3120	70290.7
140411.1	70329.2	70081.9	0.6627	0.6413	0.9931	0.3411	75612.4
139667.9	69954.4	69713.6	0.6628	0.6416	0.9976	0.3454	75237.5
149744.8	75005.1	74739.7	0.6676	0.6470	1.0267	0.3694	80288.2
160372.4	80341.8	80030.6	0.6739	0.6539	1.0638	0.3999	85625.0
159430.4	79856.7	79573.7	0.6748	0.6542	1.0689	0.4044	85139.8
163699.7	82003.6	81696.1	0.6774	0.6564	1.0803	0.4134	87286.7
171501.2	85914.3	85586.9	0.6818	0.6613	1.1053	0.4338	91197.5
179780.1	90060.0	89720.1	0.6866	0.6673	1.1351	0.4581	95343.1

Table E-6: Specimen LD3 Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
205638.4	103029.0	102609.4	0.7052	0.6844	1.2321	0.5373	108312.2
233584.3	116997.0	116587.3	0.7246	0.7032	1.3378	0.6238	122280.2
241643.4	121026.1	120617.3	0.7297	0.7087	1.3821	0.6629	126309.3
248364.8	124424.2	123940.6	0.7338	0.7130	1.4268	0.7034	129707.4
245670.3	123004.2	122666.1	0.7330	0.7099	1.4586	0.7371	128287.4
245758.4	123092.1	122666.3	0.7326	0.7085	1.4726	0.7521	128375.3
259758.6	130014.2	129744.3	0.7384	0.7118	1.5574	0.8324	135297.4
269776.8	135006.5	134770.3	0.7415	0.7150	1.6168	0.8885	140289.7
279824.1	140013.3	139810.8	0.7445	0.7180	1.6788	0.9476	145296.5
289863.6	145027.1	144836.4	0.7472	0.7208	1.7434	1.0095	150310.3
299902.2	150018.4	149883.8	0.7501	0.7215	1.8163	1.0804	155301.6
309798.8	155001.6	154797.2	0.7503	0.7216	1.9033	1.1674	160284.8
319712.7	160008.2	159704.5	0.7500	0.7222	1.9914	1.2553	165291.4
323694.7	161993.4	161701.3	0.7488	0.7218	2.0375	1.3021	167276.6
326337.8	163310.6	163027.2	0.7472	0.7207	2.0819	1.3480	168593.8
327045.7	163650.3	163395.3	0.7466	0.7182	2.1126	1.3802	168933.5
324978.3	162637.3	162341.0	0.7454	0.7114	2.1860	1.4576	167920.5

Table E-7: Specimen LD4 Shortened Dataset

P lbs	R_n lbs	R_f lbs	δ_n in.	δ_f in.	δ_m in.	Δ_{calc} in.	V_{ns} lbs
191.0	124.8	66.3	0.5012	0.4903	0.4957	0.0000	5429.3
9217.3	4706.2	4511.1	0.5483	0.5337	0.5458	0.0048	10010.7
19973.9	10118.8	9855.1	0.5715	0.5534	0.5749	0.0125	15423.3
29111.3	14700.8	14410.5	0.5849	0.5656	0.5954	0.0201	20005.3
34110.6	17208.8	16901.8	0.5907	0.5715	0.6062	0.0251	22513.3
40141.2	20231.9	19909.2	0.5975	0.5777	0.6212	0.0336	25536.4
39795.0	20048.0	19747.0	0.5979	0.5780	0.6247	0.0367	25352.5
43101.1	21702.9	21398.2	0.6007	0.5811	0.6314	0.0405	27007.4
50081.1	25203.9	24877.2	0.6071	0.5875	0.6535	0.0562	30508.4
55441.1	27895.7	27545.4	0.6113	0.5919	0.6710	0.0694	33200.2
59071.0	29704.9	29366.0	0.6140	0.5948	0.6872	0.0828	35009.4
60226.8	30300.6	29926.2	0.6152	0.5961	0.6928	0.0872	35605.1
58261.5	29315.4	28946.0	0.6158	0.5959	0.6967	0.0908	34619.9
61088.5	30727.3	30361.2	0.6173	0.5974	0.7017	0.0943	36031.8
69017.7	34698.5	34319.2	0.6223	0.6030	0.7210	0.1084	40003.0
73016.0	36706.5	36309.6	0.6251	0.6056	0.7383	0.1229	42010.9
76999.2	38699.5	38299.7	0.6281	0.6088	0.7543	0.1359	44004.0
80172.5	40295.4	39877.1	0.6305	0.6105	0.7653	0.1448	45599.9
78028.9	39228.5	38800.4	0.6312	0.6105	0.7681	0.1473	44533.0
85001.1	42699.6	42301.6	0.6348	0.6144	0.7830	0.1583	48004.0
93129.4	46781.1	46348.3	0.6398	0.6200	0.8086	0.1787	52085.6
100101.4	50288.8	49812.5	0.6426	0.6243	0.8331	0.1996	55593.3
97693.3	49082.6	48610.7	0.6446	0.6238	0.8354	0.2012	54387.0
104945.2	52700.6	52244.6	0.6469	0.6281	0.8506	0.2131	58005.0
112941.0	56701.2	56239.8	0.6499	0.6333	0.8738	0.2322	62005.7
120103.7	60296.8	59806.9	0.6523	0.6386	0.8971	0.2516	65601.2
118262.1	59391.8	58870.3	0.6523	0.6384	0.8983	0.2529	64696.2
122921.9	61707.8	61214.1	0.6534	0.6405	0.9084	0.2614	67012.3
128928.6	64715.1	64213.6	0.6554	0.6446	0.9243	0.2743	70019.6
134876.5	67700.2	67176.3	0.6571	0.6484	0.9429	0.2902	73004.7

Table E-7: Specimen LD4 Shortened Dataset

P lbs	**R_n** lbs	**R_f** lbs	**δ_n** in.	**δ_f** in.	**δ_m** in.	**Δ_{calc}** in.	**V_{ns}** lbs
140022.7	70281.2	69741.5	0.6584	0.6515	0.9602	0.3053	75585.7
138513.9	69531.4	68982.5	0.6583	0.6514	0.9613	0.3064	74835.9
142893.6	71707.6	71186.0	0.6594	0.6538	0.9706	0.3140	77012.0
148886.5	74700.3	74186.2	0.6612	0.6582	0.9888	0.3292	80004.8
160112.9	80317.8	79795.2	0.6649	0.6661	1.0242	0.3587	85622.3
158809.2	79670.4	79138.8	0.6648	0.6659	1.0260	0.3606	84974.9
162902.5	81699.8	81202.7	0.6659	0.6686	1.0354	0.3681	87004.3
168880.6	84714.8	84165.8	0.6680	0.6725	1.0520	0.3817	90019.3
188859.3	94714.0	94145.3	0.6751	0.6859	1.1152	0.4347	100018.5
208765.1	104699.0	104066.1	0.6825	0.6938	1.1795	0.4913	110003.5
228737.9	114706.4	114031.5	0.6898	0.7006	1.2449	0.5497	120010.9
248647.8	124697.1	123950.6	0.6967	0.7072	1.3126	0.6107	130001.6
265601.3	133196.5	132404.7	0.7025	0.7131	1.3754	0.6676	138501.0
268628.4	134704.2	133924.2	0.7036	0.7137	1.3889	0.6802	140008.7
272869.1	136836.5	136032.6	0.7052	0.7151	1.4103	0.7001	142141.0
274260.6	137542.6	136717.9	0.7055	0.7155	1.4292	0.7187	142847.1
273780.9	137343.5	136437.4	0.7055	0.7153	1.4397	0.7294	142648.0

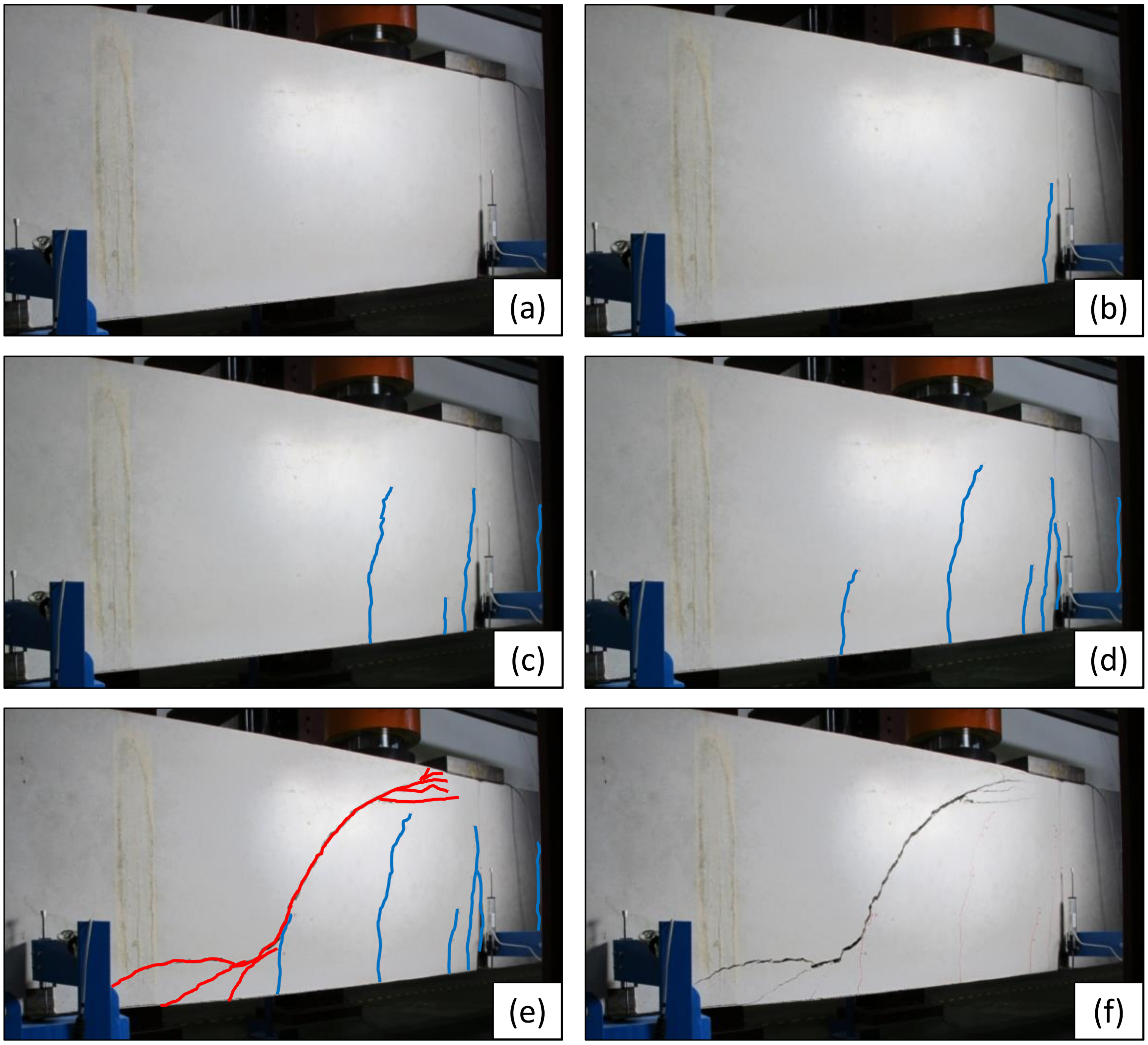


Figure E-7: Specimen LD1-N Loading Sequence Showing the Following Total Applied Loads: (a) 0 kips, (b) 40 kips, (c) 60 kips, (d) 80 kips, (e) and (f) Failure

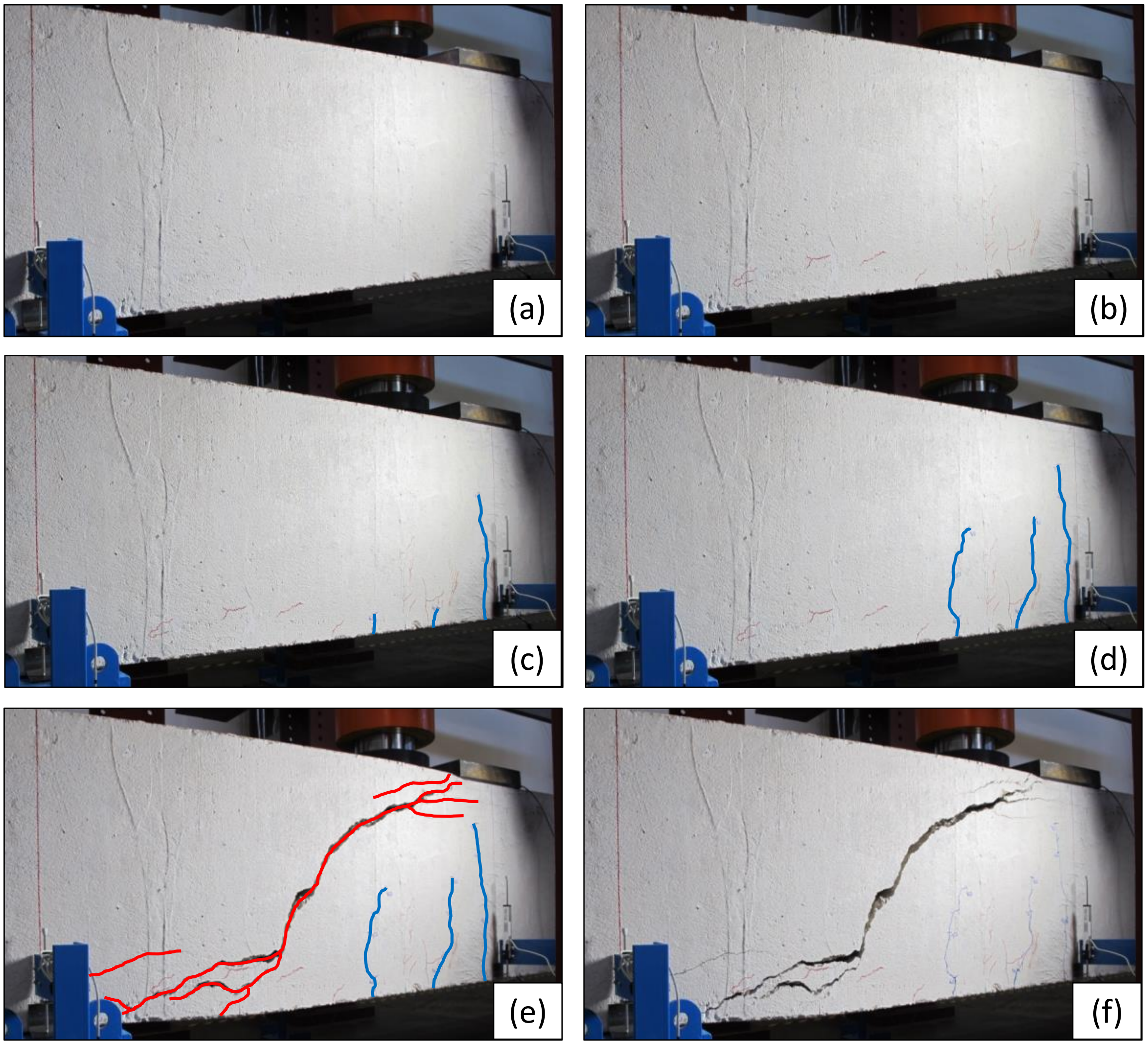


Figure E-8: Specimen LD1-S Loading Sequence Showing the Following Total Applied Loads: (a) 0 kips, (b) 40 kips, (c) 60 kips, (d) 80 kips, (e) and (f) Failure

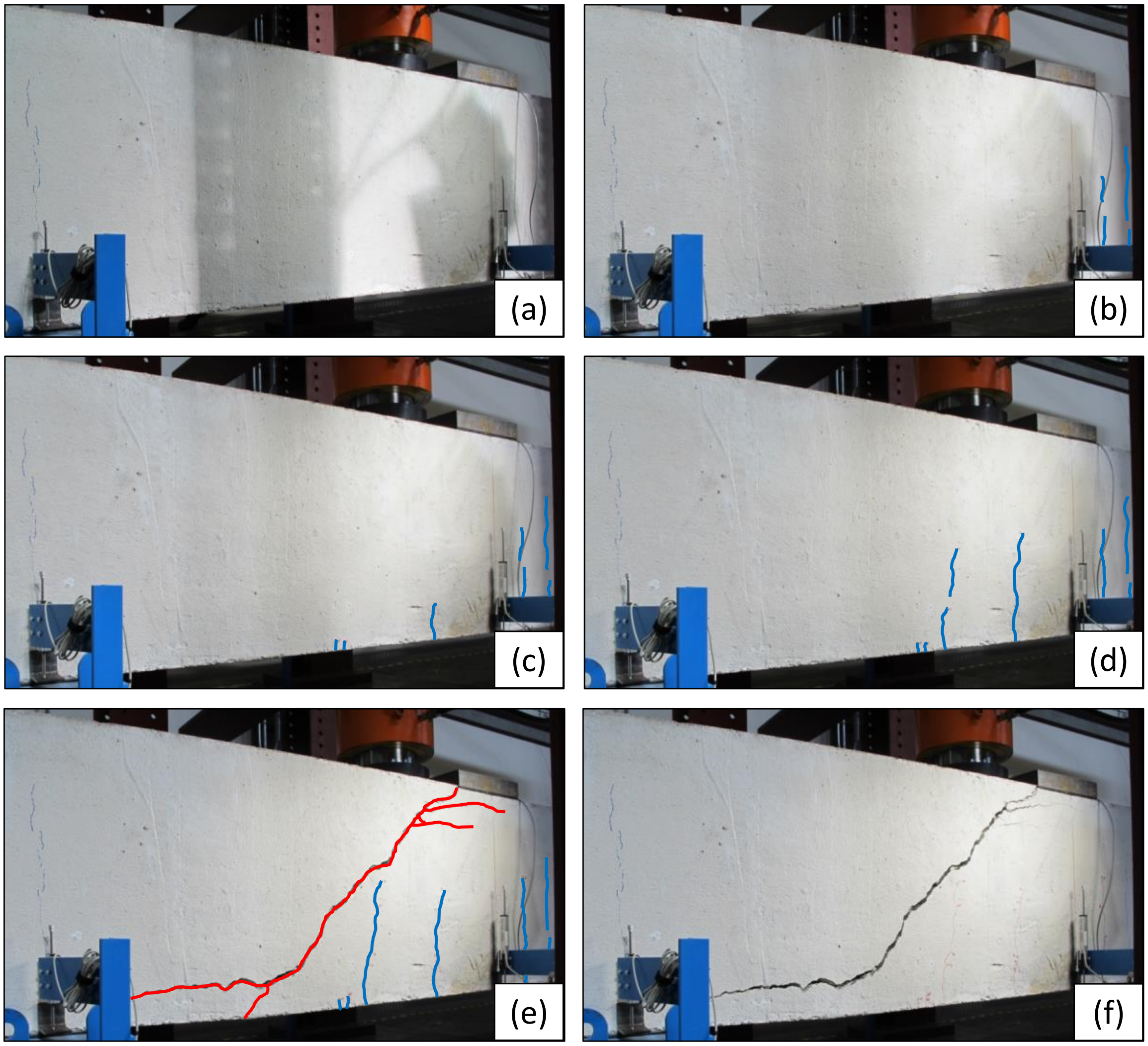


Figure E-9: Specimen SR2-S Loading Sequence Showing the Following Total Applied Loads: (a) 0 kips, (b) 40 kips, (c) 60 kips, (d) 80 kips, (e) and (f) Failure

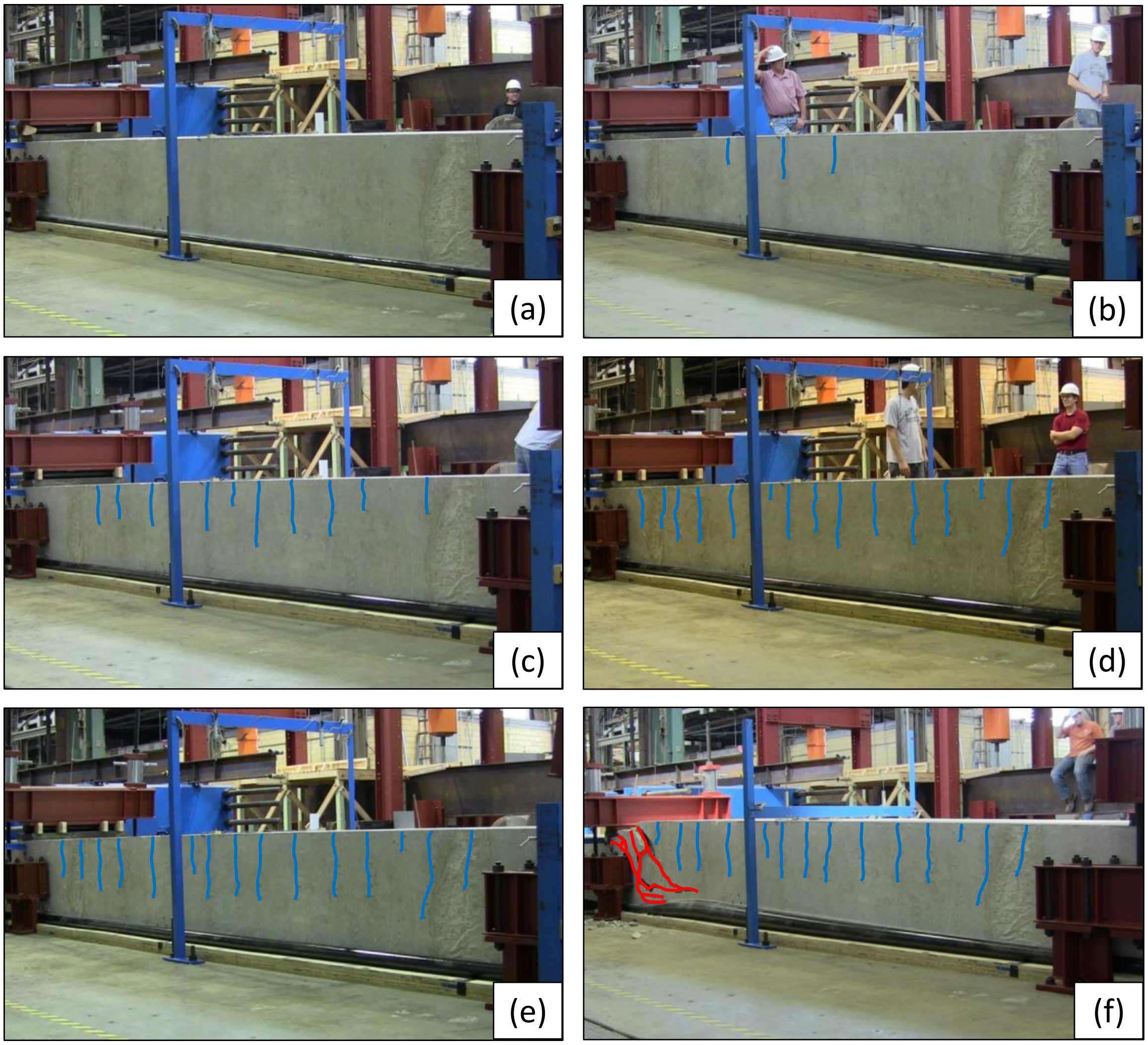


Figure E-10: Specimen LD2 Loading Sequence Showing the Following Total Applied Loads: (a) 0 kips, (b) 40 kips, (c) 80 kips, (d) 120 kips, (e) 160 kips, (f) Failure

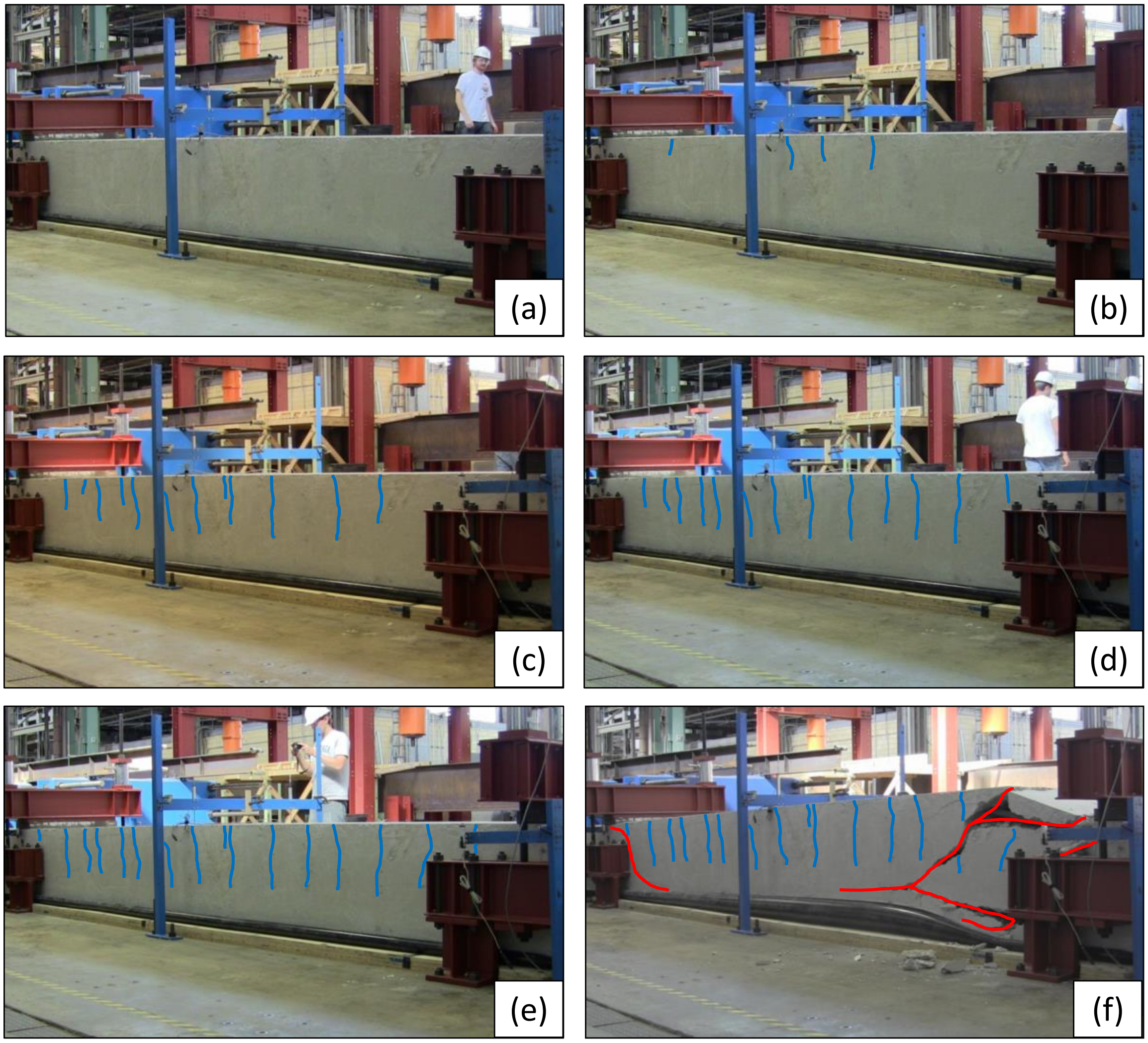


Figure E-11: Specimen LD3 Loading Sequence Showing the Following Total Applied Loads: (a) 0 kips, (b) 40 kips, (c) 80 kips, (d) 120 kips, (e) 160 kips, (f) Failure

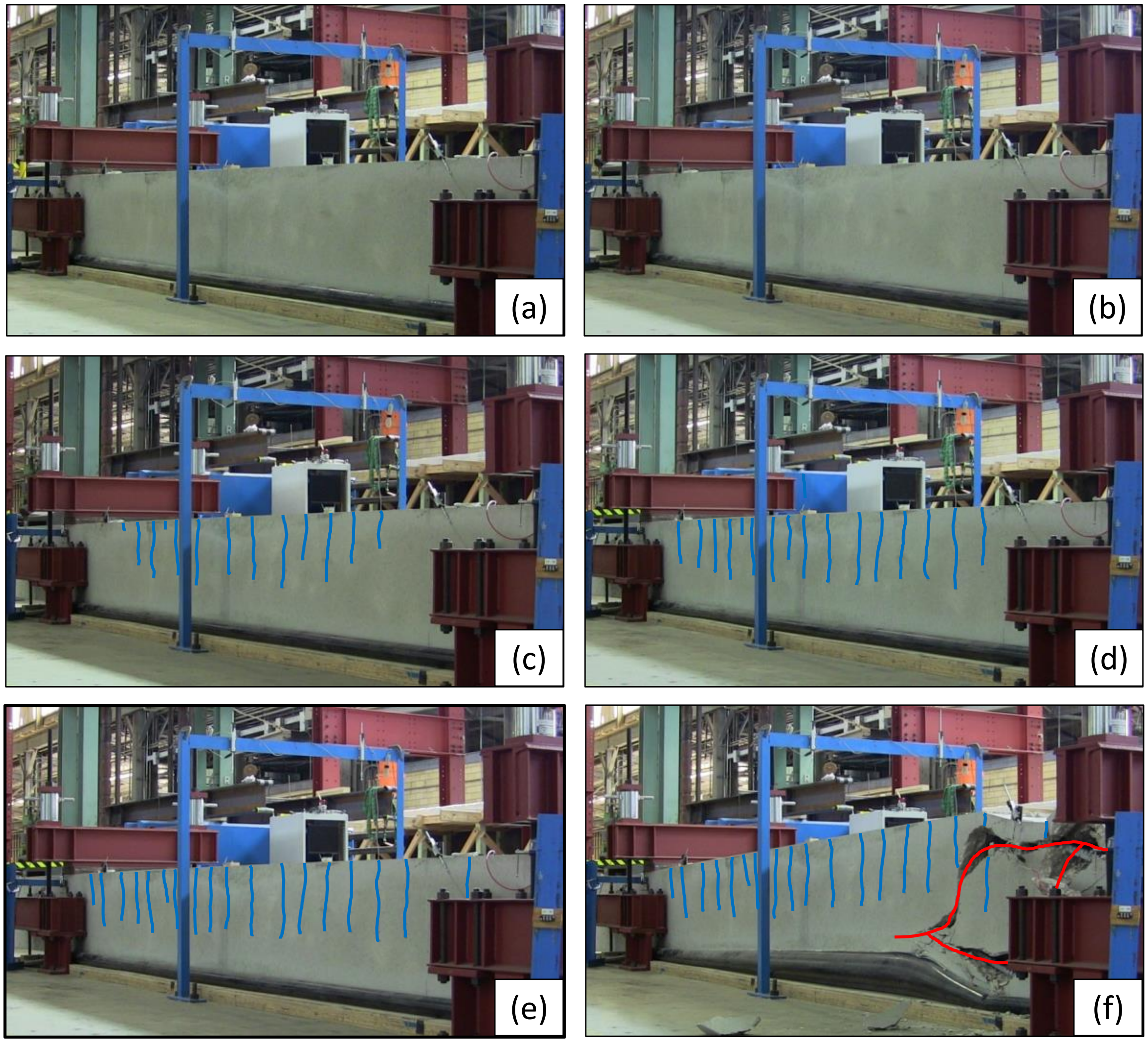


Figure E-12: Specimen LD4 Loading Sequence Showing the Following Total Applied Loads: (a) 0 kips, (b) 40 kips, (c) 80 kips, (d) 120 kips, (e) 160 kips, (f) Failure

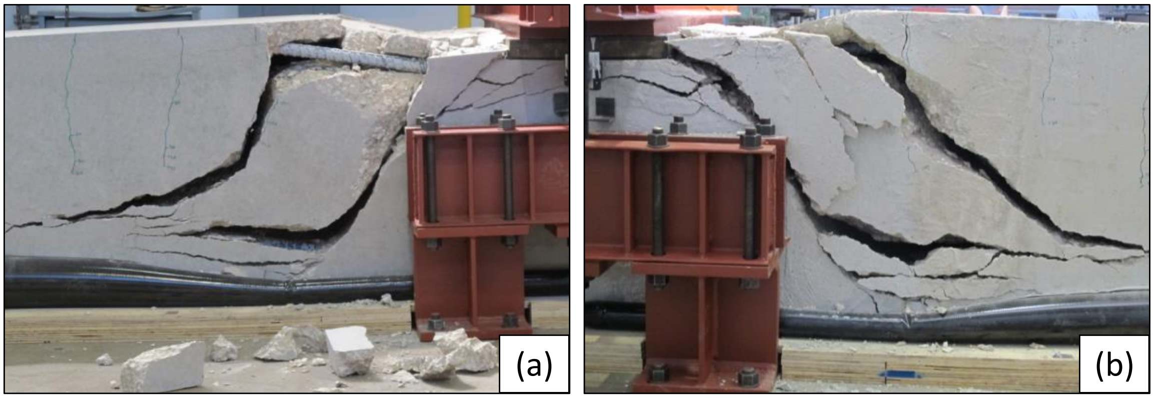


Figure E-13: Specimen LD2 Detailed Failure Photos at the Following Locations: (a) Northeast, (b) Northwest

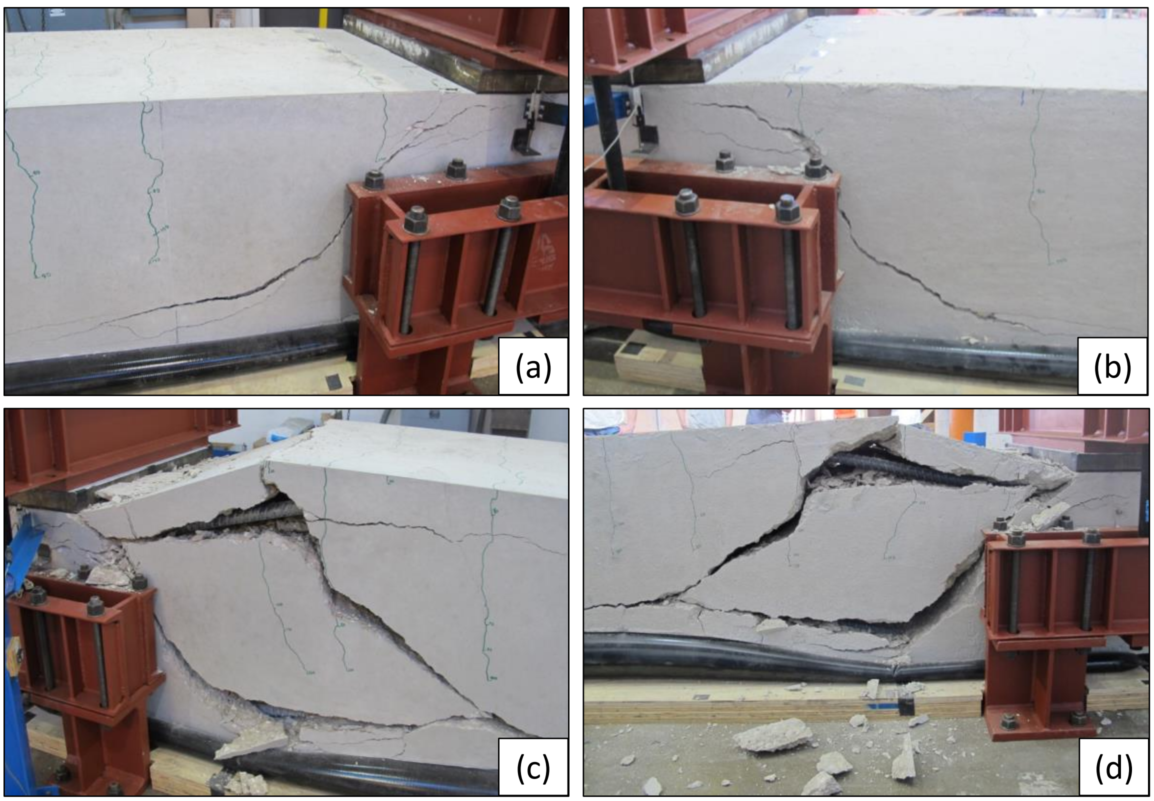


Figure E-14: Specimen LD3 Detailed Failure Photos at the Following Locations: (a) Northeast, (b) Northwest, (c) Southeast, (d) Southwest

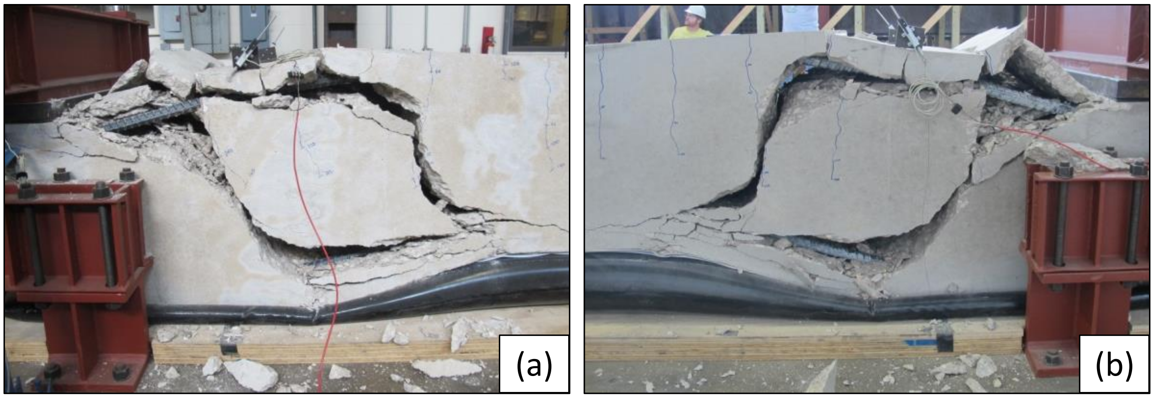


Figure E-15: Specimen LD4 Detailed Failure Photos at the Following Locations: (a) Southeast, (b) Southwest

Table E-8: Specimen LD1-N Observation Record

ACTUAL STRUCTURAL RESPONSE 4 /24 /2014

Time	Target Load	Actual Load	Comments and Observations
9:47 am	0 k	0 k	
9:51	10	10.2	No observations
9:59	20	20.2	No observatims
10:04	30	30.0	No observations
10:09	40	40.1	Flexural cracks beneath load
10:20	50	49.9	Additional flexural cracks, extension
10:30	60	60.1	" " " "
10:41	70	70.1	" " " "
10:50	80	80.1	Limited additional flexural cracking
	Failure	119.5	Well defined shear crack

Table E-9: Specimen LD1-S Observation Record

ACTUAL STRUCTURAL RESPONSE 5/1/2014

Time	Target Load	Actual Load	Comments and Observations
	0 k	0 k	
4:02 pm	10	10.1	No observations
4:08	20	20.1	No observations
4:11	30	30.1	No observations
4:16	40	40.1	Flexural cracks beneath load (1 total)
4:26	50	50.1	Additonal flexural cracks (4 total)
4:36	60	60.1	" " " (7 total)
4:45	70	70.1	" " " (8 total)
4:53	80	80.1	Extension of flexural cracks (8 total)
5:22	Failure	131.4	Well defined shear crack

Table E-10: Specimen SR2-S Observation Record

ACTUAL STRUCTURAL RESPONSE 4/28/14

Time	Target Load	Actual Load	Comments and Observations
	0 k	0 k	
	10	10.1	No observations
	20	20.1	No observations
	30	30.0	Slight initial cracking (flexural)
	40	40.1	No additional cracking
	50	50.0	Flexural cracking beneath load
	60	60.1	(estimated at 45 kips)
	70	70.2	
	80	80.1	
	90	90.1	
	Failure	117.2/155.6	Shear crack first seen at 117 kips
			Ultimate load reached 155.6 kips
			Well defined shear crack

Table E-11: Specimen LD2 Observation Record

ACTUAL STRUCTURAL RESPONSE 5/9/14 (0 to 160), 5/15/14 (Failure)

Time	Target Load	Actual Load	Comments and Observations
1:40 pm	0 k	0 k	
2:48	20	20.2	No observations
3:06	40	40.2	Flexural cracking (4 total)
3:24	60	60.2	Additional flexural cracks (9 total)
3:40	80	80.3	" " " (13 total)
3:55	100	100.2	" " " (16 total)
4:09	120	120.3	" " " (17 total)
4:22	140	140.2	Extension of flexural cracks (17 total)
	160		
	Failure	234.0/258.3	Shear crack first seen on north end
			at 234 Kips ; Ultimate load reached
			258.3 kips before failure at north end
			Sudden, brittle shear failure at north end

Table E-12: Specimen LD3 Observation Record

ACTUAL STRUCTURAL RESPONSE 5/16/2014

Time	Target Load	Actual Load	Comments and Observations
	0 k	0 k	
2:40 pm	20	20.5	No observations
2:49	40	40.2	Flexural cracking (6 total)
3:03	60	60.3	Additional flexural cracks (9 total)
3:26	80	80.9	" " " (11 total)
3:39	100	100.1	" " " (12 total)
3:52	120	120.1	" " " (14 total)
4:07	140	140.4	" " " (15 total)
4:21	160	160.4	Extension of flexural cracks (15 total)
	Failure	233.6/248.4/ 327.0	Shear crack first seen on south end
			at 233 kips; Shear crack first seen on
			north end at 248 kips; Ultimate load
			reached 327.0 kips before failure at
			south end
			Sudden, brittle shear failure at south end

Table E-13: Specimen LD4 Observation Record

ACTUAL STRUCTURAL RESPONSE 8/1/2014

Time	Target Load	Actual Load	Comments and Observations
8:55 am	20 k	20.1 k	No observations
9:07	40	40.1	No observations
9:16	60	60.3	Flexural Cracking (7 total)
9:40	80	80.2	Additional flexural cracks (12 total)
10:02	100	100.1	" " " (15 total)
10:34	120	120.2	" " " (16 total)
10:45	140	140.0	" " " (17 total)
11:01	160	160.1	" " " (18 total)
11:56	Failure	274.3	Hairline shear cracking seen on both
			north and south ends
			Sudden, brittle shear failure at south end

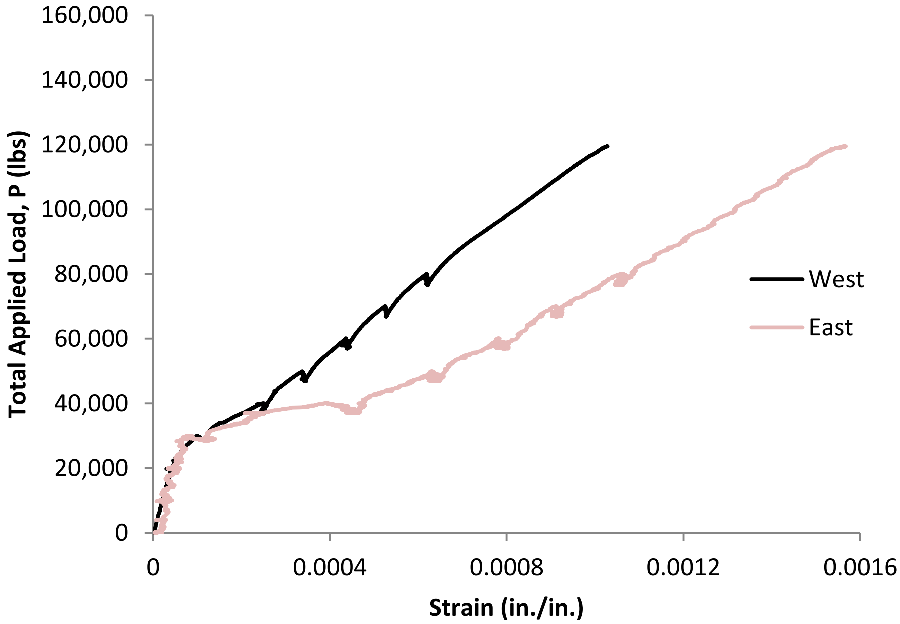


Figure E-16: Specimen LD1-N Maximum Strain in Longitudinal Tension Bars

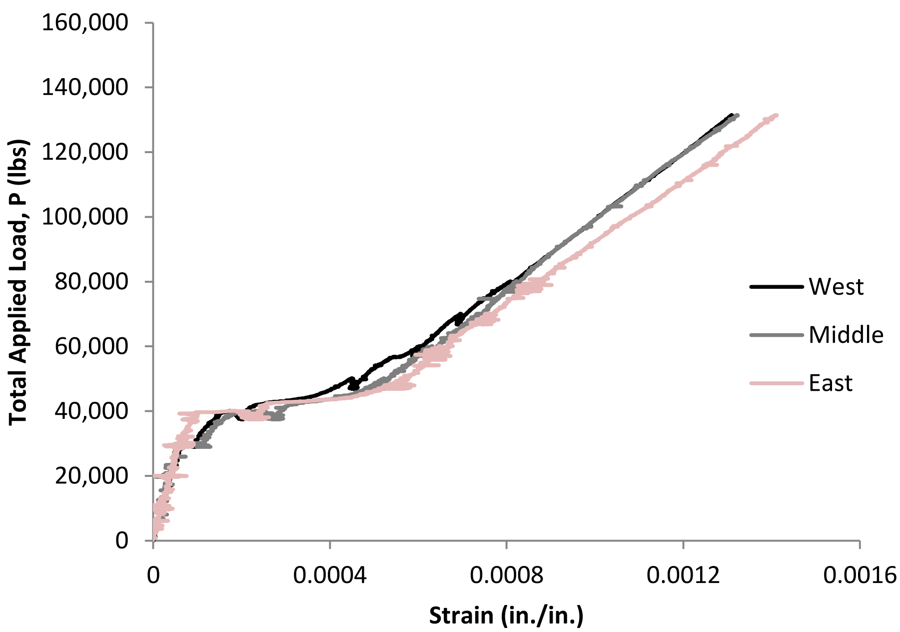


Figure E-17: Specimen LD1-S Maximum Strain in Longitudinal Tension Bars

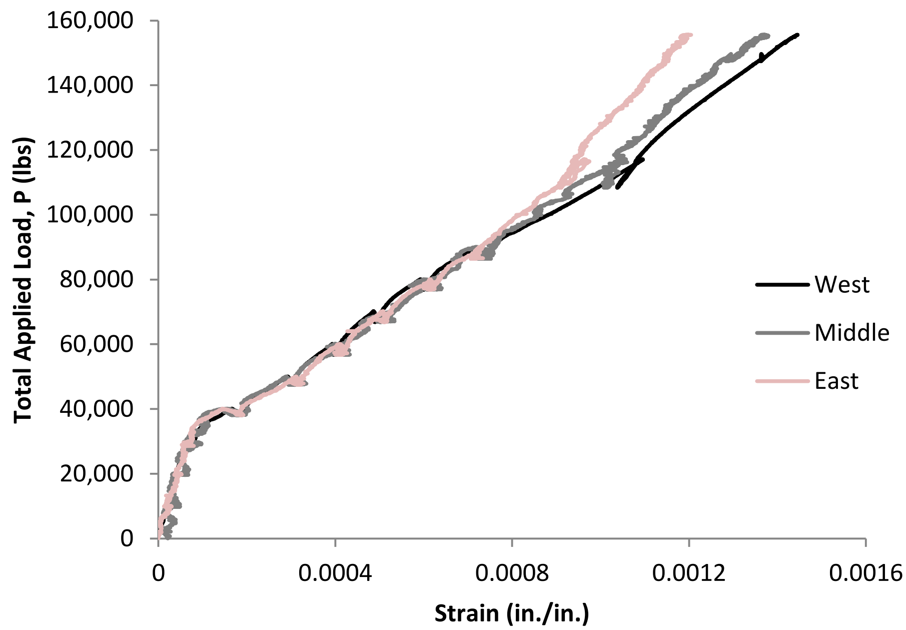


Figure E-18: Specimen SR2-S Maximum Strain in Longitudinal Tension Bars

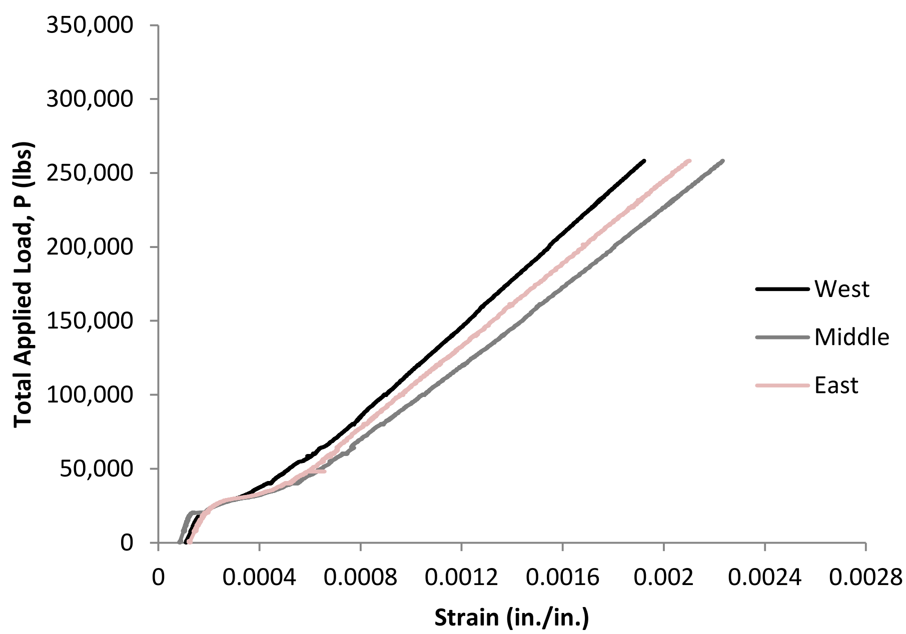


Figure E-19: Specimen LD2 Maximum Strain in Longitudinal Tension Bars

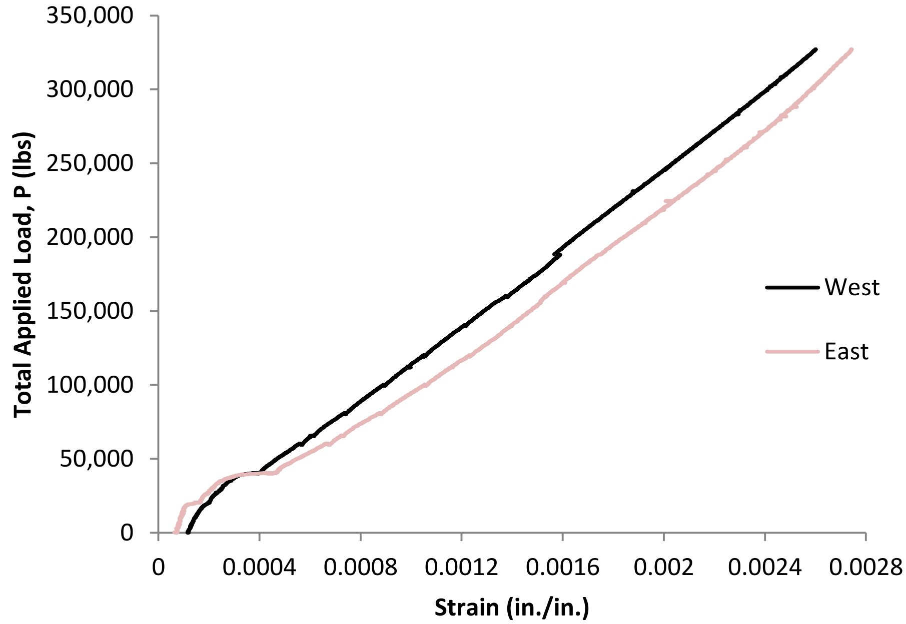


Figure E-20: Specimen LD3 Maximum Strain in Longitudinal Tension Bars

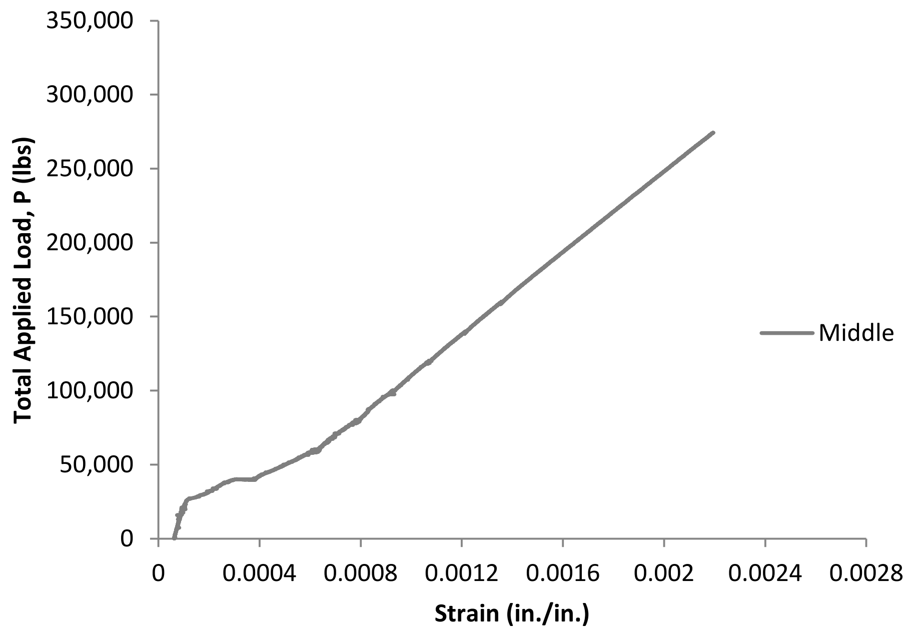


Figure E-21: Specimen LD4 Maximum Strain in Longitudinal Tension Bars

APPENDIX F

Post-Test Analysis

Appendix F includes the following three post-test analysis methods: ACI 318-11 equation 11-3, ACI 318 equation 11-5, and AASHTO LRFD 2012 shear design provisions. Analysis was completed using actual failure location at x_r away from the support for all six tests. ACI 318-11 equations were compared with first diagonal cracking load, while AASHTO LRFD 2012 shear design provisions were compared with ultimate load achieved. Summaries for the derivation of each equation can be seen in the proceeding document. Additionally, the author suggests referencing ACI 318-11 and AASHTO 2012 for more detailed information. Results are presented in the following manner:

- *Summary of Analysis Methods:* Table F-1 through Table F-4
- *Sample Calculations for Each Analysis Method:* Figure F-1 through Figure F-5

Table F-1: Comparison of First Diagonal Cracking Test Results to ACI 318-11 Equation 11-3

Test Identification	V_{xr} (kips)	f'_c (psi)	b_w (in.)	d (in.)	V_c (kips)	V_{xr}/V_c
LD1-N	87.871	3657.54	36	21.295	92.727	0.948
LD1-S	96.040	3657.54	36	21.295	92.727	1.036
SR2-S	85.909	4360.09	36	21.295	101.241	0.849
LD2	101.567	4070.71	36	21.295	97.824	1.039
LD3	101.934	3521.56	36	21.295	90.987	1.121
LD4	108.557	3712.50	36	21.295	93.421	1.162
					Mean	1.025
					Standard Deviation	0.104

Table F-2: Comparison of First Diagonal Cracking Test Results to ACI 318-11 Equation 11-5

Test Identification	V_{xr} (kips)	f'_c (psi)	ω_b (kips/in.)	ρ	b_w (in.)	d (in.)	M_u (kip-in.)	V_c (kips)	$V_c d/M_u$	V_{xr}/V_c
LD1-N	87.871	3657.54	0.0717	0.0102	36	21.295	2737.74	103.841	0.8077	0.846
LD1-S	96.040	3657.54	0.0717	0.0102	36	21.295	2737.74	103.841	0.8077	0.925
SR2-S	85.909	4360.09	0.0740	0.0102	36	21.295	2952.02	111.923	0.8074	0.768
LD2	101.567	4070.71	0.0742	0.0102	36	21.295	2351.02	112.433	1.0000	0.903
LD3	101.934	3521.56	0.0734	0.0102	36	21.295	2221.02	105.937	1.0000	0.962
LD4	108.557	3712.50	0.0738	0.0102	36	21.295	3196.52	102.000	0.6795	1.064
									Mean	0.911
									Standard Deviation	0.092

Table F-3: Constants for AASHTO 2012 Shear Design Provisions

s_x (in.)	a_g (in.)	s_{xe} (in.)	b_w (in.)	d (in.)	d_v (in.)	E_s (ksi)	A_s (in^2)
17.59	1	14.89	36	21.295	19.17	29000	7.8

Table F-4: Comparison of Ultimate Load Test Results to AASHTO 2012 Shear Design Provisions

Test Identification	V_{xr} (kips)	f'_c (ksi)	ω_b (kips/in.)	M_u (kip-in.)	V_c (kips)	ε_s	β	V_{xr}/V_c
LD1-N	87.871	3.658	0.0717	2744.09	104.079	0.00109	2.496	0.844
LD1-S	96.040	3.658	0.0717	2744.09	104.079	0.00109	2.496	0.923
SR2-S	113.455	4.360	0.0740	2915.14	110.538	0.00116	2.428	1.026
LD2	111.789	4.071	0.0742	2348.99	112.330	0.00104	2.554	0.995
LD3	140.799	3.522	0.0734	2237.12	106.751	0.00099	2.609	1.319
LD4	108.557	3.712	0.0738	3173.77	101.245	0.00118	2.410	1.072
							Mean	1.030
							Standard Deviation	0.149

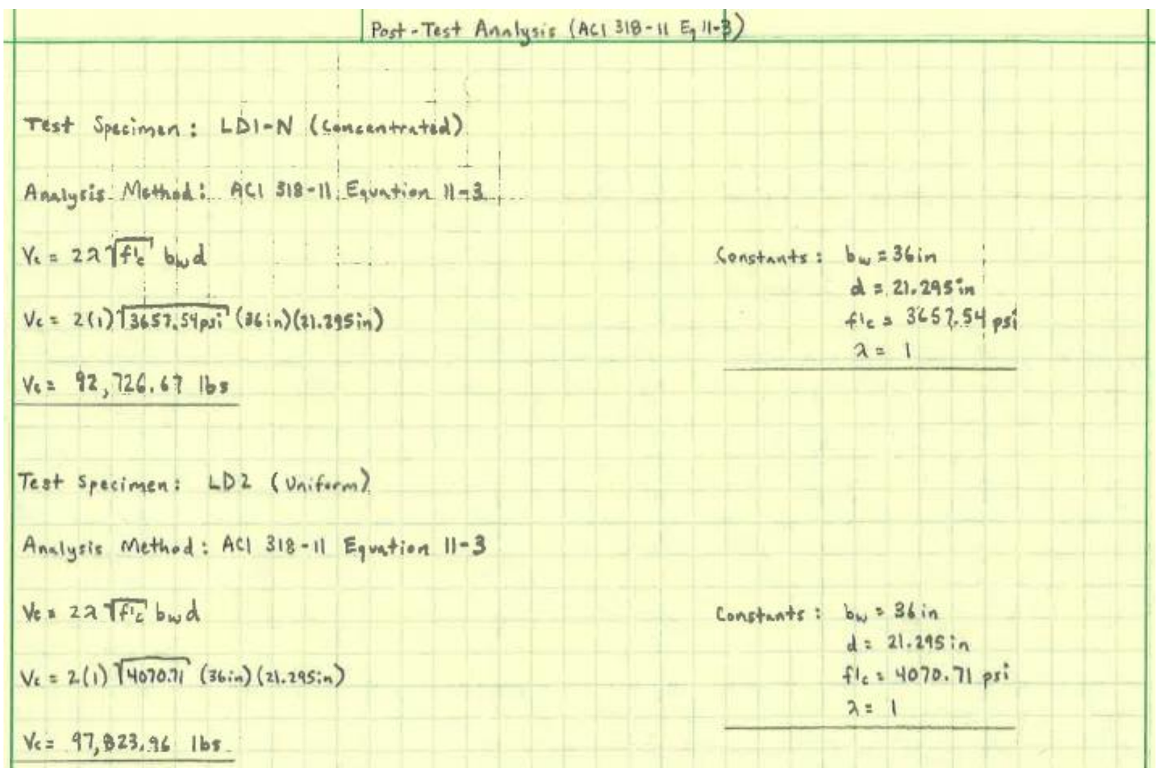


Figure F-1: ACI 318-11 Equation 11-3 Sample Calculations Showing Both Concentrated and Uniform Loading

Post-Test Analysis (ACI 318-11 Eq 11-5)

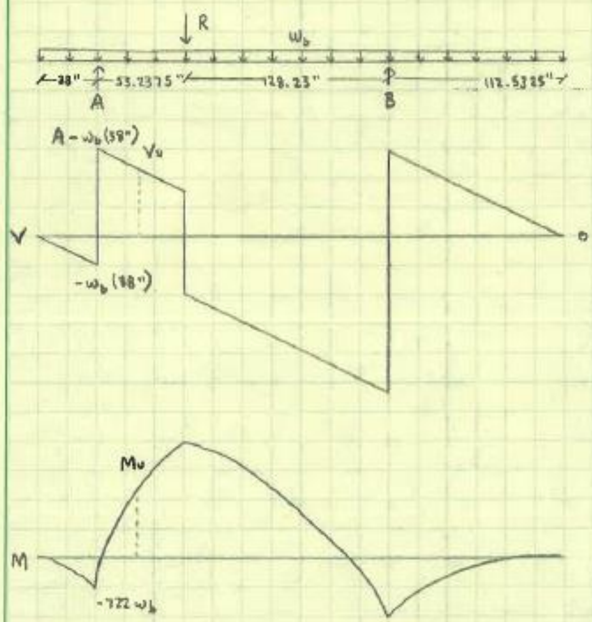
Test Specimen: LD1-N (concentrated)

Analysis Method: ACI 318-11 Equation 11-5

$V_c = \left(1.9\lambda\sqrt{f'_c} + 2500\rho_w \frac{V_u d}{M_u}\right) b_w d$

Find V_u and M_u at failure location of x_f away from the support:

Constants:
$b_w = 36$ in
$d = 21.295$ in
$f'_c = 3657.54$ psi
$\lambda = 1$
$\rho_w = 0.01017$
$x_f = 26.61875$ in
$W_b = 71.69$ lbs/in



$V_u = A - w_b(64.61875")$

$M_u = -722(w_b) + 354.279(w_b) + V_u(26.6175)$

$M_u = (A - w_b(64.61875"))(26.6175) + 367.721(w_b)$

$M_u = 26.6175"(A) - 1352.269\text{ in}^2(w_b)$

$$V_u = \left(1.9(1)\sqrt{3657.54\text{psi}} + 2500(0.01017)\left[\frac{(A) - (71.69\text{ lb/in})(64.61875"))(21.295")}{(A)(26.6175") - (71.69\text{ lb/in})(1352.269\text{ in}^2)}\right]\right)(36\text{in})(21.295\text{in})$$

$$V_u = 88{,}090.34\text{ lbs} + 19491.31\left[\frac{A(21.295") - 98649.47\text{ lb-in}}{A(26.6175") - 96944.16\text{ lb-in}}\right] \quad ①$$

$V_u = A - (71.69\text{lb/in})(64.61875")$

$V_u = A - 4632.52\text{ lbs} \quad ②$

Combine Equations ①, ② to find V_u

Note: This process was completed in Excel for all test results.

$V_u = 103{,}840.6$ lbs

Figure F-2: ACI 318-11 Equation 11-5 Sample Calculation for Concentrated Loading

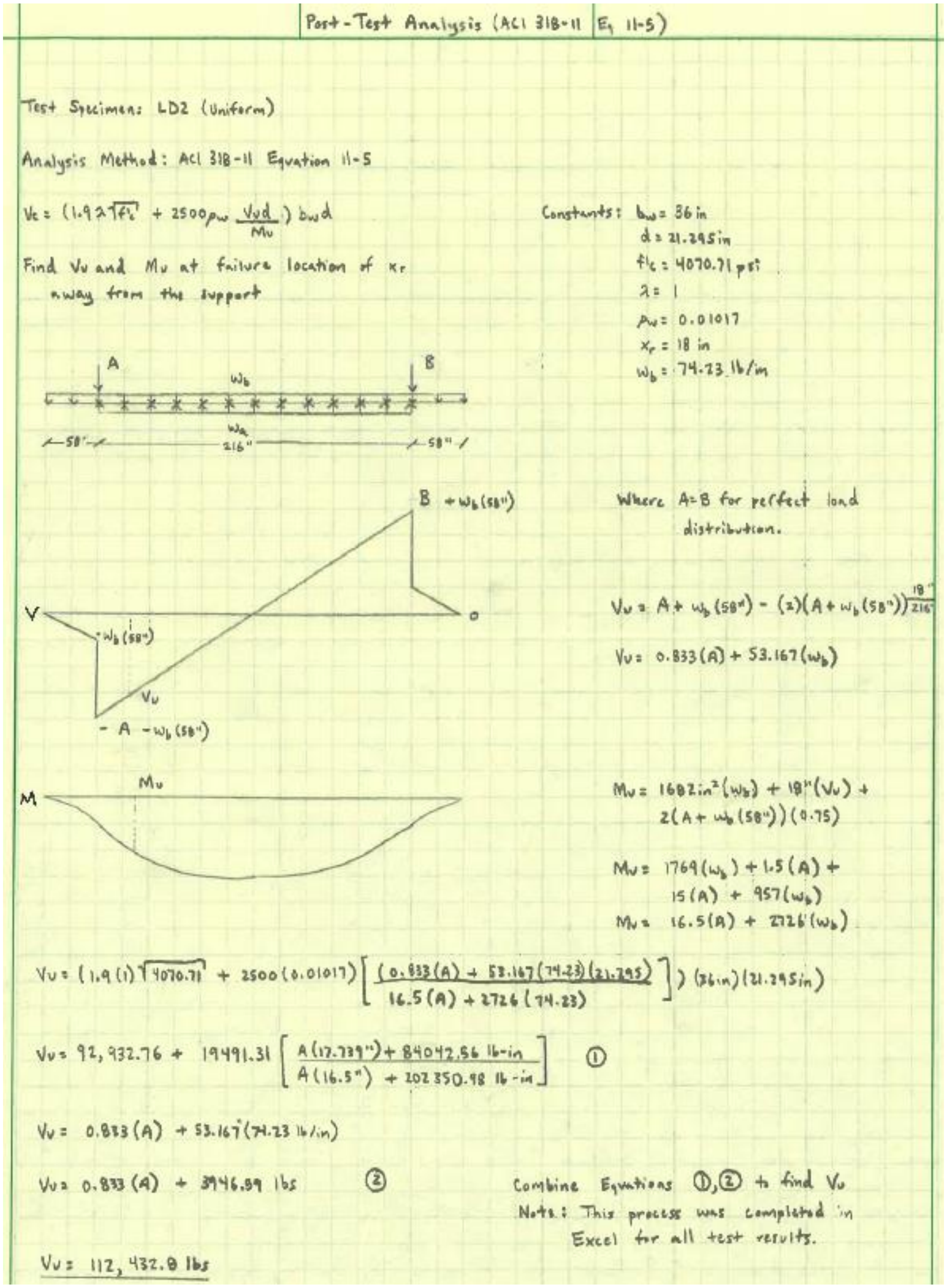
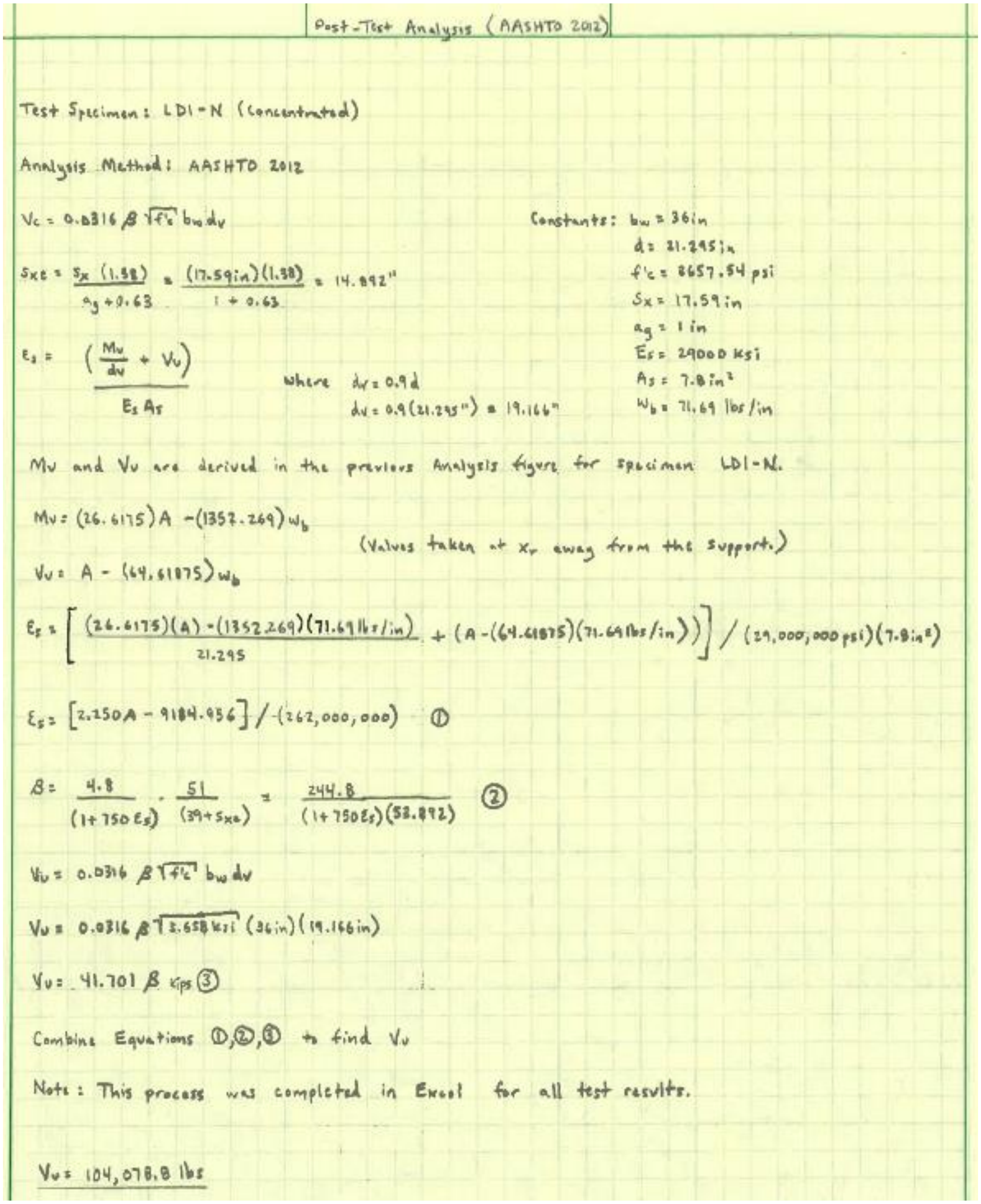


Figure F-3: ACI 318-11 Equation 11-5 Sample Calculation for Uniform Loading



Post-Test Analysis (AASHTO 2012)

Test Specimen: LDI-N (Concentrated)

Analysis Method: AASHTO 2012

$V_c = 0.0316\,\beta\sqrt{f'_c}\,b_w d_v$

Constants:
$b_w = 36\text{in}$
$d = 21.295\text{in}$
$f'_c = 8657.54\text{ psi}$
$S_x = 17.59\text{in}$
$a_g = 1\text{ in}$
$E_s = 29000\text{ ksi}$
$A_s = 7.8\text{in}^2$
$w_b = 71.69\text{ lbs/in}$

$$S_{xe} = \frac{S_x(1.38)}{a_g + 0.63} = \frac{(17.59\text{in})(1.38)}{1+0.63} = 14.892''$$

$$\varepsilon_s = \frac{\left(\frac{M_u}{d_v} + V_u\right)}{E_s A_s}$$

where $d_v = 0.9d$
$d_v = 0.9(21.295'') = 19.166''$

M_u and V_u are derived in the previous Analysis figure for specimen LDI-N.

$M_u = (26.6175)A - (1352.269)w_b$

$V_u = A - (64.61875)w_b$

(Values taken at x_r away from the support.)

$$\varepsilon_s = \left[\frac{(26.6175)(A) - (1352.269)(71.69\text{lbs/in})}{21.295} + (A - (64.61875)(71.69\text{lbs/in}))\right] / (29{,}000{,}000\text{psi})(7.8\text{in}^2)$$

$$\varepsilon_s = [2.250A - 9184.956] / (262{,}000{,}000) \quad (1)$$

$$\beta = \frac{4.8}{(1+750\varepsilon_s)} \cdot \frac{51}{(39+S_{xe})} = \frac{244.8}{(1+750\varepsilon_s)(53.892)} \quad (2)$$

$V_u = 0.0316\,\beta\sqrt{f'_c}\,b_w d_v$

$V_u = 0.0316\,\beta\sqrt{8.658\text{ksi}}\,(36\text{in})(19.166\text{in})$

$V_u = 41.701\,\beta\text{ kips} \quad (3)$

Combine Equations (1),(2),(3) to find V_u

Note: This process was completed in Excel for all test results.

$V_u = 104{,}078.8\text{ lbs}$

Figure F-4: AASHTO 2012 Shear Provisions Sample Calculation for Concentrated Loading

Post-Test Analysis (AASHTO 2012)

Test Specimen: LD2 (Uniform)

Analysis Method: AASHTO 2012

$V_c = 0.0316\,\beta\sqrt{f'_c}\,b_w d_v$

Constants: $b_w = 36$ in, $d = 21.295$ in, $f'_c = 4070.71$ psi, $S_x = 17.59$ in, $a_g = 1$ in, $E_s = 29000$ ksi, $A_s = 7.8\,in^2$, $w_b = 74.23$ lbs/in

$$S_{xe} = \frac{S_x(1.38)}{a_g + 0.63} = \frac{(17.59\,in)(1.38)}{1 + 0.63} = 14.892''$$

$$\varepsilon_s = \frac{\left(\frac{M_u}{d_v} + V_u\right)}{E_s A_s}$$

where $d_v = 0.9d$

$d_v = 0.9(21.295'') = 19.166''$

M_u and V_u are derived in the previous Analysis figure for specimen LD2.

$M_u = (16.5)A + 2726(w_b)$

$V_u = (0.833)A + 53.167(w_b)$

(Values taken at x_r away from the support)

$$\varepsilon_s = \left[\frac{(16.5)A + 2726(74.23\,lbs/in)}{21.295} + (0.833)A + 53.167(74.23\,lbs/in)\right] / (29{,}000{,}000\,psi)(7.8\,in^2)$$

$$\varepsilon_s = [1.609A + 13453.648] / (262{,}000{,}000) \quad ①$$

$$\beta = \frac{4.8}{(1+750\varepsilon_s)} \cdot \frac{51}{(39+s_{xe})} = \frac{244.8}{(1+750\varepsilon_s)(53.892)} \quad ②$$

$V_u = 0.0316\,\beta\sqrt{f'_c}\,b_w d_v$

$V_u = 0.0316\,\beta\sqrt{4.070\,ksi}\,(36\,in)(19.166\,in)$

$V_u = 43.986\,\beta$ kips ③

Combine Equations ①, ②, ③ to find V_u

Note: This process was completed in Excel for all test results.

$V_u = 112{,}330.4$ lbs

Figure F-5: AASHTO 2012 Shear Provisions Sample Calculation for Uniform Loading

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