Fall 2010

Glass fiber-reinforced polyurea strengthening of reinforced concrete

Courtney Elizabeth Greene

GLASS FIBER-REINFORCED POLYUREA STRENGTHENING OF REINFORCED CONCRETE

by

COURTNEY ELIZABETH GREENE

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN CIVIL ENGINEERING

2010

Approved by

John J. Myers, Advisor
Victor Birman
Lesley H. Sneed

PUBLICATION THESIS OPTION

This thesis is comprised of two papers for publication. Pages 1-48 will be submitted to the Journal of Civil Engineering and Architecture and pages 50-105 will be submitted to the ASCE-Journal of Composites for Construction (ASCE-JCC). Appendices have been included to complete the thesis.

ABSTRACT

Wide varieties of concrete repair-retrofit and strengthening methods have been developed and are being widely implemented. In recent years, the need for such strengthening systems has become apparent with increasing demands on aging infrastructure. These strengthening systems need to be increasingly more adaptable, providing ease of construction as well as withstanding a variety of loading conditions and hazards. Exterior-applied fiber-reinforced polymer systems are increasingly being used to meet these demands. The research contained herein investigates the strengthening benefits and characteristics from a specific glass fiber-reinforced polyurea coating system applied externally to structures by means of spraying. This coating would allow for greater ease of construction and would thus be useful in repair-retrofit situations. In addition, the coating system is intended to provide multi-hazard benefits, ranging from blast fragmentation mitigation and impact or seismic loading to general strengthening.

Investigation of the glass fiber-reinforced polyurea coating system was conducted at the Missouri University of Science & Technology (Missouri S&T) in conjunction with the Center for Awareness and Localization of Explosives-Related Threats (ALERT) through the Department of Homeland Security (DHS). The strengthening effects of the described coating system were observed on small concrete cylinders and larger reinforced concrete (RC) beams tested for flexural and shear types of failure. Results show a significant impact on the flexural strength and shear strength of RC beams strengthened with the coating system. Included is a theoretical model to estimate the additional flexural capacities of polyurea-coated RC beams which was developed and validated with test results.

ACKNOWLEDGMENTS

The pursuit of my master's degree has been a challenging and rewarding experience and would not have been possible without the efforts of several extraordinary people and organizations. First and foremost, I would like to thank my advisor, Dr. John J. Myers, for giving me this opportunity and seeing me through to its completion. I am also thankful to my committee members, Dr. Lesley Sneed and Dr. Victor Birman, for offering their time and expertise. In addition, we are thankful to the Awareness and Localization of Explosives-Related Threats (ALERT) Program for their support and funding of this research effort.

For great help during the fabrication and testing of my research specimens, I have several people to thank and commend for their talents and efforts. My most genuine thanks go to Jeff Jira and the entire team at Line-X® of Columbia, Missouri for their generous support of our endeavors, immeasurable help, and knowledgeable advice. I would also like to thank several members of our own team of research and laboratory technicians and specialists – Jason Cox, John Bullock, Steve Gabel, Gary Abbott, and Mike Lusher – for their many hours of service and advice towards this project. Additionally, I am grateful for the extra time that Jeff Thomas and Jeremy Watts offered to help me with testing of the polyurea samples.

I offer a special thanks to Natalia Carey, whose expertise and encouragement were an integral part of my experience and success. Similarly I would like to thank all my fellow students who at some point (or several) during my research offered a helping hand or quick lesson.

Finally, I would like to acknowledge all those people – my fiancé, my parents, my family and best friends – who have encouraged and supported me during this time. This has been at times a harrowing journey which I would not have been able to continue traveling without all those who are most devoted to my well-being.

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NOMENCLATURE

Symbol	Description
ε_{cu}	Ultimate Strain of RC Column (in/in)
ε_{ccu}	Ultimate Strain of Confined RC Column (in/in)
f'_c	Ultimate Strength of Concrete (psi)
f'_{cc}	Ultimate Strength of Confined Concrete (psi)
V_f	Fiber Volume Fraction (%)
E	Modulus of Elasticity (psi)
S_1	Stress at Strain of 0.000050 in/in (psi)
ε_1	Strain of 0.000050 in/in
S_2	Stress at 40% of the Ultimate Compressive Capacity (psi)
ε_2	Strain at 40% of the Ultimate Compressive Capacity (in/in)
A	Area Under the Load-Deformation Curve (lb-in)
P_n	Ultimate Beam Capacity (k)
M_n	Moment Capacity of Beam (k- in)
A_i	Area under Load-Deflection Curve of Coated Beam (lb-in)
A_c	Area under Load-Deflection Curve of Control Beam (lb-in)
V_c	Concrete Contribution to Shear Capacity (k)
V_s	Steel Reinforcement Contribution to Shear Capacity (k)
V_f	Fiber-Reinforced Polyurea Contribution to Shear Capacity (k)
V_{tot}	Total Shear Capacity (k)
A_v	Cross-Sectional Area of Shear Reinforcement (in^2)
f_{yt}	Yield Strength of Shear Reinforcement (ksi)
s	Spacing of Shear Reinforcement (in)
y_f	Distance from Tension Face to Centroid of Coating Cross-Section Below Neutral Axis (in)
b	Width of Compression Face of Member (in)
h	Overall Height of Member (in)
d	Distance from Extreme Compression Fiber to Centroid of Longitudinal Tension Reinforcement (in)

g	Distance from Centroid of Longitudinal Reinforcement to Extreme Tension Fiber (in)
t_f	Thickness of FRP Coating (in)
A_f	Area of Polyurea Coating Below Neutral Axis (in^2)
A_s	Cross-Sectional Area of Longitudinal Steel (in^2)
f_f	Tensile Yield Strength of Fiber-Reinforced Polyurea (ksi)
f_y	Tensile Yield Strength of Steel Reinforcement (ksi)
N.A.	Neutral Axis of Beam Cross-Section
c	Distance from Extreme Compression Fiber to Neutral Axis (in)
a	Depth of Equivalent Rectangular Stress Block (in)
T_f	Tension Force in the Fiber (lb)
T_s	Tension Force in the Longitudinal Steel (lb)
φ	Strength Reduction Factor

I. COMPRESSIVE BEHAVIOR OF CONCRETE CYLINDERS STRENGTHENED WITH A DISCRETE FIBER REINFORCED POLYMER SYSTEM

ABSTRACT

The phase of research described in this paper is aimed at evaluating the confinement capabilities of a glass fiber-reinforced polyurea coating system when used with concrete cylinder specimens loaded in compression. Testing parameters include concrete strength with three different target strengths tested, fiber volume fraction, and type of polymer. Analysis of the varied systems is based on measurement of ultimate compressive strength and modulus of elasticity, as well as strain data for the coating system during loading. This testing, conducted the Missouri University of Science and Technology (Missouri S&T), provides results that support the use of fiber-reinforced polyurea coating systems to attain high adhesion and contain fragmentation and debris scatter, with several recommendations for future research provided.

1. INTRODUCTION

1.1. BACKGROUND

The compressive strength of concrete and the structural behavior of columns under pure compression or axial loading is known to be improved when confinement reinforcement is included in the concrete design. In such cases, spiral columns, or columns that include spiral reinforcement, exhibit a slight increase in strength and a significantly improved ductility (Wight and Macgregor, 2009). Traditionally, this spiral reinforcement which attributes confinement is provided by internal spiral-wrapped steel reinforcement. However, in recent years, much research and field testing has been completed in the repair and/or retrofitting of existing structures with externally-applied reinforcement. These externally-applied strengthening systems typically consist of polymer coating integrated with continuous wrapped fibers which circle and encase the columns. These wrapped fiber-reinforced polymer (FRP) coatings act similarly to the internal spiral steel reinforcement previously mentioned in providing column confinement and additional ductility, making them particularly useful in retrofitting existing column members to meet current seismic codes and standards.

Recent research has considered the development and use of spray-applied external coating systems in lieu of the wet-layup or hand-applied coatings that have been shown to improve structural behavior. Spray applications of polymers and fiber-reinforced polymers have been developed for fiberglass products, such as fiberglass boating equipment, or building products such as roof coating systems for a moisture barrier, but such coating systems have not been extensively developed for strengthening of concrete structures. Development of a spray application for such a strengthening system might allow for greater ease of application as well as a shorter construction time and, accordingly, a shorter shutdown period for traffic in bridge applications.

In the past, spray-applied polyurea coatings have been developed and tested for blast and impact conditions on concrete barriers and panels. Polyurea coatings applied to the back face of concrete barriers effectively reduce spalling caused by blast or impact loading, and the elastic material is effective in containing fragmentation that might otherwise be projected towards people or goods housed in a structure (Carey, 2010).

Further research and fiber characterization testing was conducted at Missouri S&T to achieve discrete fiber reinforcement of the elastomeric material with glass fiber, pairing the high ductility of the polyurea with the strength provided by the chopped fibers (Carey and Myers, 2010). This fiber-reinforced polyurea coating was developed with infrastructural repair and retrofitting in mind, with the idea that the coating could provide multi-hazard benefits including blast and impact damage mitigation, seismic benefits, and general strengthening for maximum load-posted or similar structures.

1.2. SCOPE AND OBJECTIVES

The blast mitigation properties of polyurea coatings have been tested for damage mitigation, and fiber-reinforced polymers have been widely used throughout the United States (US) in repair and retrofit applications to provide additional strength to structures. The research information contained herein is part of an effort to develop a coating system for multi-hazard protection, providing both blast hazard mitigation through minimizing debris scatter and concrete spalling, as well as adding structural capacity and/or ductility to concrete columns for seismic repair, retrofit and general strengthening.

The main objective of this project was to evaluate whether a fiber-reinforced polyurea coating system could provide substantial confinement to a cylindrical concrete column subjected to uni-axial load so as to significantly improve on the column's compressive capacity. Furthermore, the study was meant to investigate the effects of fiber-reinforced polyurea on the concrete cylinder as compared to the effects of the plain polyurea coating for higher strength gain and/or improved strain capability. By evaluating several coating systems, the research was aimed at determining the products and material properties which would provide for a most optimal resulting performance.

In order to complete a preliminary assessment of the potential confinement characteristics of the coating systems, the coatings were tested on small-scale concrete cylinders prepared in the laboratory. Compressive testing was completed on coated concrete cylinders, and load and strain data were measured for both the concrete and the polyurea coating systems. In addition, the coating system was evaluated independently so as to provide data for confinement capabilities vs. material tensile strength.

2. RELATED WORK

2.1. FRP SYSTEMS FOR COLUMN STRENGTHENING APPLICATIONS

2.1.1. Background. According to the American Concrete Institute (ACI), externally applied FRP wraps have been used to rehabilitate RC columns and provide additional column confinement since 1981 (ACI 440.2, 2008). In addition, based on extensive research developed since that time, current design guidelines state that, "Confinement of RC columns by means of FRP jackets can be used to enhance their strength and ductility (ACI 440.2, 2008)." Research conducted by Rocca (2007) provides a useful visualization of the stress-strain confinement behavior and effects of externally-applied FRP systems (see Figure 2.1), where ε_{cu} and ε_{ccu} represent the ultimate strain of an RC column, unconfined or confined, respectively, and f'_c and f'_{cc} represent concrete strength of the unconfined and confined RC column, respectively.

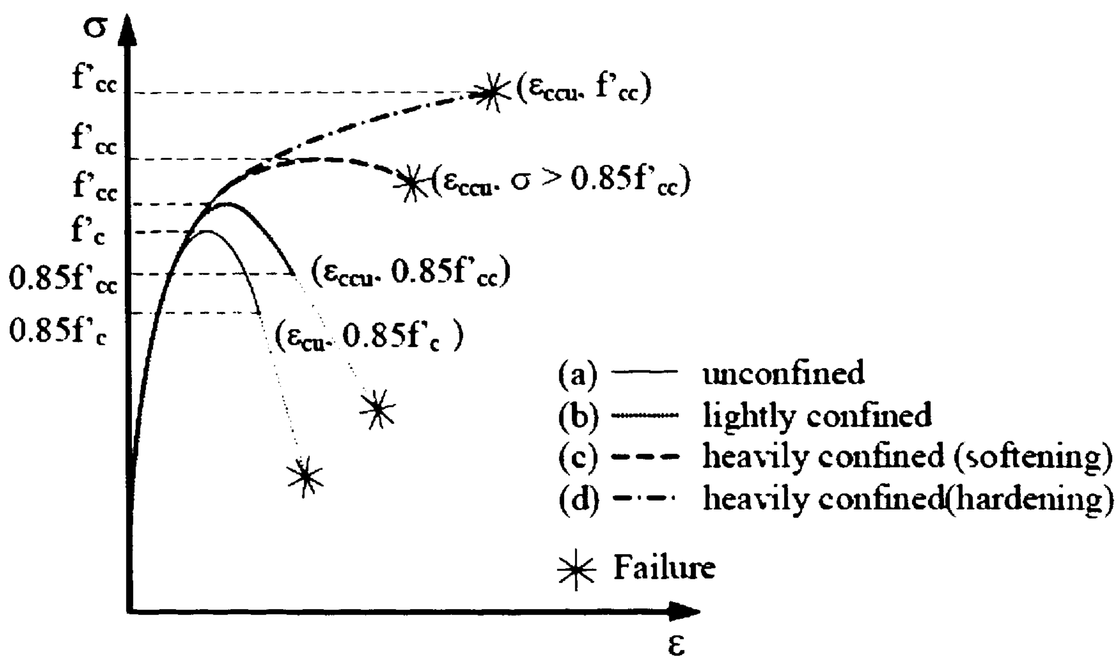


Figure 2.1. Confined Concrete Column Behavior (Rocca, 2007)

Despite the wide array of research available to explain the confinement capabilities of several popular external FRP systems, limited research is available regarding the use of polyurea or polyurea composite systems to provide confinement for concrete columns. Due to the lack of publications in this area, a review of several works regarding other types of FRP reinforcement of concrete columns was considered to provide considerations for testing as well as typical confinement expectations and insights.

2.1.2. Examples of Study. Several research studies have been completed using reduced-scale 'models' of columns to characterize the confinement capabilities of external FRP strengthening systems. Research conducted by Rochette and Labossiére (2000) is such an example. This study, completed to determine the effects of column shape and/or corners to the FRP strengthening of columns, utilized unreinforced test cylinders of approximate dimensions 4-in (100-mm) by 8-in (200-mm) and 6-in (150-mm) by 12-in (300-mm). In addition, miniature unreinforced square columns with 6-in (152-mm) width and 20-in (500-mm) height were developed. The stiffness of the FRP confinement material was also considered as an important variable. All cylinders were cast with normal strength concrete with compressive strength approximately 5800 psi (40 MPa). Fiber schemes considered included wrapped uni-directional carbon fibers and two-directional aramid fibers of different ply thicknesses. Cylinders were prepared for testing by sulfur-capping, and the following testing scheme consisted of uni-axial compression applied at a strain rate of 10 microstrain per second. Data collected included load, strain of the cylinder, and strain of the coating system, and these results were used to calculate relative ductility and axial stress. It is important to note that the axial stress of the specimen was taken to be the axial load per the concrete cross section, not considering the additional cross-section of the FRP coating, since the FRP was known to have negligible compressive stiffness. Results showed that the strength of these columns models was increased by as much as 92% with circular cross sections being most affected by the exterior strengthening system (Rochette and Labossiére, 2000).

More recent work by Chaallal et al. (2006) also considers FRP confinement using reduced scale column models. The goal of this research was to compare and evaluate available design guidelines and theoretical modeling of FRP column confinement. In order to achieve this task, experimental results were obtained to provide experimental data for comparison. This study considered more slender (long) concrete column models with cylindrical specimen dimensions of 6-in (150-mm) by 40-in (1000-mm) and 8-in (200-mm) by 40 in. (1000-mm). Two concrete design mixes were considered, representing poor concrete strength of 2.2 ksi (15 MPa) and normal concrete strength of 5 ksi (35 MPa). Cylinders were strengthened with exterior wrapped carbon fiber-reinforced polymers (CFRP) in thicknesses of either 1 or 2 plies. Compression testing was performed by a displacement-controlled system and the deformation of both the concrete, and the CFRP system was monitored utilizing longitudinal and transverse strain gauges as well as linear variable differential transducers (LVDT). Results showed a strength gain of 14% to 41% as compared to the control case for columns strengthened with a single ply of CFRP, and strength gain of 36% to 85% for strengthening systems utilizing two plies; however, column models behaved as short (non-slender) column sections despite the increased height of the cylinders (Chaallal et al., 2006).

Further work by Smith et al. (2010) considers larger diameter specimens and the stress-strain interaction of the confined concrete cylinder and the FRP wrap. This series of study utilized several unreinforced concrete cylinder specimens with 10-in (250-mm) diameter and 20-in (500-mm) height. Cylinders were wrapped with varied layer thicknesses and splice overlap lengths of CFRP. Compressive testing of capped cylinders was performed by a displacement controlled testing machine at 0.004-in (0.1-mm) per minute. In order to provide substantial data regarding the CFRP system, cylinders were also outfitted with an extensive array of strain gauges. The results of this work showed a 22% to 67% increase in ultimate strength of the cylinders, and a reasonable correlation with stress-strain behavior presented by ACI 440.2 (2008).

One limitation of certain past studies is the lack of extensive data and testing replicates to provide better statistical substantiality. A study recently released by Cui and Sheikh (2010) expanded prior results by testing a total of 112 test specimens for FRP confinement of small-scale concrete cylinder specimens. By considering more variables and including more replicate specimens, more understanding of the effects of CFRP and GRFP could be observed. For this testing, 24 control specimens and 88 FRP-wrapped specimens were prepared for uni-axial compression testing. Variables between concrete specimens included concrete strength, with three strength levels considered, as well as FRP type and number of layers. In addition, selected cylinders were pre-cracked at a load of 80% of the ultimate capacity of the cylinder to consider the strengthening or confining effects on pre-conditioned cylinders. During compression loading similar to other studies, 4 LVDT readings and 2 transverse strain gauges provided data for coating and cylinder deformation. Results showed that "pre-repair" loads of up to 80% of the capacity of the cylinders did not have significant effects on the repaired strength of the CFRP and GFRP wrapped cylinders. In addition, substantial data was collected to show that the number of layers of FRP laminate more greatly affect the ductility or deformability of the composite system rather than the ultimate compressive strength of the composite system.

2.2. FIBER-REINFORCED POLYUREA MATERIAL CHARACTERIZATION

Polyurea material characterization conducted by Carey and Myers (2010) at Missouri S&T provided a strong basis for the selection of materials used in this study. This phase of testing was conducted specifically to evaluate and compare the mechanical properties available from polyurea coating systems with the addition of discrete chopped fibers, thus developing a new type of FRP material. Variables considered included matrix material, fiber length, and fiber volume fraction integrated into the polyurea matrix. Three alternative polyurea formulations were considered for the matrix, all with different specified tensile properties. In addition, three different lengths of chopped E-glass fiber roving were selected – 1/4-in (6-mm), 1/2-in (13-mm), and 1-1/2-in (38-mm). The amount of the fiber integrated into the composite system was varied with the chopping and integration speed (Carey and Myers, 2010).

The development of a coating process was an important contribution to future work. Coupon specimens were cut from larger flat specimens prepared on an oiled metal sheet. Spraying was completed in a downward fashion on surfaces that were parallel with the floor as shown in Figure 2.2.

Figure 2.2. Polyurea-Fiber Application Process (Carey and Myers, 2010)

Coupon specimens were tested in direct tension at a displacement-controlled load rate, and stress was calculated based on the measured load and the specimen cross-section dimensions as determined by several micrometer measurements. Following tensile testing, fiber volume fraction was validated through ignition testing to remove the matrix material and determine mass of fiber in each sample.

Results presented included stress-strain relationships for several alternative polyurea-fiber combinations as well as general observations. One of the most important conclusions was that increased fiber length significantly reduced ductility. For this reason testing did not continue with the longer fiber length dimensions. The stress-strain relationships of polyurea-fiber composites with 1/4-in (6-mm) fibers were considered during the selection of materials for this phase of study.

It is important to note that while the material properties presented by Carey and Myers (2010) and also measured during materials testing for the current phase of study can be used to better predict the behavior of fiber-reinforced polyurea confined columns, the tensile properties are not equivalent to those expected during cylinder testing. Research regarding FRP confined concrete specimens shows that wrapped or confining FRP systems used for concrete do not typically reach tensile ultimate capacity as measured during standard coupon testing in the transverse or hoop direction of the concrete during cylinder testing (Teng and Lam, 2004).

2.3. TESTING PROCEDURES

Previous work completed by Beyer and Myers (2007) provided a basis to develop the testing scheme and basis for the test matrix used in this study. This previous research was developed in order to observe and evaluate the mechanical properties and strengthening effects of plain polyurea coatings when used for confinement of small concrete cylinders. Also considered were the effects of environmental conditioning (freeze-thaw cycles and de-icing agents) to the coating systems. The text matrix for study included three concrete design mixes (normal concrete, lightweight concrete, and high-strength concrete) which were cast into typical 4-in (100-mm) by 8-in (200-mm) cylinders. For each concrete strength level, four test categories were developed, which consisted of the control specimens (no coating), polyurea-coated specimens with no conditioning, polyurea coated specimens with 2 weeks of conditioning, and polyurea-coated specimens with 4 weeks of conditioning. For each test category, 4 replicate cylinders were prepared and tested. Polyurea-coated specimens were prepared with an epoxy-based polyurea coating of 1/16-in (2-mm) thickness. The polyurea selected for coating provided a yield stress of 0.58 ksi (4 MPa) and an ultimate strength of greater than 1 ksi (6.89 MPa) with a strain value at yield of 0.145. The testing scheme was developed so as to provide 4 results for compressive strength and 3 results for compressive modulus of elasticity for each testing category. In addition, two specimens from each test category were instrumented with uni-axial and transverse strain gauges to monitor the compressive and hoop strains in the coating system. The results of this testing scheme showed that polyurea alone did not significantly improve the ultimate compressive strength of the cylinders, but that the systems developed favorable bond and durability properties (Beyer and Myers, 2007).

3. EXPERIMENTAL PROGRAM

3.1. TEST MATRIX

Compressive strength testing was completed on small-scale concrete cylinders with different prescribed coating systems. The polyurea acted as the matrix material for the coating system, and discrete chopped E-glass fibers with random orientation were integrated into the coating system for additional strength. For the purposes of the described testing scope, variables considered included type and strength of concrete, type of polyurea and corresponding polyurea mechanical properties, and fiber volume fraction, V_f. The test matrix for cylinder testing is shown in Table 3.1. Two types of polyurea, referred to as "Polyurea A" and "Polyurea B" were included in the test matrix, and further details about the polyurea properties are described in Section 3.2. The fiber volume fractions attained during fabrication are presented in Chapter 4.

Table 3.1. Test Matrix – Number of Specimens Tested

Concrete Designation		Higher-Strength	Mid-Strength	Lower-Strength
Control (No Coating)		4	4	4
Polyurea A	**No Fiber**	4	4	4
	Low Fiber	4	4	4
Polyurea B	**No Fiber**	4	4	4
	Low Fiber	4	4	4
	High Fiber	4	4	4

For each testing combination, four replicate cylinders were prepared and tested. Replication of cylinder testing was used to reduce variability in testing and also to provide more complete data. All four cylinders were used to provide results for ultimate capacity, and three cylinders were used to provide data for modulus of elasticity results. In addition, two cylinders from each combination were instrumented with strain gauges to monitor strain in the polyurea coating. Further details of the testing scheme are described in Section 3.4.

In addition to the pre-selected design parameters, some variability existed between specimens based on fabrication techniques. Because the polyurea-spraying process was not automated, the resulting coating thickness during spraying did vary from specimen to specimen. This varied coating thickness was recorded as an additional important factor to potentially influence the outcome of the testing, but this variability was not built into the original test matrix.

Each specimen tested was assigned a number and a sample designation based on the properties of the concrete cylinder and the coating. In some cases, additional specimens were prepared if problems were encountered during coating that might erroneously affect the results of the testing. The full list of samples is included for reference in Appendix A.

3.2. MATERIALS

3.2.1. Concrete. Three concrete mixture proportions were used to develop three different strength levels for the concrete used during testing. The higher-strength mix was developed by Coreslab Structures in Marshall, Missouri, and the mid- and lower-strength mixes were developed at Missouri S&T. The mid- and higher-strength mixes contained ASTM Class C Fly Ash and other alternative cementitious materials as specified as partial replacement for cement, as well as an ASTM Type F high-range water-reducing admixture (HRWR). Mixture proportions are included in Table 3.2. Control specimens with no polyurea coating were prepared for testing along with coated cylinders, and compressive strength data as well as modulus of elasticity data was collected for the control specimens for comparison to the coated cylinders during the same time frame as the polyurea-coated cylinders. The calculated mechanical properties of the concrete at test age of approximately one year (depending on batch dates listed in Section 3.3.1) were as listed in Table 3.3.

Table 3.2. Concrete Cylinder Mix Proportions

Mix Designation		Higher Strength	Mid-Strength	Lower Strength
Casting Date		6/5/2009	7/9/2009	7/10/2009
Final Mix Proportions (lb/cy unless otherwise noted)	**1/2" Max. Clean Limestone**	0	1896	1650
	1/2" Max. Canyon Gray Granite	1730	0	0
	Natural River Sand FM=2.70	1245	1462	1108
	Water	242	269	308
	Cement Type I	0	489	688
	Cement Type III	750	0	0
	Microsilica	58	0	0
	Fly Ash ASTM Class C	0	219	0
	Pozzolith® 100 XR (mL/cy)	950	0	0
	HRWR ASTM Type F (mL/cy)	3550	846	0

Unit Conversions: 1 lb = 4.45 N; 1 cy = 0.765 m^3

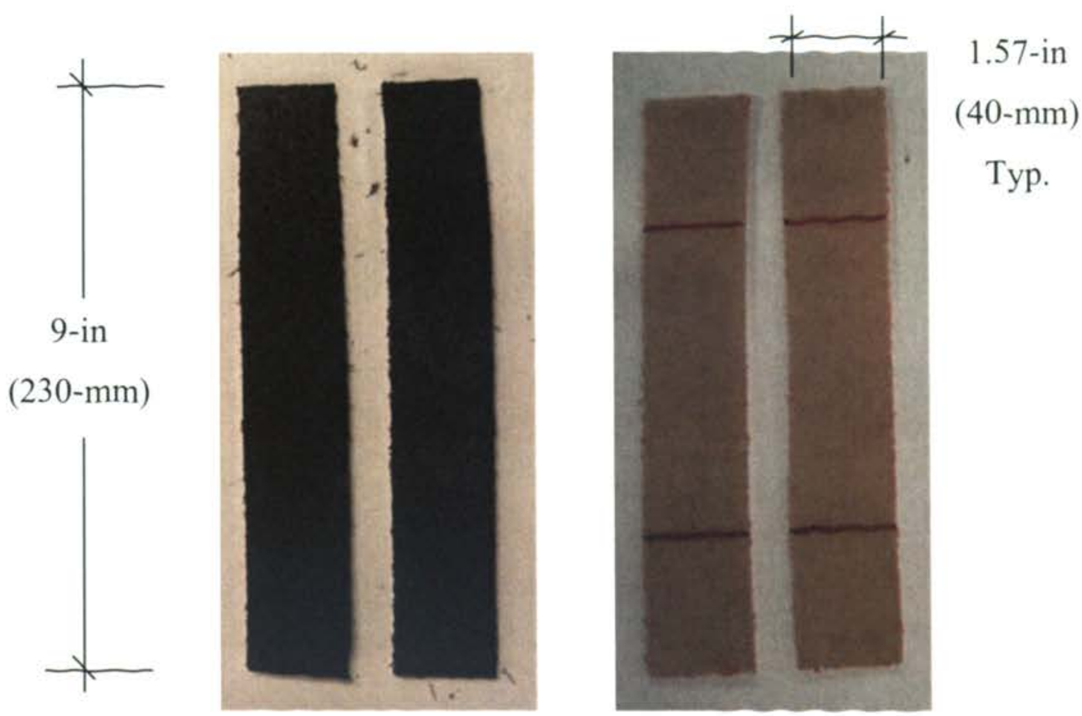
Table 3.3. Concrete Material Properties

Concrete Designation	Higher Strength	Mid-Strength	Lower Strength
Average Compressive Strength (psi) – 1 yr.	13920	12100	10270
Average Modulus of Elasticity, E (ksi) – 1 yr.	5950	7720	6920

Unit Conversions: 1 psi = 6890 Pa

Final results showed unexpectedly high strengths for all mixes, especially the lower strength concrete, as well as some inconsistency in modulus of elasticity results. The overall high strength was attributed to the extended age of the cylinders at testing as well as the long duration of temperature-controlled moist-cure conditions at which the specimens were maintained, as described in Section 3.3. While the concrete attained higher strengths than expected, the results were applicable to several older concrete structures which have experienced decades of hardening and have much higher strengths than were necessarily required by the original design.

3.2.2. Fiber-Reinforced Polyurea Systems. The coated specimens were tested with a variety of polyurea-fiber combinations as described in Section 3.1. The two polyureas denoted here as Polyurea A (shown in Figure 3.1a) and Polyurea B (shown in Figure 3.1b) were both two-component, spray elastomer systems. Specimens shown are coupon samples used for tensile testing, measuring 9-in (230-mm) in length by 1.57-in (40-mm) in width as described in Section 3.4.1.



(a) Polyurea A (b) Polyurea B

Unit Conversion: 1 in = 25.4 mm

Figure 3.1. Polyurea Samples

Both polyurea coatings have zero volatile organic compounds (VOC) and were known to provide a high bond strength and resistivity to chemicals and moisture. Polyurea A was selected for its relatively high strength as compared to other polyurea formulations. Polyurea B was also considered because of its combination of moderate strength with higher ductility, as well as its extended set time which allowed for greater ease of application. Mechanical properties of both types of polyurea as provided by the manufacturer are included in Table 3.4.

Table 3.4. Polyurea Material Properties

Polyurea Designation	A	B
Density (lbs/gal)	9.3	8.8
ASTM D 412-06a (2006) Elongation	91%	445%
ASTM D 412 a (2006) Tensile Strength (psi)	2147	2800
Gel Time (sec)	3 - 6	11 - 13
Tack Free Time (sec)	6 - 9	78 - 85

Unit Conversions: 1 lb = 4.45 N; 1 gal = 3.8 L ; 1 psi = 6890 Pa

In order to add strength to the coating, randomly-oriented discrete chopped fibers were integrated with the coating during spraying application. For this study, E-glass fiber roving was selected because of its relatively high ductility as compared to aramid or carbon fibers, as well as its ability to be automatically chopped and dispersed into the polyurea spray pattern simultaneously with spraying. Based on research from Carey and Myers (2010), 1/4-in (6-mm) fibers were selected and reasonable fiber volume fractions were chosen. The glass fiber properties as provided by the manufacturer are as listed in Table 3.5. In addition, the glass roving selected was specially formulated for chopping and spray-up applications.

Table 3.5. Fiber Material Characteristics

Fiber Type	E-Glass
Fiber Length, in.	0.25
ASTM D 638-10 (2010) Tensile Strength, psi	8490 - 14182
ASTM D 638-10 (2010) Tensile Modulus, ksi	1094 - 2160

Unit Conversions: 1 in = 25.4 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa

During specimen fabrication described in Section 3.3, a mechanical gun was used to simultaneously distribute the polyurea, chop the glass fiber roving, and disperse the glass fibers into the coating system, creating an integrated fiber-reinforced polyurea system. Analysis of the FRP coating system was developed during cylinder testing by use of coupon specimens tested as described in Section 3.4.1. The properties of the FRP as determined through this testing are presented in Chapter 4 along with extensive results of the cylinder testing.

3.3. SPECIMEN FABRICATION

3.3.1. Concrete Preparation. Cylindrical concrete specimens were cast according to ASTM C 31-09 (2009) and ASTM C 192-07 (2007), finished, and covered during curing. Removable cylinder lids were used during curing in an effort to minimize moisture loss and deformation of the plastic cylinder molds. After initial hardening, all specimens were placed in moist-cure conditions at a constant temperature and humidity. Forty cylinders representing the higher-strength concrete (target strength approximately 13,000 psi at 28 days) were fabricated on June 5, 2009 at CoreSlab in Marshall, Missouri. Cylinders were cured at the plant until they could be transported to Missouri S&T and placed in the moist-cure chamber. In addition, forty cylinders of mid-strength concrete (target strength approximately 10,000 psi at 28 days) were batched at Missouri S&T on July 9, 2009. Cylinders were batched under lab conditions and cured for 24 hours in lab conditions. Cylinders were then moved to the moist-cure environment. The final forty cylinders representing the lower-strength concrete (target strength 7,000 psi after 28 days) were batched on July 10, 2009 at Missouri S&T. Specimens were formed in the similar lab conditions and after a short curing period moved to the moist-cure conditions. Target strengths of test specimens were set relatively high as compared to typical design mixes to represent the expected field compressive strength (f'_c) results from core samples of aged existing structures.

All specimens were removed from moist-cure prior to coating and were end-ground (see Figure 3.2) with an automated diamond-grinding machine to ensure a flat testing surface. After end-grinding, cylinders were allowed to dry for a minimum of 2 weeks prior to coating to ensure that the strongest bond between the concrete and polyurea was attained, and also to ensure that further hydration of the specimens did not take place after coating. Hydration of cement in the cylinders after coating could have caused release of gasses under the polyurea and would have weakened the coating bond, creating pockets of gas under the coated surface.

Figure 3.2. Cylinder End-Grinding

3.3.2. Cylinder Coating Process. The prepared cylinders were transported to a spraying facility in Columbia, Missouri for coating in several installments during the months of April and May, 2010. Cylinders were first prepared for coating with a primer to maximize the coating bond to the concrete (see Figure 3.3). The primer was applied by spraying in a controlled environment to a thickness of 2-3 mils and had a set time of 45 to 60 minutes after which the desired coating could be applied. Cylinders which were primed prematurely, thereby outside of the 'window' of preferred coating time, were gently roughened to the concrete surface after which the primer was re-applied in the same fashion as previously described.

Figure 3.3. Priming of Concrete Cylinders

The polyurea and glass fibers were sprayed onto the concrete surfaces simultaneously by the use of a Glascraft chopper/spray gun capable of combining and dispersing the two-part mixture of polyurea, while chopping the glass fiber roving (strands) and distributing the chopped glass fibers into the spray pattern so that the fiber would be randomly and evenly oriented in the polyurea. Figure 3.4 shows a certified trained technician in full protective gear using the gun to apply polyurea and fiber to a flat metal panel for coupon testing. In addition to coating the cylinders, flat samples were prepared in this way to provide specimens for determining the mechanical properties of the coating and the exact fiber volume fraction in each set of specimens. The chopper spray gun that was used for application presented some limitations during coating, and the applicators found greater ease of application on horizontal planes laying below the sprayer, parallel to the floor, similar to the metal sheet pictured in Figure 3.4. In order to spray the cylinders in this fashion as shown in Figure 3.5, an apparatus was created to hold the cylinders horizontally and rotate them to allow for thorough coating of the entire circumference. For reference, a photo of this device is shown in Figure 3.6 with a schematic drawing in Figure 3.7.

Figure 3.4. Polyurea-Fiber Spraying Process

Figure 3.5. Cylinder Coating Application

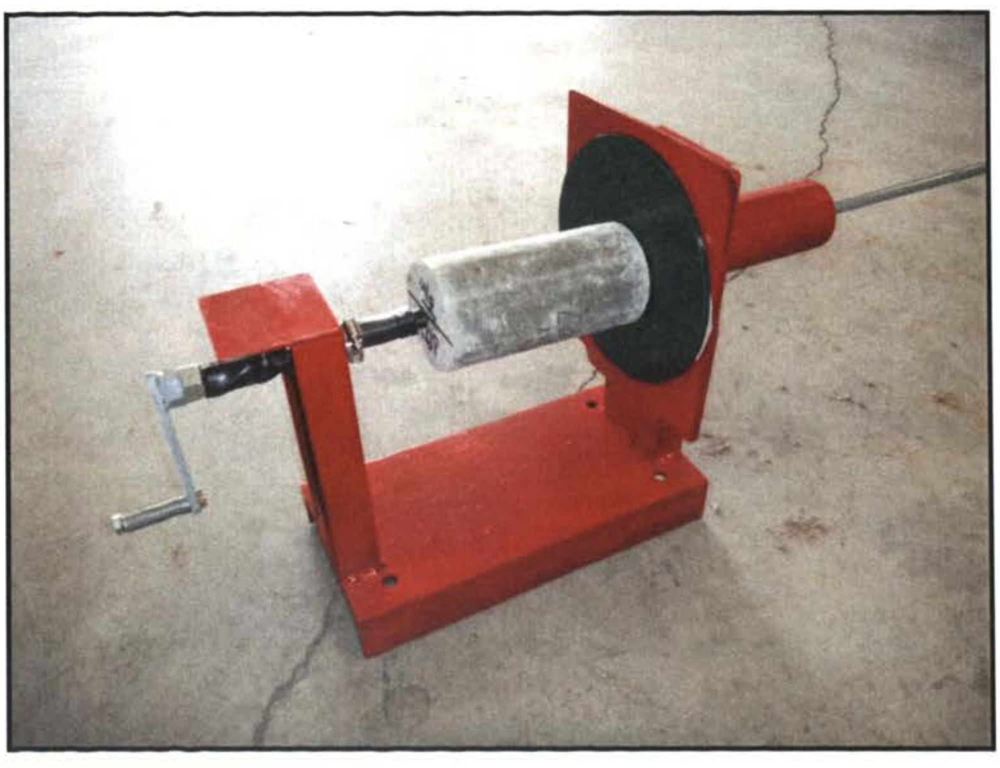
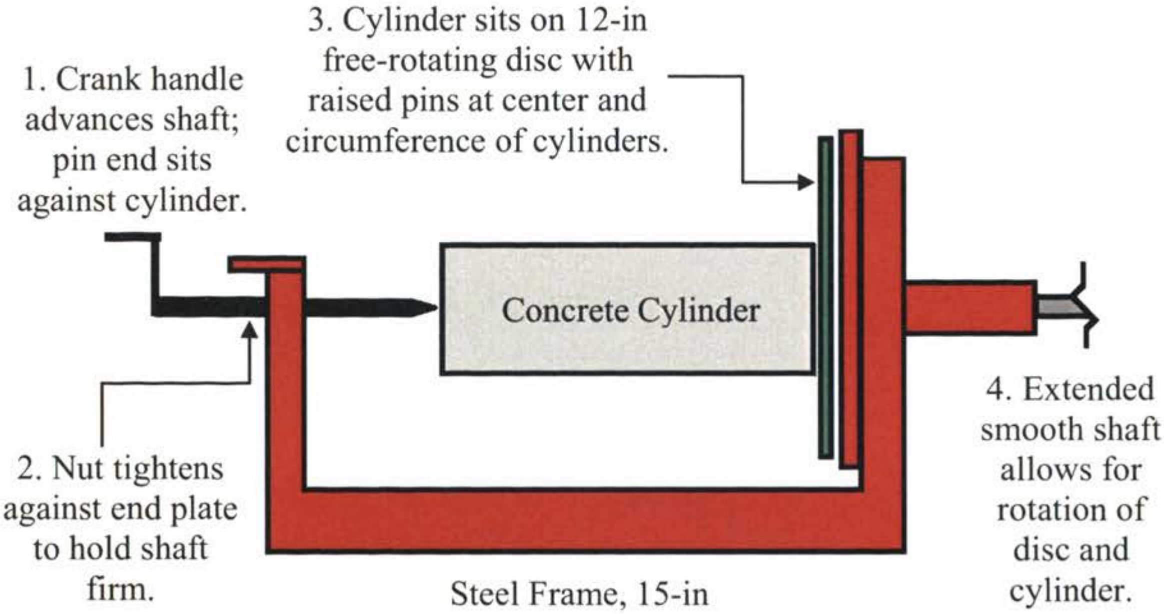


Figure 3.6. Cylinder Rotating Apparatus



Unit Conversion: 1 in = 25.4 mm (Drawing not to scale.)

Figure 3.7. Cylinder Rotating Apparatus - Schematic

A drill motor was used to automate and regulate the rotation of each cylinder. It is important to note that this specialized application process would not necessarily be required if coating a larger member such as a bridge pier or building column. A variety of chopper spray guns are available and the process of applying a glass composite material is a well-developed industry. This specific application process was required in this particular project based on economy (using materials and equipment that were already purchased) and on the relatively very small scale of the specimens which were to be coated.

3.4. TESTING SETUP AND PROCEDURE

3.4.1. Fiber-Reinforced Polyurea Testing. In order to validate the expectations for the coating mechanical properties and fiber volume fraction based on prior test results from Carey and Myers (2010) flat coating specimens were prepared as described in Section 3.3. The larger specimens were cut using a saw into coupon specimens measuring 9-in (230-mm) in length by 1.57-in (40-mm) in width. These specimens were tested in tension according to ASTM D 3039-08 (2008). Based on similar test methods and results developed by Carey and Myers (2010), the coupons were tested directly in roughened, flat grips without the use of metal end-tabs, sandpaper, or any alternative means of grip. The specimens were loaded at a rate of 0.5-in/min (12.7-mm/min) until failure occurred or the specimen attained full displacement capacity of the testing machine. A minimum of seven coupon specimens were tested for each separate coating system in the test matrix.

When all coupon specimens had been tested and the tensile strength and elongation data collected, a representative group of specimens from each coating category in the test matrix was selected for fiber ratio testing. A small sample measuring 2-in (51-mm) by 1 ½-in (38-mm) was cut from each selected tensile test coupon sample and the weight was recorded. The samples were placed in a furnace at a temperature of 1112°F (600°C) for 2 hours to burn off all of the polyurea, leaving glass substrates with fiber only. The weight of the fiber was recorded and used to calculate the fiber volume fraction of the sample in accordance with ASTM D 3171-09 (2009).

3.4.2. Compressive Strength. The ultimate compressive strength of each replicate cylinder was determined and recorded generally following the ASTM C 39-09a (2009) guidelines. The cylinders were loaded directly between two flat plates, in part because of the limitations caused by the increased cross-sectional area of the coated cylinders, and also because the cylinders exhibited high strengths beyond the limits of sulfur-capping and even beyond neoprene pads in some cases. Because the cylinder ends were ground flat before coating they met the requirements for testing per the standard. The cylinders were loaded in compression at a rate of 500 lb (2225 N) to 565 lb (2514 N) per second, as is required for cylinders measuring 4-in (100-mm) diameter by 8-in (200-mm) height, either by a computer-automated hydraulic loading system (in the case of cylinders instrumented with strain gauges) or by a user-controlled hydraulic pump. After failure, the cylinders were observed for failure mode in cases where the failure plane could be observed. In several cases, the polyurea coating contained the concrete fragmentation so completely that no failure could be examined with initial visual inspection. In these cases, a representative group of the cylinders was selected for further visual inspection, which involved cutting open the polyurea coating.

3.4.3. Modulus of Elasticity. The compressive modulus of elasticity was determined for three replicates from each combination in the test matrix per the guidelines presented in ASTM C 469-02 (2002), with some modifications based on case-specific limitations. Because of the limited availability of cylinders and polyurea coating chemicals, each replicate cylinder after the first cylinder was tested for modulus of elasticity, E, before being tested for ultimate compressive strength. The cylinders were loaded in compression at a rate of 440 lb (1958 N) to 500 lb (2225 N) per second by a computer-controlled hydraulic pump. The cylinders were instrumented using a standard compressometer for 4-in (100-mm) by 8-in (200-mm) cylinders and an LSCT transducer for automatic deflection measurements as shown in Figure 3.8.

Figure 3.8. Modulus of Elasticity Test Setup

The load and strain measurements were recorded automatically by the data acquisition system and used to calculate the modulus of elasticity based on equation 1 shown below, where S_1 and ε_1 represent the stress and corresponding strain when the strain in the cylinder is 0.00005-in/in (mm/mm), and S_2 and ε_2 represent the stress and corresponding strain when the cylinder is loaded to 40% of its ultimate capacity as determined by prior compressive strength tests on cylinders from the same batch.

$$E = \frac{(S_2 - S_1)}{(\varepsilon_2 - \varepsilon_1)} \quad (1)$$

3.4.4. Strain. In order to monitor the coating on the cylinder during loading, selected cylinders were instrumented with strain gauges applied directly to the polyurea. The gauges were general-purpose 120-ohm resistance, linear strain gauges with a gauge length of 0.25-in (6.35-mm). Strain gauges were applied to the coating following manufacturer's guidelines. The surface of the coating was prepared with rough sandpaper and a catalyst supplied with the strain gauges before the gauges were glued directly to the coating. One replicate from each test category was measured for axial strain, with the strain gauge mounted vertically, and one replicate from each category was measured for both axial and hoop strains, with strain gauges mounted in two directions (see Figure 3.9) in the center of the cylinder. Strain gauges were connected to a data acquisition system during testing.

Figure 3.9. Strain Gauge Application on Cylinders

4. EXPERIMENTAL TEST RESULTS

4.1. FIBER-REINFORCED POLYUREA COATINGS

As described, several coating samples were prepared for direct tension testing as well as ignition testing to determine fiber volume fraction. Several samples from each composite system test category were prepared in order to determine representative average results for fiber volume fraction, tensile modulus of elasticity, maximum tensile stress, and elongation at failure of the coating system (see Table 4.1). The percentage of fiber by volume in the samples was consistent with prior testing with similar materials (Carey and Myers 2010). As shown, both the modulus of elasticity of the coating as well as the tensile strength showed improvement with the addition of the glass fiber. Accordingly, the elongation at failure was reduced with the addition of fiber. Yield results were not attained for Polyurea B which, as previously discussed in Section 3.2.2, had an expected elongation in excess of 400%, which was beyond the limits of the available testing equipment.

Table 4.1. Fiber-Reinforced Polyurea Properties

Coating Designation	V_f (%)	E (ksi)	Max Stress (psi)	Elongation (%)
Polyurea A No Fiber	No Fiber	18.37	1234	94.9%
Polyurea A Lower Fiber Ratio	11.9%	121.32	1690	3.9%
Polyurea B No Fiber	No Fiber	19.42	Yield Limit Not Attained	
Polyurea B Lower Fiber Ratio	7.0%	87.35	1089	21.6%
Polyurea B Higher Fiber Ratio	12.5%	181.41	2023	8.7%

Unit Conversions: 1 psi = 6890 Pa; 1 ksi = 6.9 MPa

4.2. COMPRESSIVE STRENGTH

For each specimen category from the test matrix, at least four replicates were tested for ultimate compressive strength as described in Section 3.4.2. The average compressive strength value and standard deviation (as denoted by error bars) was then determined for each category as shown in Figure 4.1. These results as well as average coating thickness values are summarized in Table 4.2 with complete data included in Appendix A. As shown in Figure 4.1, raw results showed statistically little impact on compressive strength due to the addition of a polyurea coating or polyurea with fiber. However, this analysis did not include the consideration of variable coating thickness.

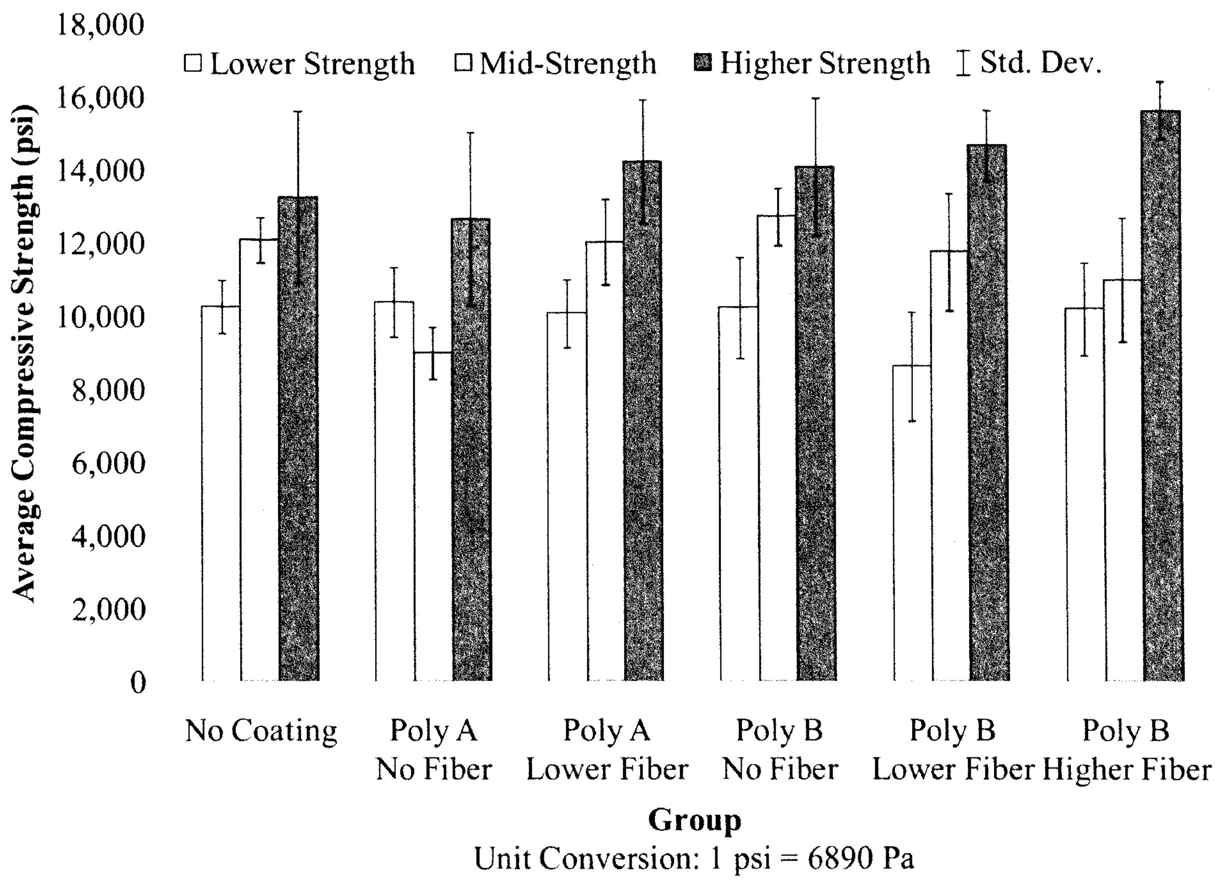


Figure 4.1. Average Compressive Strength Comparison

Table 4.2. Compressive Strength Results Summary

Group	Avg. Coating Thickness (in)	Average Compressive Strength (psi)	Strength Std. Dev. (psi)
7 ksi - No Coating	N/A	10,270	740
7 ksi - Polyurea A - No Fiber	0.30	10,390	940
7 ksi - Polyurea A - Lower Fiber	0.19	10,070	940
7 ksi - Polyurea B - No Fiber	0.34	10,230	1380
7 ksi - Polyurea B - Lower Fiber	0.39	8,620	1490
7 ksi - Polyurea B - Higher Fiber	0.46	1,080	1280
10 ksi - No Coating	N/A	12,100	610
10 ksi - Polyurea A - No Fiber	0.33	9,000	710
10 ksi - Polyurea A - Lower Fiber	0.16	12,030	1180
10 ksi - Polyurea B - No Fiber	0.31	12,720	790
10 ksi - Polyurea B - Lower Fiber	0.38	11,750	1610
10 ksi - Polyurea B - Higher Fiber	0.46	10,980	1710
13 ksi - No Coating	N/A	13,270	2360
13 ksi - Polyurea A - No Fiber	0.32	12,670	2370
13 ksi - Polyurea A - Lower Fiber	0.20	14,240	1700
13 ksi - Polyurea B - No Fiber	0.32	14,080	1900
13 ksi - Polyurea B - Lower Fiber	0.33	14,660	980
13 ksi - Polyurea B - Higher Fiber	0.39	15,620	780

Unit Conversions: 1 in = 25.4 mm; 1 psi = 6890 Pa

The average coating thickness for coated cylinders test categories ranged between 0.16-in (4.1-mm) and 0.46-in (11.7-mm). For further investigation, results were analyzed considering both coating category and coating average thickness. For the lower-strength concrete cylinder specimens (see Figure 4.2), some important observations were made. For specimens with polyurea A coating with no fiber and also with low fiber, the cylinder compressive strength was statistically equivalent. However, the average coating thickness for the cylinders coating with polyurea A and fiber was significantly less than the thickness for cylinders coated with plain polyurea A only. Alternatively, in coating systems utilizing polyurea B, average coating thickness was higher for specimens containing more fiber, but significant strength increases were not observed. It should be noted that because the fiber is discrete in nature, rather than a continuous wrapped fiber, the confining effects are limited compared to more traditional, stiffer, confinement systems.

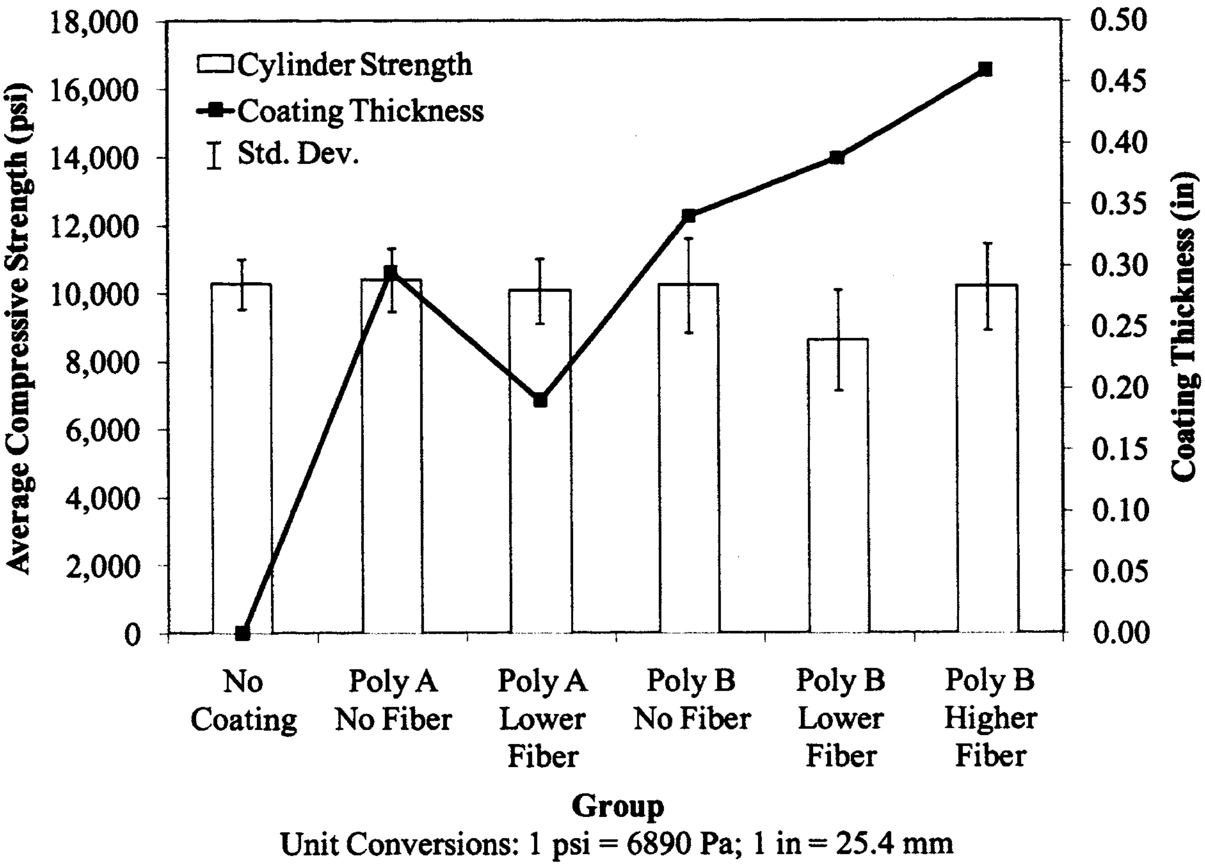


Figure 4.2. Compressive Strength and Coating Thickness for Lower-Strength Samples

A similar analysis was completed for the mid-strength concrete cylinder specimens (see Figure 4.3). As with the lower-strength concrete specimens coated with polyurea A coating combinations, the thickness of the coating with fiber was significantly less than the thickness of the coating without fiber, and in this case, the strength of the specimens coated with fiber-reinforced polyurea A as compared to plain polyurea A was statistically greater. The mid-strength concrete specimens displayed similar behaviors to the lower-strength specimens with polyurea B coating systems as well; even though coating thickness and fiber volume fraction increased, the average cylinder strength exhibited statistically similar results when considering the associated standard deviation.

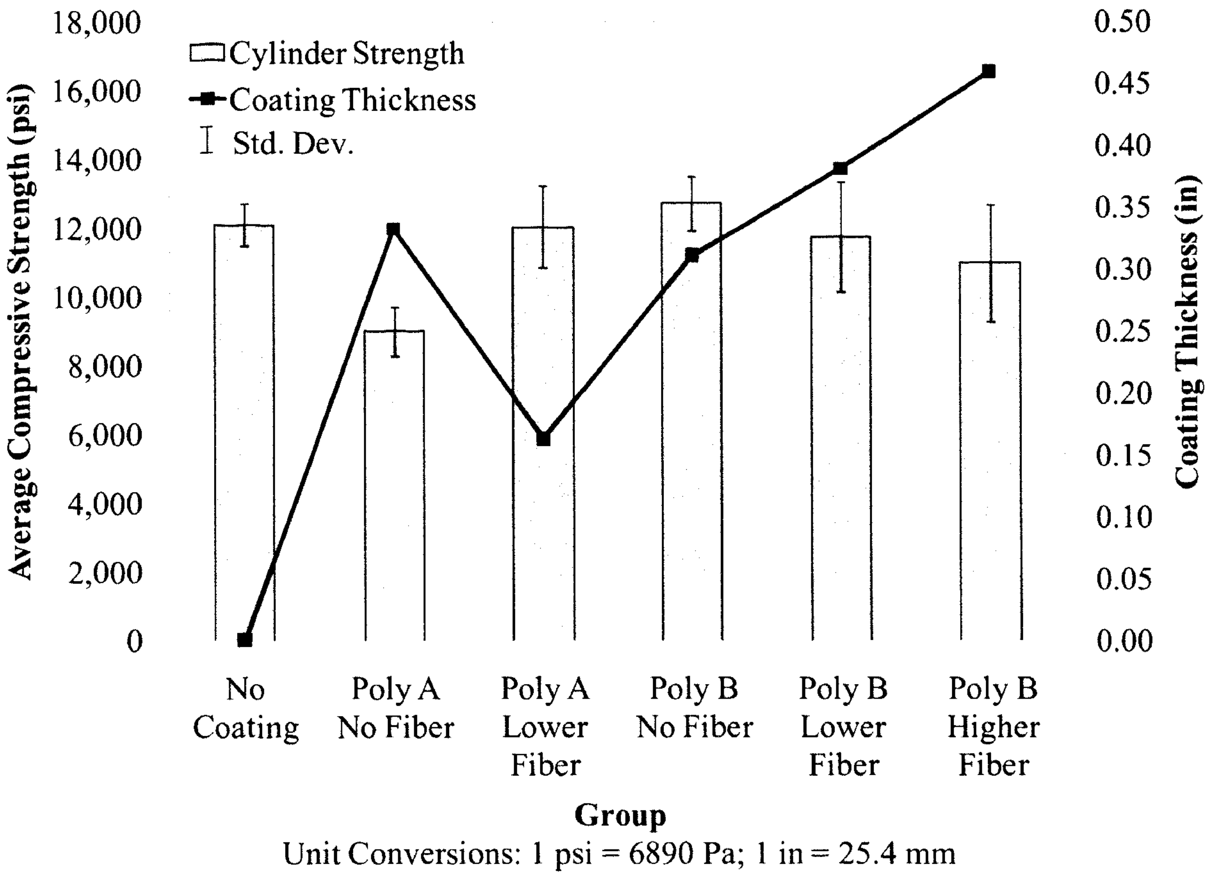


Figure 4.3. Compressive Strength and Coating Thickness for Mid-Strength Samples

Finally, the same analysis was completed for the higher-strength concrete specimens (see Figure 4.4). The coating thicknesses and strength results for coatings with polyurea A were consistent with the results from the other two strength categories. Also, polyurea B coating systems developed statistically similar concrete strength results despite increased fiber volume fraction and coating thickness.

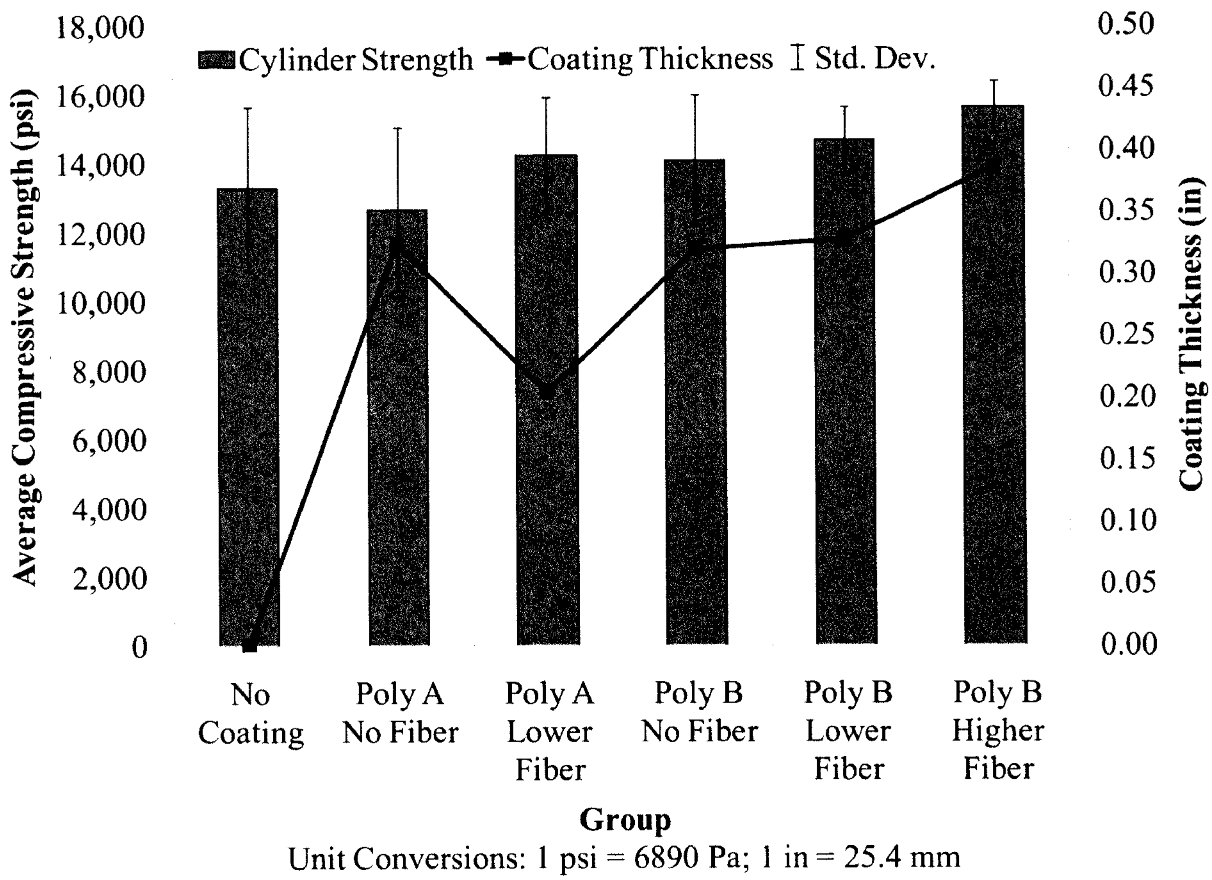


Figure 4.4. Compressive Strength and Coating Thickness for Higher-Strength Samples

4.3. MODULUS OF ELASTICITY

As described in Section 3.4.3, the modulus of elasticity, E, was determined for three replicates from each test alternative. These calculated values were combined to determine average results which are summarized in Figure 4.5 and Table 4.3, with complete results included in Appendix A. As can be seen in Figure 4.5, no statistically significant trends were produced when comparing the different coating systems. This result was not entirely unlikely, as the compressive modulus of elasticity for concrete is much greater than that for the coating system described.

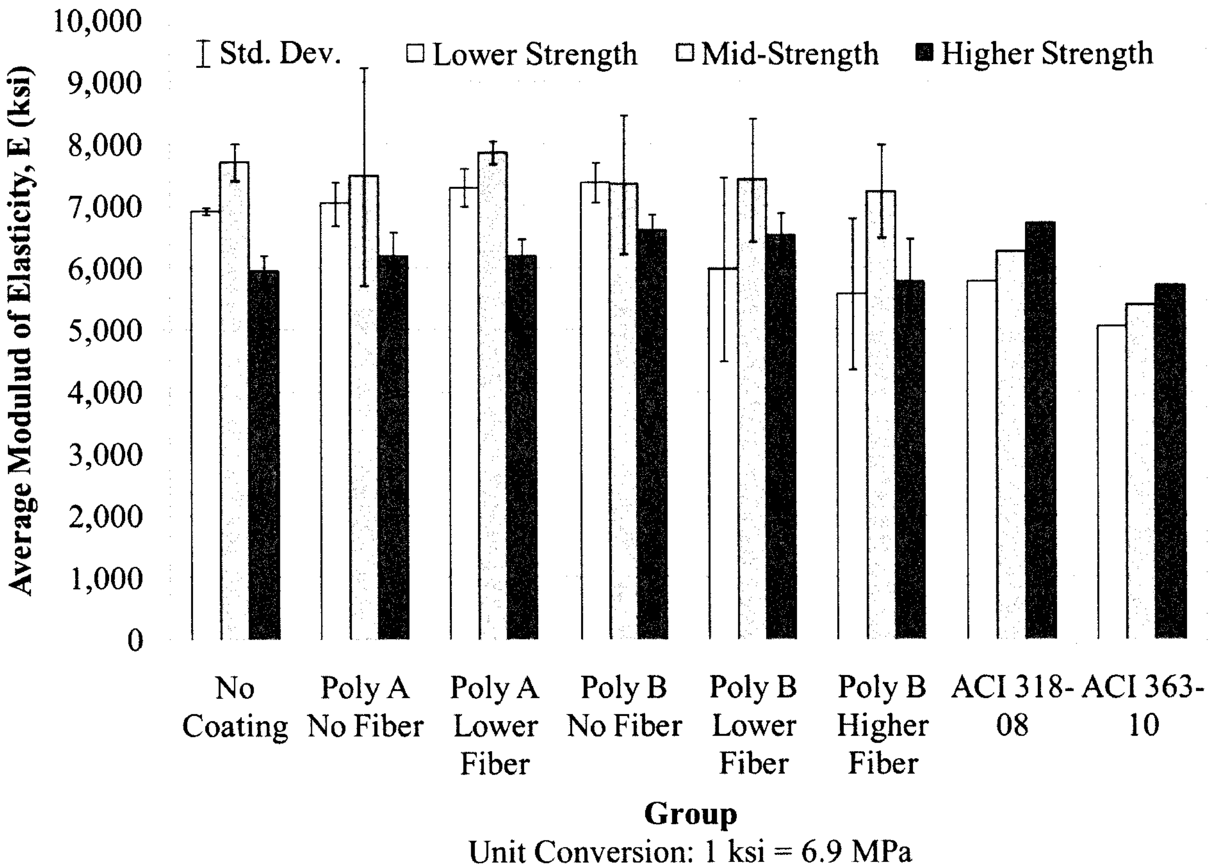


Figure 4.5. Average Modulus of Elasticity Comparison

For reference, the ACI bounds for calculated modulus of elasticity according to compressive strength are shown in Figure 4.5. These values are provided by ACI 318 (2008) and ACI 363 (2010) for high-strength concrete. ACI 318 (2008) provides an average expected value based on compressive strength. ACI 363 provides a lower bound for modulus of elasticity based on compressive strength, taking into account that high-strength concrete does not behave in the same manner as normal strength concrete.

Table 4.3. Modulus of Elasticity Results Summary

Group	Avg. Coating Thickness (in.)	Average E (ksi)	E Std. Dev. (ksi)
7 ksi - No Coating	0.00	6,917	58
7 ksi - Polyurea A - No Fiber	0.30	7,050	350
7 ksi - Polyurea A - Lower Fiber	0.19	7,300	312
7 ksi - Polyurea B - No Fiber	0.34	7,383	325
7 ksi - Polyurea B - Lower Fiber	0.39	5,983	1484
7 ksi - Polyurea B - Higher Fiber	0.46	5,583	1219
10 ksi - No Coating	0.00	7,717	301
10 ksi - Polyurea A - No Fiber	0.33	7,483	1762
10 ksi - Polyurea A - Lower Fiber	0.16	7,867	189
10 ksi - Polyurea B - No Fiber	0.31	7,350	1127
10 ksi - Polyurea B - Lower Fiber	0.38	7,417	988
10 ksi - Polyurea B - Higher Fiber	0.46	7,233	752
13 ksi - No Coating	0.00	5,950	265
13 ksi - Polyurea A - No Fiber	0.32	6,183	388
13 ksi - Polyurea A - Lower Fiber	0.20	6,183	293
13 ksi - Polyurea B - No Fiber	0.32	6,617	252
13 ksi - Polyurea B - Lower Fiber	0.33	6,517	369
13 ksi - Polyurea B - Higher Fiber	0.39	5,767	701

Unit Conversions: 1 in.= 25.4 mm; 1 ksi = 6.9 MPa

In general, the modulus of elasticity was slightly greater for specimens coated with Polyurea A coating systems as opposed to Polyurea B coating systems, although the addition of fiber the polyurea did not result in higher modulus results. In some cases, Polyurea A produced much higher modulus values as opposed to the control specimens as well as the Polyurea B specimens, but with the limited number of specimens tested during this phase of study, this result could not be supported statistically when considering the standard deviation of the results.

The measured modulus of elasticity for the higher-strength concrete specimens was notably lower than that for the lower and mid-strength specimens. As can be observed, however, the modulus of elasticity for these higher-strength specimens generally falls above the lower bound provided by ACI 363 (2010). In addition, it is important to recall that this mixture proportion contained less coarse aggregate than the mid-strength mixture proportion which may also provide some account for the lower stiffness of these specimens.

4.4. STRAIN AND DUCTILITY

Strain, load, and cylinder deformation data was collected during both modulus of elasticity and strength testing. All resulting stress-strain plots showing cylinder strain, coating axial strain, and coating hoop strain versus stress in the cylinder are included in Appendix B. In all cases, the coating experienced tensile strains in the transverse or hoop direction, but the elastic limit was not approached in this plane. This suggests that the coating system did engage and take some of the stress caused by Poisson's effect (i.e. bulging effect) with tensile strains at mid-height of the cylinder during loading, but that the low stiffness and discontinuous nature of the fiber and coating was not adequate to provide substantial confinement to the concrete section. The coating typically developed compressive strains in the axial or vertical direction during loading, and these strains were less than the strain in the concrete cylinder at the corresponding load level also due to the lower relative coating stiffness.

To further analyze the ductility effects of the coating systems, the load-deflection curves were developed (see Figures 4.6-4.9) for representative samples of coated concrete cylinders representing the lower-strength and mid-strength cylinders. The group of cylinders representing the higher strength was not included in this analysis. The area under the load-deformation curve (A) was also calculated to further analyze the apparent deformation-based ductility based on the load-deformation response. For the examples shown, additional strength is attained beyond the control load provided by uncoated cylinder testing. In both cases, Polyurea A with fiber developed greater strength and relative ductility (as high as 1.43 times) than that of Polyurea A without fiber; however, this behavior was not observed with the use of Polyurea B. The significance of this data is limited by the stiffness of the testing machine and the ability of the testing and data collection equipment to capture genuine post-peak behavior. Supplementary research would be required to garner further understanding of this behavior.

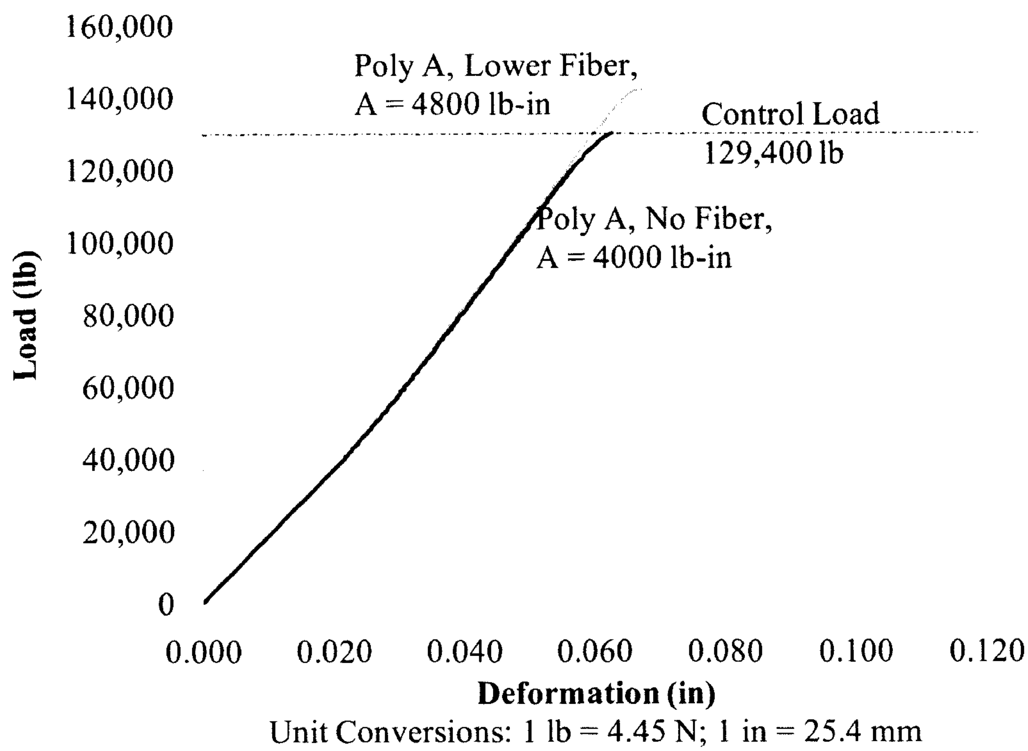


Figure 4.6. Load versus Deformation for Lower Strength Concrete, Polyurea A

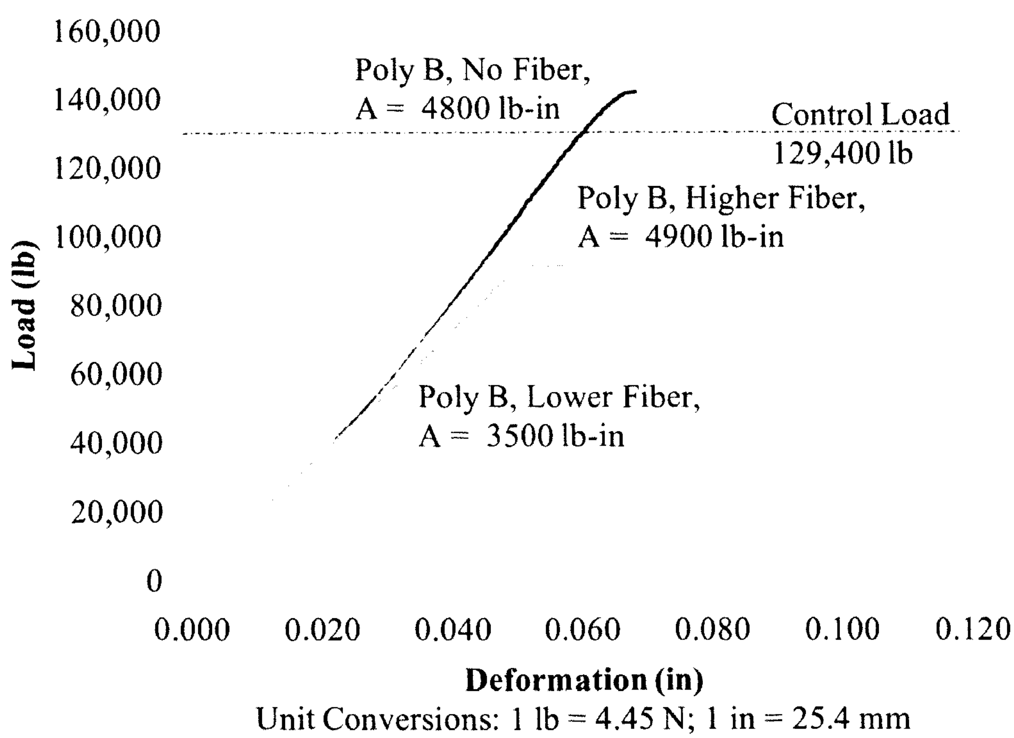


Figure 4.7. Load versus Deformation for Lower Strength Concrete, Polyurea B

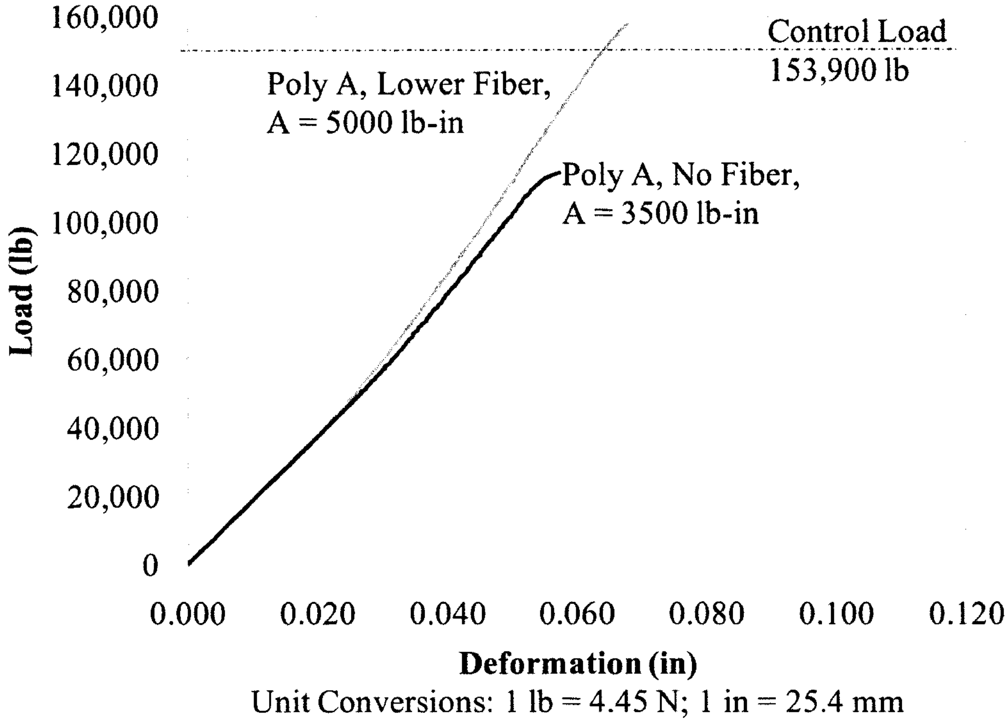


Figure 4.8. Load versus Deformation for Mid-Strength Concrete, Polyurea A

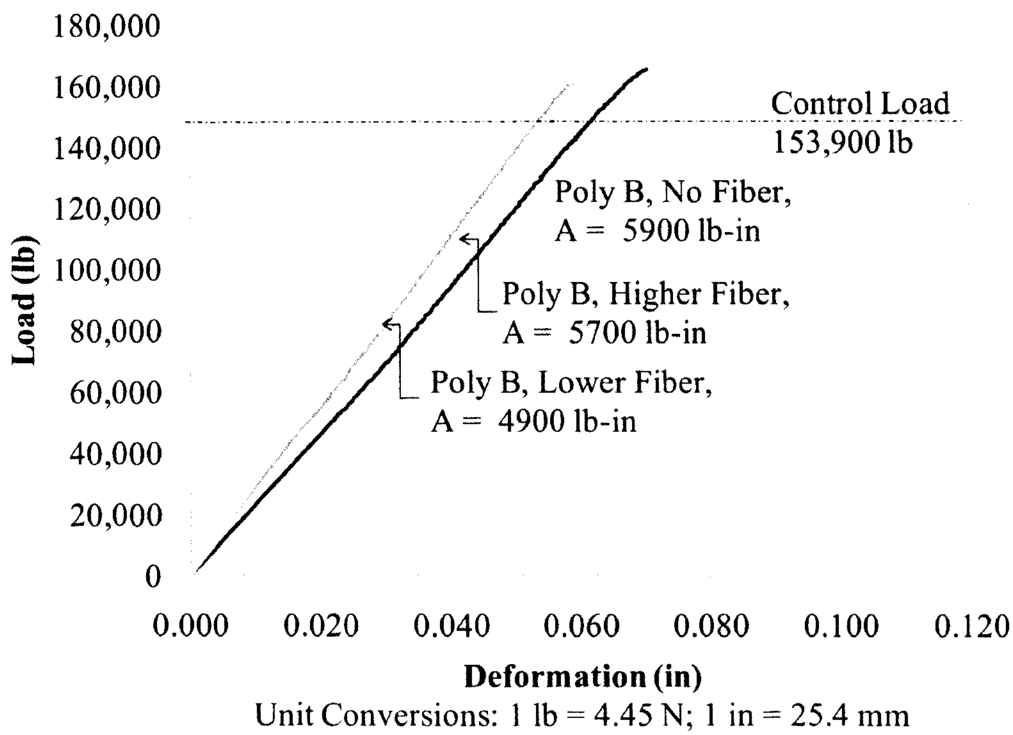


Figure 4.9. Load versus Deformation for Mid-Strength Concrete, Polyurea B

4.5. FRAGMENTATION AND FAILURE MODES

With all the coating systems considered, both polyurea formulations showed important improvements to fragmentation containment and preservation of the original cylinder shape. Typical concrete cylinders loaded in compression until the true ultimate load are normally expected to exhibit considerable fragmentation in what is sometimes a quite explosive failure, particularly for higher strength concrete, requiring safety gear for testing personnel and precautionary measures such as wraps and cages to contain the concrete debris scatter. While similar precautions were taken when testing the polyurea-coated cylinders, these cylinders exhibited a great reduction in debris scatter, sometimes to an extent that failure could not be visually observed during testing. According to ASTM C 39-09a (2009), a full compression test is complete only after "the load is decreasing steadily" and has dropped to a maximum of 95% of the ultimate load. In addition, ASTM C 39-09a notes that the cylinder should display a "well-defined fracture pattern." In many cases during testing, the end of the test was determined by a substantial drop in load as well as the sound that usually accompanies fracture of the concrete. A typical concrete cylinder failure can be seen in Figure 4.10a. As shown, a major portion of the cylinder was separated from the original mass, and a diagonal fracture was apparent. Figures 4.10b -4.10f show a representative sample of lowest-strength coated cylinders which have been tested to failure.

(a) No Coating

(b) Polyurea A, No Fiber

(c) Polyurea A, Lower Fiber

(d) Polyurea B, No Fiber

(e) Polyurea B, Lower Fiber

(f) Polyurea B, Higher Fiber

Figure 4.10. Lower-Strength Concrete Cylinder Samples

In many cases, (see Figures 4.10b-c) no failure patterns or fragmentation were evident. In some other cases, (see Figure 4.10d) a bulging of the coating and deformation of the cylinder could be seen, but the mass stayed intact and no fragmentation, FRP tearing, or loss of FRP adhesion was apparent. Finally, during some tests with extended load duration, the FRP coating would exhibit tearing, although no loss of adhesion was apparent. Results were typical for all coating systems and concrete strengths tested (see Figures 4.11-4.12).

(a) No Coating

(b) Polyurea A, No Fiber

(c) Polyurea A, Lower Fiber

(d) Polyurea B, No Fiber

(e) Polyurea B, Lower Fiber

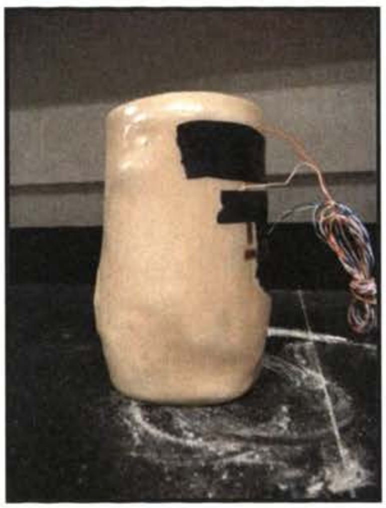
(f) Polyurea B, Higher Fiber

Figure 4.11. Mid-Strength Concrete Cylinder Samples

(a) No Coating

(b) Polyurea A, No Fiber

(c) Polyurea A, Lower Fiber



(d) Polyurea B, No Fiber

(e) Polyurea B, Lower Fiber

(f) Polyurea B, Higher Fiber

Figure 4.12. Higher-Strength Concrete Cylinder Samples

ASTM C 39-09a (2009) advises that concrete cylinders which do not fail with a "well-defined fracture pattern," fracturing rather at the top or sides of the cylinder during loading, may not have actually attained the concrete's true ultimate capacity and may exhibit lower ultimate strength than similar cylinders which are tested in such a way as to prevent premature failure. In order to ensure that the testing methods were providing adequate conditions for accurate ultimate strength, cylinders were either loaded until the failure could be observed, or cut open to observe the properties of the concrete contained in the coating. Figure 4.13 shows two typical failure patterns that were observed in cylinders coated with polyurea A. In both cases, the concrete is well-bonded to the FRP coating, and internally, well developed fragmentation occurred.

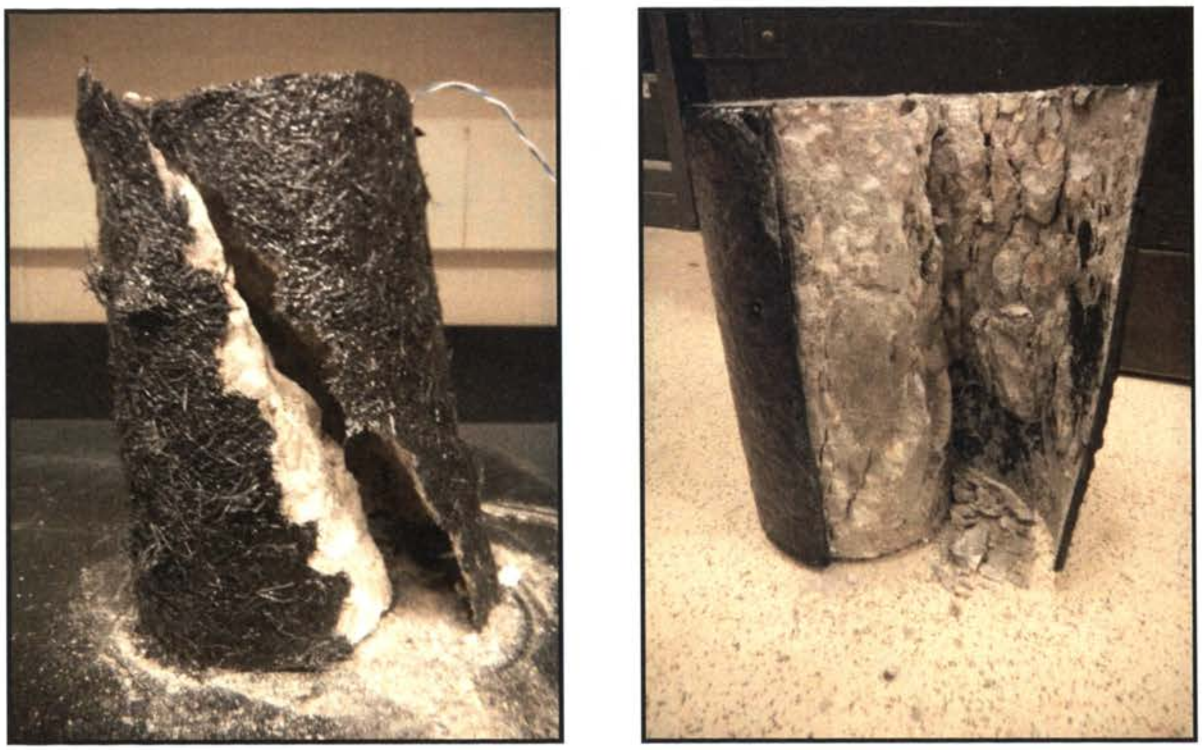


Figure 4.13. Failure Modes of Cylinders with Polyurea A

Figure 4.14 similarly shows two representative failed cylinders with a polyurea B coating. In both cases, it is readily observed that almost no loss of concrete-FRP adhesion is apparent and typical concrete fragmentation developed. The containment of concrete debris and the strong adhesion which was apparent during concrete testing are both important characteristics that support the continued use of polyurea coating systems for concrete applications.

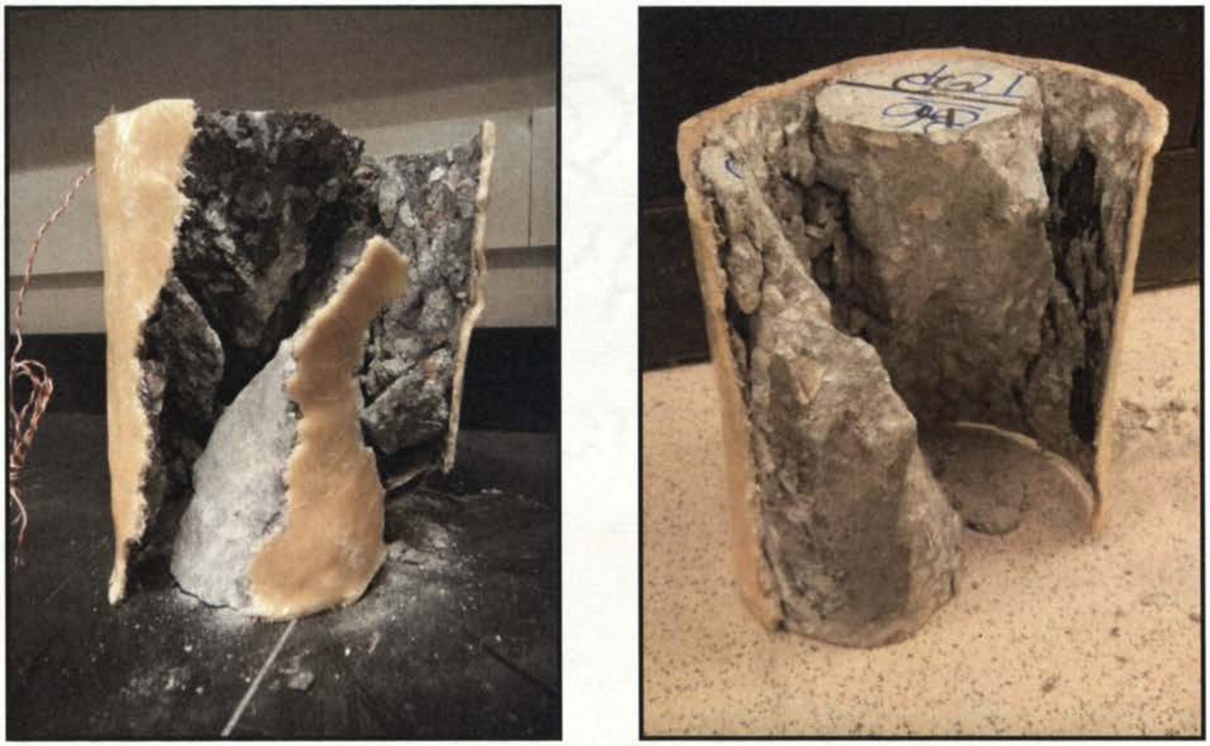


Figure 4.14. Failure Modes of Cylinders with Polyurea B

5. CONCLUSIONS

5.1. GENERAL

The testing scheme described provided significant results to evaluate the confinement characteristics of a fiber-reinforced polyurea coating system. While test results generally suggest that the prescribed coating system did not benefit ductility or overall strength, several important conclusions can be drawn from the study, with a specific interest into fragmentation containment and failure patterns.

5.2. STRENGTH, MODULUS OF ELASTICITY, AND DUCTILITY

The statistically insignificant benefits for strength, modulus of elasticity, and ductility of the confined columns suggest that the coating systems tested during this phase of study did not sufficiently confine the cylinders so as to improve the mechanical properties. As the coating was applied in this application, it would not be suitable for retrofitting of structural column elements for enhanced seismic performance, and general enhancement in axial and ductility behavior not be expected. Several additional conclusions have been made to consider possible reasons for such imprecise and unfavorable results:

1. The cylinder specimens failed with typical failure patterns as described by the testing standard. This fact suggests that the end surface preparation and testing procedures were sufficient to provide accurate results for the coated cylinders.
2. The compressive modulus of elasticity for concrete is much greater than that for the fiber-reinforced polyurea coating systems, which provided minimal confining effects. In addition, the modulus of elasticity or relative stiffness of the FRP system was much smaller than that for conventional steel that is used for spiral column reinforcement. This was likely a major factor contributing to the lack of additional strength or ductility development.
3. The short discontinuous fibers integrated into the FRP system were selected because of favorable results in direct tension testing. The lack of strength gain

or additional ductility between the cylinders coated with polyurea coating only and those coated with fiber-reinforced polyurea suggests that even though the fibers are known to provide additional tensile strength to the coating system, they were not able to confine the column in compression so as to provide substantial hoop confinement. This may be specifically due to the discontinuous nature of the fibers rather than a more conventional wrapped fiber.

4. The amount of fiber, type of fibers (and corresponding mechanical properties), and discrete nature of the fibers likely also contributed to the low strength and ductility gain. Again, even though the mechanical properties of the composite system are shown to improve in direct tension tests, the results of the cylinder testing suggest that the fibers were not engaged in such a way as to provide strength or ductility benefits beyond that of plain polyurea coating.
5. The results provided describe the behavior of concrete columns exhibiting relatively high compressive strengths as compared with some existing structures that would be eligible for repair and/or retrofitting. As such, it can be concluded that the coating system described would not be appropriate for the axial and ductility enhancement of high-strength existing concrete structures, but it cannot yet be verified that the coating system would not be beneficial for lower-strength concrete structures.

5.3. COATING SYSTEM AND FRAGMENTATION

By far, the most promising results from the described phase of testing to support its use in infrastructural applications resulted from the qualitative results that were observed during testing and described in Section 4.4. The polyurea coating system showed superior bond with the concrete cylinders and was quite effective in containing fragmentation. Thus, positive conclusions were drawn regarding the failure aspects of the cylinders which utilized the fiber-reinforced polyurea coating system:

1. As shown in previous studies (Carey and Myers 2010), the results support the conclusion that the coating system described can be expected to provide substantial protection from fragmentation and debris scatter
2. In addition to providing the expected protection from blast or impact fragmentation and debris scatter, the FRP coatings also encapsulate the concrete elements in such a way to prevent debris scatter or spalling during structural overload or massive failure.
3. The observed concrete-FRP bond or adhesion suggests that polyurea specifically can be a favorable polymer matrix material for FRP coating systems.
4. The effectiveness of the concrete-FRP bond also supports findings that the spray application of polyurea or fiber-reinforced polyurea can be a favorable application method for exterior reinforcing or repair.

6. FUTURE RECOMMENDATIONS

6.1. TESTING PROCEDURES

The encapsulation of debris scatter and superior bond of the polyurea coating system suggests that additional research may be beneficial to developing a fiber-reinforced polyurea coating system that provides more strength and ductility and results in a measurable improvement to the structure. The testing procedures described herein provided for typical concrete failure and accurate results but the following recommendations may be considered to expand the results of the study and develop a better understanding of the structural reinforcement properties.

1. More concrete strength levels should be considered so as to provide wider breadth of knowledge of the reinforcing aspects of the composite coating system. In addition, testing on lower strength concrete levels may yield findings that the coating system can make greater improvements on these materials.
2. The small unreinforced concrete test specimens could be replaced by larger, reinforced specimens to more accurately represent a structural concrete column with steel reinforcement. The concrete cylinder can only represent a short column, but more substantial results may develop if considered with a long column that is typical for structural elements.
3. Additional research should be conducted to better capture and analyze the post-peak load-deformation behavior of coated concrete cylinders. This may require a stiffer testing machine and faster data collection.
4. If further research provided positive results supporting strength or ductility gain on tested concrete specimens, it would be necessary to develop a new process or complete an investigation of current equipment so as to provide a spray application process that mimics the current spray pattern used but is better suited to larger structural elements.

6.2. FIBER-REINFORCED POLYUREA COATING SYSTEMS

As previously noted, the research suggests that the low stiffness of the coating system as well as the inability for the glass fibers to engage additional strength or stiffness to confine the column contributed to the lack of positive strength or ductility effects. Thus, several improvements specific to the coating system are recommended:

1. A variety of fiber lengths should be considered in addition to the short 1/4-in (6 mm) fibers used during this phase of testing. The longer fiber lengths may provide more continuous confinement properties than the shorter fibers.
2. In addition to adapting fiber length, additional fiber types should be considered. Aramid or carbon fibers present higher costs and more complicated application difficulties, but may be preferable to glass fibers because of their superior mechanical properties and potential for enhancing ductility.
3. The fiber volume fraction developed in this study is relatively low as compared to most typical FRP strengthening systems that have been developed or used in the past. A fiber-reinforced polyurea system with a higher percentage of fiber may provide the stiffness required to have substantial effects on the strength or ductility of the concrete cylinders or columns to be tested.
4. While it would be most desirable (for construction practices) to develop a system which utilizes chopped fibers to develop strength in the FRP system, additional strengthening techniques such as continuous wrapped fibers in conjunction with polyurea coating systems should be investigated to measure to strengthening effects of the spray-application fiber-reinforced polyurea coating as compared to fiber-wrapped columns or cylinders.
5. The qualitative observations of the superior bond or adhesion of the coating system to the concrete suggest that further investigation of the polyurea bond strength may be beneficial and that polyurea is a favorable polymer to use for multi-hazard coating systems, if additional coating strength can be developed by means of some method described above.

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II. FLEXURAL AND SHEAR BEHAVIOR OF REINFORCED CONCRETE MEMBERS STRENGTHENED WITH A DISCRETE FIBER-REINFORCED POLYMER SYSTEM

ABSTRACT

Research was conducted at the Missouri University of Science & Technology (Missouri S&T) to evaluate the flexural and shear reinforcement capabilities of glass fiber-reinforced polyurea coating systems. Testing parameters included type of structural failure, type of polyurea, and fiber volume fraction. In addition, the effects of the thickness of the composite coating system were considered. Analysis is based on beam ultimate capacity and deflection and overall ductility as well as the coating systems' shear contribution and the qualitative observations of coating adhesion and fragmentation confinement. In addition, a theoretical model is developed and validated to describe the flexural behavior of the polyurea-coated beams and normalize the test data for comparison. Results presented suggest measurable strengthening for both flexure and shear provided by the coating system, as well as substantial gains in ductility.

1. INTRODUCTION

1.1. BACKGROUND

The flexural properties of concrete beams reinforced with deformed steel bars, or rebar, have been widely studied and reinforced concrete (RC) beams are used throughout the infrastructure of the United States (US) and the world. While the concrete itself is weak in tension, the forces on the tension face of beams, and the resulting moment capacity, can be greatly improved with the use of longitudinal rebar to carry the tensile forces. However, as the US infrastructural system ages, greater demands are placed on existing structures which are frequently required to meet more stringent updated safety and structural codes and standards or become part of a renovated or additional structure presenting greater dead loads. As one testament to the effects of these growing demands, last year's 'Report Card for America's Infrastructure' cited that 26% of the bridges within the US are considered "structurally deficient or functionally obsolete" (ASCE, 2009). In addition, the incidence of structural deficiency in bridges is actually increasing more in urban areas where infrastructure plays an especially vital role.

In order to meet the growing structural demands, many repair and retrofit methods have been developed to strengthen RC beams externally. One external strengthening system that can be used is fiber-reinforced polymers (FRP). Often FRP strengthening can be completed with minimal preparation to the existing structure, and the most attractive systems can provide significant tensile reinforcement similar to the rebar installed in the concrete. Traditionally, the most widely used FRP strengthening systems are applied by hand in a "wet lay-up" manner. A new coating system is being developed that would have a spray application, further minimizing the construction time and efforts required to complete external strengthening.

Polyurea is an elastic polymer which has high elongation capabilities and has been evaluated in the past for its superior blast damage mitigation potential. Polyurea coatings applied to the back face of concrete barriers effectively reduce spalling caused by blast or impact loading, and the elastic material is effective in containing fragmentation that might otherwise be projected towards people or goods housed in a structure Carey and Myers (2010). Recent research has considered the addition of discrete chopped fibers to the polyurea to add strength to the coating system. Fiber characterization of this polyurea system was developed by Carey and Myers (2010) at Missouri S&T and used as a basis for this study. Additional research investigating the potential for seismic performance and ductility has also been completed using reduced-scale coated concrete cylinders (Greene and Myers, 2010). In this manner it is hopeful that such a coating system could provide multi-hazard protection for the repair and retrofit of infrastructure, allowing for seismic reinforcement, blast damage mitigation, and general strengthening.

1.2. SCOPE AND OBJECTIVES

Based on prior research on the blast and impact damage mitigation effects from polyurea coating, this research project was aimed at investigating the general strengthening aspects of fiber-reinforced polyurea coating systems in order to design a system appropriate for multi-hazard repair and retrofit applications. This phase of research focused on the flexural and shear strengthening effects of glass fiber-reinforced polyurea coating when used in conjunction with RC beams subjected to a four-point loading scheme.

The testing described considers the differences between a polyurea coating and a fiber-reinforced polyurea coating, as well as the effects of coating thickness. A limited number of beams were tested with consistent concrete properties and steel reinforcement in order to focus mainly on the effects of the coating rather than the interaction between beam strength and coating strength. The required end result was to determine the strengthening capabilities, if any, of the coating system, and to provide recommendations for which materials and material properties have the greatest effect and ease of application for future studies and applications. In order to provide sufficient data to reach these conclusions, several factors were monitored during testing, including overall beam deflection and loading capacity as well as strain in the steel, concrete, and polyurea coating system, and this raw data is evaluated in Chapter 4. In addition, the results of beam testing were used to develop and validate a theoretical model described in Chapter 5 by which the test data could be normalized and also by which more alternatives could be considered.

2. RELATED WORK

2.1. GENERAL

Containment with polyurea coating systems has been shown to reduce concrete spalling, fragmentation, and debris scatter caused during blast and impact events (Carey, 2009). Compressed air cannon impact testing of 46.5-in (1.18-m) square panels fabricated with 1/8-in (3.2-mm) thick polyurea coating applied to the tension face showed that, "polyurea coating contained the fragmentation and spalling throughout repeated impact until failure and rupture (Carey, 2009)." In addition, blast testing results showed that plain polyurea and polyurea with added chopped E-glass fibers applied to the back or tension face of concrete panels resulted in a 40-60% damage reduction and a 10-25% reduction in mass loss (Carey, 2009). These results support the consideration of fiber-reinforced polyurea coating systems for multi-hazard protection and suggest that strengthening of polyurea systems with chopped fibers would not diminish the damage mitigation enhancements provided by the coating system.

While some investigation has been completed to consider the flexural and shear strengthening capabilities of polyurea coatings, an extensive understanding of the strengthening effects of the system is still developing. However, external strengthening using fiber-reinforced polymer systems has been widely researched and developed for repair applications. The types of strengthening materials and application methods that have been developed are numerous and provide substantial background to relate to the present work.

Based on extensive research in the field, the American Concrete Institute (ACI) has developed ACI 440.2 (2008), a design guide for the use of external FRP strengthening systems in lieu of alternative exterior strengthening techniques, "such as steel plate bonding, section enlargement, and external post-tensioning." ACI sites specific benefits of utilizing exterior FRP systems, including weight, ease of installation, and durability, and notes that external FRP reinforcement is useful in a variety of applications.

2.2. EXTERNAL FRP APPLICATIONS FOR CONCRETE STRENGTHENING

2.2.1. FRP Laminates. Externally-applied FRP laminates can be manufactured from a wide variety of materials. Particularly popular, carbon fiber-reinforced polymers (CFRP) are known to provide the highest stiffness and strength of fibers that are widely used. These systems have been used for many years to strengthen beams for flexural and shear capacity gain, and they can be applied in a variety of patterns, including a 'U-wrap' which covers the sides and bottom of an exposed beam or girder, or flat layers applied only specified faces of beams, and also in a continuous system or individual strips of laminate. Such strengthening can yield significant increases in ultimate capacity on both flexure-controlled and shear-controlled regions of beams or girders.

Research studies conducted by Khalifa (1999) at Missouri S&T (formerly University of Missouri – Rolla) showed substantial gains in ultimate capacity using CFRP laminates. These studies considered simply-supported rectangular beams designed to observe shear failure as well as continuous rectangular beams and T-section beams. Testing for the simply-supported rectangular beams was developed using a text matrix of 12 specimens that were prepared by water-blasting of coated surfaces and rounding corners to a 0.59-in (15-mm) radius. With span lengths ranging from 6-ft (1.83-m) to 8-ft, 4-in (2.54-m), and 4-point loading with constant moment regions of 12-in (305-mm) and 8-in (203 mm), beams exhibited CFRP shear strengthening of 40% to 138% as compared to the control (non-coated) specimens. In addition, testing of T-beams showed that the U-wrap CFRP strips yielded an 80% capacity increase as compared to the control, while CFRP strips applied to only to the 2 sides of the beam in similar strips yielded less than half (35%) of that capacity gain (Khalifa, 1999).

More recent research also suggests that CFRP laminates provide substantial stiffness during cyclic loading (Ekenel and Myers, 2009). During the testing of 8 CFRP laminate strengthened beams, results showed that the stiffness after 2 million loading cycles of these beams was approximately twice that of the non-strengthened control beam. Related research by Ekenel et al. (2006) showed that theoretical capacities of CFRP strengthened beams could increase as much as 100% to 200% based on accepted design guidelines.

Another popular external laminate strengthening system in glass fiber-reinforced polymer (GFRP). Glass fibers are widely known to exhibit lower strength and higher ductility than carbon fibers and thus the strengthening technique yields different results than CFRP laminates. Research conducted by Hosney et al. (2006) considered the combination of both carbon and glass fibers in a polymer matrix to yield a hybrid fiber-reinforced polymer system (HFRP). In this case, several simply-supported RC beams with load span of approximately 9.8-ft (3000-mm) were subjected to 4-point cyclic loading. Variables between beams included type of laminate strengthening system (CFRP, GRFP, or HFRP), amount of strengthening, location of laminates and fiber direction, and anchorage details. After cyclic loading, results showed ultimate capacity increases ranging from 10.3% to 69.7%.

In addition to substantial research on the general strengthening properties of CFRP and other laminate systems, the consideration of polyurea as an alternative polymer matrix material for FRP systems was studied by Hrynyk and Myers (2007). This research was used to develop an understanding of the expected or indicative blast mitigation properties of polyurea coatings through static out-of-plane load testing on wall systems, and the flexural and shear behavior of these wall systems was an important measured property to develop this understanding. During two phases of study, a variety of unreinforced masonry (URM) wall systems retrofitted with polyurea strengthening systems were subjected to out-of-plane loading. The URM wall systems consisted of a variety of materials including clay and concrete, with well-known historical practice showing that the wall systems typically exhibit extremely low flexural strength. To improve these out-of-plane properties, walls were strengthened with two reinforcement schemes – polyurea without fibers, and polyurea with GRFP grid reinforcement. Walls during testing for phase I were subjected to uniform pressure by means of an airbag, and phase II walls were tested in a 4-point bending test. Additionally, phase II walls were slender, while phase I walls were not. Extensive analysis and normalization of results showed that phase I walls with polyurea coating experienced a load capacity 1.4 times that of the non-reinforced control wall, and that walls with polyurea and GFRP grid developed load capacities 2.7 times that of the control. Alternatively, the slender, simply-supported walls for Phase II testing exhibited a relative load capacity with polyurea coating of 4.1 as compared to the control, and with polyurea and GFRP grid, a relative capacity of 25.6 (Hrynyk and Myers, 2007).

2.2.2. FRP Near-Surface-Mounted Bars. In addition to surface mounted FRP lamina, another popular means of exterior retrofit and strengthening is achieved by means of near surface mounted (NSM) bars. While this method of strengthening is considerably different than the use of polyurea coatings, in that the surface of the exposed beam or girder is not encapsulated, it has proven to be an effective strengthening method. To achieve strengthening, a groove is first cut into the surface of the member to be strengthened. The smallest dimension possible for the groove is used in order to maintain clear cover for existing steel reinforcement. To install the FRP bars, first an epoxy paste (or sometimes a cement grout) is applied inside the groove, then the bar is laid in, and finally covered with more epoxy paste. Finally, the surface of the installation is smoothed and finished (Stone et al., 2002).

Studies by Merkle and Myers (2006) considered long-term load testing on bridges retrofitted with both FRP laminates and NSM bars. In this case, five existing Missouri bridges were inspected and evaluated, then strengthened as necessary. Later analysis presented in this study consisted of load testing with modern surveying equipment as well as calculation of theoretical load capacities. The analytical study showed that girders reinforced for flexural behavior could expect capacity increases of 15% to 56%, and that girders reinforced for shear behavior could expect capacity increases of 185 to 64% (Merkle and Myers, 2006).

Rizzo and De Lorenzis (2009) considered specifically the shear reinforcement capabilities of NSM CFRP systems. In order to further understand the shear strengthening capabilities of NSM systems, 9 rectangular RC beams were tested. All beams were designed to fail in shear on a specified "weak" half of each beam. In additional to one control beam featuring no external reinforcement, another beam used for comparison featured a single-ply 'U-wrap' externally bonded CFRP laminate. The remaining 7 beams were prepared according to the typical application methods for NSM reinforcement. For additional variation, both round reinforcement (bars) and thin rectangular reinforcement (strips) were used, and they were mounted at different angles of 45 degrees and 90 degrees and different spacing dimensions. Finally, two different epoxy encasements were considered. All beams were subjected to 4-point loading until failure with a shear span to depth ratio of 3. Results showed that the standard CFRP laminate reinforcement provided an ultimate capacity increase of 16% over that of the control case. Alternatively, the NSM methods discussed yielded ultimate capacities ranging from 22% to 44% greater than the control case. This corresponded to an FRP contribution to shear capacity of 4.3 k (19.3 kN) to 12.2 k (54.2 kN) (Rizzo and De Lorenzis, 2009).

2.3. FABRICATION AND TESTING PROCEDURES

2.3.1. Polyurea Coating Considerations. An important factor that influences the effectiveness of FRP laminates and is therefore accounted for in a majority of studies is stress concentrations developed in coating systems at sharp interfaces, or corners of test members. Research by Yang et al. (2001) specifically considered this issue. In order to determine the effects of corner properties (angle or radius) on FRP strength and failure modes, CFRP sheets were tested in tensile loading over variable corner radii ranging from the representation of a circular cross-section to a square cross section (zero radius). In addition, the study considered the effects of single and double ply sheet thicknesses to test the vulnerability of thinner cross sections. Based on measurements of strain and ultimate load as well as observations of failure location and failure mode, the geometry of the corners about which the sheets were loaded had a significant impact on the effectiveness of the CFRP. In general, the ultimate tensile strength of the CFRP was observed to be higher with a larger corner radius, and additional ply-thickness reduced the impact of the corner. These results were found to be true throughout testing with the exception of only the definite square and circular cross sections (Yang et al., 2001).

Another important factor that is considered during FRP laminate strengthening is the thickness of the lamina or ply and the total thickness of the applied coating. This factor is widely considered as a variable to account for during testing of FRP strengthening applications. Additionally, manufacturers in the coatings industry typically stress the importance of attaining the specified coating thickness for a project. As part of the 2009 Paint and Coatings Expo (PACE), Primeaux and Bower (2009) released important information regarding the importance of polyurea coating thickness as well as methods for inspection of polyurea thickness during projects. Not surprisingly, polyurea coatings which are excessively thin, contain substantial voids, or do not exhibit uniformity and consistency have the potential to yield weak systems. They may not exhibit the manufacturer's reported properties, and may experience degradation or premature failure. While several options are available in order to check or monitor the coating thickness during application, all methods in this study were evaluated by comparison with averaged micrometer measurements taken on destructive test samples obtained from the coating systems. The importance of average results was stressed due to the uneven, so-called "orange-peel" texture of the fast-set polyurea surface (Primeaux and Bower, 2009). The inclusion of several thickness measurements to obtain an average is also included in ASTM D 1005 (1995), "Standard Test Method for Measurement of Dry-Film Thickness of Organic Coatings Using Micrometers." This standard requires that a minimum of 3 determinations of thickness be taken from any one test film, and that measurements be taken at minimum 1-in (25-mm) from the original edge of any test panel.

2.3.2. Flexural and Shear Beam Tests. The testing methods developed in this study and described in Section 3.4 to observe flexural and shear failures in the test beams were largely developed based on prior research conducted at Missouri S&T by Brewe (2009). In this case, the concern was the shear and flexural behaviors of high-strength self consolidating concrete girders, and 3 specimens each were tested for flexural behavior and shear behavior. Flexural girder testing was conducted in 4-point loading in order to develop a constant moment region, and supports were placed 3-in (76-mm) from the ends of the members, developing a load span of 14.5-ft (4.4-m). A hydraulic jack placed at mid-span distributed a load to the test girder by means of a 2-ft (610-mm) spreader beam with 2 loading points. The load was applied at approximately 1000 lb/sec (4450 N/sec) and halted at selected intervals to observe and monitor cracking. For the flexural beams, sufficient shear reinforcement (stirrups) were provided so that flexural capacity would the determining failure mode (Brewe, 2009).

Shear specimens and testing procedures were developed similar to those for flexural testing. A similar test setup produced a load span of 9-ft (2.7-m) for each beam test section. For these tests, however, the beams were fabricated in longer lengths to provide two tests section per each single beam. The first test section on one end of the beam contained no shear reinforcement and thus only concrete contributed to the shear resistance of the cross section. The second test section on the opposite end of the beam did contain shear reinforcement, and as such, the steel reinforcement contribution to shear capacity could be measured during testing. In both cases, adequate flexural reinforcement (longitudinal bars) were included in the design so as to ensure that shear capacity was the limiting failure criteria.

3. EXPERIMENTAL PROGRAM

3.1. TEST MATRIX

In order to observe the reinforcement aspects of the described coating system, two separate but similar beam and test setup designs were developed, one to observe flexural behavior, and the second to observe shear behavior. The shear beam design and test setup was developed in such a way that two individual tests were to be completed on each single shear testing beam. The resulting test matrix included a total of eight beams which allowed for eleven separate tests as portrayed in Figure 3.1.

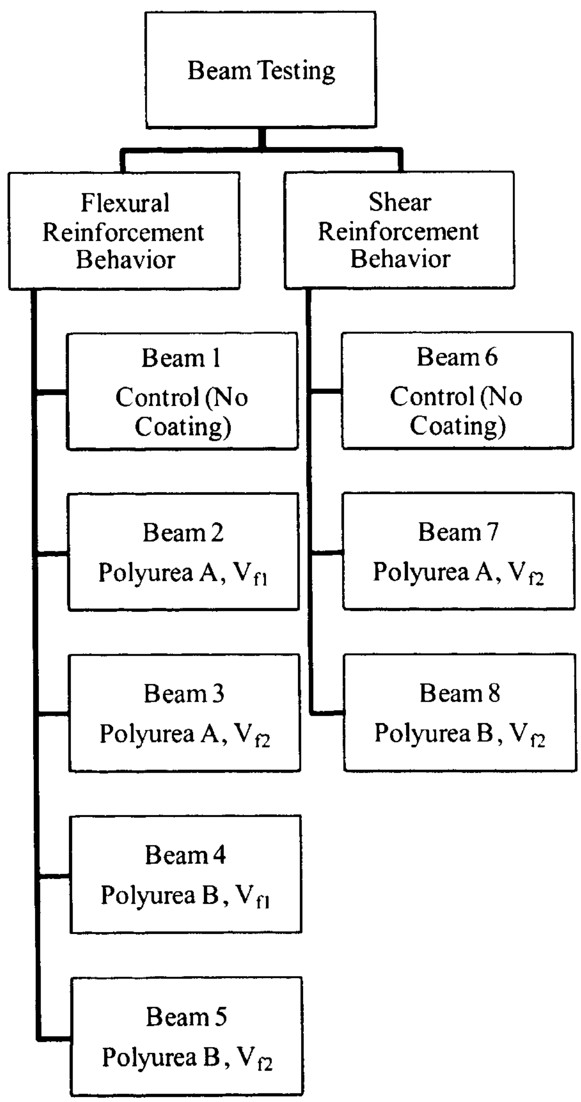


Figure 3.1. Test Matrix Schematic

All beams were developed with the same concrete mix and concrete strength as well as consistent steel reinforcement properties. To obtain a greater diversity of results, no replicate tests were completed for this phase of testing. As shown, the variables considered during testing development were type of polyurea and volume fraction of fiber, V_f. Two separate compositions of polyurea, labeled here as "Polyurea A" and "Polyurea B" were considered. While the type of fiber used was consistently an E-glass fiber, the amount of fiber dispersed into the system during coating was varied to obtain different fiber volume fractions as discussed in Section 3.3. It should be noted that because the beam coating process was not automated some differences in coating thickness were observed and were considered during analysis of the results, although this discrepancy was not part of the original range of test variables. The final test matrix and notations for referencing each beam are shown in Table 3.1.

Table 3.1. Final Test Matrix and Notation

Beam	**Test**	**Beam Type**	**Polyurea**	**Fiber Level**	**Notation**
1	F	P	A	0	F-P-A-0
2	F	P	A	L	F-P-A-L
3	F	P	B	H	F-P-B-H
4	F	P	B	L	F-P-B-L
5	F	C	N/A	0	F-C
6A	SN	C	N/A	0	SN-C
6B	SR	C	N/A	0	SR-C
7A	SN	P	A	L	SN-P-A-L
7B	SR	P	A	L	SR-P-A-L
8A	SN	P	B	H	SN-P-B-H
8B	SR	P	B	H	SR-P-B-H

Key:

Test:
- F - Flexure Test
- SN - Shear Test, Non-Reinforced
- SR - Shear Test, Reinforced

Beam Type:
- C - Control
- P - Polyurea-Coated

Fiber:
- 0- None
- L - Low
- H - High

Polyurea:
- A
- B

3.2. MATERIALS

3.2.1. Concrete. Compressive strength, f'_c, of the concrete used for the beams was determined per ASTM C 39-09a (2009) using typical cylinder specimens measuring 4-in (100-mm) diameter by 8-in (200-mm) height. Three replicates each were tested at 28 days, beginning of testing, and ending of testing (see Table 3.2). Cylinders were also tested to determine the modulus of elasticity, E, per ASTM C 469-02 (2002) at the same time intervals as compressive strength, with results presented in Table 3.3. The modulus of rupture (MOR) of the concrete used for the beam testing was also obtained, per ASTM C 78-09 (2009). Typical specimens measured 6-in (150-mm) wide by 6-in (150-mm) in height, by 24-in (610-mm) in length. Two specimens were tested at 28 days after the fresh concrete was poured, as well as two more specimens during the beam testing (see Table 3.4).

Table 3.2. Concrete Material Properties – Compressive Strength

Test Period	Date	Average Reported Comp. Strength (psi)
28-Day	2/23/2010	6590
Test Age	7/20/2010	8050

Unit Conversion: 1 psi = 6890 Pa

Table 3.3. Concrete Material Properties – Modulus of Elasticity

Test Period	Date	Measured E (ksi)	ACI 318-08 (2008) (ksi)
28-Day	2/23/2010	5675	4627
Test Age	7/24/2010	5413	5114

Unit Conversion: 1 ksi = 6.9 MPa

Table 3.4. Concrete Material Properties – Modulus of Rupture

Test Period	Date	Average Measured MOR (psi)	ACI 318-08 (2008) (psi)
28-Day	2/23/2010	560	610
Test Age	7/21/2010	1030	670

Unit Conversion: 1 psi = 6890 Pa

3.2.2. Reinforcing Steel. All steel reinforcing bars used for the test beams were Grade 60. The design called for No. 3 and No. 4 deformed bars as well as No. 2 smooth bars to aid in specimen fabrication as described in Section 3.3. Samples of the No. 3 and No. 4 steel reinforcement were tested in accordance with ASTM A 370-09a (2009) to validate the yield strength, ultimate strength, and strain at failure. The tensile test was performed with a loading rate of ½-in (12.7-mm) per second and a gauge length of 8-in (200-mm). Figure 3.2 shows the test configuration used for the steel testing. Measured mechanical properties of the steel that was used in the beams are included in Table 3.5. The smooth No. 2 wire used to place stirrups was considered to have negligent reinforcement value and was therefore not tested for compliance with standards.

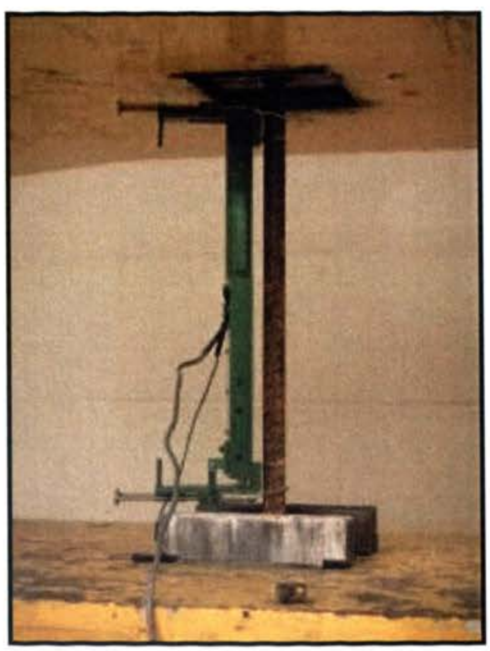


Figure 3.2. Tensile Test for Steel Reinforcing Bars

Table 3.5. Steel Reinforcing Bar Material Properties

Bar Type	Area (in^2)	Average Yield Stress at 0.5% Offset (psi)	Average Peak Stress (psi)	Average Elongation
No.3	0.11	68000	105500	13.1%
No.4	0.20	71000	101500	14.6%

Unit Conversion: 1 in^2 = 645 mm^2; 1 psi = 6890 Pa

3.2.3. Fiber-Reinforced Polyurea Systems. The test matrix described in Section 3.1 included the use of two types of polyurea in addition to variable fiber volume fraction. While the two polyurea types consisted of different chemical compositions and mechanical properties, both systems were two-component, spray elastomer systems. The polyurea types tested were consistent with previous testing completed on concrete cylinders to observe the potential reinforcement aspects of the coating system on columns. As such, both polyureas were two-component elastomer systems, each with relatively high tensile strength as compared to other types of polyurea. In addition, both polyurea coatings have excellent chemical and moisture resistance properties and zero volatile organic compounds (VOC). Polyurea B exhibited enhanced ductility properties as compared to Polyurea A. Another important factor was the set time; the two polyureas tested exhibited a great difference in set time, which affected the fabrication process. Mechanical properties as provided by the manufacturer for both types of polyurea are included in Table 3.6.

Table 3.6. Polyurea Material Properties

Polyurea Designation	A	B
Density (lbs/gal)	9.3	8.8
ASTM D 412-06a (2006) Elongation	91%	445%
ASTM D 412 a (2006) Tensile Strength (psi)	2147	2800
Gel Time (sec)	3 - 6	11 - 13
Tack Free Time (sec)	6 - 9	78 - 85

Unit Conversions: 1 lb = 4.45 N; 1 gal = 3.8 L ; 1 psi = 6890 Pa

The E-glass fiber roving used during this phase of testing was also consistent with previous testing on concrete cylinders as described in the first segment of this study (Greene and Myers, 2010). All fibers were chopped to a length of ¼-in (6-mm) based on research results from Carey and Myers (2010). The fibers were distributed into the coating during the spraying process as later described in Section 3.3 which resulted in a randomly-oriented fiber system. The properties of this glass which was specially developed by the manufacturer for spray-up applications are included in Table 3.7.

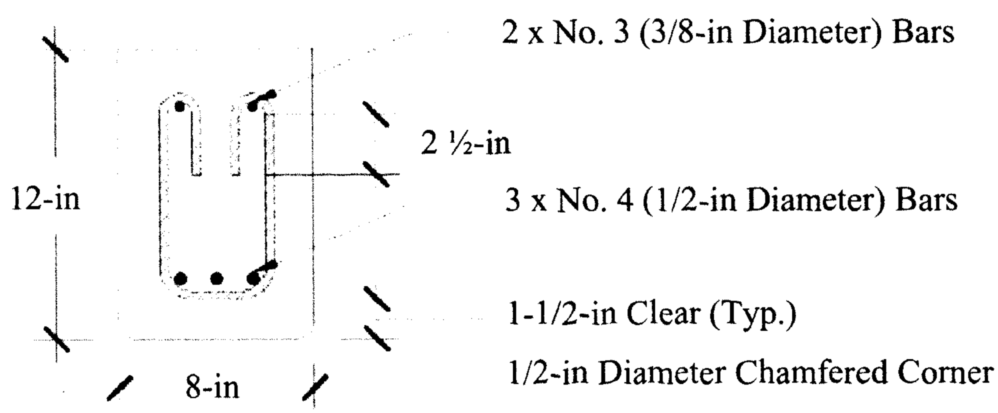
Table 3.7. Fiber Material Characteristics

Fiber Type	E-Glass
Fiber Length, in.	0.25
ASTM D 638-10 (2010) Tensile Strength, psi	8490 - 14182
ASTM D 638-10 (2010) Tensile Modulus, ksi	1094 - 2160

Unit Conversions: 1 in = 25.4 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa

3.3. SPECIMEN FABRICATION

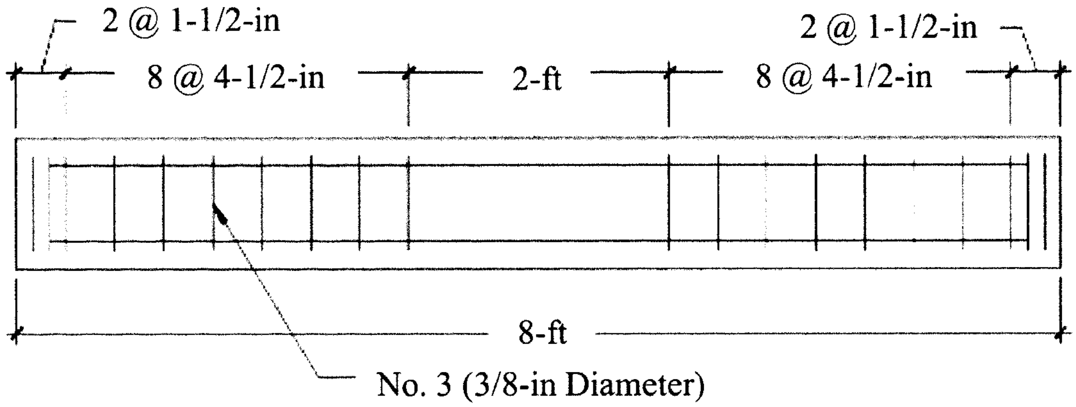
3.3.1. Concrete Beam Preparation. All eight beams described in Section 3.1 were fabricated on January 25, 2010 in the Structural Engineering Research Laboratory (SERL) in Butler-Carlton Hall on the Missouri S&T campus. All beams were prepared with a typical cross-section shown in Figure 3.3.



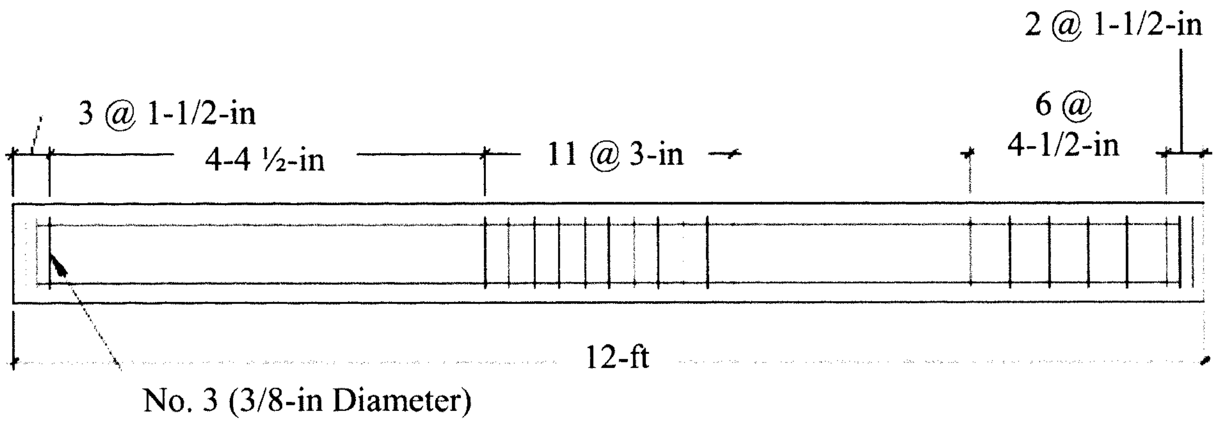
Unit Conversions: 1 in = 25.4 mm

Figure 3.3. Typical Beam Cross-Section

In order to minimize stress concentrations at the bottom coated corners of the beams, a chamfered corner of 1 ½-in (38-mm) diameter was developed during casting. The reinforcement layouts and lengths for each set of beams (flexural testing and shear testing) are shown in Figure 3.4. Before casting, the shear reinforcement (stirrups) were cut and bent to specifications as shown in Figure 3.5, and cages were tied also according to the aforementioned specifications, as shown in Figure 3.6.



(a) Flexural Testing Beam Layout



(b) Shear Testing Beam Layout

Unit Conversions: 1 ft. = 305 mm; 1 in. = 25.4 mm

Figure 3.4. Beam Length and Reinforcement Diagrams

(a) Shear Reinforcement Stirrups

(b) Strain Gauges Applied to Longitudinal Bars

Figure 3.5. Reinforcement Fabrication Figures

After the reinforcement cages were prepared, longitudinal reinforcement for each test section in the beams was instrumented with two strain gauges at mid-span for later testing purposes (see Figure 3.5). The forms were assembled inside the lab and modified with quartered sections of polyvinyl chloride (PVC) piping installed with caulking for a tight seal to obtain the chamfered corner. The forms were then oiled before the cages were placed. The beams were cast with ready-mix concrete from Rolla Ready-Mix. In addition, concrete testing samples (cylinders and small beams) were prepared from the same batch of concrete for acceptance testing according to ASTM C 31-09 (2009). Bent rebar hooks were placed in the tops of the beams after casting to allow for lifting points, and all specimens were covered to contain moisture and kept in controlled lab conditions throughout the coating and testing process.

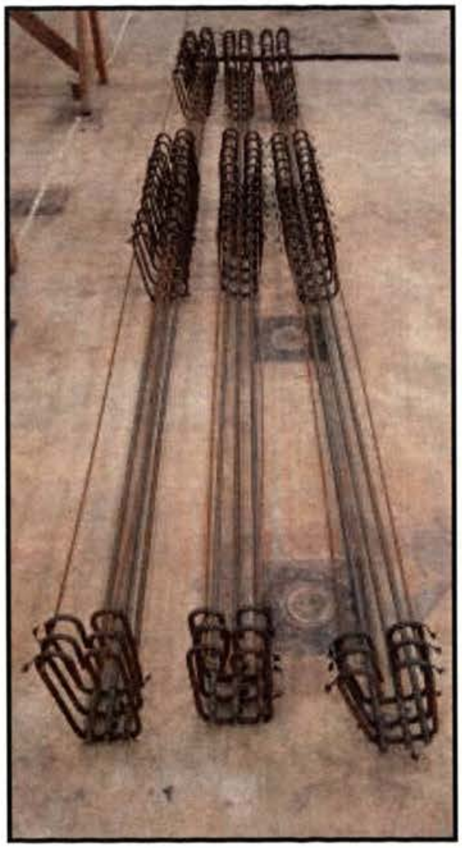
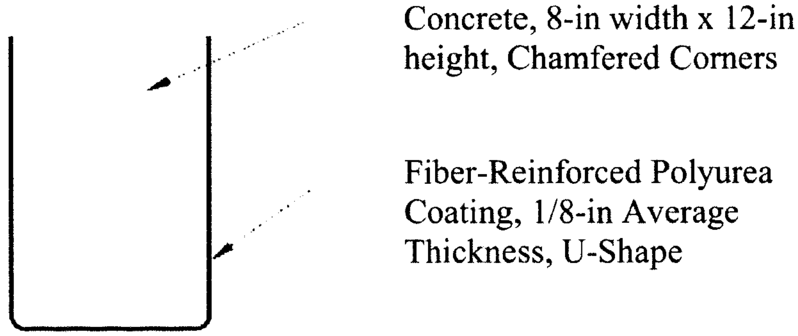


Figure 3.6. Tied Reinforcement Cages

3.3.2. Coating Systems. After the concrete beams were allowed to cure, the selected beams as described in the test matrix were prepared and coated on May 11, 2010 in the Engineering Research Lab (ERL) on the Missouri S&T campus by a polyurea supplier and installer located in Columbia, MO. A moderate amount of surface preparation was completed by roughening the surfaces of the concrete beams and applying a specially developed primer to a thickness of 2 to 3 mils. The primer was allowed to cure a minimum of 45 minutes prior to polyurea coating. The coating was applied in a "U" shaped jacket (see Figure 3.7) by resting the beams upside down to display the three sides to be coated.



Unit Conversion: 1 in = 25.4 mm

Figure 3.7. U-Coating Schematic

A Glascraft chopper spray gun was used to develop and apply the fiber-polyurea coating mixture. The gun that was used simultaneously mixed the two-part polyurea chemical and sprayed it onto the surface of the beams, while it also chopped the glass fiber roving (strand) and projected the resulting chopped fibers into the spray pattern so that the resulting coating was a discrete fiber-reinforced polyurea system with a random orientation of fibers. The coating process was completed by a qualified professional using extensive safety gear. In addition to coating the beams, small separate coating samples were prepared by spraying directly onto oiled metal sheets and removing the coating. These samples were prepared for further testing of the coating for mechanical properties as well as the specific composition of each coating systems in the test matrix. Results for the coating thickness and fiber volume fraction based on ignition testing are presented in Chapter 4, but it is important to note that later results showed reasonably consistent coating thickness and fiber volume fraction along the beams and also were consistent with the extra samples prepared for testing. While certain variability did exist between different beams, samples taken from each single beam and its corresponding test panel were reasonably congruent.

3.4. TESTING SETUP AND PROCEDURE

3.4.1. Fiber-Reinforced Polyurea Testing. Similar to prior testing for fiber-reinforced polyurea-wrapped concrete cylinders developed by Greene and Myers (2010), flat coupon specimens were prepared to evaluate the specific coating mechanical properties and fiber volume fraction for each beam. Specimens measuring 9-in (230-mm) in length by 1.57-in (40-mm) in width were subjected to a tensile loading test according to ASTM D 3039-08 (2008) and ASTM D 7565-10 (2010). As allowed by ASTM D 3039, specimens were tested in deformed grips with no end tabs, based on similar testing provided by Carey and Myers (2010). The specimens were tested until failure at a loading rate of 0.5-in/min (12.7-mm/min) and an extensometer was used to measure deformation (see Figure 3.8). Several specimens were tested for each coating system.

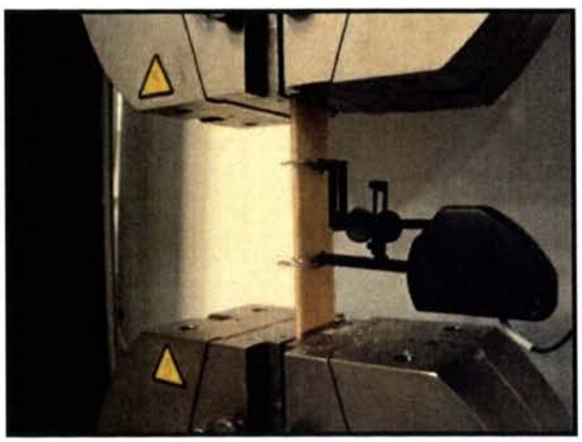
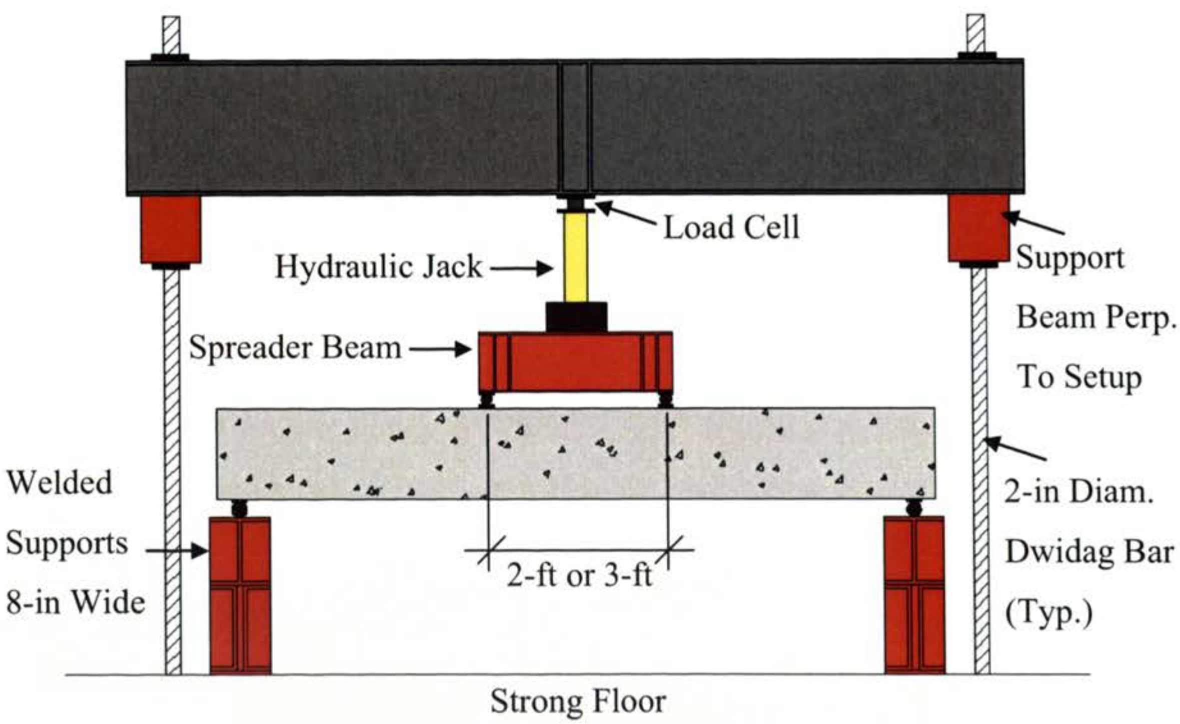


Figure 3.8. Coupon Tensile Test

Selected tested specimens were then prepared for testing for fiber volume fraction according to ASTM D 3171 D 3171-09 (2009). Specimens were cut to measure 2-in (51-mm) by 1 ½-in (38-mm), and placed in a furnace at a temperature of 1112˚F (600˚C) for 2 hours. Original weights and resulting weight of the fiber similar to that shown in Figure 3.9 was recorded and the fiber volume fraction for each sample was calculated.

Figure 3.9. Resulting Fiber After Ignition Test

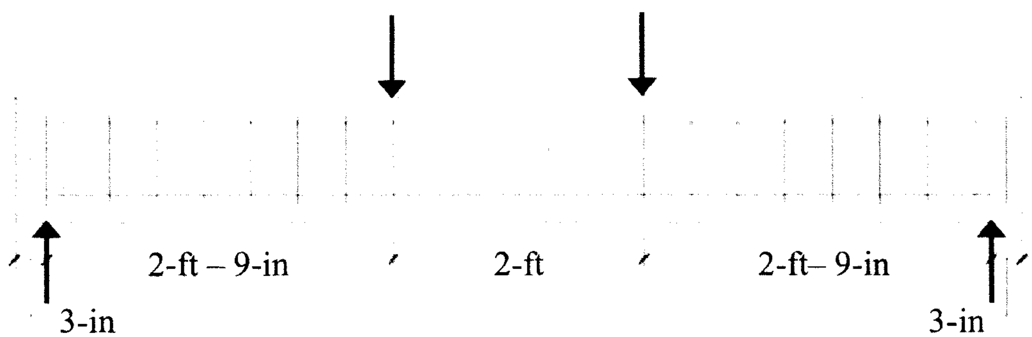
3.4.2. Test Setup. Both types of beams were tested in similar testing frames (see Figure 3.10) utilizing different loading and support points as required. The load was applied across a spread beam by means of a hydraulic jack braced against a stiff steel girder.



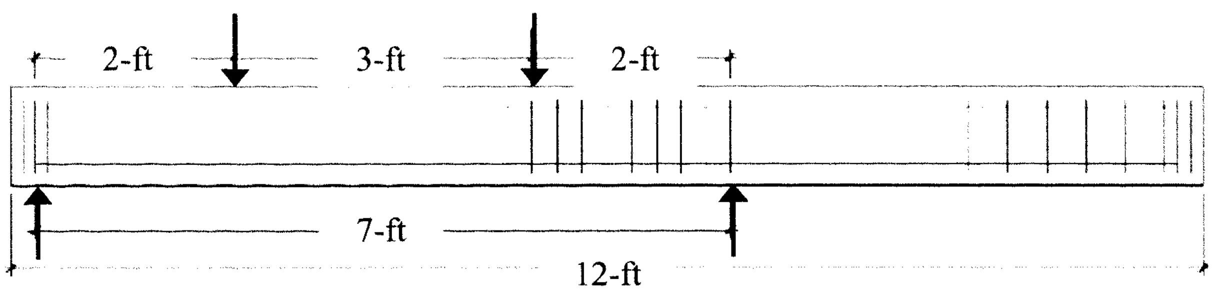
Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm

Figure 3.10. Beam Test Setup

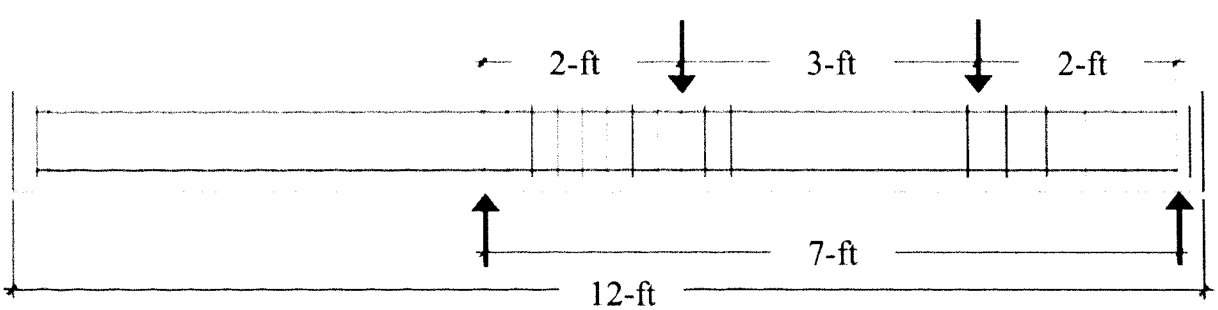
Different spreader beams and the movement of support systems provided for the different testing schematics required for the two types of beams. The flexural testing beams were supported at points 3-in (76-mm) from the ends of the beam with loading points spread 2-ft (610-mm) apart at mid-span (see Figure 3.11). The shear testing beams were supported in 7-ft (2134-mm) spans with a loading span of 3-ft (914-mm).



(a) Flexure Beam Loading Points



(b) Shear Beam Loading Points – Test 1



(c) Shear Beam Loading Points – Test 2

Unit Conversions: 1 in. = 25.4 mm; 1 ft. = 305 mm

Figure 3.11. Beam Specimen Loading Diagrams

3.4.3. Test Procedure and Data Collection. Before testing, beams were instrumented for data collection. Strain in the reinforcing steel was measured using strain gauges that were applied during fabrication (Section 3.3). In addition, each test included several strain gauges on the exterior of the beam, either on the concrete or on the fiber-reinforced polyurea coating. The total load on the beam was recorded using a load cell, and deflection was measured using direct-current linear variable differential transducers (DC LVDT). Instrumentation locations and types are summarized in Table 3.8. Beams were loaded at a rate of approximately 1000 lb/sec (4.45 kN/sec) until failure of the entire cross-section of concrete. During the testing of the control beams which had no coating, loading was temporarily halted to observe cracking at increments of approximately 5000 lb (22.3 kN).

Table 3.8. Beam Instrumentation Summary

	Flexural Test Beams
Uni-Axial Strain Gauges	Strain in Reinforcing Steel (2) Strain in Concrete, Top of Beam, Mid-Span Strain in Concrete or Coating, Bottom of Beam, Mid-Span Strain in Concrete or Coating, Bottom of Beam, 12 inches from support
DC LVDT	Vertical Deflection, Mid-Span Vertical Deflection, 18 inches from support Longitudinal Deflection, End of Beam
Load Cell	Total Load
	Shear Test Beams
Uni-Axial Strain Gauges	Strain in Reinforcing Steel (2) Strain in Concrete, Top of Beam, Mid-Span Strain in Concrete or Coating, Bottom of Beam, Mid-Span Strain in Concrete or Coating, Bottom of Beam, 12 inches from support Strain in Coating, Vertical Face of Beam, 12 inches from support, Vertical Strain in Coating, Vertical Face of Beam, 12 inches from support, Longitudinal
DC LVDT	Vertical Deflection, Mid-Span Vertical Deflection, 24 inches from support (under load point) Lateral Deflection, End of Beam
Load Cell	Total Load

3.4.4. Pull-Off Testing. After concrete beam specimens were tested, pull-off testing to evaluate the adhesion properties of the fiber-reinforced polyurea coating systems as applied to the concrete substrate was also completed generally following the testing methods described in ASTM D 7522, with some exceptions. Because testing equipment was not readily available during structural testing of the beams, the pull-off test was completed on failed concrete specimens rather than the standard which requires a pull-off test prior to testing. To evaluate the concrete which was degraded the least by structural testing, samples were taken near the end supports of the beams. In addition, only two samples were taken to provide an average tensile strength.

The exterior polyurea surface of each test section was prepared using an automatic sander to provide a flat, textured surface. Each test was conducted using a deformed circular plate (dolly) measuring 1.97-in (50-mm) in diameter. A core was drilled into the substrate as indicated in the testing specifications, and the dolly was applied to the prepared substrate using a two-part epoxy and allowed to set for a minimum of 8 hours. After the adhesive epoxy was completely set, the dolly was pulled off and the forced measured utilizing a Proceq Dyna pull-off testing, following the test specifications and the equipment manual guidelines. The tensile strength of the pull-off test and the observations of the failure plane were recorded and reported.

4. EXPERIMENTAL TEST RESULTS

4.1. FIBER-REINFORCED POLYUREA COATINGS

FRP coupon samples were prepared and tested as described in Chapter 3. The properties of these samples were measured to estimate the mechanical properties of the coatings on the test beams as well as to validate the expected flexural and shear capacities for the beams. In addition, small samples of coating were removed from the beams after testing to confirm the estimated values for fiber volume fraction, V_f. For each coupon sample, a direct tensile test was performed and the modulus of elasticity, E, the maximum stress attained, and the elongation at failure were calculated (see Table 4.1). Properties for plain polyurea (without fiber) are included in Table 3.6. Fiber volume fraction and coating thickness were reasonably consistent along each single beam.

Table 4.1. Fiber-Reinforced Polyurea Properties

Beam	Coating Designation	V_f (%)	E (ksi)	Max Stress (psi)	Elongation (%)
		Flexural Beams			
2	A-L	3.0%	40.82	1004	13.3%
3	B-H	10.8%	163.61	1859	9.3%
4	B-L	7.2%	94.96	1403	13.2%
		Shear Beams			
7	A-L	3.0%	40.82	1004	13.3%
8	B-H	10.8%	163.61	1859	9.3%

Unit Conversions: 1 psi = 6890 Pa; 1 ksi = 6.9 MPa

Coating Designation Key: Polyurea-Fiber

Polyurea:
- A – Polyurea A
- B – Polyurea B

Fiber:
- 0 - None
- L - Low
- H - High

In accordance with the test matrix, two of the flexural test beams were prepared with Polyurea A, and two with Polyurea B. Because of the shorter set time of Polyurea A, lower fiber volume fractions of 3.0% and 0% (plain polyurea) were used. The longer set time of Polyurea B allowed for higher fiber volume fractions, 7.2% and 10.8%. As expected, the modulus of elasticity and the elongation at failure decreased as the amount of fiber in the polyurea was increased. Also as expected, Polyurea B developed a much higher strength with the addition of fiber. However, Polyurea A during this application attained a lower strength with fiber than Polyurea A with no fiber. This result suggests that during the application process, environmental factors and the fast set time of Polyurea A did not allow for optimal dispersion of the chopped glass fibers, creating discontinuities in the composite systems which caused increased weakness rather than strength. The longer set time of Polyurea B more consistently provided for proper dispersion of chopped fibers such that mechanical properties were improved as expected with the addition of the stiffer chopped fibers. The longer set time of Polyurea B also increased the ease of application for the spray technician. While the set time was longer for Polyurea B, the material has a relatively high viscosity and therefore, there were not complications with sag or dripping as the coating was applied. As a reference it is important to recall that Polyurea B has an expected elongation (as reported by the manufacturer) of well over 400%.

In addition to variable polyurea coating properties, the thickness of the composite coating systems was also changed during beam fabrication. This factor was added in order to develop more variables with which to validate a theoretical model of the beams, as well as to develop more pronounced differences in flexural and shear capacity of the beams.

4.2. ULTIMATE CAPACITY

Beams were tested according to the procedure described in Section 3.4. The ultimate capacity of each beam was recorded (see Table 4.2) as a major value with which to show general strengthening provided by the FRP coating system, as well as to validate the design model for the strengthening characteristics (described later in Chapter 5) which was used to predict the beam capacities during the design phase of the study. The raw ultimate capacities as compared to the coating designations for the flexural test beams are shown in Figure 4.1. For additional reference, the thickness of the coating system for each beam is included on the alternate axis in Figure 4.1. Normalization for these results to account for the variable coating thickness between beams is included in Chapter 5.

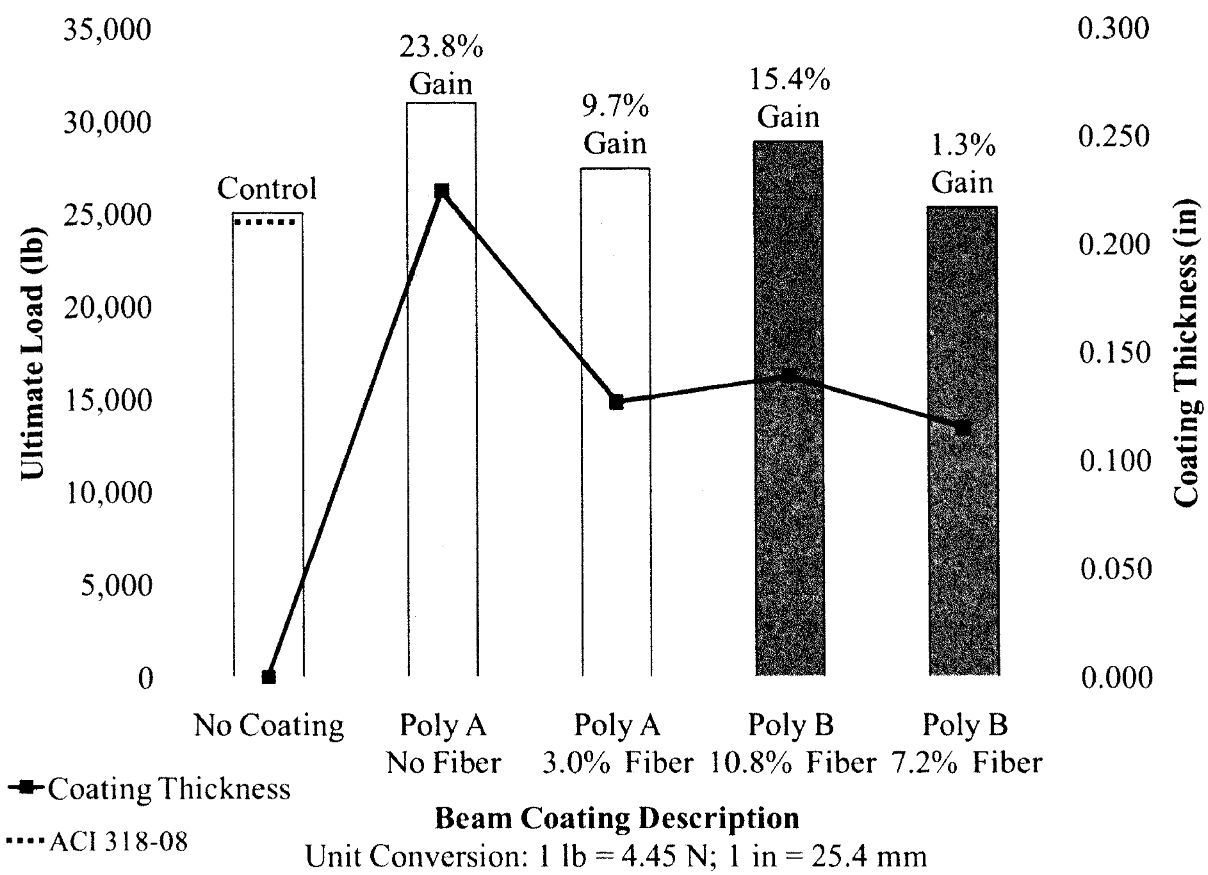


Figure 4.1. Flexural Beam Ultimate Load Comparison

As shown in Figure 4.1, the expected ultimate capacity P_n of the control specimen based on design guidelines provided in ACI 318-08 (2008) was 24,500 lb (109 kN). This calculation did not consider any load or safety factors as the goal was to estimate the true expected capacity. This calculation was completed by determining the flexural moment capacity M_n using equations 1-3. The discussions of calculations considering the FRP contribution to flexural capacity are included in Chapter 5 as well as design schematics to define the parameters used for calculation.

$$0.85 f'_c ba = A_s f_y \tag{1}$$

$$M_n = 0.85 f'_c ba\left(d - \frac{a}{2}\right) \tag{2}$$

$$P_n = \frac{2M_n}{a} \tag{3}$$

As shown, each FRP-coated beam developed greater ultimate strength than the control beam with no coating system applied. The greatest ultimate capacity increase of nearly 24% was produced with the plain Polyurea A coating with no fiber. The thicker Polyurea B coating with 10.8% fiber also developed a measurable improvement with a strength gain of 15.4% as compared with the control beam. As was expected due to the decrease in strength of Polyurea A with the addition of fiber, the beam utilizing fiber-reinforced Polyurea A developed less strength gain than the beam utilizing Polyurea A only. The lowest strength gain was observed on the beam with the smallest thickness of Polyurea B coating with low fiber volume fraction. The 1.3% difference between the control case and the specimen coated with Polyurea with a lower fiber volume fraction does not statistically prove that strengthening was attained; however, none of the cases considered resulted in a strength loss.

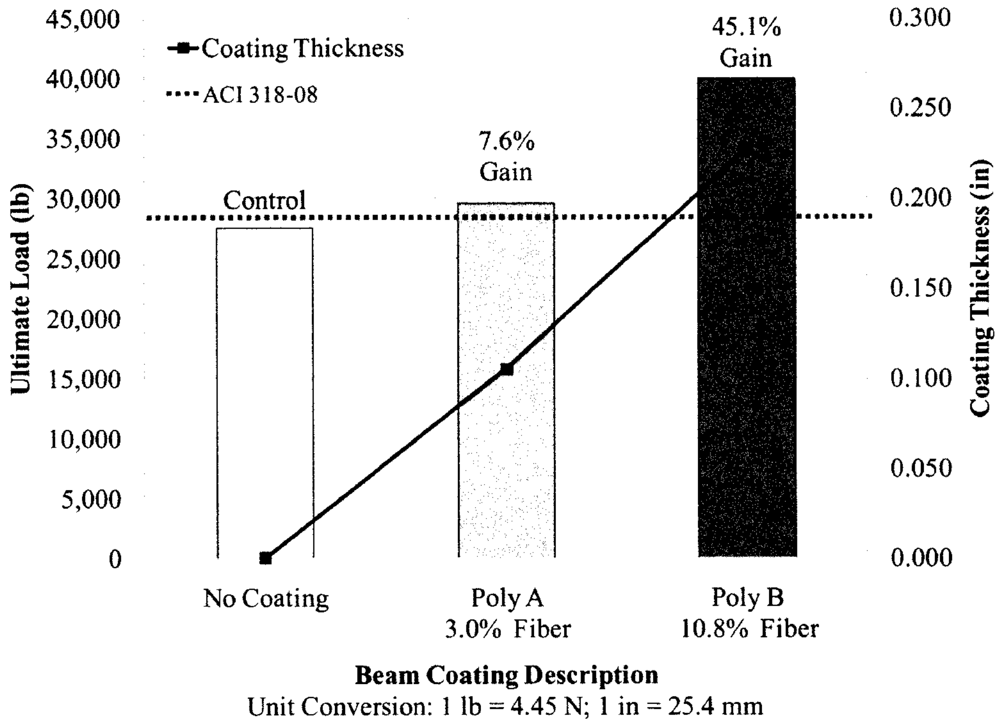
The ultimate capacities listed for the flexural test specimens all portrayed similar modes of failure. While flexural cracking could not be monitored on the polyurea-coated test specimens, the non-coated control case developed flexural crack patterns propagating from the tensile face of the beam. Strain gauges mounted internally on the rebar verified yielding of the longitudinal tensile steel reinforcement. Ultimately, failure was observed in each beam as crushing in the compression section (top) of the beam at mid-span.

Table 4.2. Ultimate Load Results for All Tested Beams

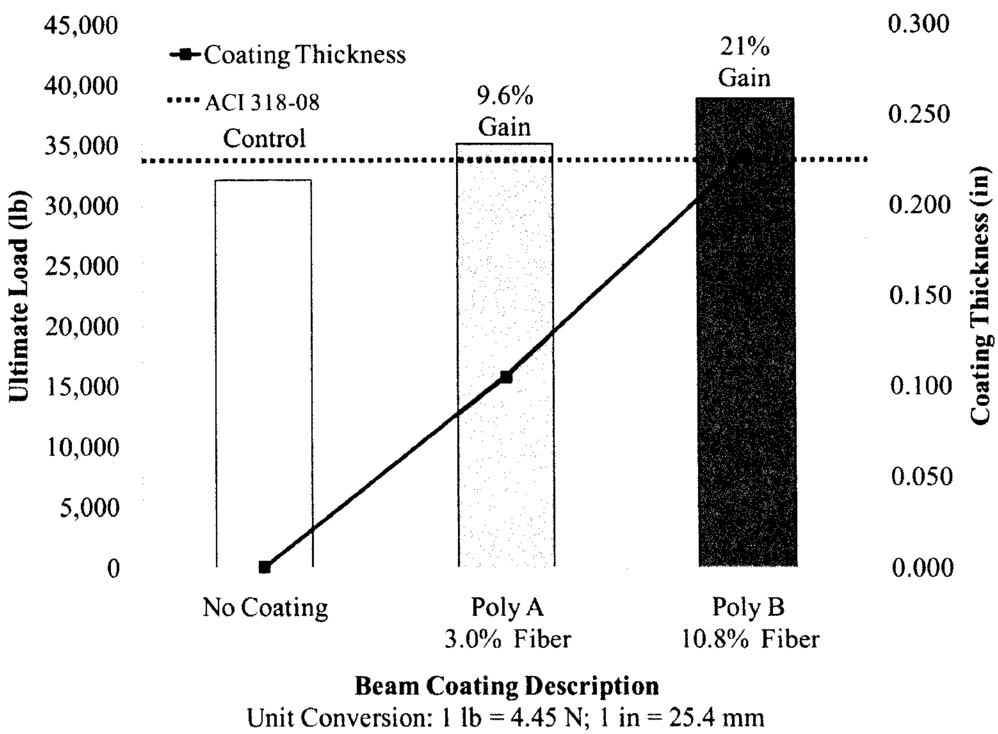
Test Order	Beam	Beam Notation	V_f (%)	Coating Thickness (in)	Ultimate Load (lb)	Additional Capacity (%)
			Flexural Specimens			
1	5	F-C	N/A	0.000	25020	N/A
2	1	F-P-A-0	0.0%	0.225	30970	23.8%
3	2	F-P-A-L	3.0%	0.127	27460	9.7%
4	3	F-P-B-H	10.8%	0.139	28890	15.4%
5	4	F-P-B-L	7.2%	0.115	25330	1.3%
			Shear Specimens			
6	6A	SN-C	N/A	0.000	27490	N/A
7	6B	SR-C	N/A	0.000	32050	N/A
8	7A	SN-P-A-L	3.0%	0.105	29590	7.6%
9	7B	SR-P-A-L	3.0%	0.105	35120	9.6%
10	8A	SN-P-B-H	10.8%	0.227	39900	45.1%
11	8B	SN-P-B-H	10.8%	0.227	38780	21.0%

Unit Conversions: 1 lb = 4.45 N; 1 in = 25.4 mm
Test: F - Flexure; SN - Shear Non-Reinforced; SR - Shear Reinforced
Beam Type: C - Control; P - Polyurea-Coated
Polyurea: A - Polyurea A; B - Polyurea B
Fiber: 0 - None; L - Low; H - High

The beam ultimate capacity was also improved during the shear beam testing (see Figure 4.2). In this case, the greatest capacity increases of 21% and 45% were developed utilizing Polyurea B coating systems. This was in keeping with flexural test results that showed that Polyurea B with fiber provided more additional capacity than Polyurea A with fiber because of the greater tensile strength of the Polyurea B-fiber composite system. Polyurea A also showed measurable improvement in ultimate capacity despite the markedly smaller coating thickness, resulting in 8% to 10% ultimate capacity gain.



(a) Non-Shear-Reinforced Test Section



(b) Shear-Reinforced Test Section

Figure 4.2. Shear Beam Ultimate Load Comparison

Due to unexpectedly high concrete strength described in Section 4.4, some shear test beams sections portrayed a flexural failure mode rather than the intended shear mode of failure. Test beam sections 6A (SN-C) and 7A (SN-P-A-L) both failed in a typical shear failure pattern as shown in Figure 4.3. Further analysis of the shear test beam results is included in Section 4.4.

Figure 4.3. Shear Failure Pattern

4.3. DEFLECTION AND DUCTILITY

Another important factor that was monitored during beam testing was the deflection of the beam (see Table 4.3). The ultimate deflection at mid-span of the beam for each flexural beam is shown in Figure 4.4 as compared to the coating systems' properties and thickness plotted on the secondary axis. As expected, coating systems which provided the greatest increase in ultimate strength also allowed for greater ductility of the beam and produced greater deflections. Load-deflection plots for all beams are included in Appendix C. These observations were also generally consistent with the deflection results for the shear test beams (shown in Figure 4.5 and Table 4.4). In this case, some of the deflections seemed unexpectedly varied; however, this is likely due to the fact that different tested sections of the beam (as shown in Figure 3.11) developed different, unexpected modes of failure due to unexpectedly high strength (Section 4.3).

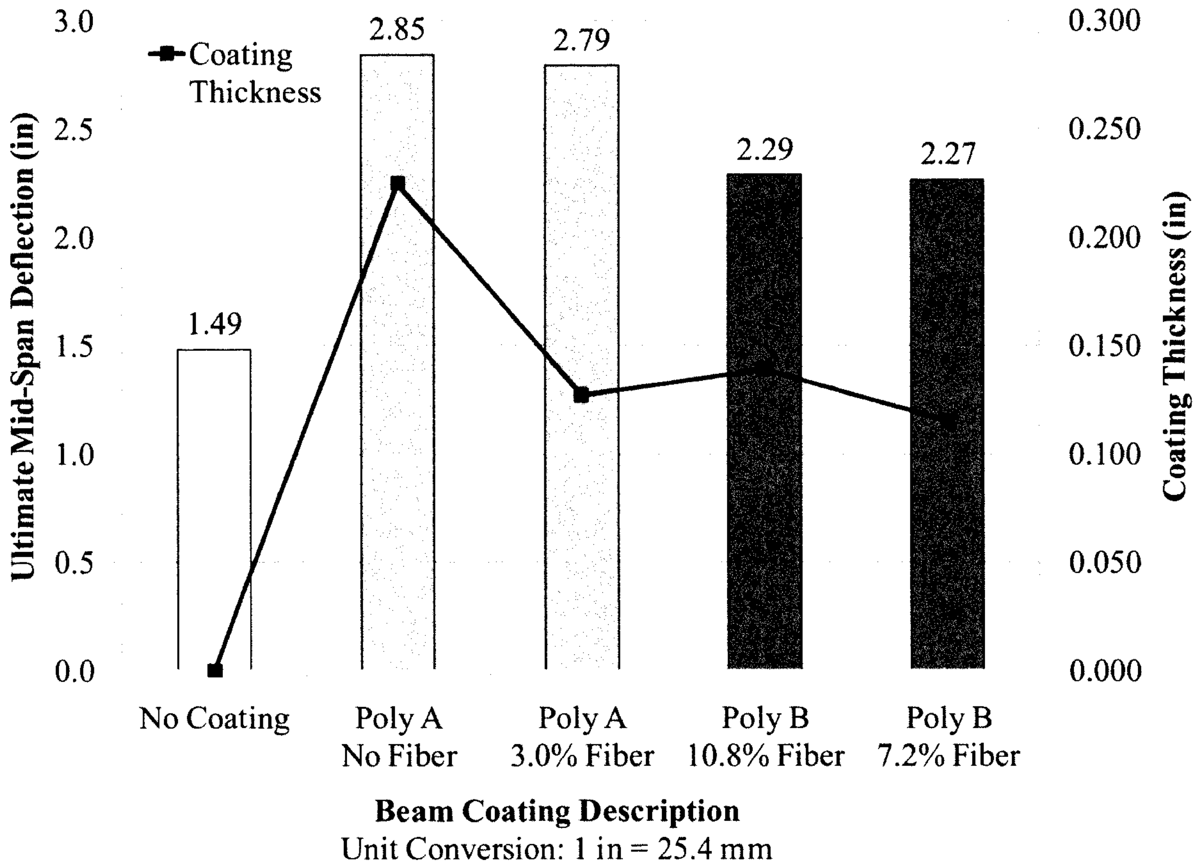


Figure 4.4. Flexural Beam Deflection Comparison

Table 4.3. Ultimate Deflection Results for Flexural Test Beams

Beam	Beam Description	V_f (%)	Coating Thickness (in)	Ultimate Load (lb)	Ultimate Mid-Span Deflection (in)
		Flexural Specimens			
5	F-C	N/A	0.000	25020	1.49
1	F-P-A-0	0.0%	0.225	30974	2.85
2	F-P-A-L	3.0%	0.127	27458	2.79
3	F-P-B-H	10.8%	0.139	28885	2.29
4	F-P-B-L	7.2%	0.115	25332	2.27

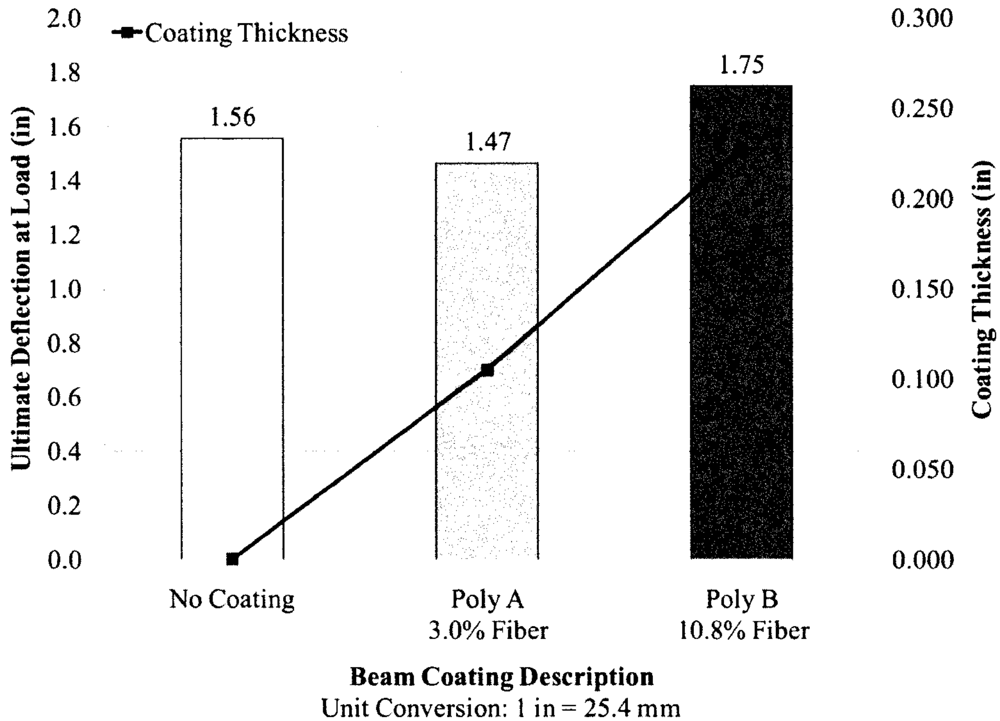
Unit Conversions: 1 lb = 4.45 N; 1 in = 25.4 mm

Test: F - Flexure; SN - Shear Non-Reinforced; SR - Shear Reinforced

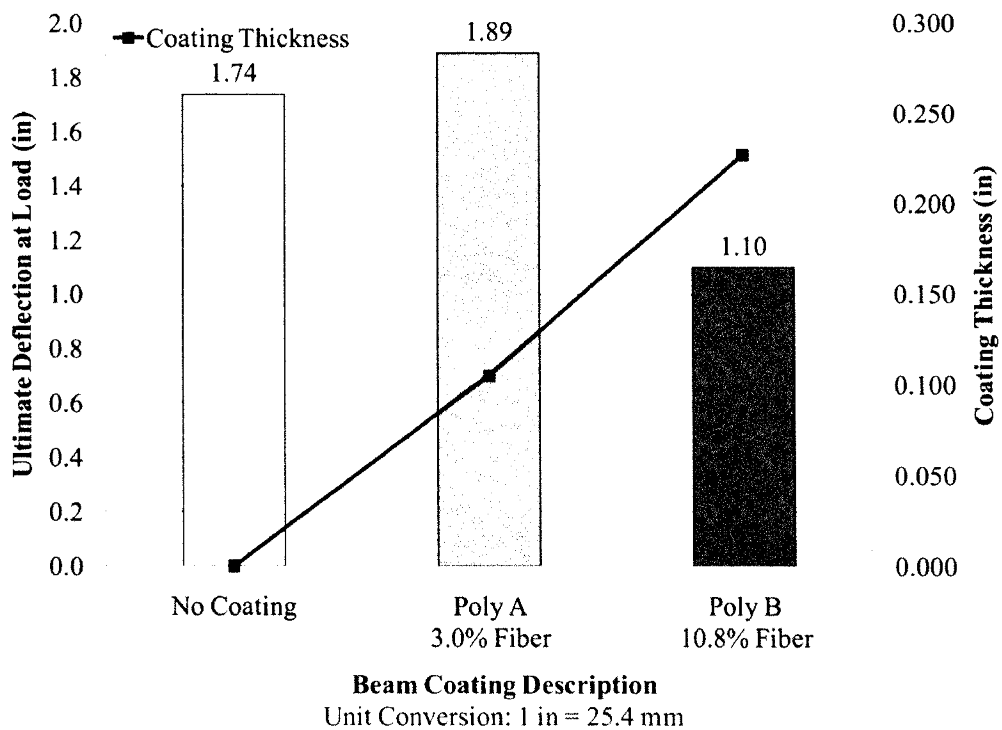
Beam Type: C - Control; P - Polyurea-Coated

Polyurea: A - Polyurea A; B - Polyurea B

Fiber: 0 - None; L - Low; H - High



(a) Non-Shear-Reinforced Test Sections



(b) Shear-Reinforced Test Sections

Figure 4.5. Shear Beam Deflection Comparison

Table 4.4. Ultimate Deflection Results for Shear Test Beams

Beam	Beam Description	V_f (%)	Coating Thickness (in)	Ultimate Load (lb)	Peak Deflection at Load (in)
		Shear Specimens			
6A	SN-C	N/A	0.000	27486	1.56
6B	SR-C	N/A	0.000	32052	1.74
7A	SN-P-A-L	3.0%	0.105	29588	1.47
7B	SR-P-A-L	3.0%	0.105	35116	1.89
8A	SN-P-B-H	10.8%	0.227	39896	1.75
8B	SN-P-B-H	10.8%	0.227	38784	1.10

Unit Conversions: 1 lb = 4.45 N; 1 in = 25.4 mm

Test: F - Flexure; SN - Shear Non-Reinforced; SR - Shear Reinforced

Beam Type: C - Control; P - Polyurea-Coated

Polyurea: A - Polyurea A; B - Polyurea B

Fiber: 0 - None; L - Low; H - High

Because the overall deflection of the coated beams was consistently greater than that of the uncoated control beam, a secondary analysis was developed to evaluate the flexural beams' relative ductility. The area under each load deflection-curve, A_i, was estimated and then divided by the area under the load-deflection curve of the control beam, A_c in order to obtain a ductility index (DI) as shown in equation 4.

$$DI = \frac{A_i}{A_c} \tag{4}$$

In the case of the flexure beams, A_5 representing the control case was estimated to be approximately 27,750 lb-in (3,137 N-m). The coated beams presented substantially greater ductility than the control beam (Table 4.5). Beam 1 (F-P-A-O) developed ductility greater than 2.5 times that of the control beam. Perhaps even more notable was the fact that Beam 4 (F-P-B-L), which had a negligible increase in ultimate capacity, still presented a ductility index of 1.3, suggesting a 30% increase in ductility developed by the Polyurea B coating with a low fiber volume fraction.

Table 4.5. Ductility Index Summary

Beam	Notation	Area (lb-in)	D.I.
1	F-P-A-0	72350	2.6
2	F-P-A-L	59490	2.1
3	F-P-B-H	43975	1.6
4	F-P-B-L	36300	1.3

Unit Conversion: 1 lb = 4.45 N; 1 in = 25.4 mm

4.4. SHEAR PERFORMANCE

Shear analysis was conducted for beams 6, 7, and 8 (S-C, S-P-A-L, and S-P-B-H) in order to determine the additional shear capacity, if any, provided by the polyurea coating systems. Unfortunately, due to unexpectedly high strengths of concrete and steel reinforcement, in addition to the rebar stirrups in the shear-reinforced portion of the beam, the shear-reinforced test section of the beams (6B, 7B, and 8B) presented much lower total capacity for flexural behavior and excessively high shear capacity. As expected, these test sections failed in flexure, but as discussed in Section 4.3, they did exhibit approximately 10% to 20% gain in total capacity.

As designed, and considering the high strength of the concrete and steel, the non-shear-reinforced sections of beam were all expected to exhibit shear failure, with a total capacity based on shear performance lower than that based on flexural performance. Sections 6A (SN-C) and 7A (SN-P-A-L) did exhibit shear failure and results are depicted in Figure 4.6.

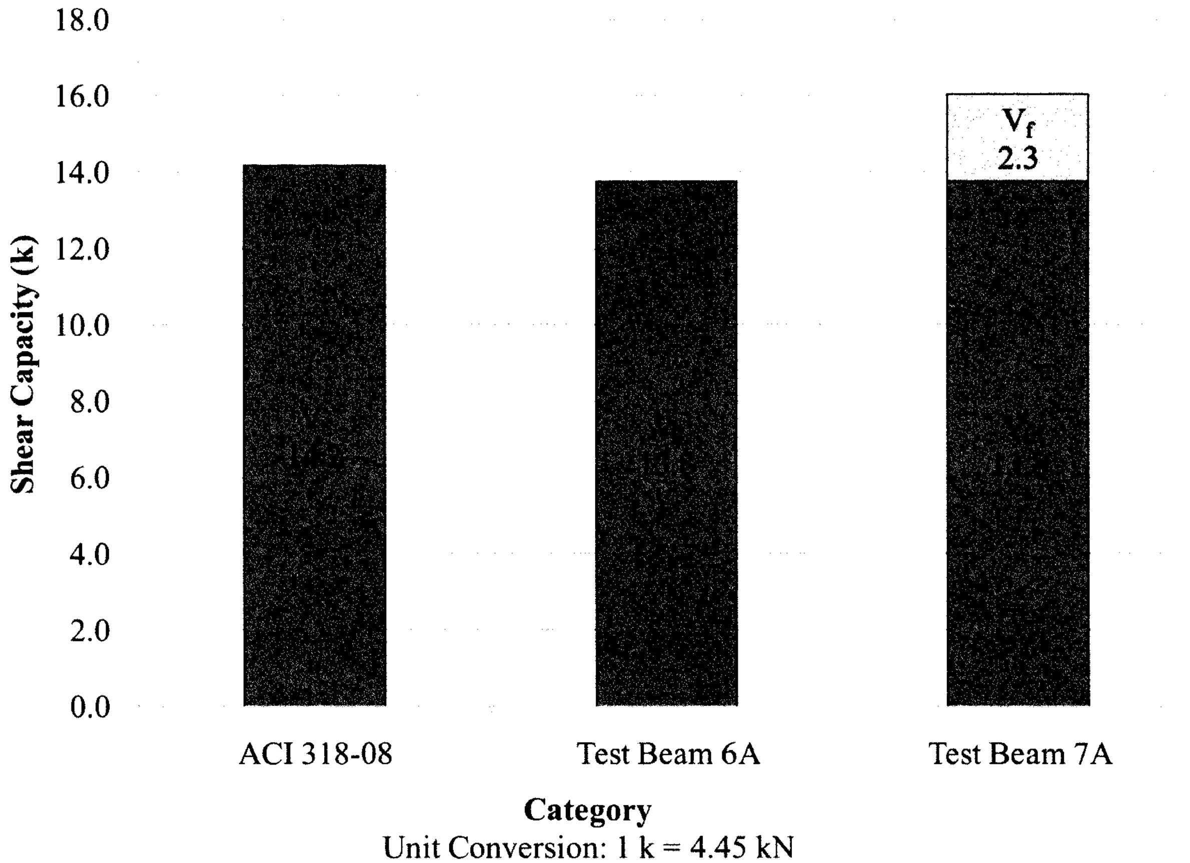


Figure 4.6. Shear Capacity Comparison

According to calculations completed following ACI 318-08 (2008) for shear capacity, the expected concrete component of shear capacity, V_c, was approximately 14 k (62.3 kN), and this value was compatible with results measured in the control beam 6A. Beam 7A (SN-P-A-L), however, was measured to have a capacity 2.3 k (10.2 kN) greater than the capacity expected by the concrete alone, suggesting that the Polyurea A coating system with a low fiber ratio provided a substantial shear capacity increase. These calculations and those following were completed using equations 5-8.

$$V_c = 2bd\sqrt{f'_c} \tag{5}$$

$$V_s = \frac{A_v f_{yt} d}{s} \tag{6}$$

$$V_f = V_{tot} - V_c - V_s \quad (7)$$

$$P_n = 2(V_c + V_s + V_f) \quad (8)$$

In this case, V_c, V_S, V_f, and V_{tot} represent the shear capacity contribution provided by, respectively, the concrete, the steel reinforcement, the fiber-reinforced polyurea reinforcement, and all capacities in total. Beam dimensions are as defined in Chapter 5. Other parameters include the area of shear reinforcement, A_v, the yield strength of the shear reinforcement, f_{yt}, and the shear reinforcement spacing, s. Finally, the total ultimate capacity of the beam is calculated is P_n.

Results for beam 8A (SN-P-B-H) were less predictable than those for 6A and 7A. According to a theoretical model (development and validation described in Chapter 5) which was developed to estimate the expected capacities of all beams, and with the consideration of the flexural failure of test 8B, the beam's flexural capacity would sustain a total load of approximately 40 k (178 kN). The shear capacity of the beam was provided by the concrete, contributing approximately 13.8 k (61.2 kN) coordinating to a total ultimate load of 27.5 k (125 kN), and the unknown contribution of the reinforced polyurea coating, V_f, suggesting that a shear failure would be expected. However, the beam failed in a flexural mode at a total load of 39.9 k (177.6 kN). The fact that the beam reached its flexural limit before presenting a shear failure suggests that the additional shear component provided by the fiber-reinforced polyurea B coating was in excess of 6.2 k (27.6 kN) corresponding to a total beam load of 12.4 k (96.1 kN).

4.5. COATING ADHESION

As observed during previous testing with fiber-reinforced polyurea coated cylinders (Greene and Myers 2010), the failure patterns of all tested beams suggested a good adhesion between the FRP coating system and the concrete face. Inspection of failed beams (see Figures 4.7-4.11) showed several examples of fractured concrete fragments adhered to the coating system even after the highest loads were applied. Based on this observation, and to further investigate the coating system compliance with ACI 440.2 (2008) standards, adhesion testing was completed on sections of tested beams to determine the actual adhesion strength.

Figure 4.7. Top View of Failed Test Beam SR-P-A-L

Figure 4.8. Side View of Failed Test Beam F-P-B-L

Figure 4.9. Top View of Failed Test Beam F-P-A-L

Figure 4.10. Side View of Failed Test Beam F-P-A-L

Figure 4.11. Top View of Failed Test Beam F-P-A-0

Pull-off testing was completed on two failed flexural testing beams – that with Polyurea A and no fiber (F-P-A-0) and that with Polyurea A and a lower fiber volume fraction (F-P-A-L). Two samples sections per each beam were prepared near the end support regions of the beams and a pull-off test was completed for each of these 4 sample regions according to the procedures described in Section 3.4.4. Results from these tests are summarized in Table 4.6. ACI 440.2 (2008) requires that the average tensile strength of fiber-reinforced polyurea coatings applied to concrete substrates be at minimum, 200 psi (1.4 MPa), as determined by a pull-off test. As shown, the samples tested did not meet this requirement. However, the tensile strength requirement is applicable only to test results completed prior to concrete specimen testing or failure; the pull-off tests presented here were determined after concrete failure, due to the unavailability of pull-off testing equipment at the time of beam specimen testing. Thus, the pull-off test results shown cannot be directly compared to the ACI tensile strength requirement.

Table 4.6. Pull-Off Test Results Summary

Sample	Beam Notation	Load (lb)	Area (in^2)	Bond Strength (psi)	Avg. Bond Strength (psi)
1	F-P-A-0	571.0	3.04	187.6	155.1
2		373.2	3.04	122.6	
3	F-P-A-L	361.9	3.04	118.9	106.4
4		285.5	3.04	93.8	

Unit Conversions: 1 lb = 4.45 N; 1 in^2 = 645 mm^2; 1 psi = 6890 Pa

Pull-off specimens were also observed for qualitative analysis of the tensile properties of the polyurea coating systems. Representative examples are included in Figure 4.12. As shown, significant amounts of concrete are adhered to the fiber-reinforced polyurea coating surface. This suggests that pull-off tensile failure was controlled by the concrete tensile strength. ASTM D 7522 (2009) suggests that an "initially degraded substrate" can result in favorable failure modes but low tensile strength results. The testing and failure of the concrete specimens prior to pull-off testing is believed to have damaged the concrete integrity in the pull-off testing areas; however, the qualitative results suggest that if tested prior to concrete failure, pull-off testing of the polyurea coating systems would prove an adequate bond tensile strength.

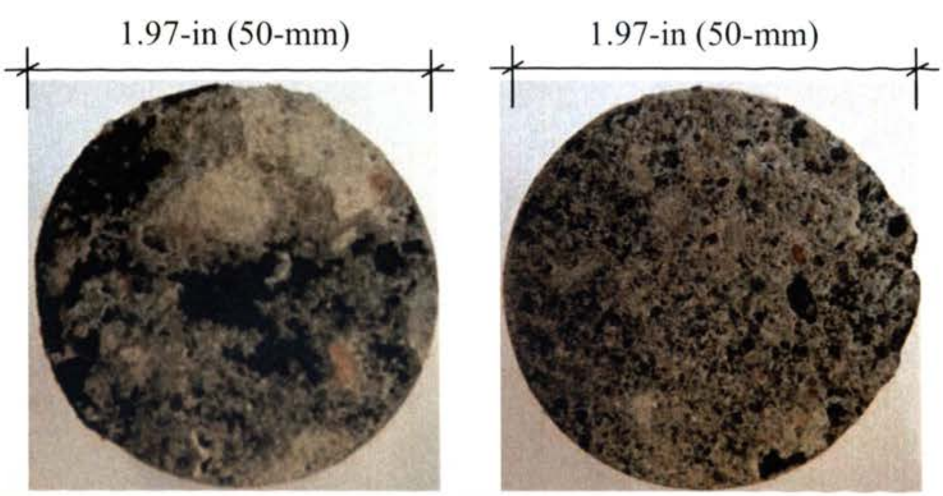


Figure 4.12. Example Pull-Off Test Samples

4.6. FRAGMENTATION CONTAINMENT

In addition to superior adhesion or bond, the coating systems' high elongation and tensile capabilities provided for encapsulation or containment of fracturing and crack patterns. Figure 4.13 shows the control beam from the flexural testing beam group after failure with crack patterns marked for better visibility. Flexural cracks through the section of the beam developed significant debris during testing, and as the ultimate load was reached and pressure was continued to be applied on the beam, cracking at the top of the section developed even greater debris. Figure 4.14 also shows a flexural beam after failure, with the load still applied to show ultimate deflection. The coated beams in the flexural testing group developed no cracks in the polyurea coating system and contained all debris from cracking and concrete rupture. Only during the final shear failures in the shear test sections was any tearing in the polyurea coating apparent.

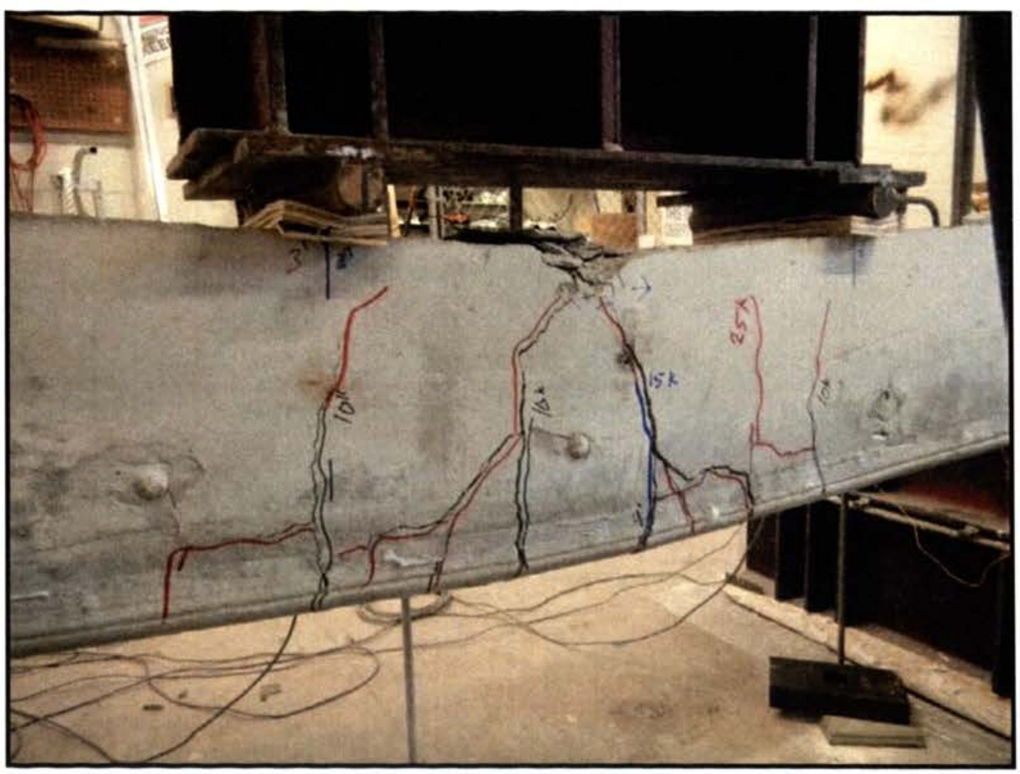


Figure 4.13. Fracture Patterns of Flexural Control Beam

Figure 4.14. Coated Flexure Beam at Maximum Deflection

5. PARAMETRIC STUDY

5.1. FLEXURAL CAPACITY MODELING AND VALIDATION

The design for the described test beams for this phase of study was based on guidelines from ACI 318-08, Building Code and Commentary (2008). Design calculations are included in Appendix D with results summarized in Table 5.1.

Table 5.1. Flexural Beam Calculated Capacity

Beam	Beam Description	Predicted Total Capacity (k)	Actual Total Capacity (k)	Variation from Predicted (%)
5	F-C	24.5	25.0	2.0%
1	F-P-A-0	30.5	31.0	1.6%
2	F-P-A-L	26.1	27.5	5.4%
3	F-P-B-H	27.8	28.9	4.0%
4	F-P-B-L	26.5	25.3	-4.5%

Unit Conversion: 1 k = 4.45 kN
Test: F - Flexure; SN - Shear Non-Reinforced; SR - Shear Reinforced
Beam Type: C - Control; P - Polyurea-Coated
Polyurea: A - Polyurea A; B - Polyurea B
Fiber: 0 - None; L - Low; H - High

Beam 5, representing the control beam case with no coating applied, was designed as a typical simply-supported beam with two load points and two supports. Calculation equations for beam 5 are included in Chapter 4. Material properties shown represent realistic material properties measured in accordance with ASTM standards as described in Chapter 3. In order to estimate the additional capacity provided by the FRP coating, the cross-section of polyurea was assumed to carry a tensile force in addition to the tensile force carried by the steel (see Figure 5.1). This tensile force was assumed to act at a distance y_f from the tensile face and with this additional force represented in the cross-section, the moment capacity of the beam was calculated as a typical concrete beam (Equations 9-12).

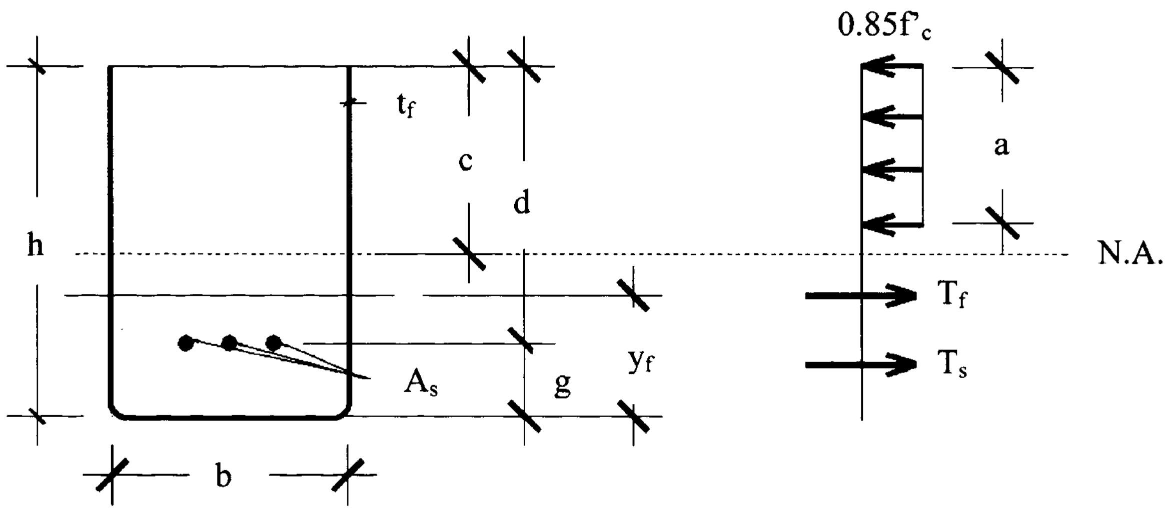


Figure 5.1. Beam Design Schematic

$$A_f = (b - 2t_f)(t_f) + 2t_f(h - c) \tag{9}$$

$$y_f = \frac{(b - 2t_f)\left(\frac{t_f^{\,2}}{2}\right) + 2t_f\left(\frac{(h-c)^2}{2}\right)}{A_f} \tag{10}$$

$$0.85f'_c ba = A_f f_f + A_s f_y \tag{11}$$

$$M_n = 0.85f'_c ba\left(d - \frac{a}{2}\right) - A_f f_f (y_f - g) \tag{12}$$

In the equations shown, beam dimensions b and h represent the width and depth, respectively of the beam. Additionally, beam dimensions d and g represent the distance from the compression fiber to the longitudinal reinforcement and the distance from the longitudinal reinforcement to the extreme tension fiber. The fiber is applied in thickness t_f. A_f represents the area of the polyurea coating below the neutral axis, and the steel reinforcement cross-section is represented by A_s. The tensile yield of the fiber-reinforced polyurea and the steel reinforcement, respectively, are f_f and f_y. The neutral axis of the concrete cross section is shown as N.A. with the compression section of the beam having a height c and a representative compression block of height a as defined by ACI 318-08 (2008). The strength of the concrete is denoted as f'_c and the tensile forces in the FRP coating and the longitudinal steel reinforcement are, respectively, T_f and T_s.

For these calculations, several assumptions were made in order to complete a theoretical analysis. Assumptions include:

1. The strength reduction factor, φ, included in Section 9.3 of ACI 318-08 (2008) is not considered and no safety factors were applied to loads because the calculation is meant to describe actual results rather than modified assumptions for safety.
2. The properties of the FRP coating were as determined per methods discussed in Chapter 3 with results presented in Section 4.1. The strength of Polyurea A without fiber was assumed to be as reported by the manufacturer. All member dimensions and characteristics were as described in Chapter 3.
3. Premature bond failure or relative slip at the concrete-polyurea interface was ignored and the coating system was assumed to be perfectly bonded with the concrete substrate.
4. The concrete contribution to tensile capacity and the polyurea contribution to compressive capacity are both considered to be zero.
5. The tensile force carried by the polyurea coating system was assumed to act through the centroid of the cross-section of the coating system.
6. For calculation purposes, the cross-section of the beam was assumed to be perfectly rectangular.

As shown in Table 5.1, the predicted capacities based on the described design method and the actual capacities measured during beam testing were consistently within an approximately 5% accuracy. However, with one exception, the model over-predicted the capacities of the beams, suggesting that use of the model may need to be modified by a safety factor in order to determine a conservative estimate. The results nonetheless suggest that the assumptions made during this design process closely predict the expected strength addition provided by the fiber-reinforced polyurea. Detailed calculation worksheets are included for reference in Appendix D.

5.2. NORMALIZATION AND STUDY OF ALTERNATIVES

Using the model previously developed and described in Section 5.1, several cases of variable concrete strengths were considered for a beam design similar to that used for this phase of testing. Calculations for this parametric study are included in Appendix D with a summary of results included in Table 5.2 for a 1/8-in (3-mm) coating thickness and Table 5.3 for a 1/16-in (2-mm) coating thickness. For each case, the beam cross-section was held constant with the dimensions used during testing, and typical mechanical properties for steel with a yield limit of 60 ksi were assumed. For each concrete strength level considered, the beam total capacity was calculated for a plain (non-coated) concrete beam as well as two alternatives for concrete beams coated with a 1/8-in (3-mm) FRP coating – Polyurea B with 10% volume fraction of fiber, and Polyurea A without fiber. These alternatives were also considered when determining the additional capacity provided by a 1/16 in (2-mm) coating thickness. Estimations show that Polyurea B with 10% volume fraction of E-glass fiber could increase ultimate capacity of a beam loaded in 4-point flexure by at least 7% up to 15% and higher for the one beam design considered. Polyurea A showed expected capacities of up to 18% greater than the control case. Polyurea B was considered here as a representative example of a coating system that would be easiest to apply and would most likely allow for consistent and effective dispersion of chopped fibers throughout the matrix material and also provided superior strength addition when glass fibers were included in the coating system. Polyurea A was considered because it provided the greatest tensile strength without fiber and resulting strength increase to the beam.

Table 5.2. Summary of Alternatives, 1/8-in Coating Thickness

Parametric Beam Set	**f'c (psi)**	**Control Capacity (k)**	**Poly B, 10% Fiber 1/8-in Thickness**		**Poly A 1/8-in Thickness**	
			Coated Capacity (k)	**Strength Gain (%)**	**Coated Capacity (k)**	**Strength Gain (%)**
1, 2, 23	4,000	20.1	22.8	13.4%	23.2	15.4%
3, 4, 24	5,000	20.4	23.2	13.7%	23.7	16.2%
5, 6, 25	6,000	20.6	23.5	14.1%	23.9	16.0%
7, 8, 26	7,000	20.7	23.7	14.5%	24.1	16.4%
9, 10, 27	8,000	20.8	23.8	14.4%	24.3	16.8%
11, 12, 28	9,000	20.9	23.9	14.4%	24.4	16.7%
13, 14, 29	10,000	21.0	24.0	14.3%	24.5	16.7%
15, 16, 30	11,000	21.0	24.1	14.8%	24.6	17.1%
17, 18, 31	12,000	21.1	24.2	14.7%	24.7	17.1%
19, 20, 32	13,000	21.1	24.2	14.7%	24.7	17.1%
21, 22, 33	14,000	21.1	24.3	15.2%	24.8	17.5%

Unit Conversions: 1 psi = 6890 Pa; 1 k = 4.45 kN

Table 5.3. Summary of Alternatives, 1/16-in Coating Thickness

Parametric Beam Set	**f'c (psi)**	**Control Capacity (k)**	**Poly B, 10% Fiber 1/16-in Thickness**		**Poly A 1/16-in Thickness**	
			Coated Capacity (k)	**Strength Gain (%)**	**Coated Capacity (k)**	**Strength Gain (%)**
1, 34, 45	4,000	20.1	21.5	7.0%	21.7	8.0%
3, 35, 46	5,000	20.4	21.8	6.9%	22.0	7.8%
5, 36, 47	6,000	20.6	22.1	7.3%	22.3	8.3%
7, 37, 48	7,000	20.7	22.2	7.2%	22.5	8.7%
9, 38, 49	8,000	20.8	22.3	7.2%	22.6	8.7%
11, 39, 50	9,000	20.9	22.4	7.2%	22.7	8.6%
13, 40, 51	10,000	21.0	22.5	7.1%	22.8	8.6%
15, 41, 52	11,000	21.0	22.6	7.6%	22.8	8.6%
17, 42, 53	12,000	21.1	22.6	7.1%	22.9	8.5%
19, 43, 54	13,000	21.1	22.7	7.6%	22.9	8.5%
21, 44, 55	14,000	21.1	22.7	7.6%	23.0	9.0%

Unit Conversions: 1 psi = 6890 Pa; 1 k = 4.45 kN

6. CONCLUSIONS

6.1. GENERAL

Based on the analysis of beam testing, as well as the observation of application procedures, several conclusions can be drawn pertaining to the fiber-reinforced polyurea coating systems described.

1. In general, Polyurea B provided greater ease of application due to the longer set time associated with it. As a result, Polyurea B allowed for greater dispersion of chopped fibers and more random orientations, and developed greater tensile strength with the addition of more fiber.
2. Unfortunately, due to the rapid set time of Polyurea A, the additional chopped fibers did not disperse properly and as a result actually weakened the system rather than strengthening it.
3. The addition of more chopped fibers to Polyurea B in the cases considered here developed higher strength than did less fiber addition. It is also likely that the addition of fibers with higher strength, such as aramid or carbon fibers, would also result in greater composite system strength. Also, the addition of a higher volume fraction of fiber may increase the tensile strength of Polyurea B and increase the total capacity of the test beams.
4. The polyurea coating systems were markedly affective in the containment of fragmentation and debris scatter.
5. Qualitative results suggest an adequate bond between the concrete substrates and polyurea coating systems using the described fabrication process.

6.2. STRUCTURAL PERFORMANCE, DUCTILITY

The coating systems investigated during this phase of study showed notable improvements in flexural capacity, shear strength, ductility, and beam deflection. As such, several specific conclusions are drawn:

1. The polyurea coating systems provided additional flexural reinforcement that resulted in ultimate capacities as much as 24% greater than the control case (non-coated beam).
2. The deflection of polyurea-coated beams as opposed to non-coated beams was up to 94% greater.
3. The ductility of the coated beams was substantially greater than that of the non-coated beams. Polyurea B with 7% fiber volume fraction developed an increase in ductility of 30% and overall ductility was increased by as high as 160% with various polyurea coating systems.
4. The shear capacity of the coating system was measured to be 2.3 k (10.2 kN) in the case of Polyurea A with low fiber volume fraction, and greater than 6.2 k (27.6 kN) in the case of Polyurea B with high fiber and larger coating thickness.

6.3. THEORETICAL MODELING

The measured results of beam testing validate the theoretical model that was developed to estimate the flexural capacity of beams coated with discrete chopped glass fiber-reinforced polyurea coating systems. The validation of this model supports its functionality in conjunction with additional fiber-polyurea characterization data in order to economically investigate further strengthening solutions and consider other fiber-reinforced polyurea alternatives in addition to other beam design alternatives. Because the test results support the intuitive understanding that stronger, thicker coating systems would develop greater additional flexural capacity, and also because the test results show substantial ductility increases because of the ductility of the coating systems, a wide variety of coating systems could be modeled using this design method to determine the best alternatives.

7. FUTURE RECOMMENDATIONS

7.1. FABRICATION AND TESTING PROCEDURES

Based on the certain difficulties that were encountered during this phase of testing, several recommendations can be made to improve future research in this topic:

1. Because of the longer set time, Polyurea B would be preferred for practicality and ease of construction, as well as for its strength gain with the addition of discrete chopped fibers.
2. Because the strength of Polyurea B increased with the addition of more fiber, means to develop higher fiber volume fractions in conjunction with Polyurea B should be investigated. This may require the development of re-designed chopper/spray equipment or investigation of alternative equipment available in the market.
3. Polyurea A without fiber developed the greatest strength addition overall to the flexural test beams. Development of a better means to disperse fibers into the fresh coating system could yield Polyurea A as the preferable choice to Polyurea B, however further research into application systems would need to be investigated as noted previously.
4. The favorable structural results suggest that the coating system could be beneficial to exterior repair and retrofit of existing structures. In order to accomplish this result, more research is required in the subject of application methods and fabrication procedures to provide consistently superior coating and fiber dispersion.
5. E-glass fibers are known to be somewhat environmentally sensitive. Therefore, the ability of the polyurea systems to protect the fibers under aggressive environments should be investigated.
6. Pull-off testing of non-degraded coated concrete samples is required validate the suggestion that the system developed an adequate bond strength as fabricated.

7.2. AREAS FOR FUTURE INVESTIGATION

The positive results of this study support the need for additional research pertaining to fiber-reinforced polyurea coating systems. Several specific recommendations apply:

1. The chopped glass fibers used for this phase of study provided measurable strength increases and were compatible with the chop-spray application used. Stronger fibers such as aramid and carbon, as well as the methods required to chop and/or distribute those fibers, should be considered. It may be necessary to develop a means to distribute pre-chopped fibers due to the high strength of the alternative fibers.
2. Because of the validation of the experimental model described in Chapter 5, statistical analysis of several theoretical alternatives should be considered as an economical approach to further investigation of alternative beam designs and coating systems. This analysis should include alternate beams sections and loading schemes, varied reinforcement layouts and concrete properties, and iterations of coating alternatives considering coating thickness, matrix material, type of chopped fiber, and fiber volume fraction.
3. As previously mentioned, the ultimate capacity of longer spans and deeper beam sections should be investigated. In addition, different steel reinforcement ratios and concrete strengths should be considered.
4. The properties (thickness, strength, fiber volume fraction, etc.) of the composite coating system should be varied to determine the best alternatives. Further modeling of the ductility of the beam and composite coating may yield a means to consider the balance of strength gain with ductility gain.

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APPENDIX A

CYLINDER TESTING MATRIX AND RESULTS

Table A1. Lower-Strength Concrete Samples

Group	Sample	Sample Designation	Concrete Design Strength (ksi)	Polyurea	Fiber Category	Replicate
Lower-Strength Concrete, No Coating	65	7-None-None-1	7	None	None	1
	66	7-None-None-2	7	None	None	2
	67	7-None-None-3	7	None	None	3
	68	7-None-None-4	7	None	None	4
Lower-Strength Concrete, Polyurea A No Fiber	73	7-A-None-1	7	A	None	1
	74	7-A-None-2	7	A	None	2
	75	7-A-None-3	7	A	None	3
	76	7-A-None-4	7	A	None	4
Lower-Strength Concrete, Polyurea A Low Fiber	69	7-A-Low-1	7	A	Lower	1
	70	7-A-Low-2	7	A	Lower	2
	71	7-A-Low-3	7	A	Lower	3
	72	7-A-Low-4	7	A	Lower	4
Lower-Strength Concrete, Polyurea B No Fiber	81	7-B-None-1	7	B	None	1
	82	7-B-None-2	7	B	None	2
	83	7-B-None-3	7	B	None	3
	84	7-B-None-4	7	B	None	4
Lower-Strength Concrete, Polyurea B Low Fiber	85	7-B-Low-2	7	B	Lower	2
	86	7-B-Low-1	7	B	Lower	1
	87	7-B-Low-3	7	B	Lower	3
	88	7-B-Low-4	7	B	Lower	4
Lower-Strength Concrete, Polyurea B High Fiber	89	7-B-High-3	7	B	Higher	3
	90	7-B-High-1	7	B	Higher	1
	93	7-B-High-2	7	B	Higher	2
	94	7-B-High-4	7	B	Higher	4

Unit Conversion: 1 ksi = 6.9 MPa

Table A2. Mid-Strength Concrete Samples

Group	Sample	Sample Designation	Concrete Design Strength (ksi)	Polyurea	Fiber Category	Replicate
Mid-Strength Concrete, No Coating	33	10-None-None-1	10	None	None	1
	34	10-None-None-2	10	None	None	2
	35	10-None-None-3	10	None	None	3
	36	10-None-None-4	10	None	None	4
Mid-Strength Concrete, Polyurea A No Fiber	41	10-A-None-1	10	A	None	1
	42	10-A-None-2	10	A	None	2
	43	10-A-None-3	10	A	None	3
	44	10-A-None-4	10	A	None	4
Mid-Strength Concrete, Polyurea A Low Fiber	37	10-A-Low-2	10	A	Lower	2
	38	10-A-Low-3	10	A	Lower	3
	39	10-A-Low-1	10	A	Lower	1
	40	10-A-Low-4	10	A	Lower	4
Mid-Strength Concrete, Polyurea B No Fiber	49	10-B-None-1	10	B	None	1
	50	10-B-None-2	10	B	None	2
	51	10-B-None-3	10	B	None	3
	52	10-B-None-4	10	B	None	4
Mid-Strength Concrete, Polyurea B Low Fiber	53	10-B-Low-3	10	B	Lower	3
	54	10-B-Low-1	10	B	Lower	1
	55	10-B-Low-2	10	B	Lower	2
	56	10-B-Low-4	10	B	Lower	4
Mid-Strength Concrete, Polyurea B High Fiber	61	10-B-High-1	10	B	Higher	1
	57	10-B-High-3	10	B	Higher	3
	58	10-B-High-4	10	B	Higher	4
	59	10-B-High-2	10	B	Higher	2
	60	10-B-High-5	10	B	Higher	5

Unit Conversion: 1 ksi = 6.9 MPa

Table A3. Higher-Strength Concrete Samples

Group	Sample	Sample Designation	Concrete Design Strength (ksi)	Polyurea	Fiber Category	Replicate
Higher-Strength Concrete No Coating	1	13-None-None-1	13	None	None	1
	2	13-None-None-2	13	None	None	2
	3	13-None-None-3	13	None	None	3
	4	13-None-None-4	13	None	None	4
Higher-Strength Concrete Polyurea A No Fiber	9	13-A-None-1	13	A	None	1
	10	13-A-None-2	13	A	None	2
	11	13-A-None-3	13	A	None	3
	12	13-A-None-4	13	A	None	4
Higher-Strength Concrete Polyurea A Low Fiber	5	13-A-Low-1	13	A	Lower	1
	6	13-A-Low-2	13	A	Lower	2
	7	13-A-Low-3	13	A	Lower	3
	8	13-A-Low-4	13	A	Lower	4
Higher-Strength Concrete Polyurea B No Fiber	17	13-B-None-1	13	B	None	1
	18	13-B-None-2	13	B	None	2
	19	13-B-None-3	13	B	None	3
	20	13-B-None-4	13	B	None	4
Higher-Strength Concrete Polyurea B Low Fiber	13	13-B-Low-2	13	B	Lower	2
	21	13-B-Low-1	13	B	Lower	1
	22	13-B-Low-4	13	B	Lower	4
	23	13-B-Low-3	13	B	Lower	3
	24	13-B-Low-5	13	B	Lower	5
Higher-Strength Concrete Polyurea B High Fiber	25	13-B-High-1	13	B	Higher	1
	26	13-B-High-2	13	B	Higher	2
	27	13-B-High-4	13	B	Higher	4
	28	13-B-High-3	13	B	Higher	3

Unit Conversion: 1 ksi = 6.9 MPa

Table A4. Lower-Strength Concrete Cylinder Strength Data

Group	Sample	Ultimate Load (lb)	Cross-Section (in^2)	Average Coating Thickness (in.)	Sample Strength, f'c (psi)	Average Strength, f'c (psi)	Standard Deviation of Strength (psi)
Lower-Strength Concrete, No Coating	65	116415	12.62	NA	9222	10270	743
	66	138390	12.61	NA	10972		
	67	130125	12.58	NA	10347		
	68	132855	12.63	NA	10521		
Lower-Strength Concrete, Polyurea A No Fiber	73	132331	12.59	0.32	10509	10390	936
	74	116250	12.62	0.20	9214		
	75	144909	12.60	0.38	11500		
	76	130001	12.57	0.29	10344		
Lower-Strength Concrete, Polyurea A Low Fiber	69	129015	12.63	0.20	10211	10070	935
	70	121935	12.65	0.19	9641		
	71	115093	12.61	0.21	9129		
	72	142313	12.59	0.17	11308		
Lower-Strength Concrete, Polyurea B No Fiber	81	137310	12.59	0.34	10905	10230	1384
	82	131745	12.56	0.38	10486		
	83	103362	12.57	0.31	8222		
	84	141918	12.53	0.33	11324		
Lower-Strength Concrete, Polyurea B Low Fiber	85	125970	12.57	0.30	10019	8620	1489
	86	122880	12.53	0.40	9804		
	87	92840	12.60	0.44	7370		
	88	92001	12.60	0.42	7304		
Lower-Strength Concrete, Polyurea B High Fiber	89	139649	12.61	0.36	11077	10180	1283
	90	125730	12.57	0.66	10002		
	93	106335	12.61	0.36	8430		
	94	140934	12.59	0.45	11197		

Unit Conversions: 1 lb = 4.45 N; 1 in^2 = 645 mm^2; 1 in = 25.4 mm; 1 psi = 6890 Pa

Table A5. Mid-Strength Concrete Cylinder Strength Data

Group	Sample	Ultimate Load (lb)	Cross-Section (in^2)	Average Coating Thickness (in.)	Sample Strength, f'c (psi)	Average Strength, f'c (psi)	Standard Deviation of Strength (psi)
Mid-Strength Concrete, No Coating	33	157065	12.65	NA	12415	12100	609
	34	152865	12.64	NA	12090		
	35	142260	12.65	NA	11250		
	36	159450	12.62	NA	12640		
Mid-Strength Concrete, Polyurea A No Fiber	41	107385	12.55	0.39	8553	9000	709
	42	125640	12.61	0.37	9967		
	43	105757	12.60	0.33	8392		
	44	114337	12.61	0.24	9068		
Mid-Strength Concrete, Polyurea A Low Fiber	37	135150	12.61	0.16	10719	12030	1178
	38	168805	12.58	0.14	13415		
	39	144555	12.59	0.15	11483		
	40	157658	12.61	0.20	12504		
Mid-Strength Concrete, Polyurea B No Fiber	49	168675	12.53	0.27	13463	12720	793
	50	145995	12.54	0.33	11639		
	51	159143	12.56	0.30	12666		
	52	165481	12.61	0.35	13123		
Mid-Strength Concrete, Polyurea B Low Fiber	53	166875	12.60	0.50	13244	11750	1613
	54	121290	12.55	0.38	9665		
	55	141915	12.54	0.41	11317		
	56	160789	12.59	0.24	12771		
Mid-Strength Concrete, Polyurea B High Fiber	61	139785	12.59	0.41	11099	10980	1712
	57	112732	12.52	0.42	9001		
	58	171374	12.59	0.38	13610		
	59	139530	12.55	0.63	11117		
	60	126855	12.61	0.46	10057		

Unit Conversions: 1 lb = 4.45 N; 1 in^2 = 645 mm^2; 1 in = 25.4 mm; 1 psi = 6890 Pa

Table A6. Higher-Strength Concrete Cylinder Strength Data

Group	Sample	Ultimate Load (lb)	Cross-Section (in^2)	Average Coating Thickness (in.)	Sample Strength, f'c (psi)	Average Strength, f'c (psi)	Standard Deviation of Strength (psi)
Higher-Strength Concrete, No Coating	1	185190	12.63	NA	14658	13920	1136
	2	172620	12.63	NA	13667		
	3	188535	12.62	NA	14941		
	4	156675	12.60	NA	12430		
Higher-Strength Concrete, Polyurea A No Fiber	9	163065	12.63	0.29	12916	12670	2366
	10	198825	12.64	0.34	15735		
	11	126892	12.63	0.34	10049		
	12	151739	12.66	0.32	11986		
Higher-Strength Concrete, Polyurea A Low Fiber	5	186255	12.65	0.27	14727	14240	1695
	6	169125	12.60	0.20	13426		
	7	206334	12.61	0.12	16361		
	8	156877	12.61	0.22	12445		
Higher-Strength Concrete, Polyurea B No Fiber	17	188790	12.54	0.34	15050	14080	1872
	18	187140	12.61	0.31	14845		
	19	190421	12.57	0.31	15147		
	20	142119	12.60	0.31	11277		
Higher-Strength Concrete, Polyurea B Low Fiber	13	189765	12.59	0.33	15071	14660	976
	21	180120	12.59	0.27	14306		
	22	202091	12.58	0.28	16060		
	23	169023	12.58	0.31	13438		
	24	181455	12.59	0.45	14410		
Higher-Strength Concrete, Polyurea B High Fiber	25	186420	12.58	0.42	14816	15620	782
	26	195555	12.55	0.42	15584		
	27	193678	12.58	0.35	15400		
	28	209612	12.56	0.35	16687		

Unit Conversions: 1 lb = 4.45 N; 1 in^2 = 645 mm^2; 1 in = 25.4 mm; 1 psi = 6890 Pa

Table A7. Lower-Strength Concrete Cylinder Modulus of Elasticity Data

Group	Sample	Cross-Section (in^2)	Average Coating Thickness (in.)	Sample Modulus, E (ksi)	Average Modulus, E (ksi)	Standard Deviation of Modulus (ksi)
Lower-Strength Concrete, No Coating	65	12.62	NA	N/A	6917	58
	66	12.61	NA	6950		
	67	12.58	NA	6850		
	68	12.63	NA	6950		
Lower-Strength Concrete, Polyurea A No Fiber	73	12.59	0.32	N/A	7050	350
	74	12.62	0.20	6900		
	75	12.60	0.38	7450		
	76	12.57	0.29	6800		
Lower-Strength Concrete, Polyurea A Low Fiber	69	12.63	0.20	N/A	7300	312
	70	12.65	0.19	7200		
	71	12.61	0.21	7050		
	72	12.59	0.17	7650		
Lower-Strength Concrete, Polyurea B No Fiber	81	12.59	0.34	N/A	7383	325
	82	12.56	0.38	7050		
	83	12.57	0.31	7400		
	84	12.53	0.33	7700		
Lower-Strength Concrete, Polyurea B Low Fiber	85	12.57	0.30	7100	5983	1484
	86	12.53	0.40	N/A		
	87	12.60	0.44	4300		
	88	12.60	0.42	6550		
Lower-Strength Concrete, Polyurea B High Fiber	89	12.61	0.36	6050	5583	1219
	90	12.57	0.66	N/A		
	93	12.61	0.36	4200		
	94	12.59	0.45	6500		

Unit Conversions: 1 in^2 = 645 mm^2; 1 in = 25.4 mm; 1 ksi = 6.9 MPa

Table A8. Mid-Strength Concrete Cylinder Modulus of Elasticity Data

Group	Sample	Cross-Section (in^2)	Average Coating Thickness (in.)	Sample Modulus, E (ksi)	Average Modulus, E (ksi)	Standard Deviation of Modulus (ksi)
Mid-Strength Concrete, No Coating	33	12.65	NA	N/A	7717	301
	34	12.64	NA	8000		
	35	12.65	NA	7750		
	36	12.62	NA	7400		
Mid-Strength Concrete, Polyurea A No Fiber	41	12.55	0.39	N/A	7483	1762
	42	12.61	0.37	8450		
	43	12.60	0.33	8550		
	44	12.61	0.24	5450		
Mid-Strength Concrete, Polyurea A Low Fiber	37	12.61	0.16	7650	7867	189
	38	12.58	0.14	8000		
	39	12.59	0.15	N/A		
	40	12.61	0.20	7950		
Mid-Strength Concrete, Polyurea B No Fiber	49	12.53	0.27	N/A	7350	1127
	50	12.54	0.33	6050		
	51	12.56	0.30	8050		
	52	12.61	0.35	7950		
Mid-Strength Concrete, Polyurea B Low Fiber	53	12.60	0.50	6350	7417	988
	54	12.55	0.38	N/A		
	55	12.54	0.41	8300		
	56	12.59	0.24	7600		
Mid-Strength Concrete, Polyurea B High Fiber	61	12.59	0.41	N/A	7233	752
	57	12.52	0.42	6450		
	58	12.59	0.38	7300		
	59	12.55	0.63	7950		
	60	12.61	0.46	N/A		

Unit Conversions: 1 in^2 = 645 mm^2; 1 in = 25.4 mm; 1 ksi = 6.9 MPa

Table A9. Higher-Strength Concrete Cylinder Modulus of Elasticity Data

Group	Sample	Cross-Section (in^2)	Average Coating Thickness (in.)	Sample Modulus, E (ksi)	Average Modulus, E (ksi)	Standard Deviation of Modulus (ksi)
Higher-Strength Concrete, No Coating	1	12.63	NA	N/A	5950	265
	2	12.63	NA	6050		
	3	12.62	NA	6150		
	4	12.60	NA	5650		
Higher-Strength Concrete, Polyurea A No Fiber	9	12.63	0.29	N/A	6183	388
	10	12.64	0.34	6500		
	11	12.63	0.34	5750		
	12	12.66	0.32	6300		
Higher-Strength Concrete, Polyurea A Low Fiber	5	12.65	0.27	N/A	6183	293
	6	12.60	0.20	6300		
	7	12.61	0.12	6400		
	8	12.61	0.22	5850		
Higher-Strength Concrete, Polyurea B No Fiber	17	12.54	0.34	N/A	6617	252
	18	12.61	0.31	6650		
	19	12.57	0.31	6850		
	20	12.60	0.31	6350		
Higher-Strength Concrete, Polyurea B Low Fiber	13	12.59	0.33	6100	6517	369
	21	12.59	0.27	N/A		
	22	12.58	0.28	6800		
	23	12.58	0.31	6650		
	24	12.59	0.45	N/A		
Higher-Strength Concrete, Polyurea B High Fiber	25	12.58	0.42	N/A	5767	701
	26	12.55	0.42	6550		
	27	12.58	0.35	5200		
	28	12.56	0.35	5550		

Unit Conversions: 1 in^2 = 645 mm^2; 1 in = 25.4 mm; 1 ksi = 6.9 MPa

APPENDIX B

CYLINDER TEST STRESS VERSUS STRAIN PLOTS

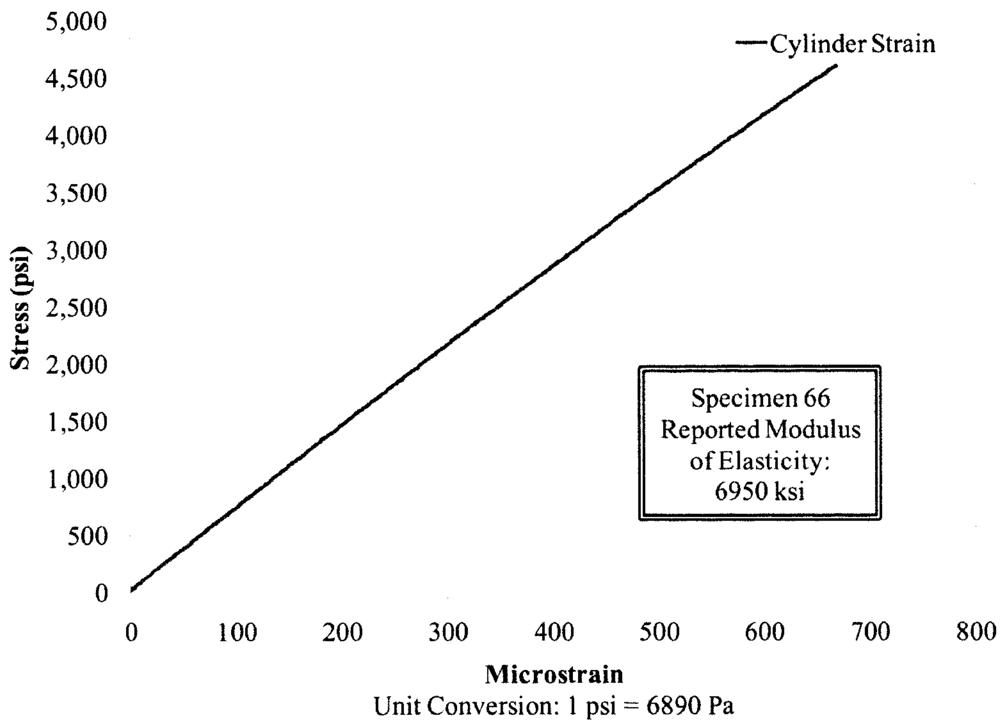


Figure B1. MOE Test for Lower-Strength Concrete, No Coating

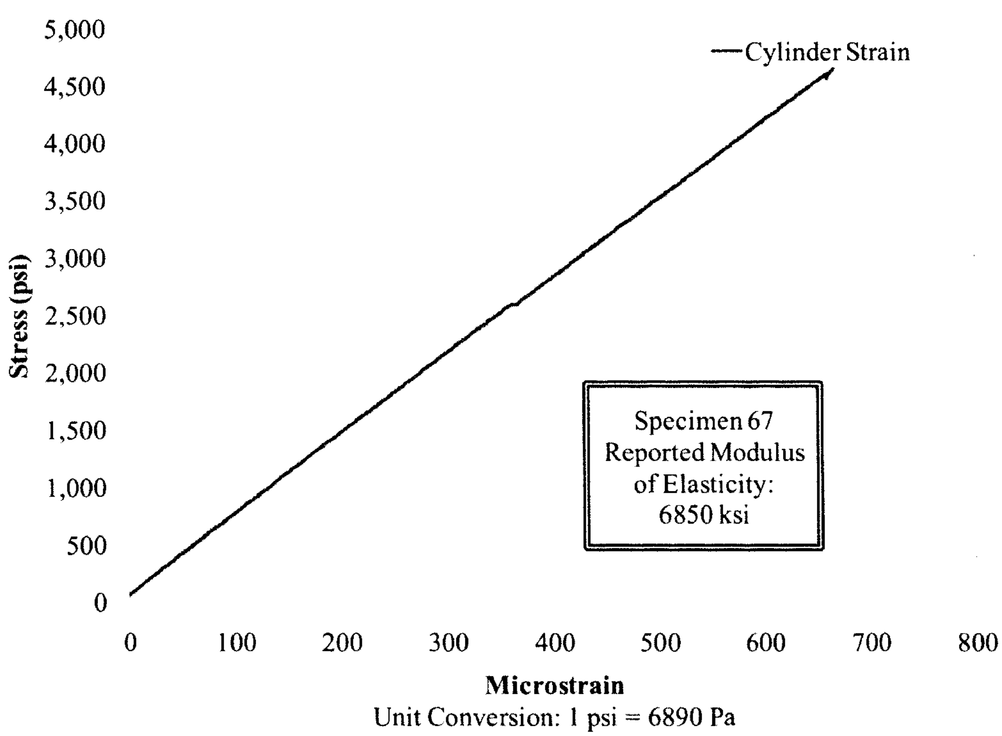
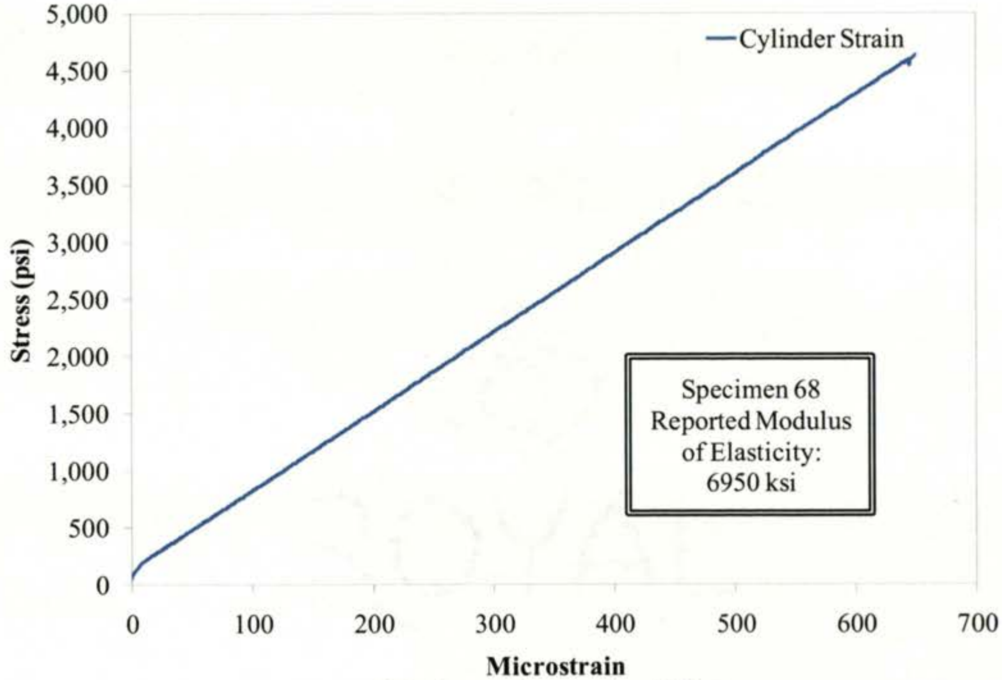
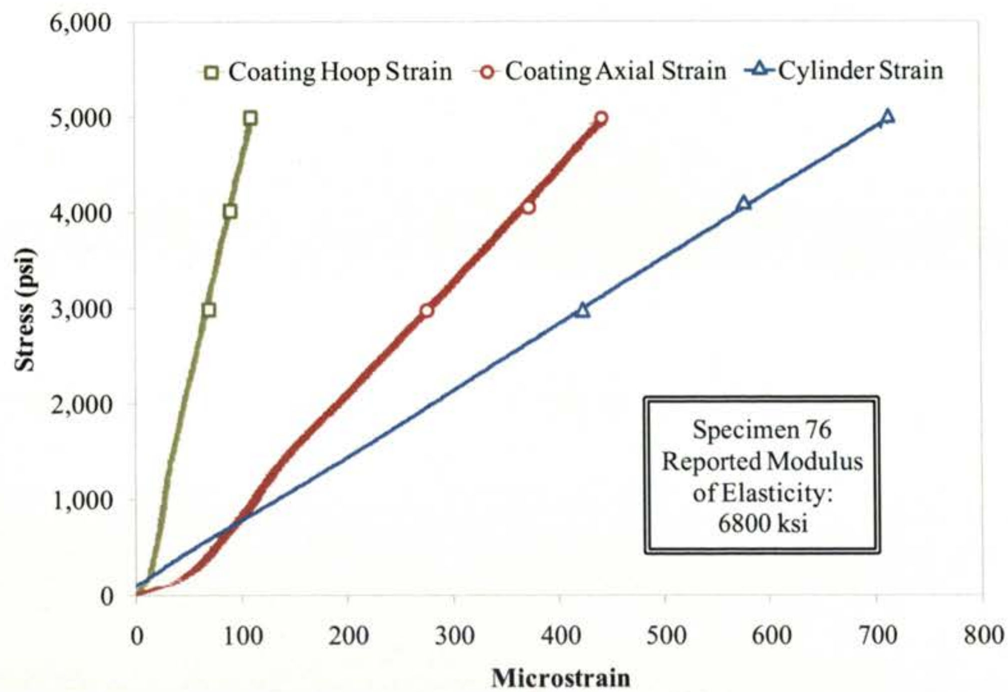


Figure B2. MOE Test for Lower-Strength Concrete, No Coating



Unit Conversion: 1 psi = 6890 Pa

Figure B3. MOE Test for Lower-Strength Concrete, No Coating



Unit Conversion: 1 psi = 6890 Pa

Figure B4. MOE Test for Lower-Strength Concrete, Polyurea A, No Fiber

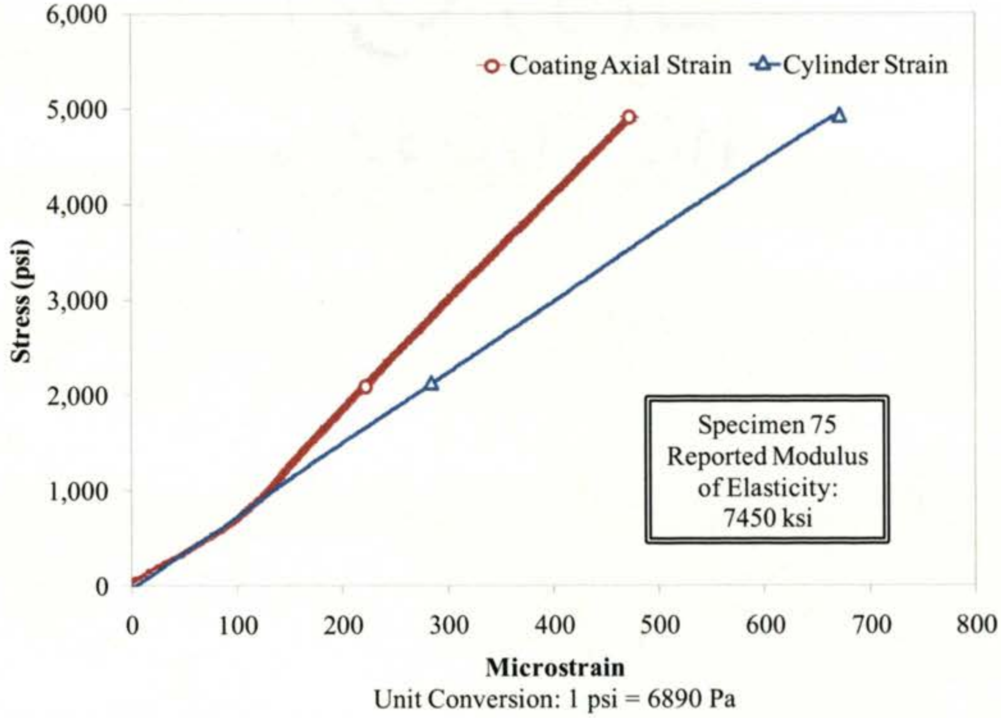


Figure B5. MOE Test for Lower-Strength Concrete, Polyurea A, No Fiber

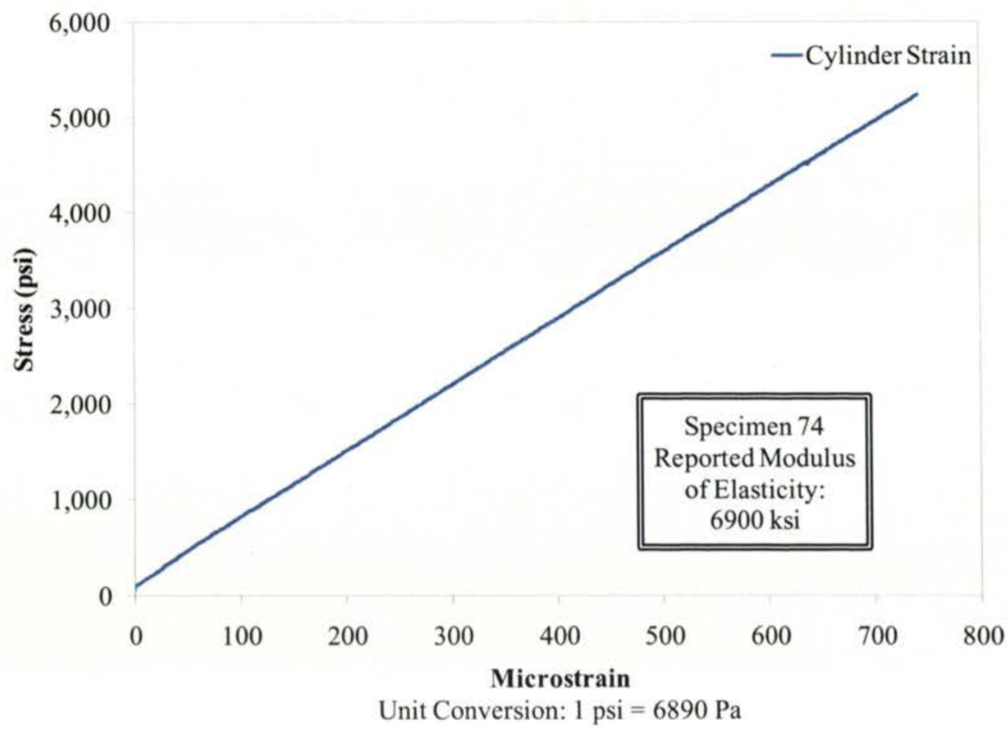


Figure B6. MOE Test for Lower-Strength Concrete, Polyurea A, No Fiber

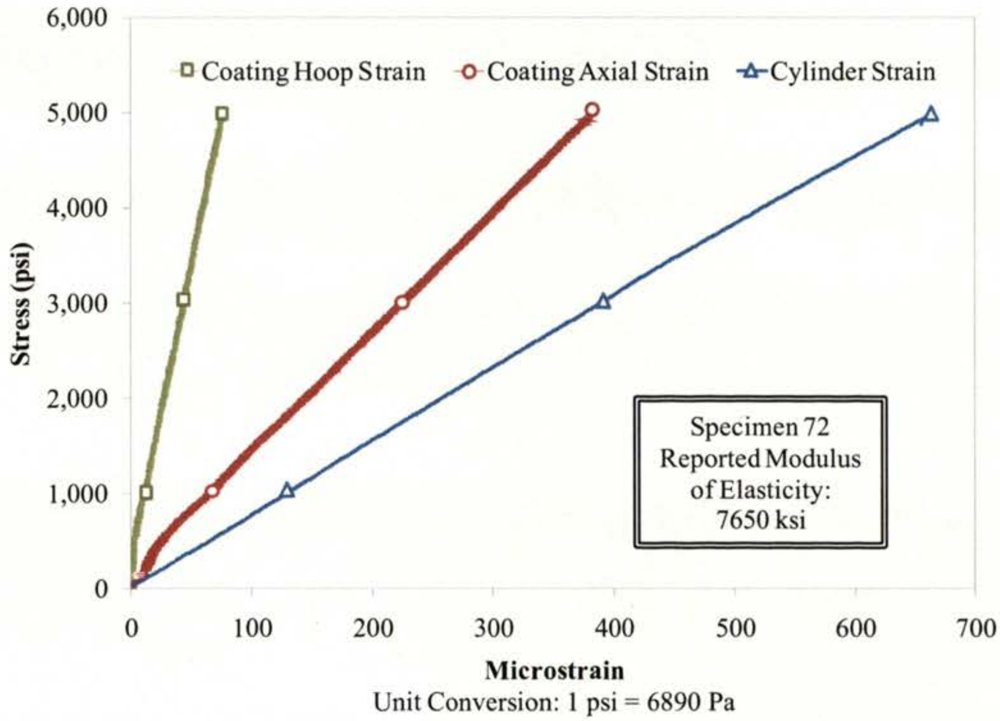


Figure B7. MOE Test for Lower-Strength Concrete, Polyurea A, Lower Fiber

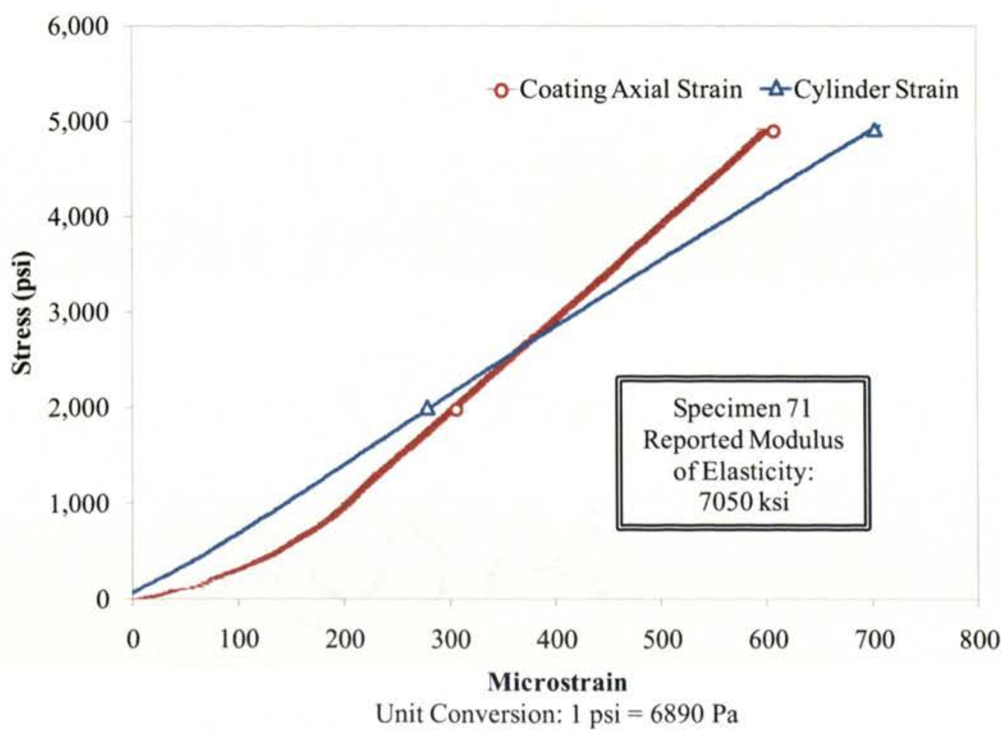


Figure B8. MOE Test for Lower-Strength Concrete, Polyurea A, Lower Fiber

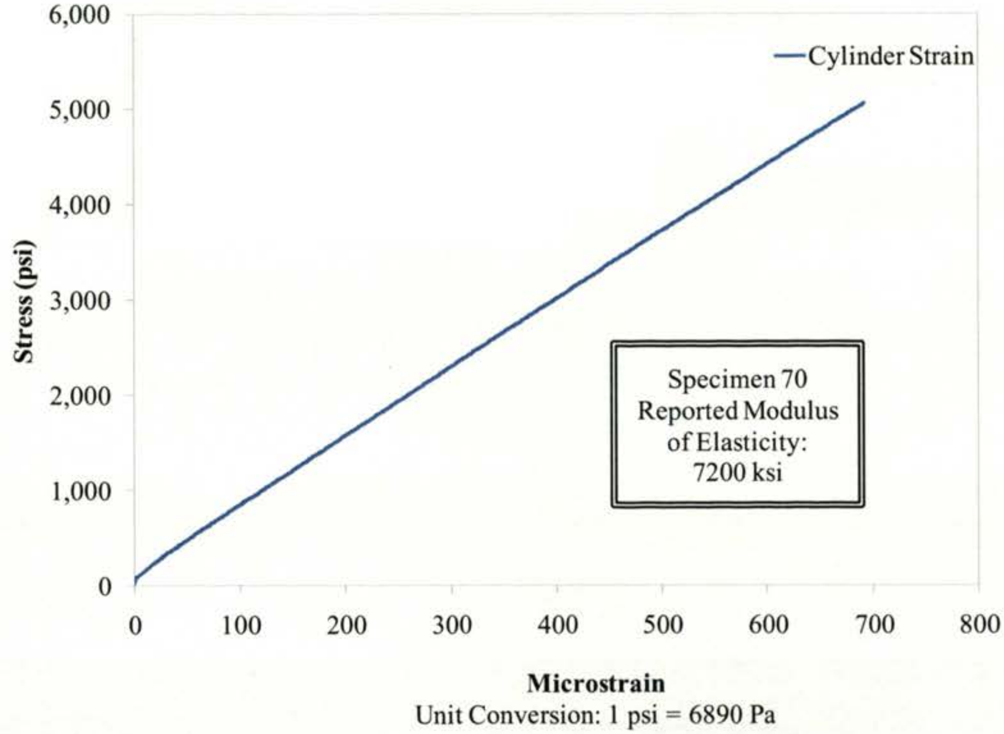


Figure B9. MOE Test for Lower-Strength Concrete, Polyurea A, Lower Fiber

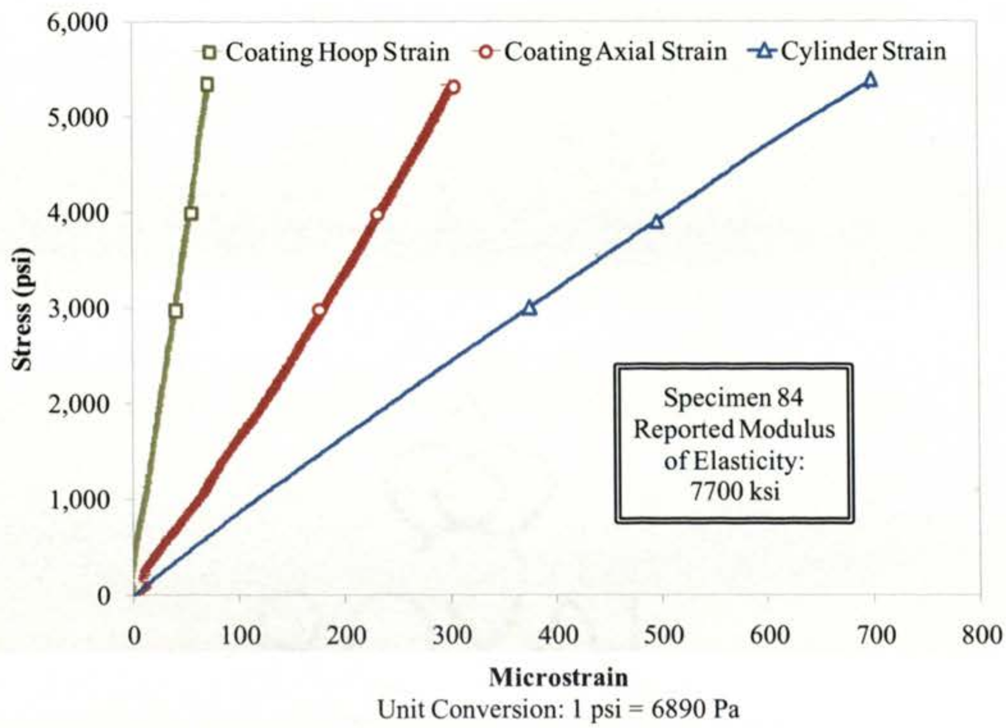


Figure B10. MOE Test for Lower-Strength Concrete, Polyurea B, No Fiber

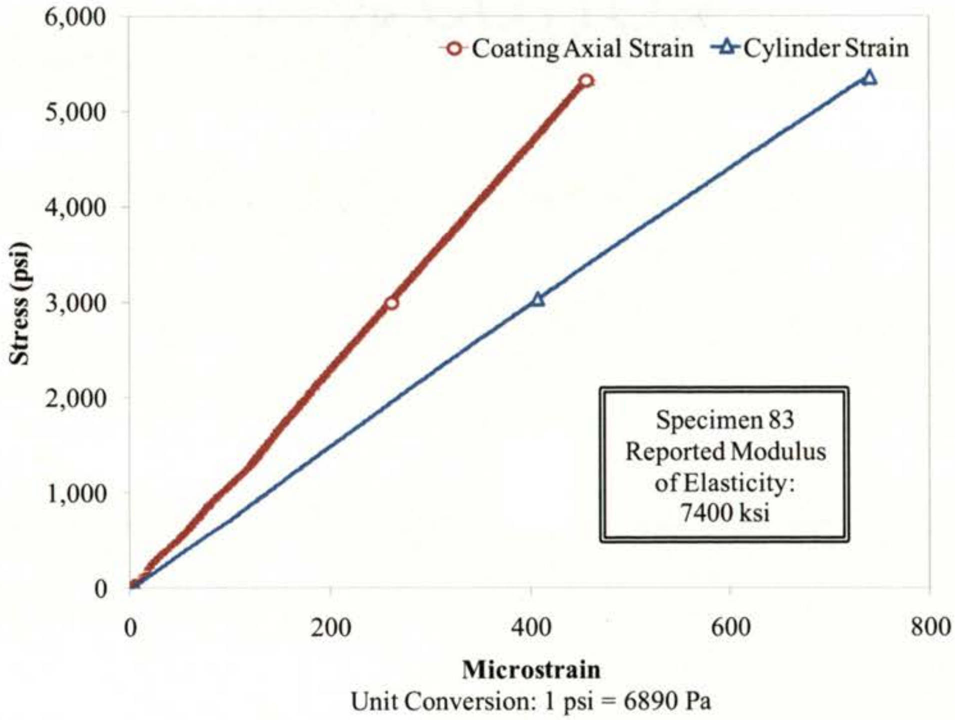


Figure B11. MOE Test for Lower-Strength Concrete, Polyurea B, No Fiber

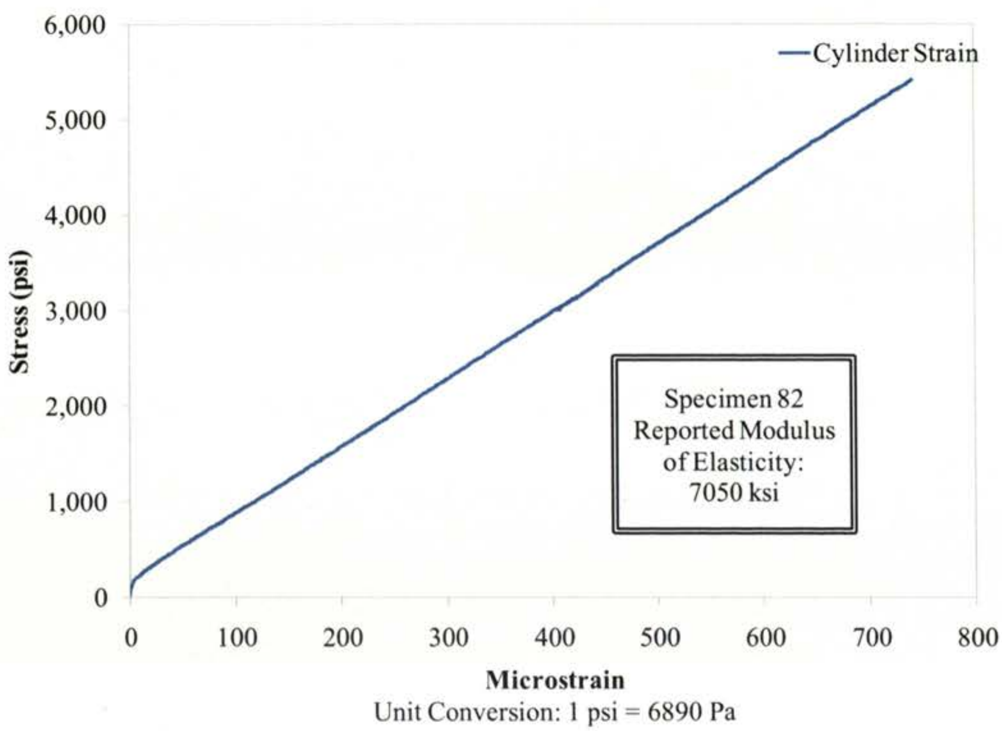


Figure B12. MOE Test for Lower-Strength Concrete, Polyurea B, No Fiber

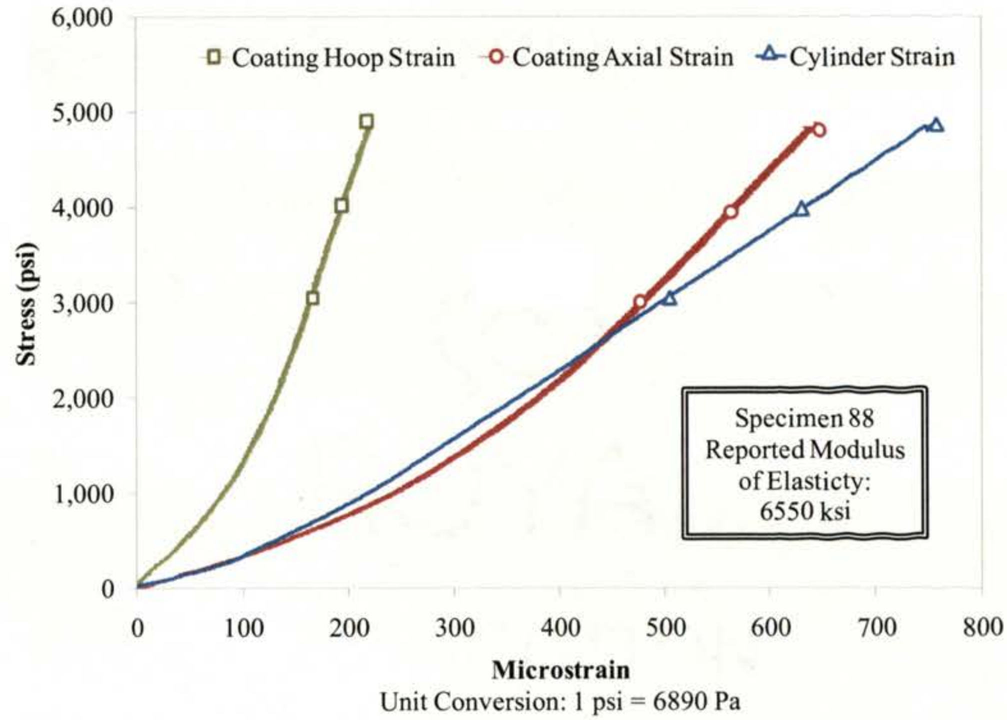


Figure B13. MOE Test for Lower-Strength Concrete, Polyurea B, Lower Fiber

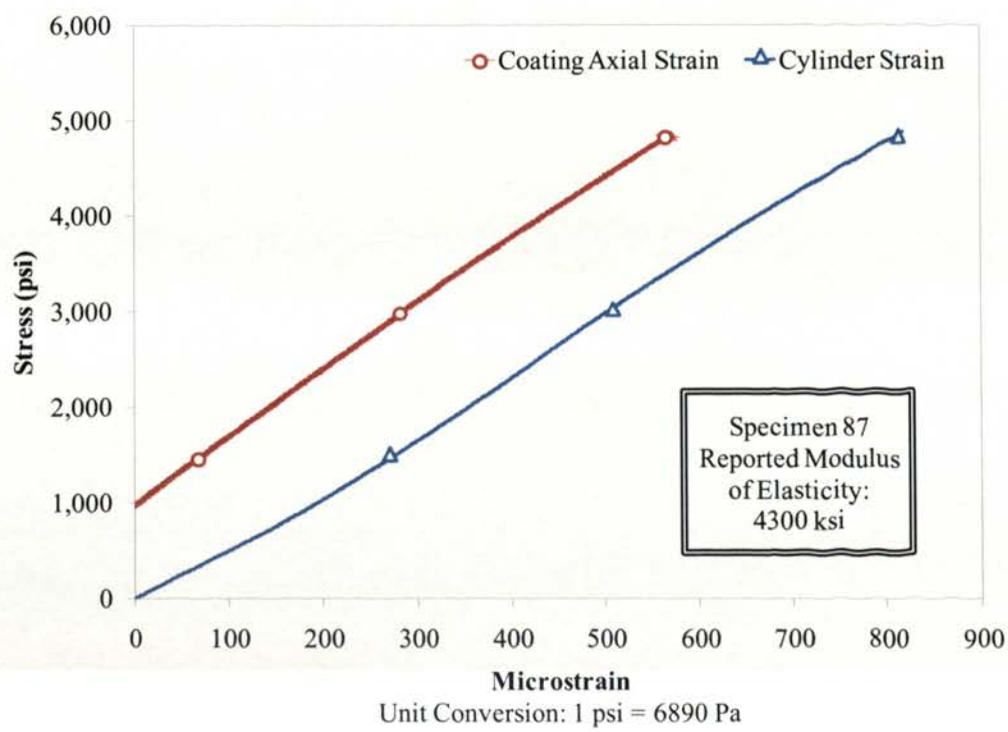


Figure B14. MOE Test for Lower-Strength Concrete, Polyurea B, Lower Fiber

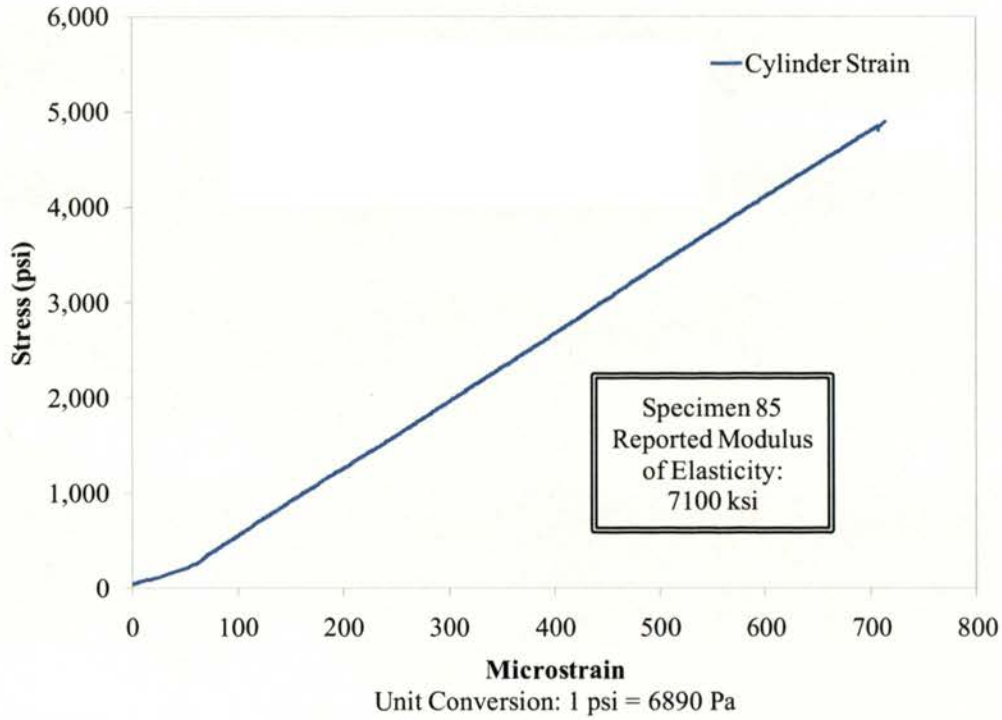


Figure B15. MOE Test for Lower-Strength Concrete, Polyurea B, Lower Fiber

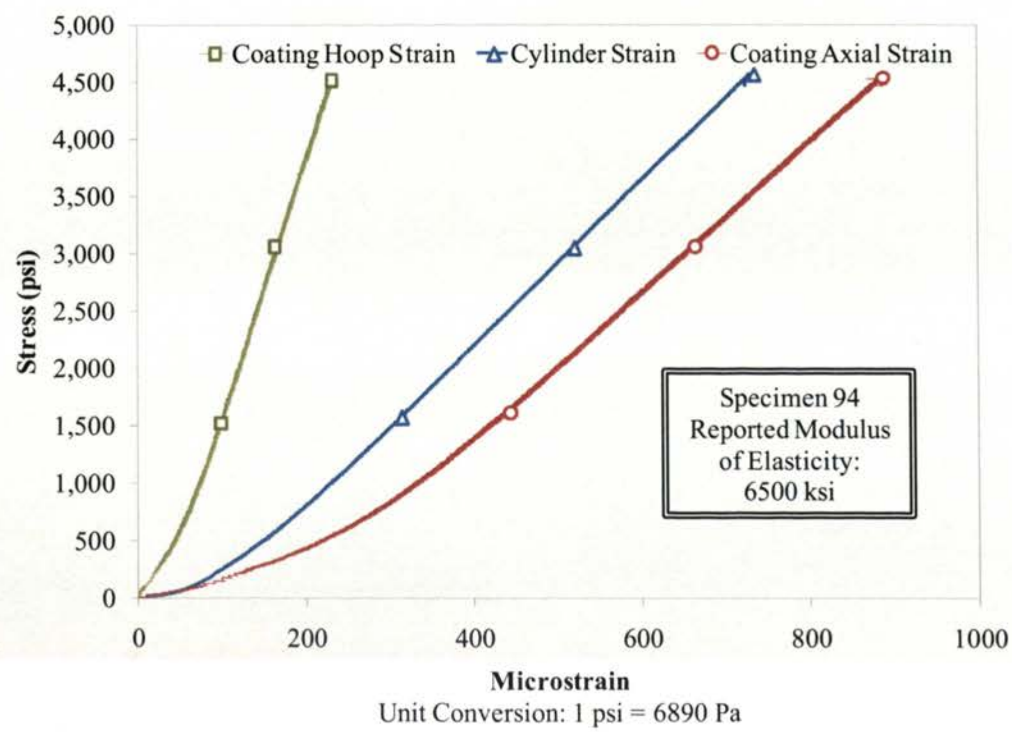


Figure B16. MOE Test for Lower-Strength Concrete, Polyurea B, Higher Fiber

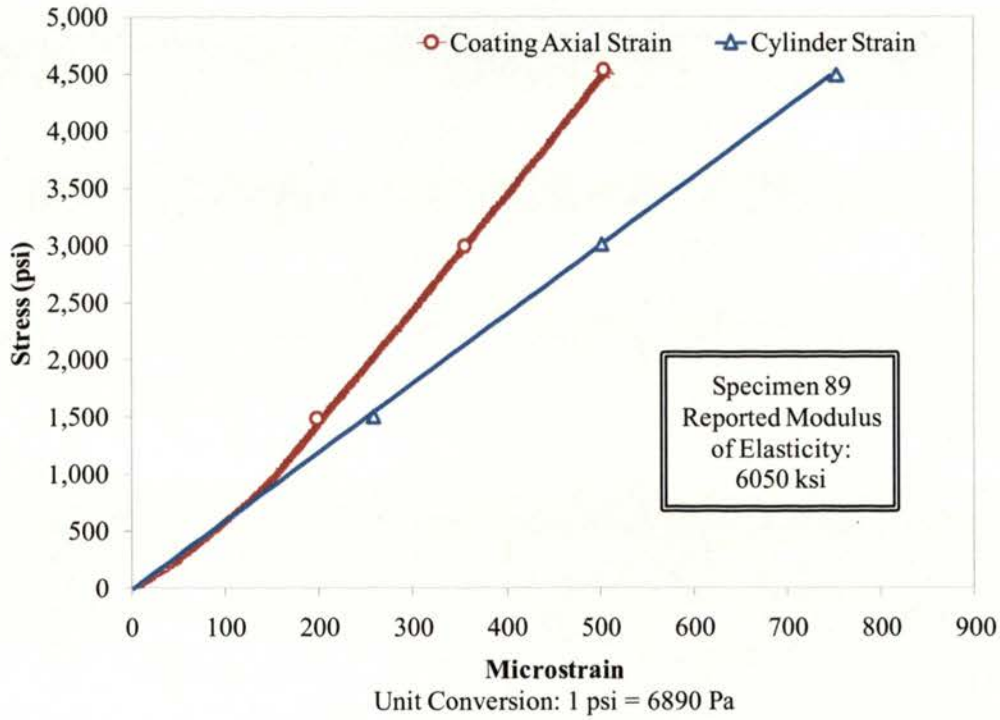


Figure B17. MOE Test for Lower-Strength Concrete, Polyurea B, Higher Fiber

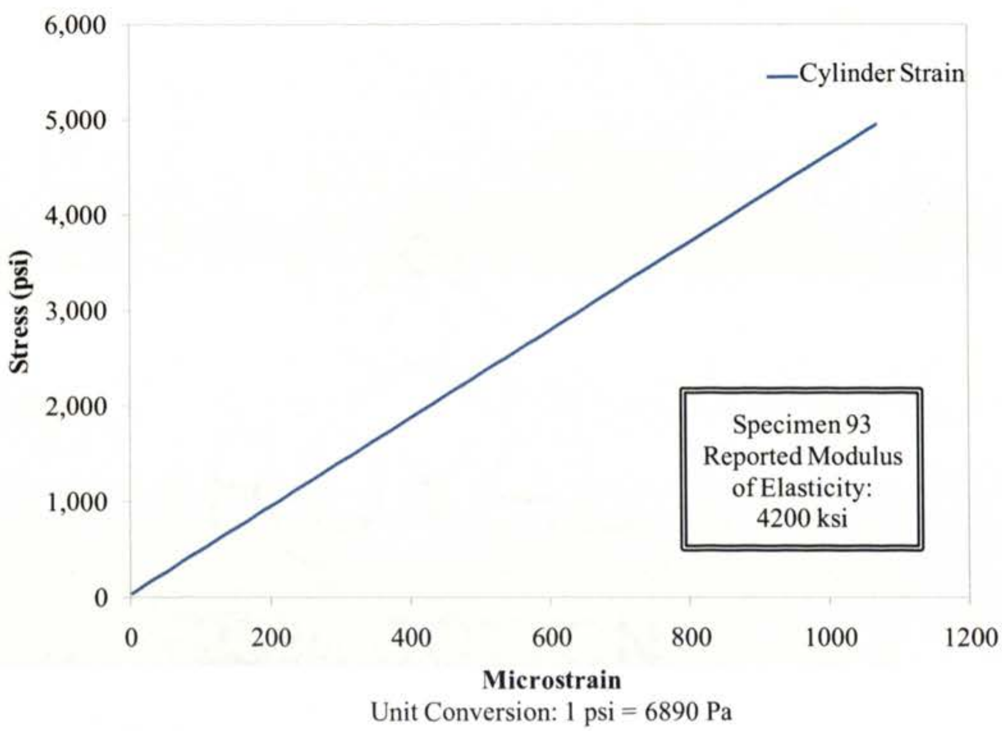


Figure B18. MOE Test for Lower-Strength Concrete, Polyurea B, Higher Fiber

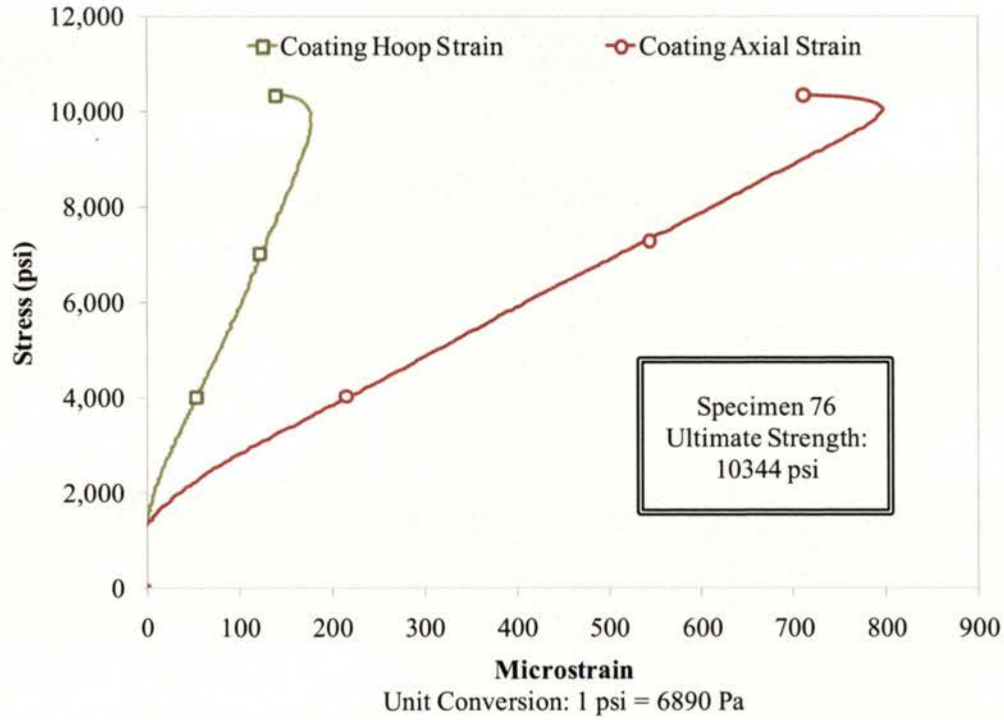


Figure B19. Strength Test for Lower-Strength Concrete, Polyurea A, No Fiber

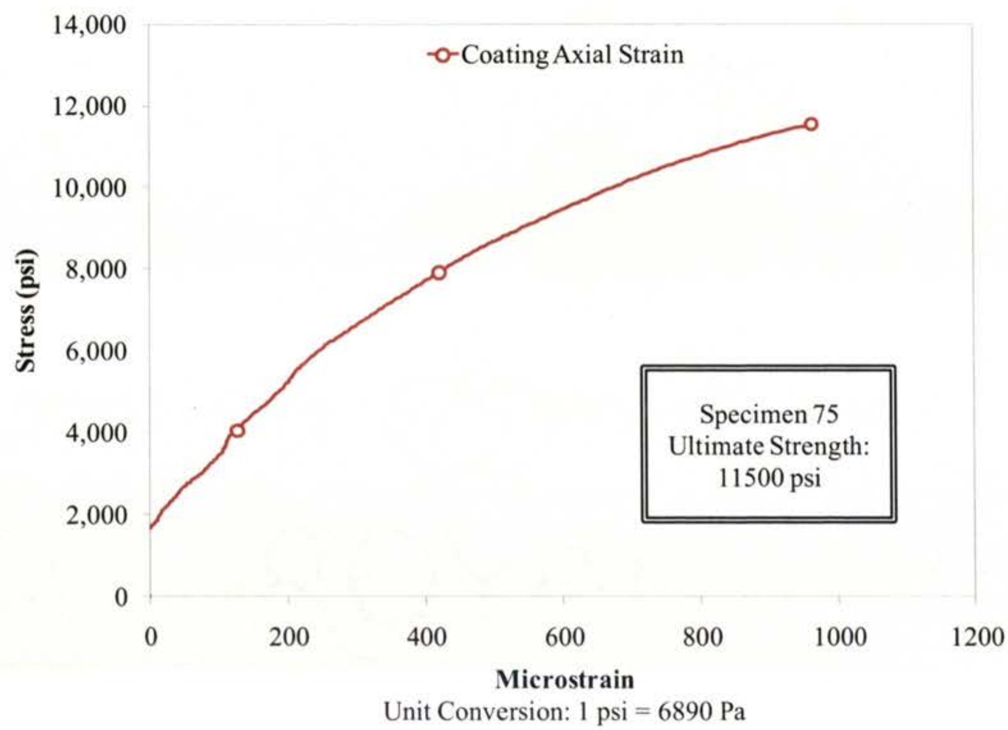


Figure B20. Strength Test for Lower-Strength Concrete, Polyurea A, No Fiber

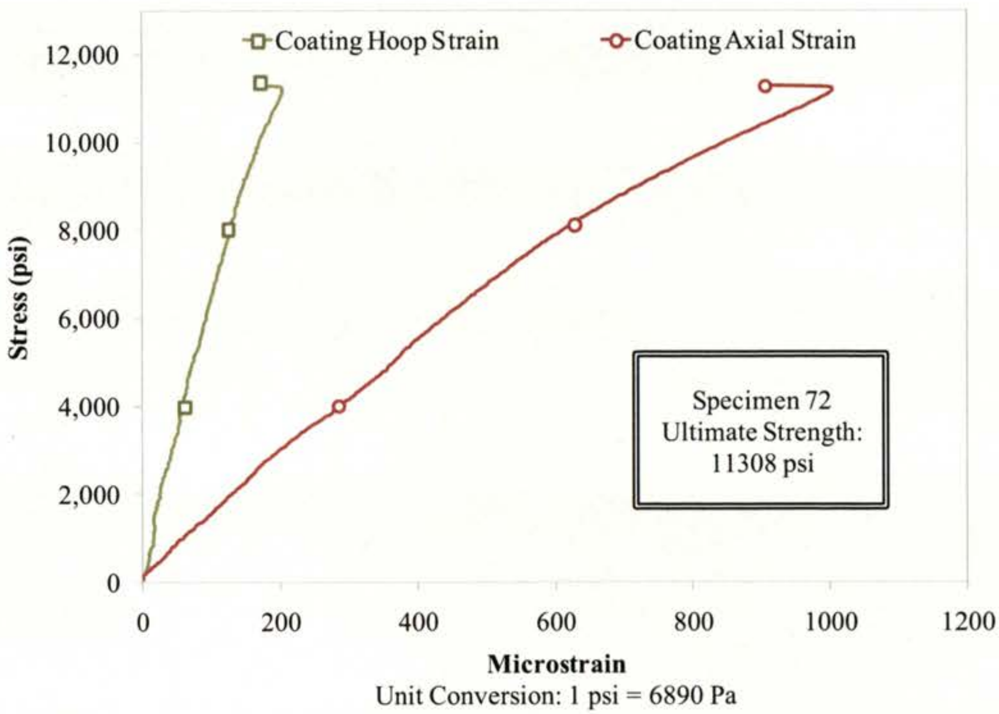


Figure B21. Strength Test for Lower-Strength Concrete, Polyurea A, Lower Fiber

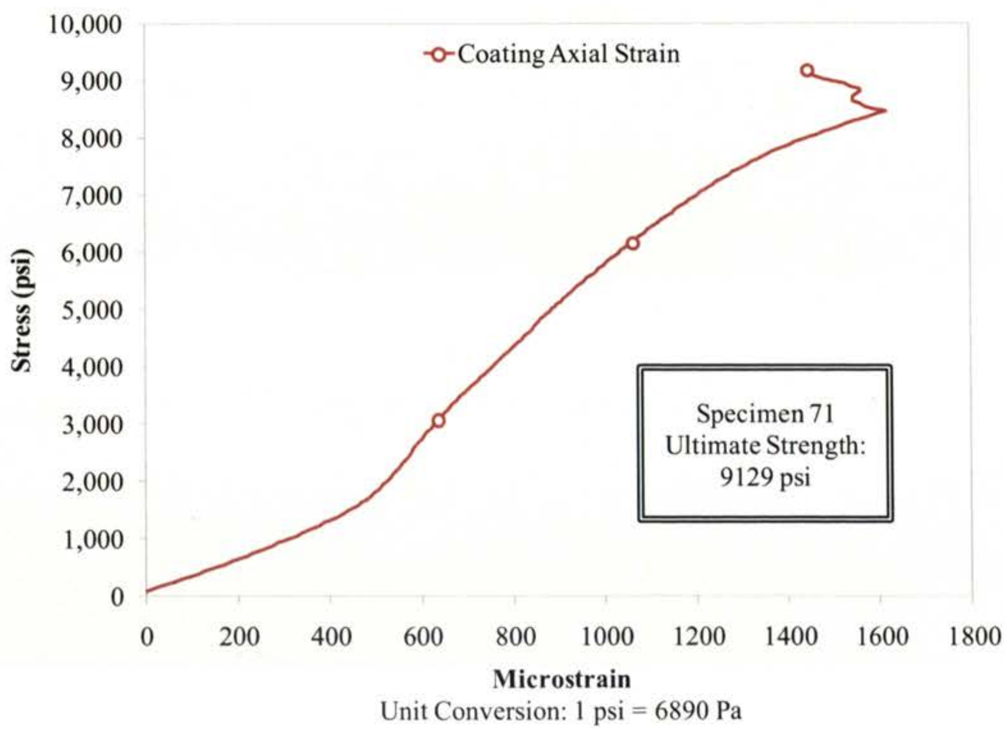


Figure B22. Strength Test for Lower-Strength Concrete, Polyurea A, Lower Fiber

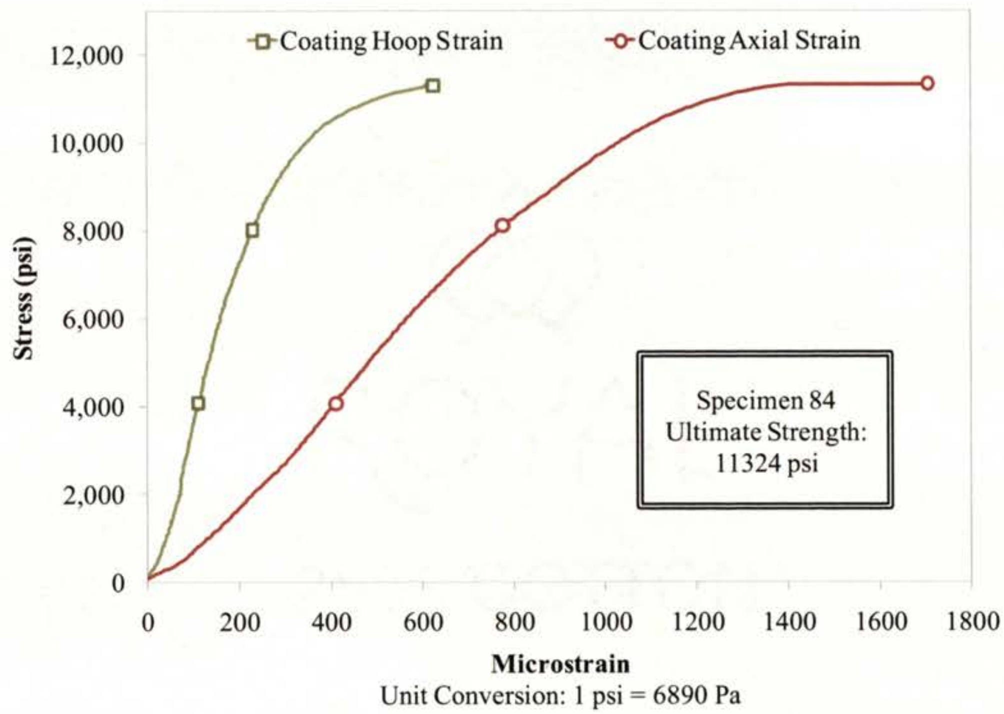


Figure B23. Strength Test for Lower-Strength Concrete, Polyurea B, No Fiber

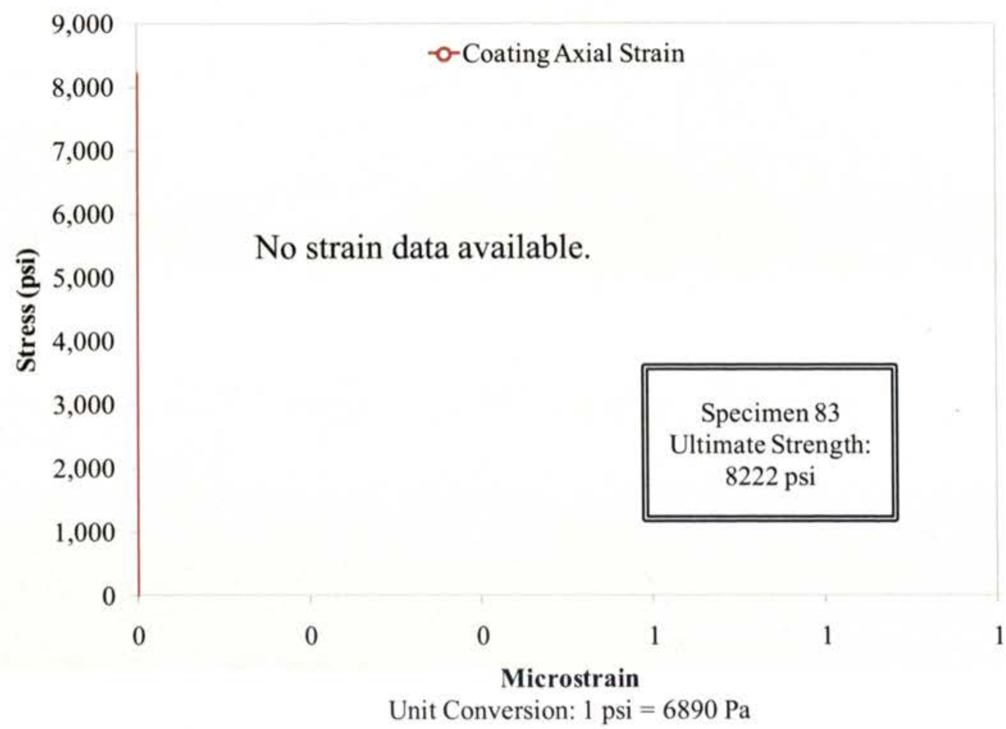
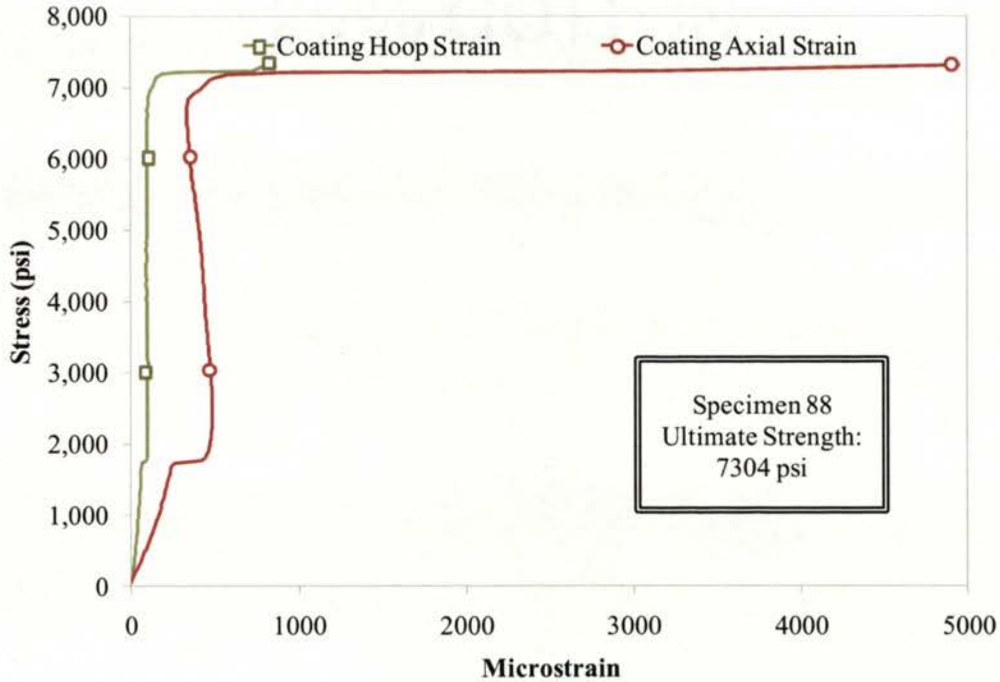
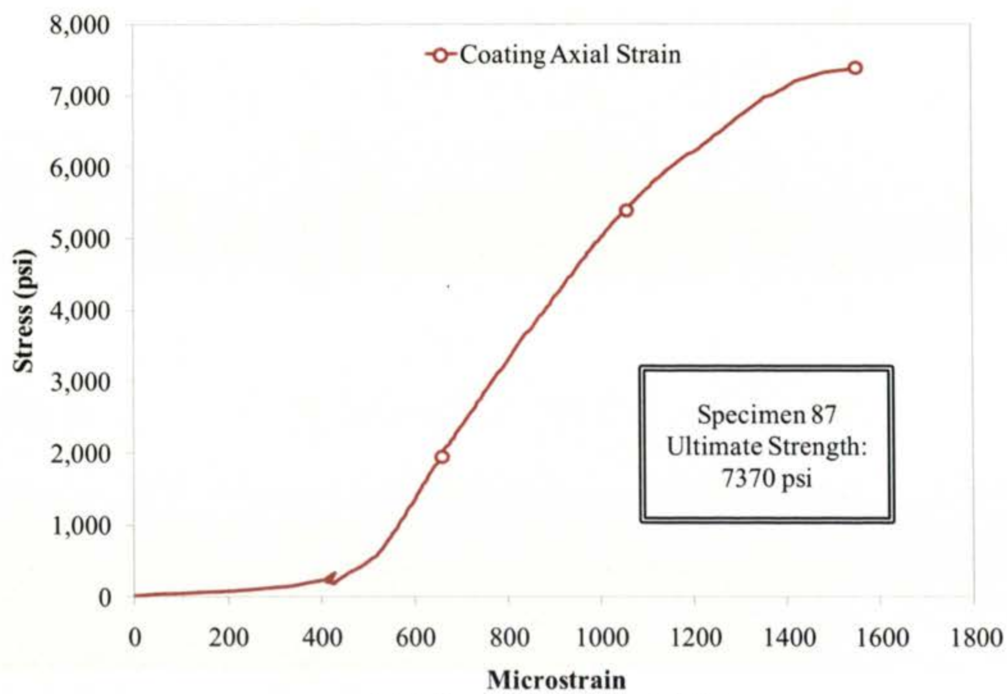


Figure B24. Strength Test for Lower-Strength Concrete, Polyurea B, No Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B25. Strength Test for Lower-Strength Concrete, Polyurea B, Lower Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B26. Strength Test for Lower-Strength Concrete, Polyurea B, Lower Fiber

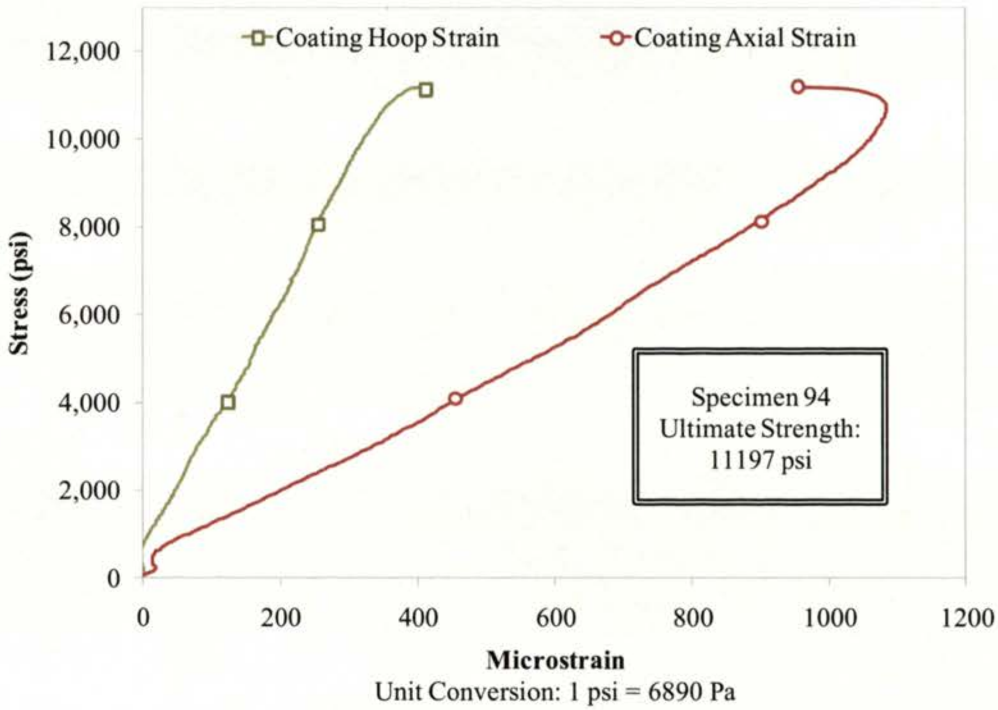


Figure B27. Strength Test for Lower-Strength Concrete, Polyurea B, Higher Fiber

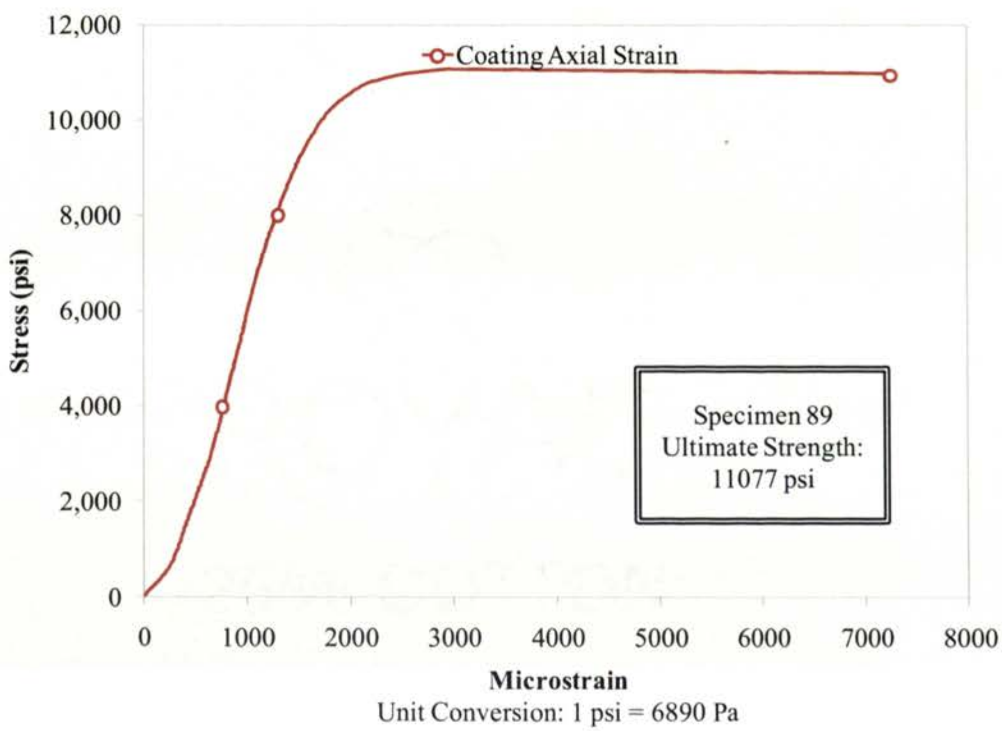


Figure B28. Strength Test for Lower-Strength Concrete, Polyurea B, Higher Fiber

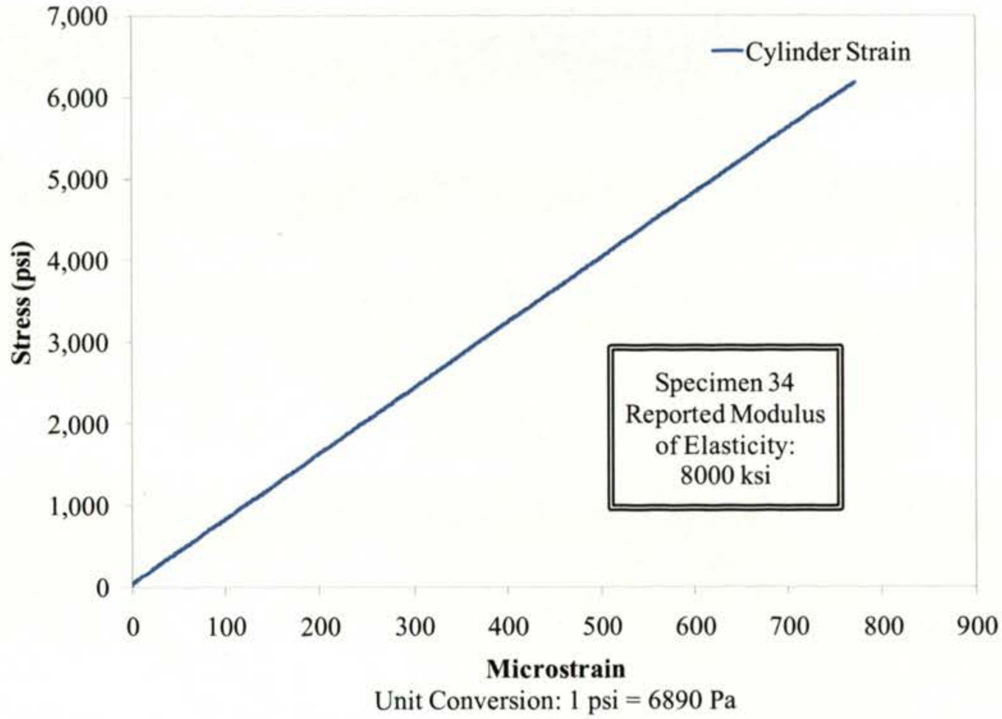


Figure B29. MOE Test for Mid-Strength Concrete, No Coating

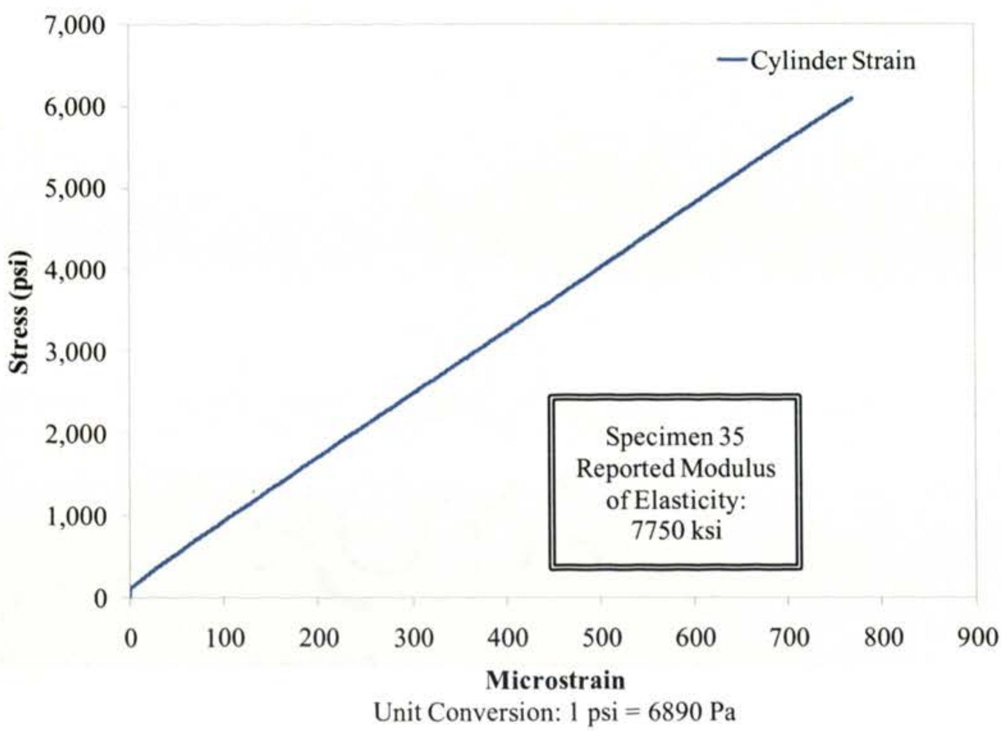
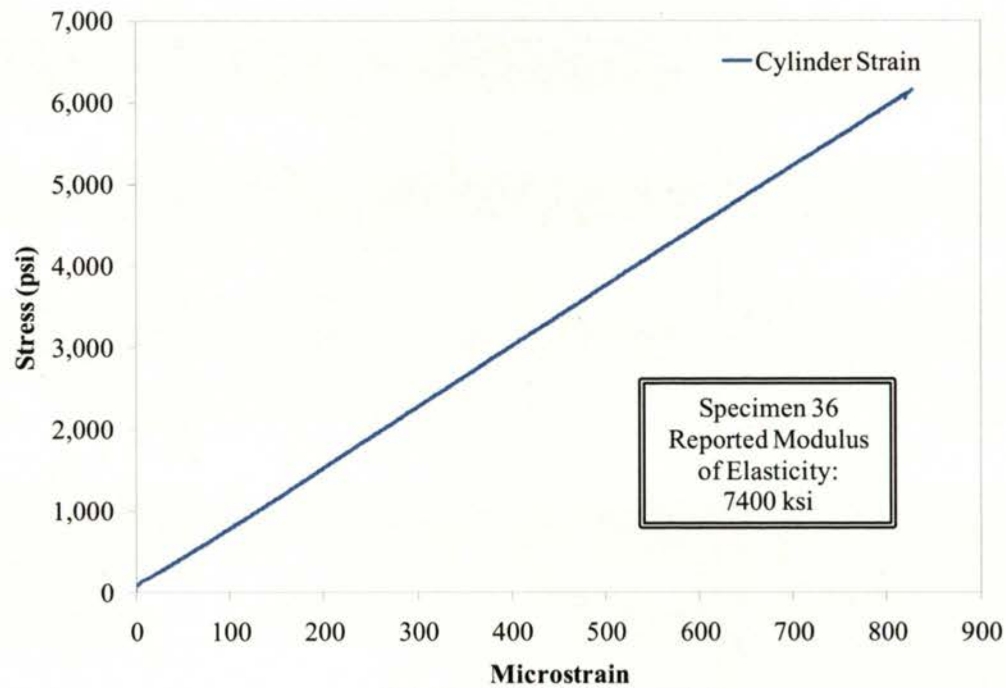
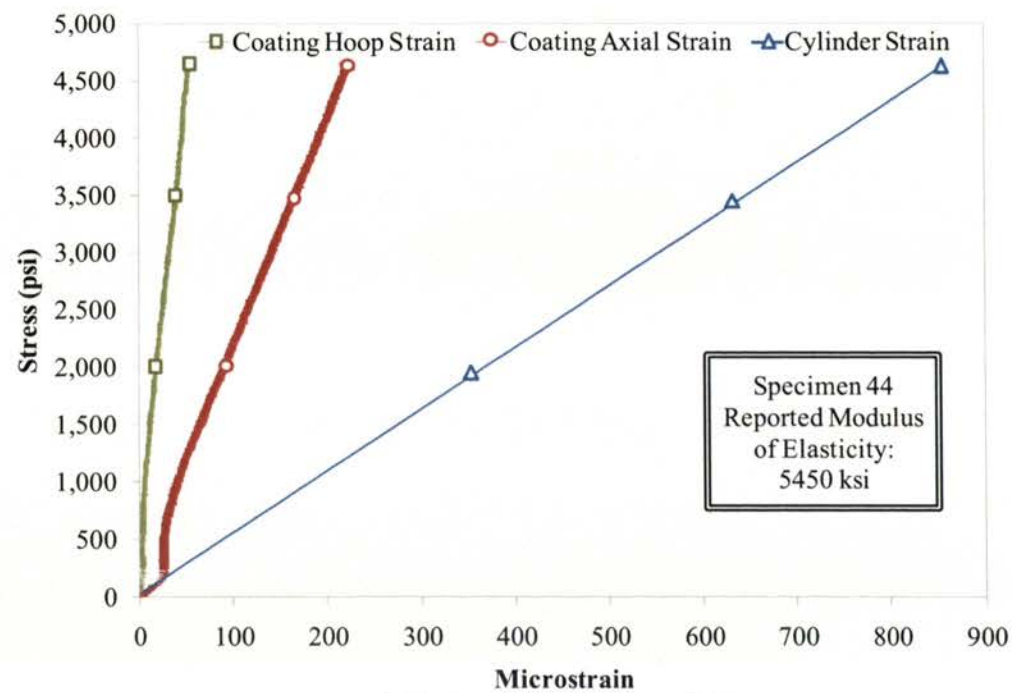


Figure B30. MOE Test for Mid-Strength Concrete, No Coating



Unit Conversion: 1 psi = 6890 Pa

Figure B31. MOE Test for Mid-Strength Concrete, No Coating



Unit Conversion: 1 psi = 6890 Pa

Figure B32. MOE Test for Mid-Strength Concrete, Polyurea A, No Fiber

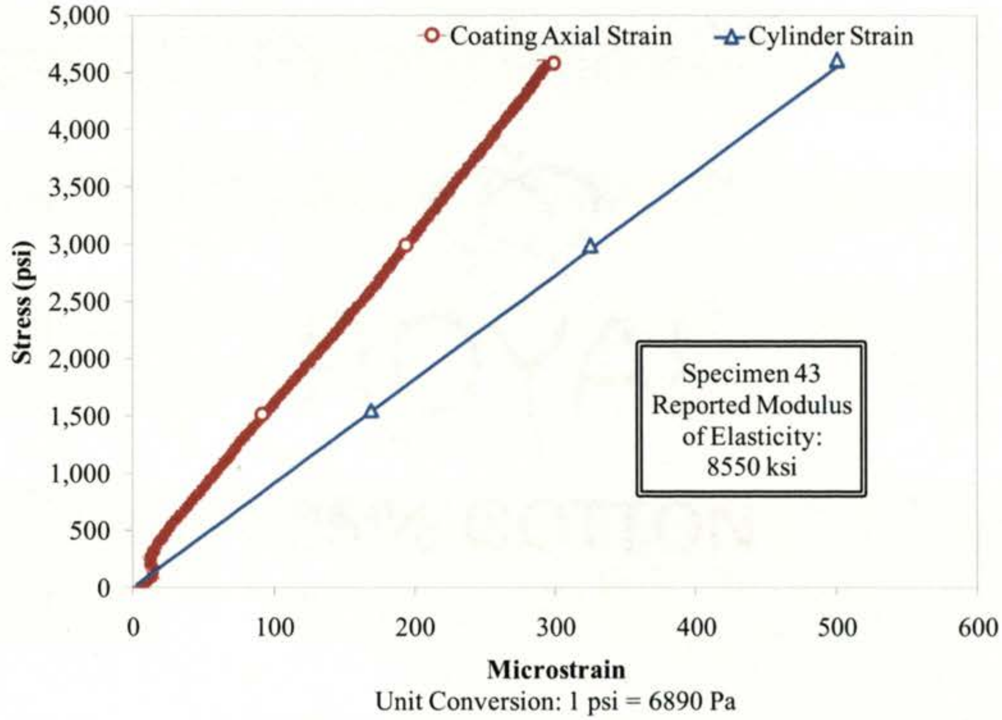


Figure B33. MOE Test for Mid-Strength Concrete, Polyurea A, No Fiber

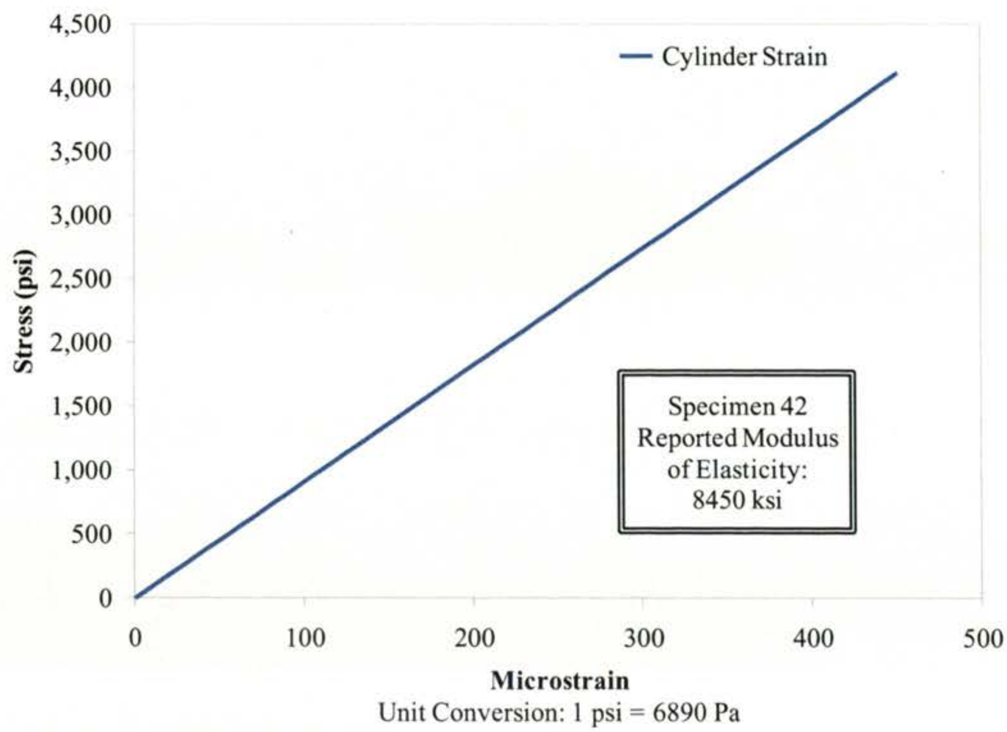


Figure B34. MOE Test for Mid-Strength Concrete, Polyurea A, No Fiber

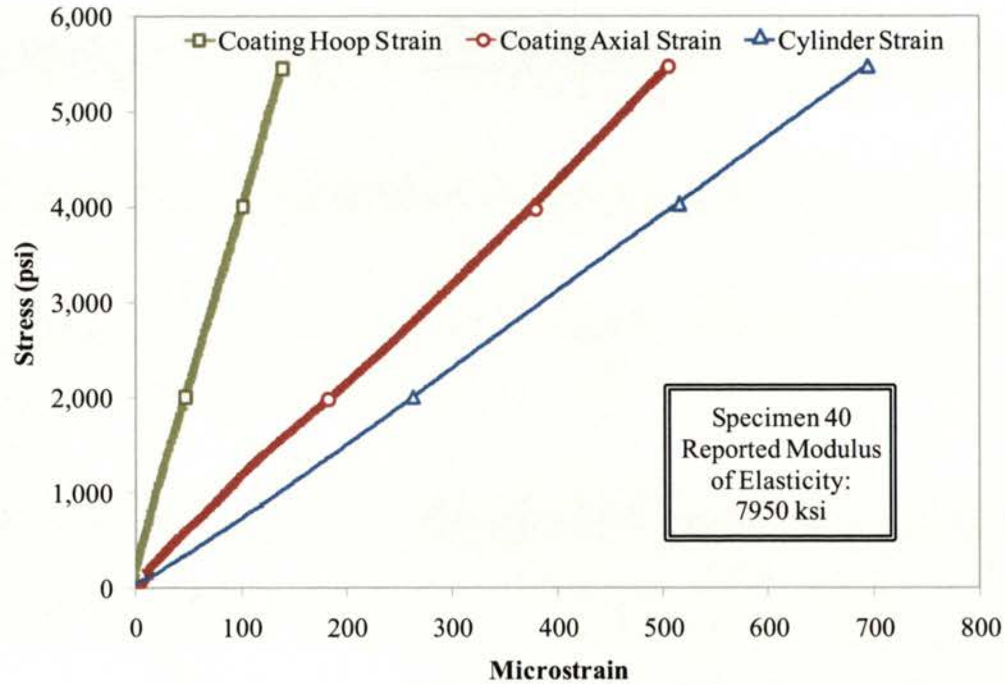


Figure B35. MOE Test for Mid-Strength Concrete, Polyurea A, Lower Fiber

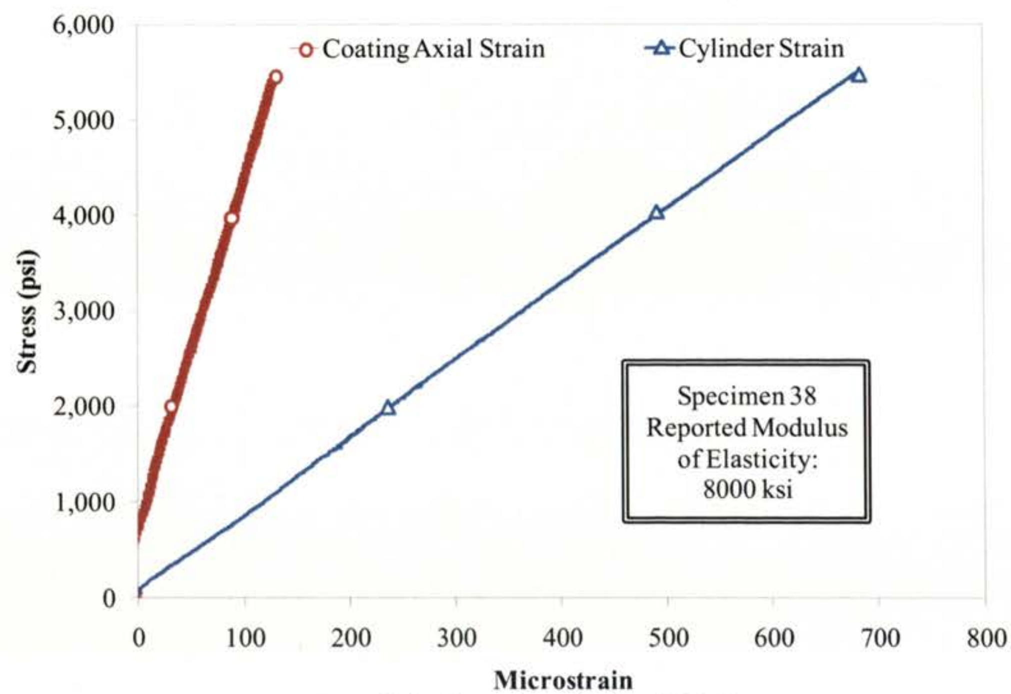


Figure B36. MOE Test for Mid-Strength Concrete, Polyurea A, Lower Fiber

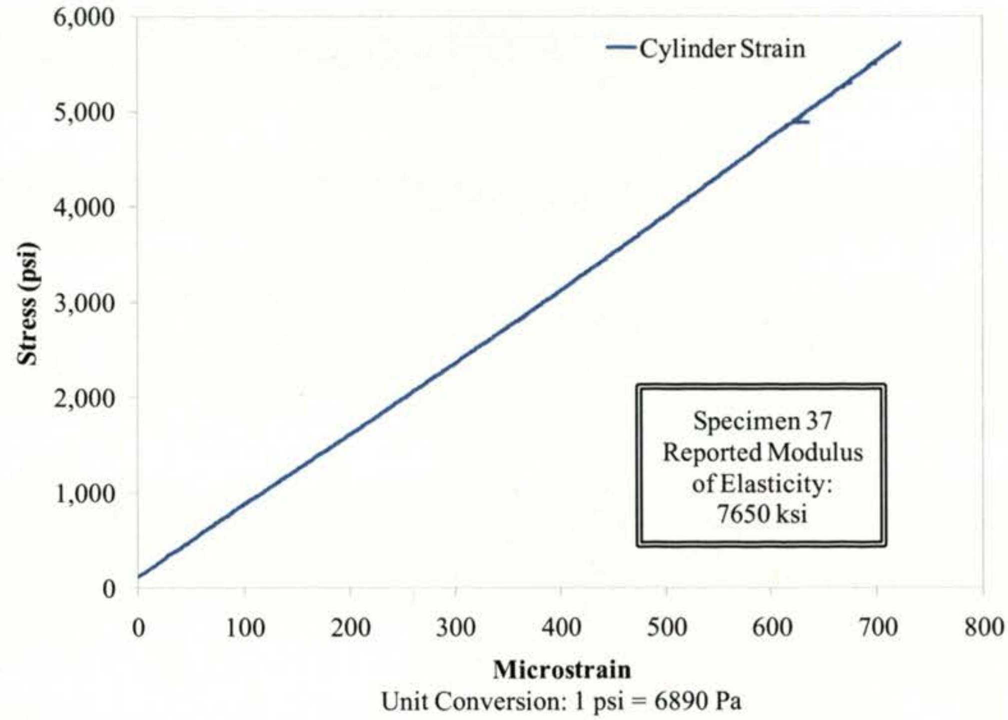


Figure B37. MOE Test for Mid-Strength Concrete, Polyurea A, Lower Fiber

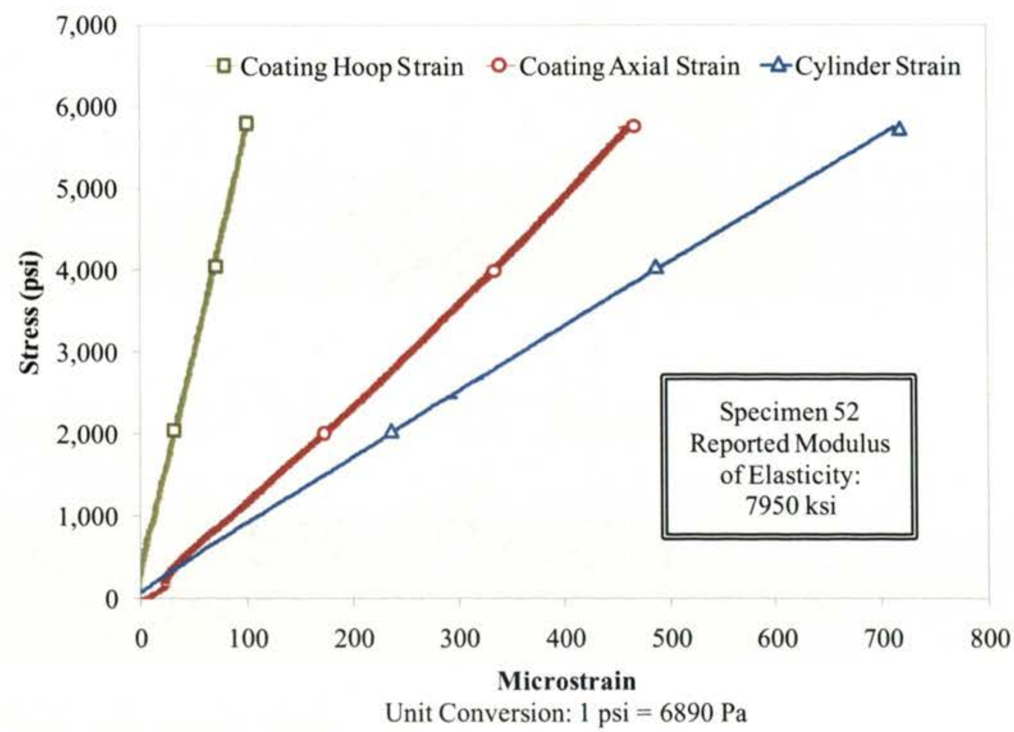


Figure B38. MOE Test for Mid-Strength Concrete, Polyurea B, No Fiber

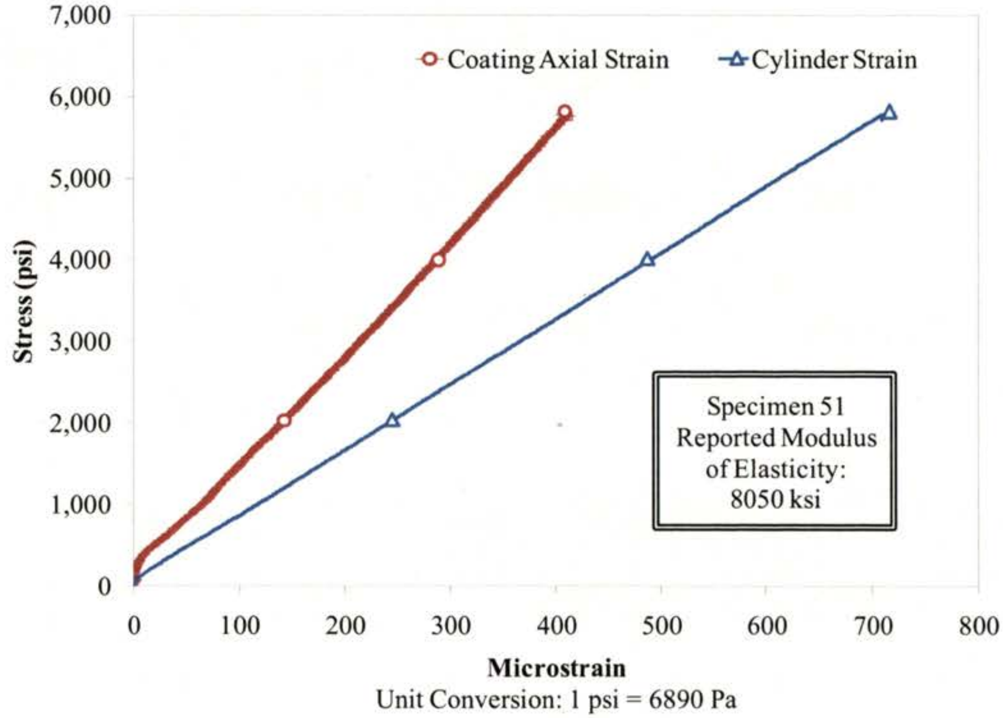


Figure B39. MOE Test for Mid-Strength Concrete, Polyurea B, No Fiber

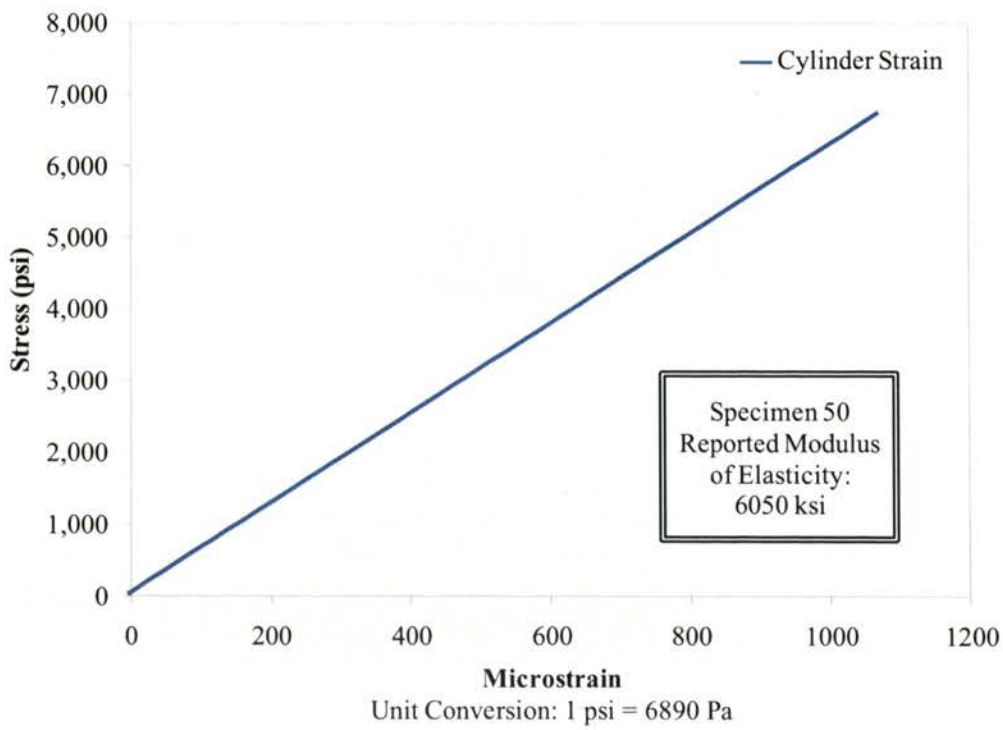
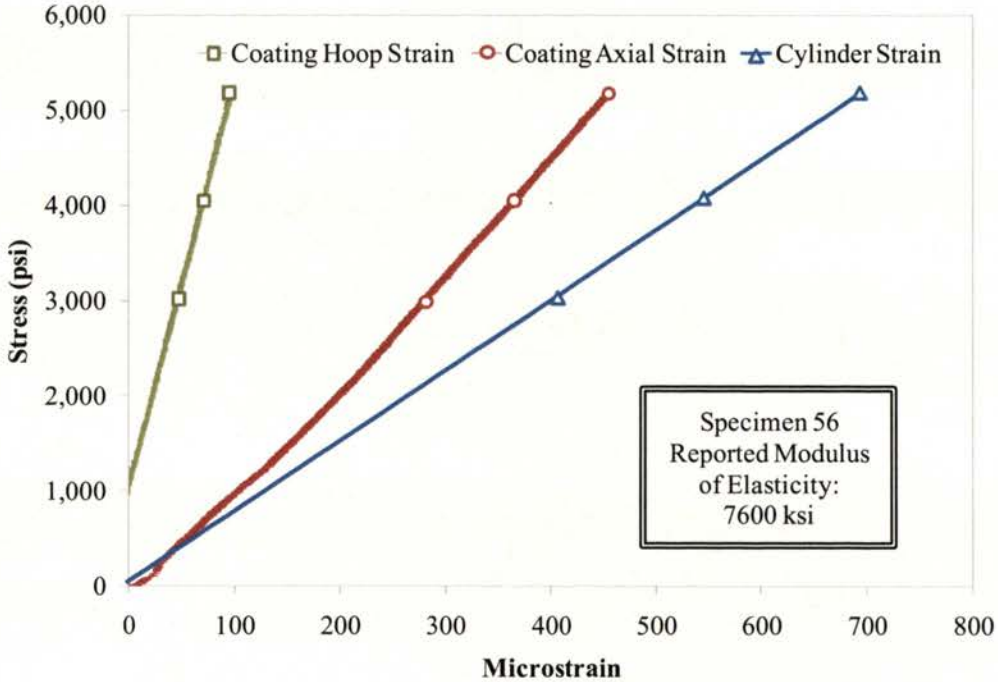
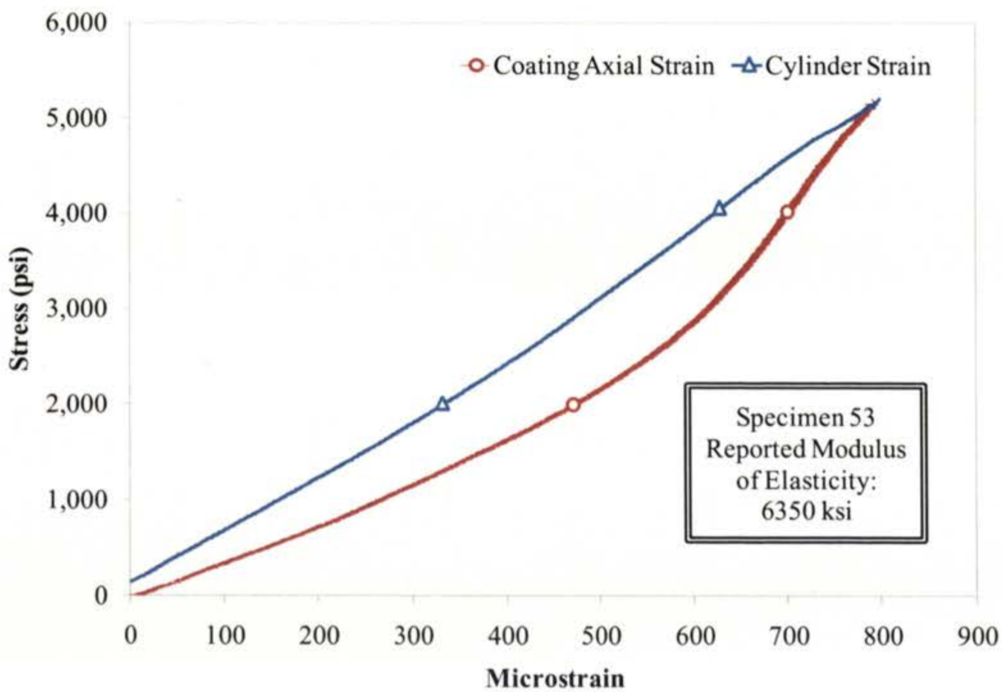


Figure B40. MOE Test for Mid-Strength Concrete, Polyurea B, No Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B41. MOE Test for Mid-Strength Concrete, Polyurea B, Lower Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B42. MOE Test for Mid-Strength Concrete, Polyurea B, Lower Fiber

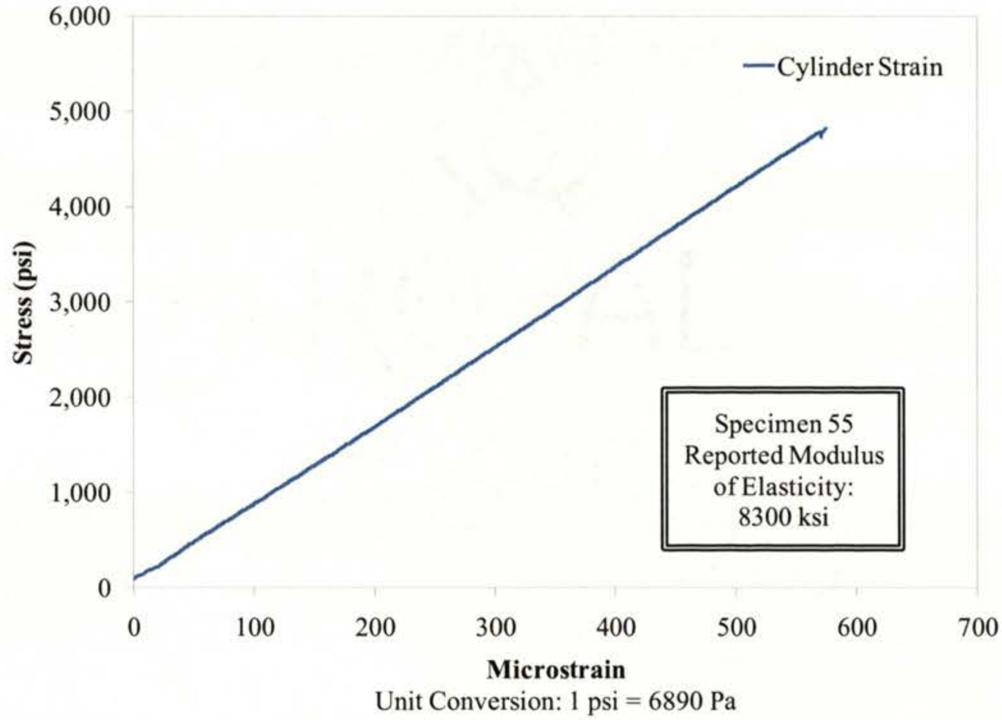


Figure B43. MOE Test for Mid-Strength Concrete, Polyurea B, Lower Fiber

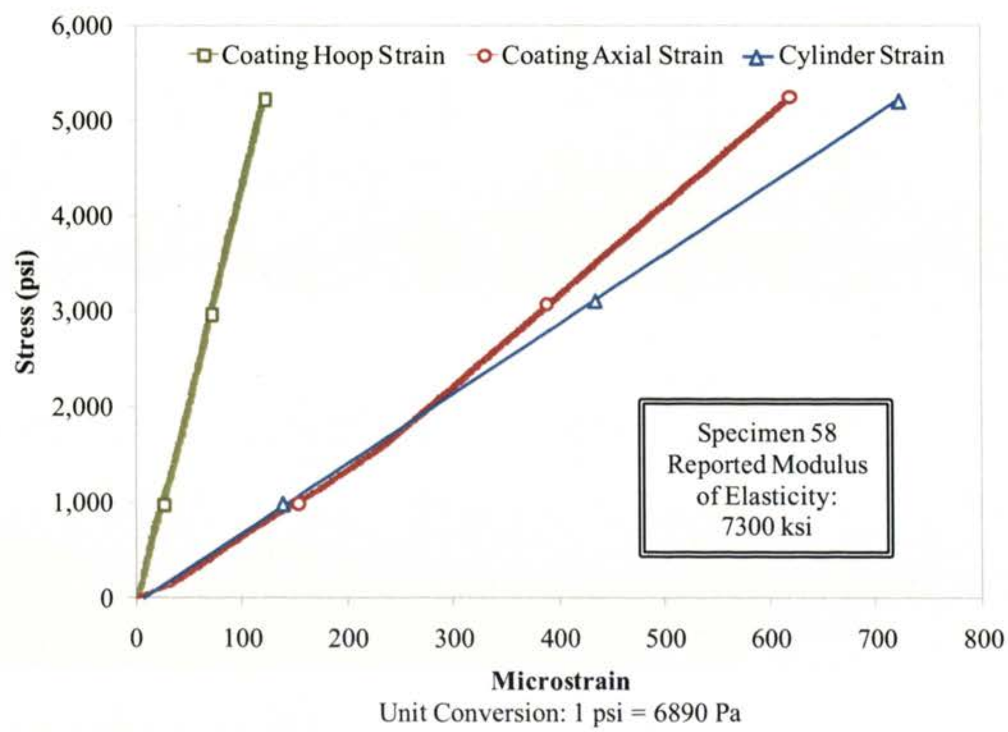
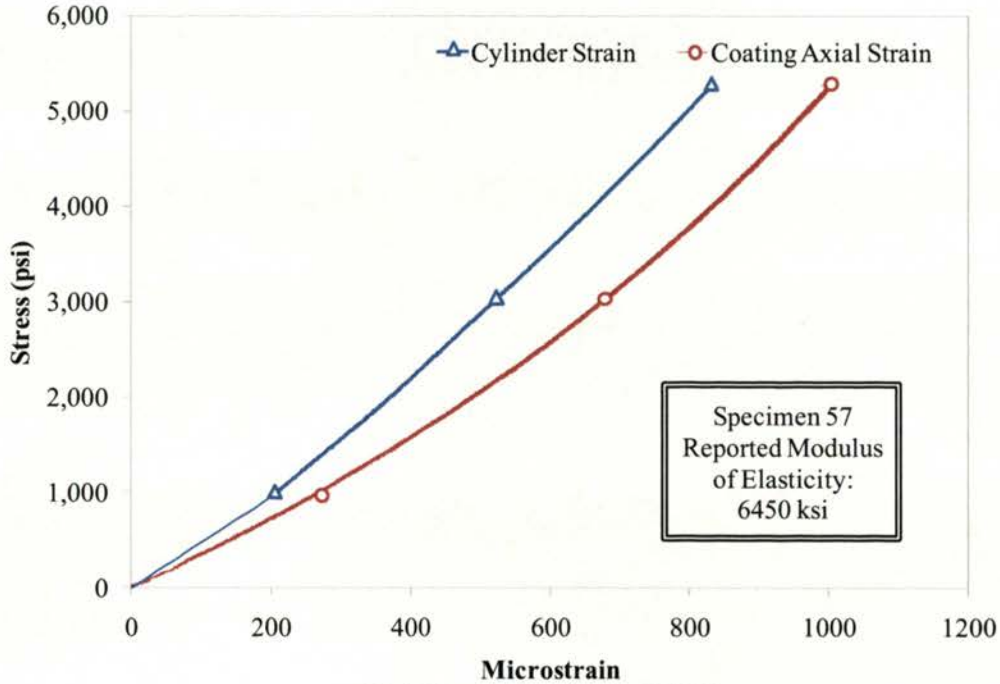
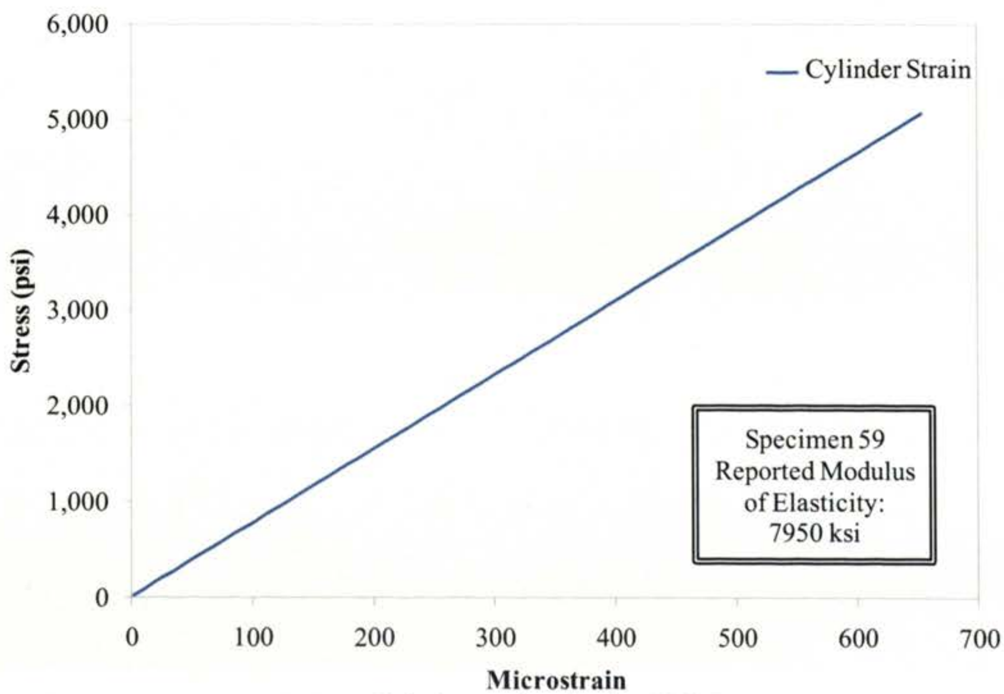


Figure B44. MOE Test for Mid-Strength Concrete, Polyurea B, Higher Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B45. MOE Test for Mid-Strength Concrete, Polyurea B, Higher Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B46. MOE Test for Mid-Strength Concrete, Polyurea B, Higher Fiber

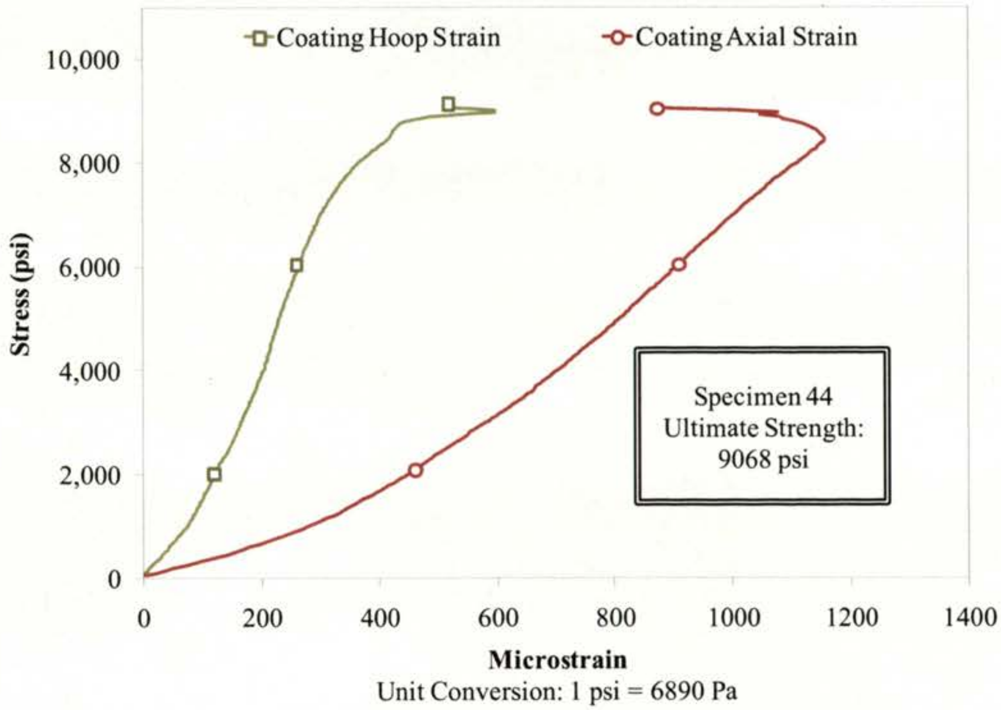


Figure B47. Strength Test for Mid-Strength Concrete, Polyurea A, No Fiber

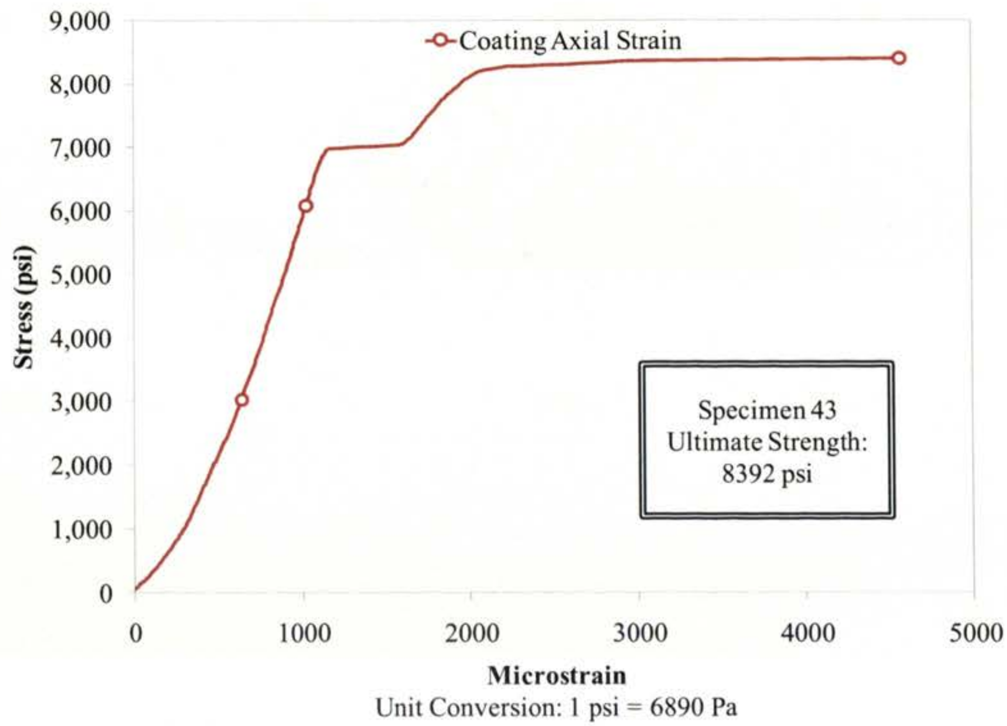


Figure B48. Strength Test for Mid-Strength Concrete, Polyurea A, No Fiber

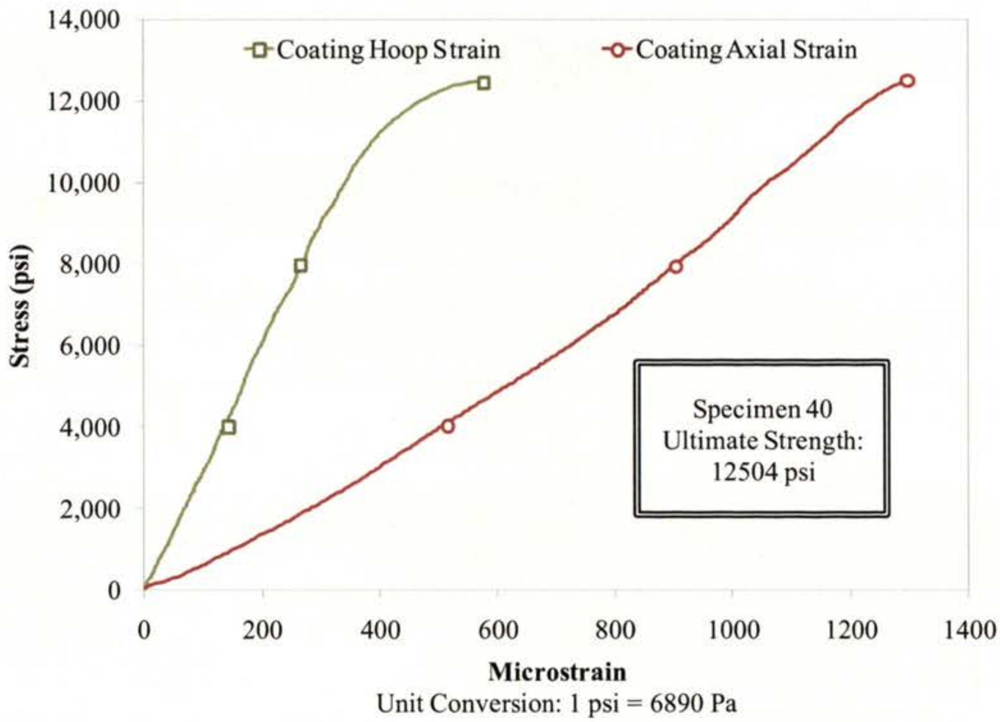


Figure B49. Strength Test for Mid-Strength Concrete, Polyurea A, Lower Fiber

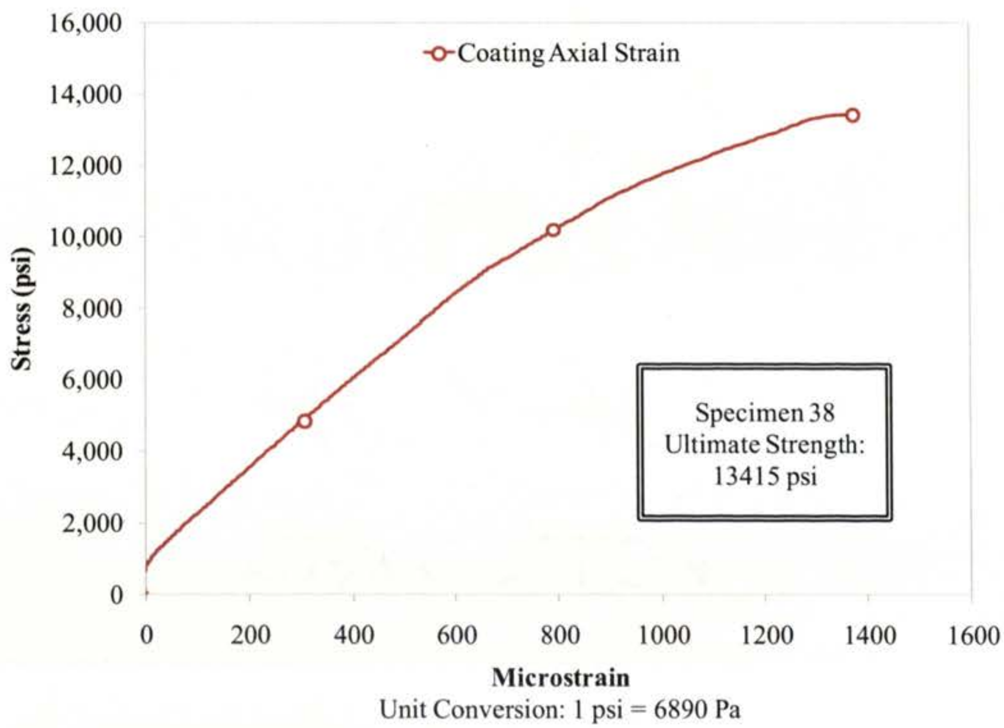


Figure B50. Strength Test for Mid-Strength Concrete, Polyurea A, Lower Fiber

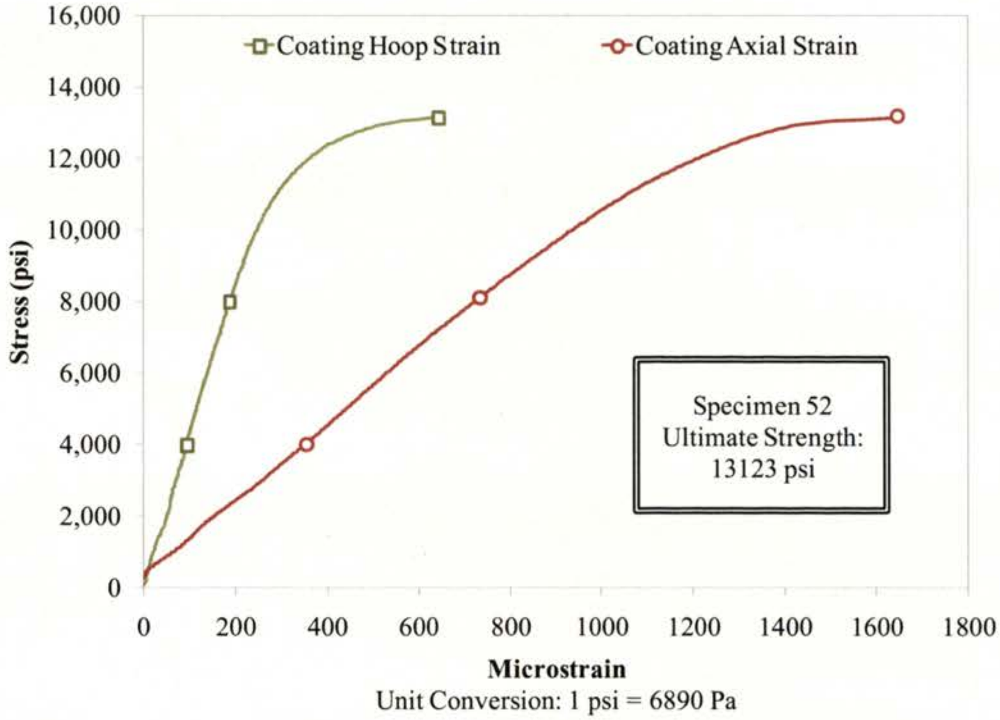


Figure B51. Strength Test for Mid-Strength Concrete, Polyurea B, No Fiber

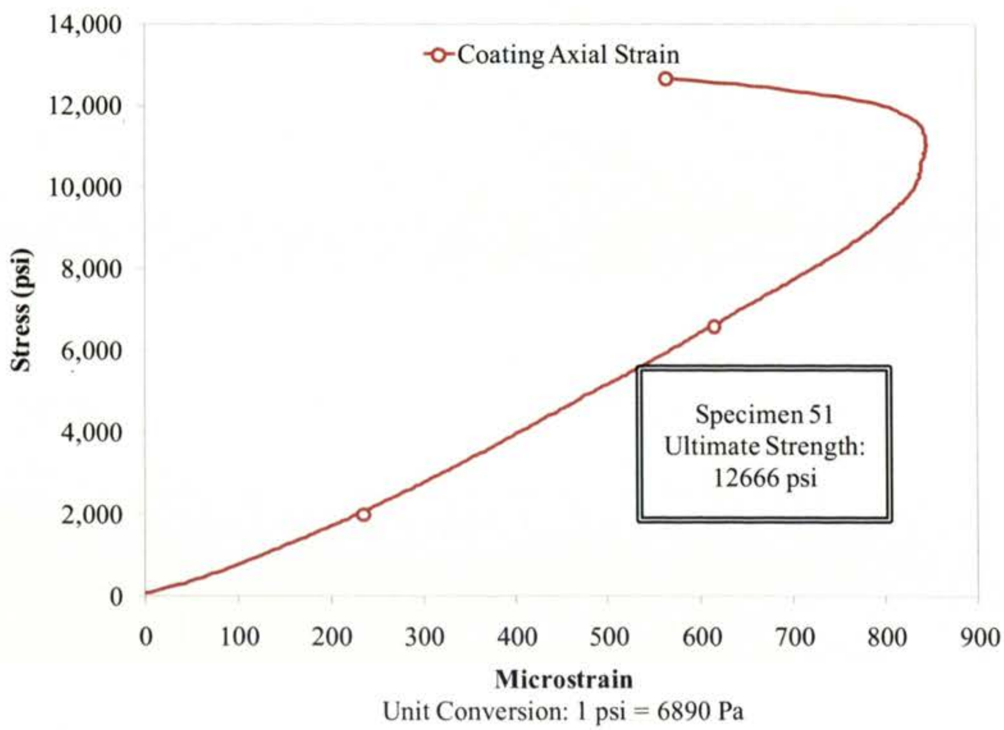


Figure B52. Strength Test for Mid-Strength Concrete, Polyurea B, No Fiber

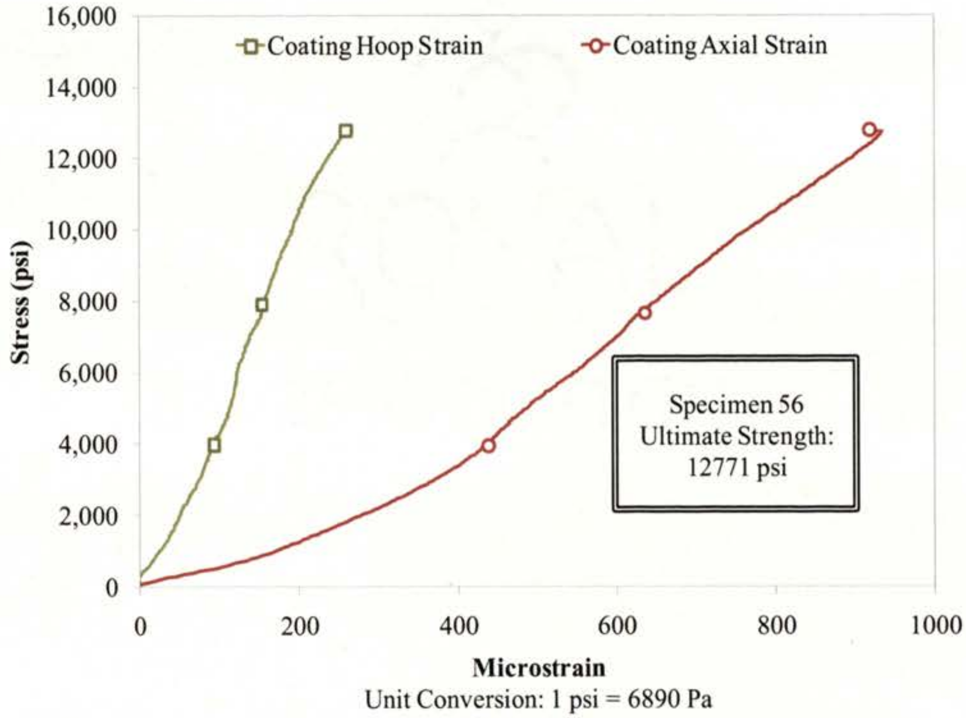


Figure B53. Strength Test for Mid-Strength Concrete, Polyurea B, Lower Fiber

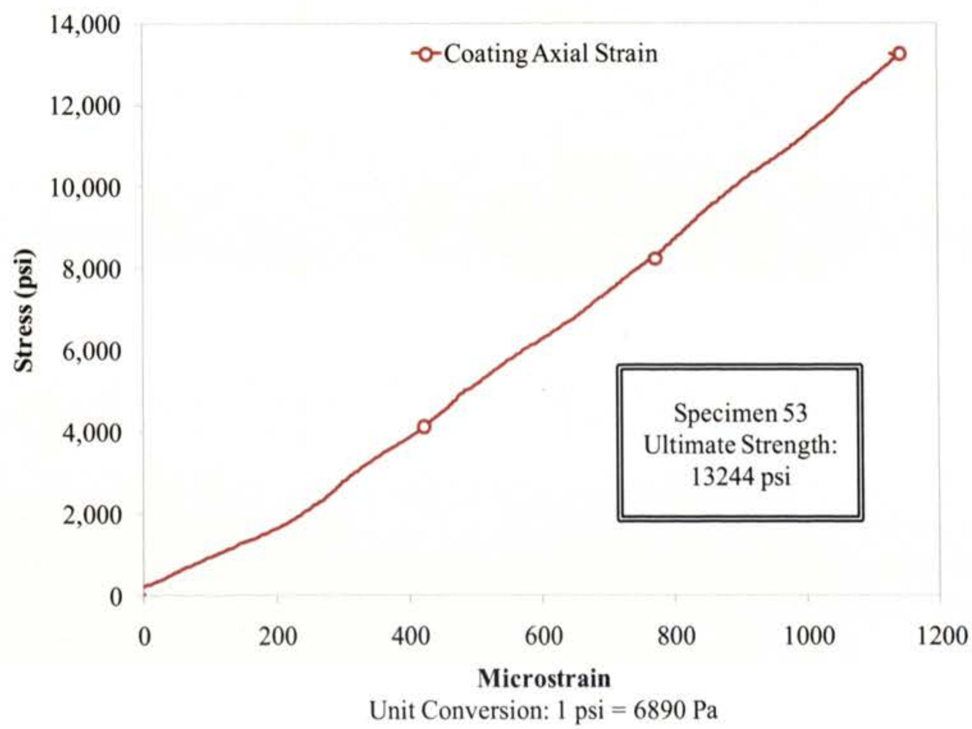
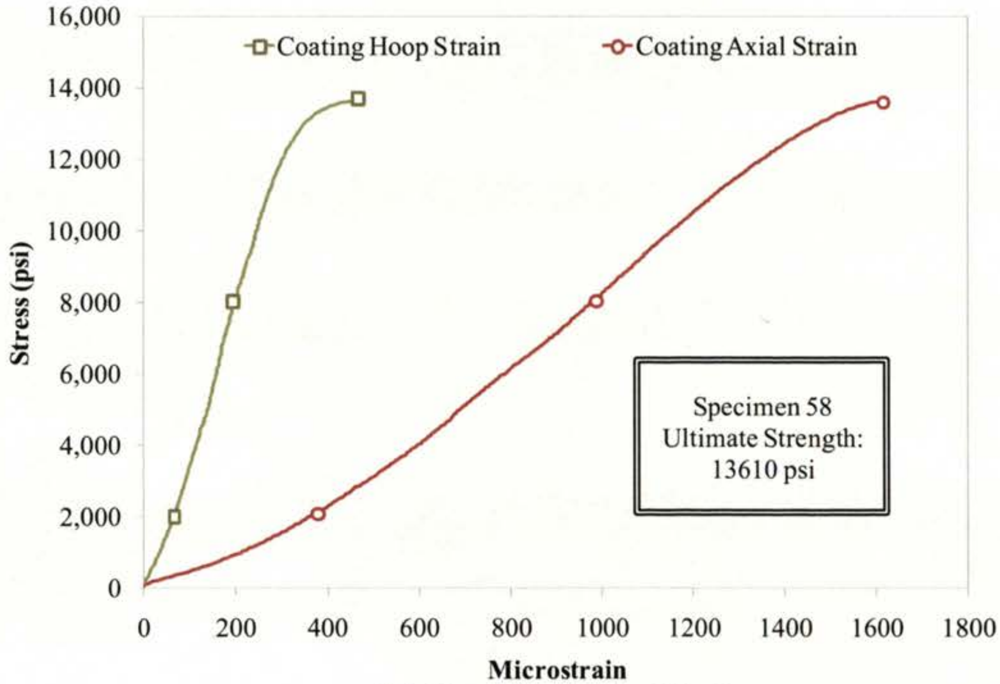
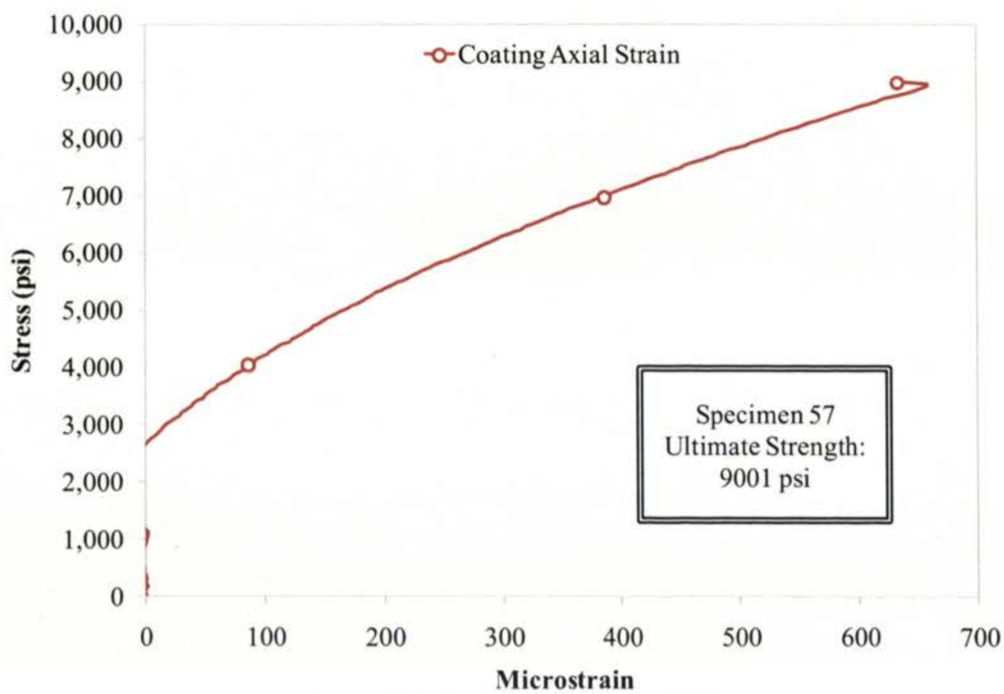


Figure B54. Strength Test for Mid-Strength Concrete, Polyurea B, Lower Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B55. Strength Test for Mid-Strength Concrete, Polyurea B, Higher Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B56. Strength Test for Mid-Strength Concrete, Polyurea B, Higher Fiber

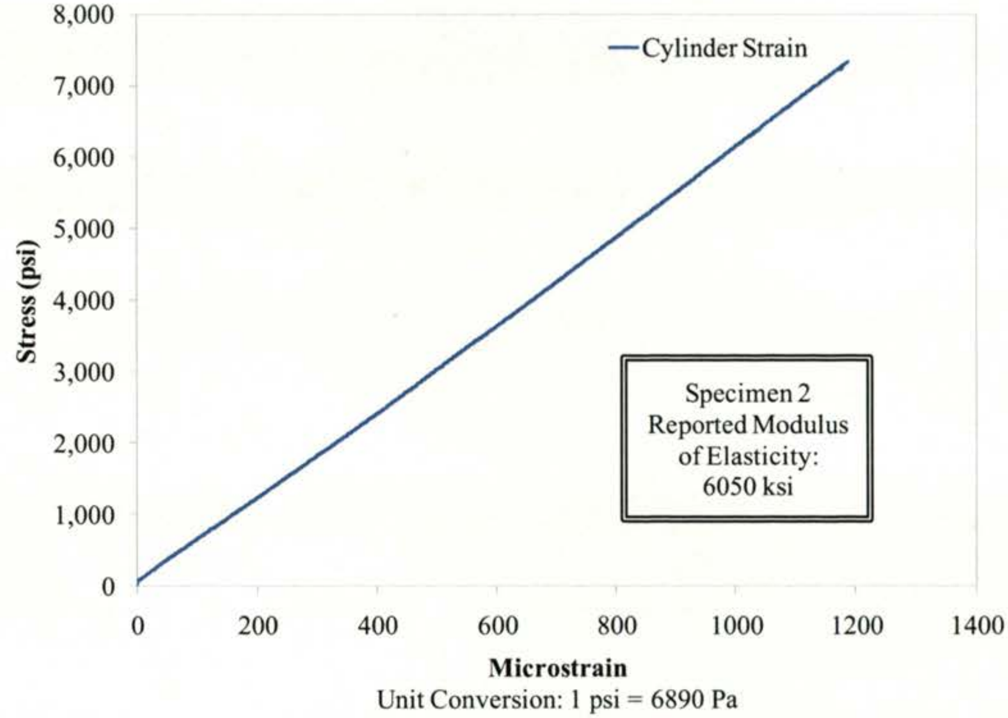


Figure B57. MOE Test for Higher-Strength Concrete, No Coating

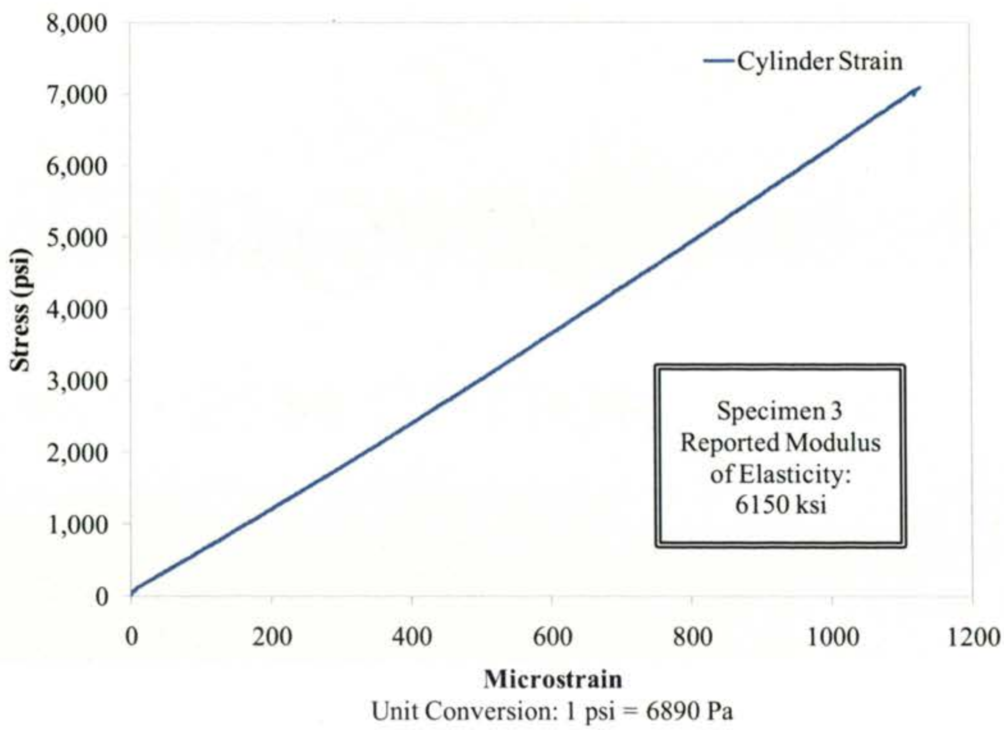
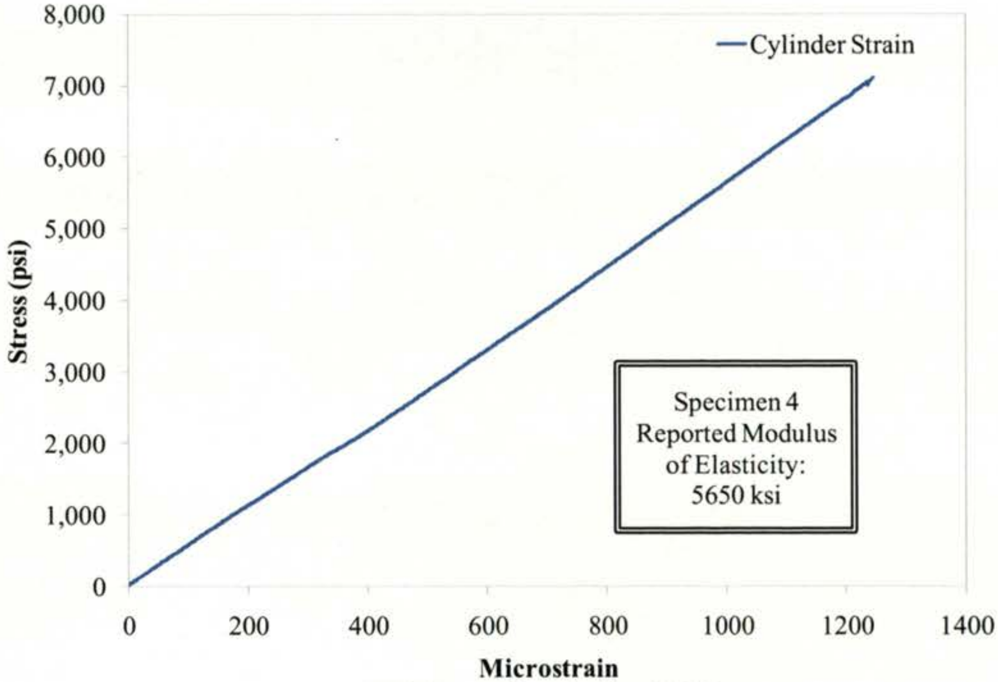
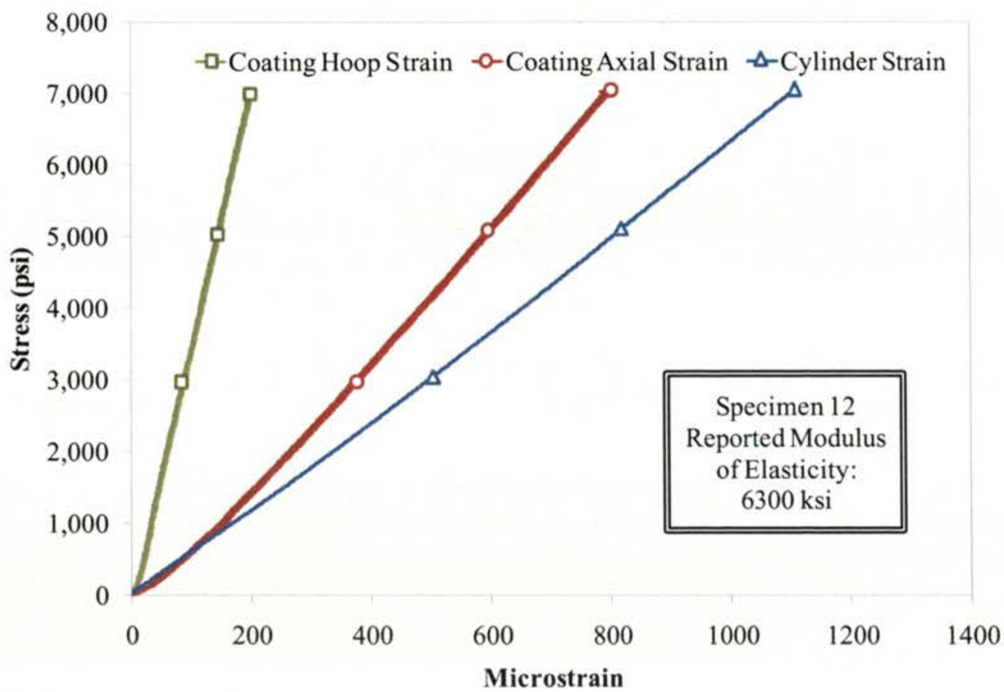


Figure B58. MOE Test for Higher-Strength Concrete, No Coating



Unit Conversion: 1 psi = 6890 Pa

Figure B59. MOE Test for Higher-Strength Concrete, No Coating



Unit Conversion: 1 psi = 6890 Pa

Figure B60. MOE Test for Higher-Strength Concrete, Polyurea A, No Fiber

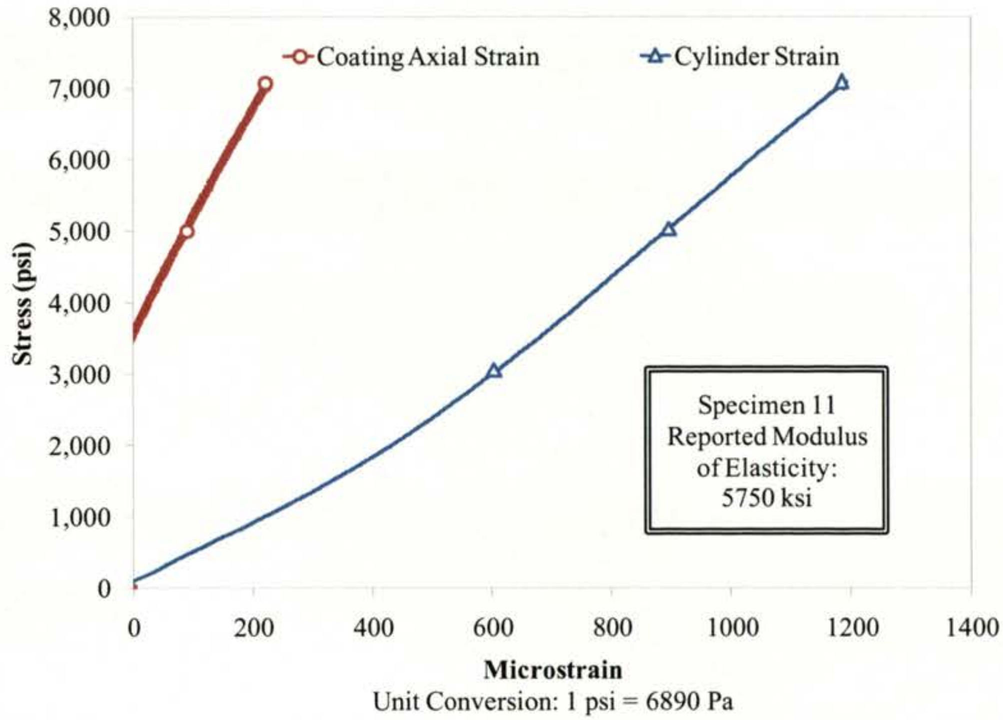


Figure B61. MOE Test for Higher-Strength Concrete, Polyurea A, No Fiber

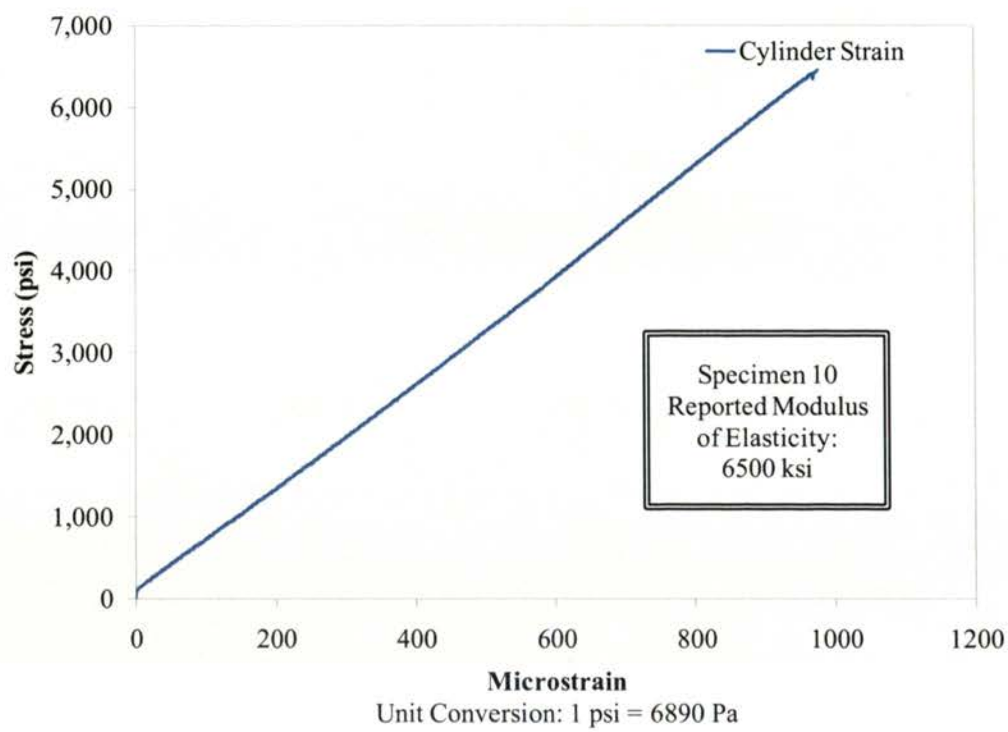
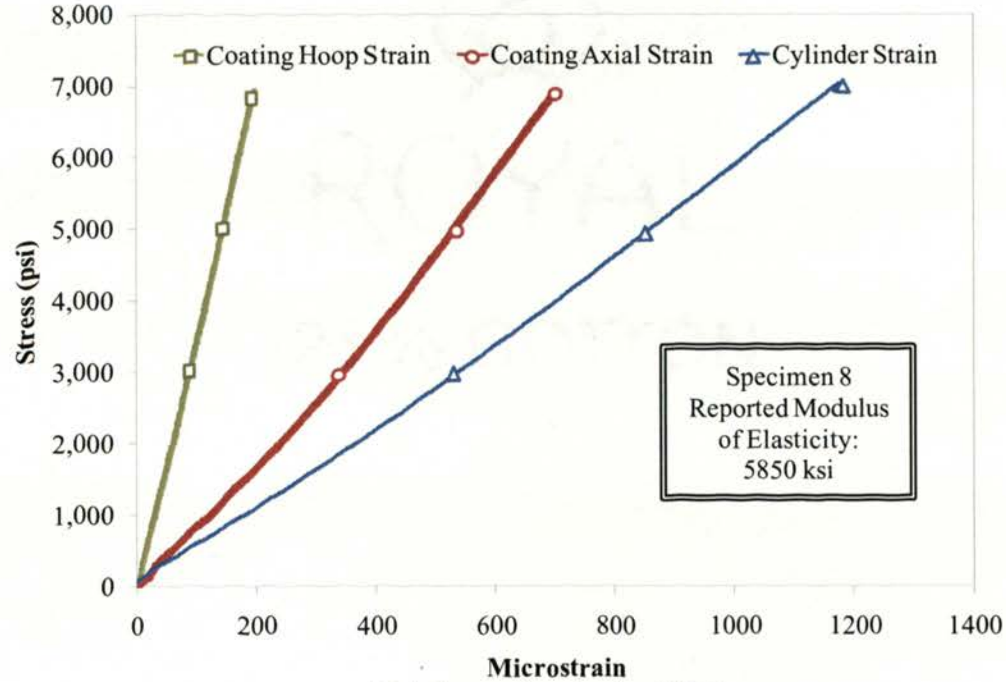
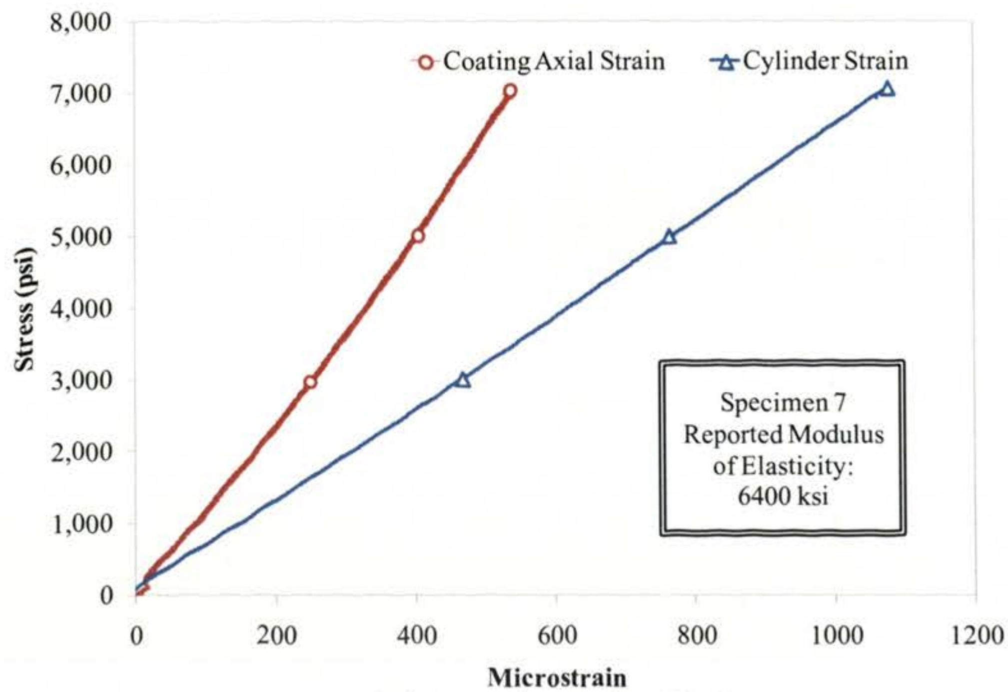


Figure B62. MOE Test for Higher-Strength Concrete, Polyurea A, No Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B63. MOE Test for Higher-Strength Concrete, Polyurea A, Lower Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B64. MOE Test for Higher-Strength Concrete, Polyurea A, Lower Fiber

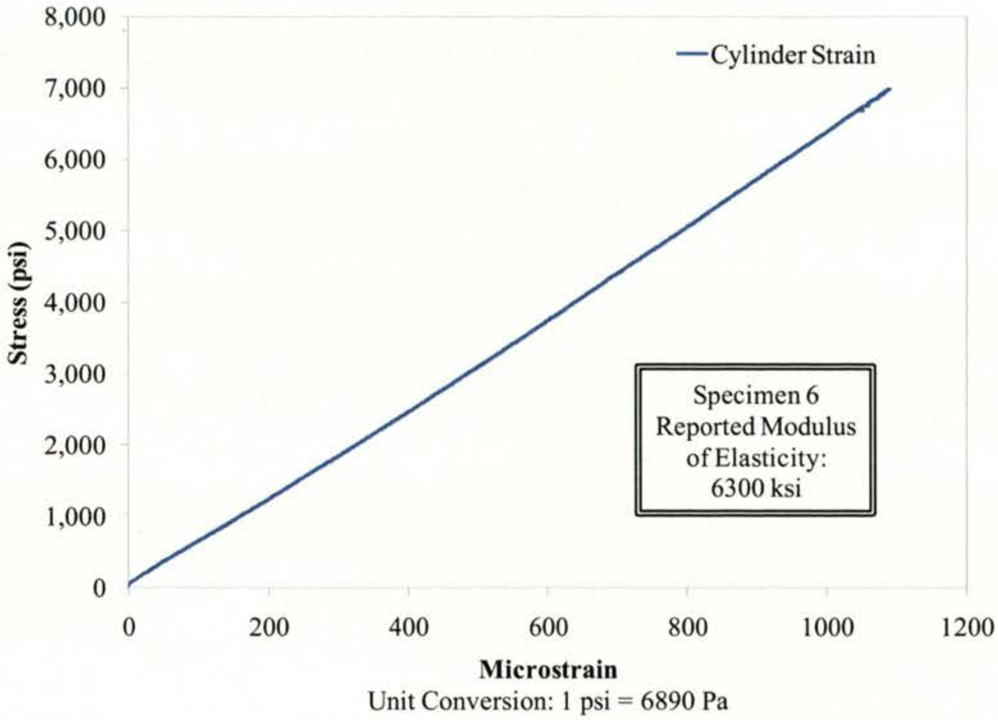


Figure B65. MOE Test for Higher-Strength Concrete, Polyurea A, Lower Fiber

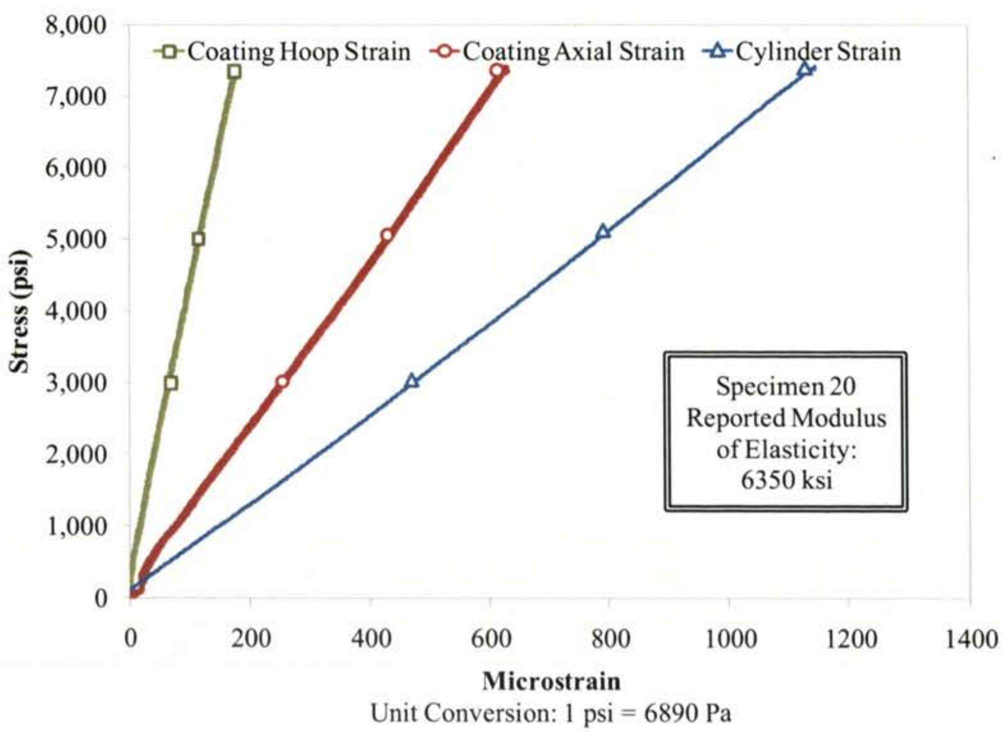


Figure B66. MOE Test for Higher-Strength Concrete, Polyurea B, No Fiber

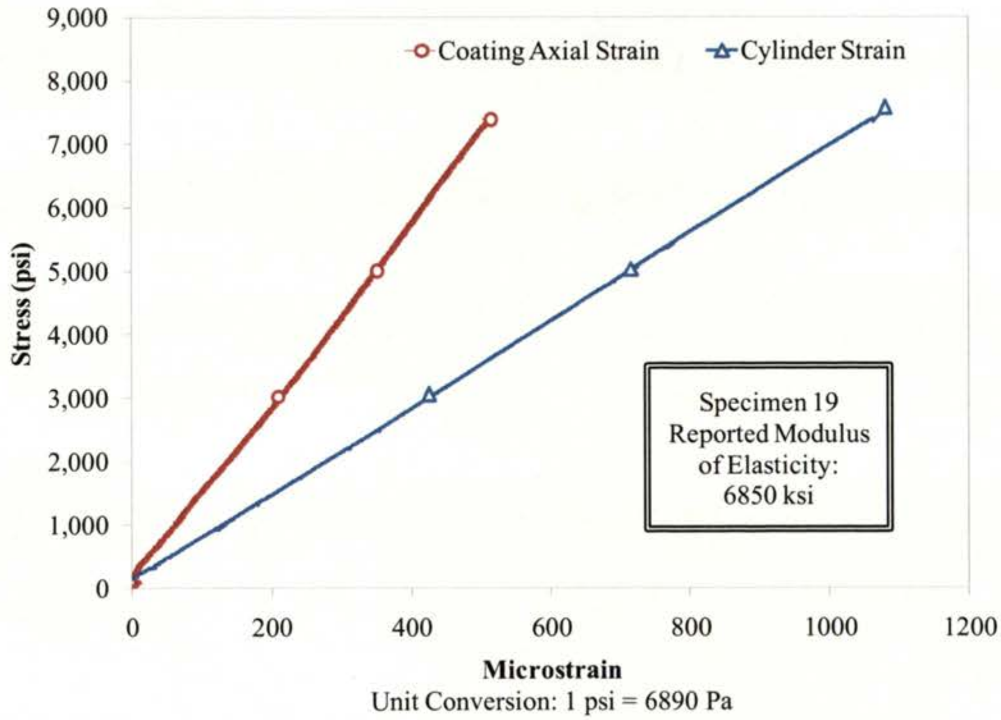


Figure B67. MOE Test for Higher-Strength Concrete, Polyurea B, No Fiber

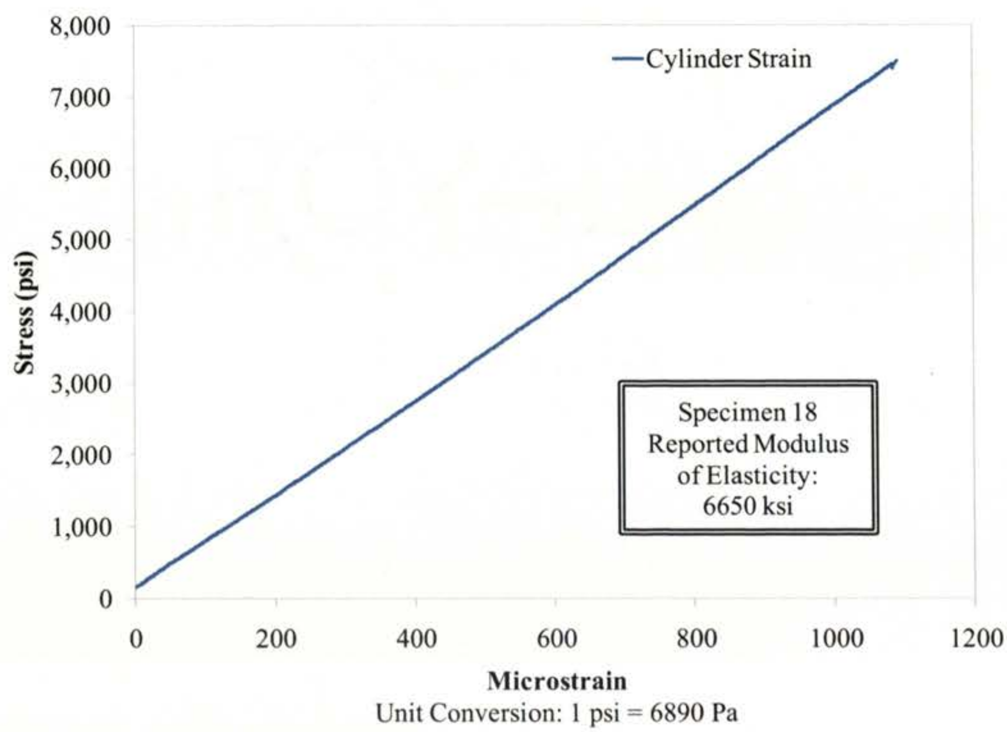


Figure B68. MOE Test for Higher-Strength Concrete, Polyurea B, No Fiber

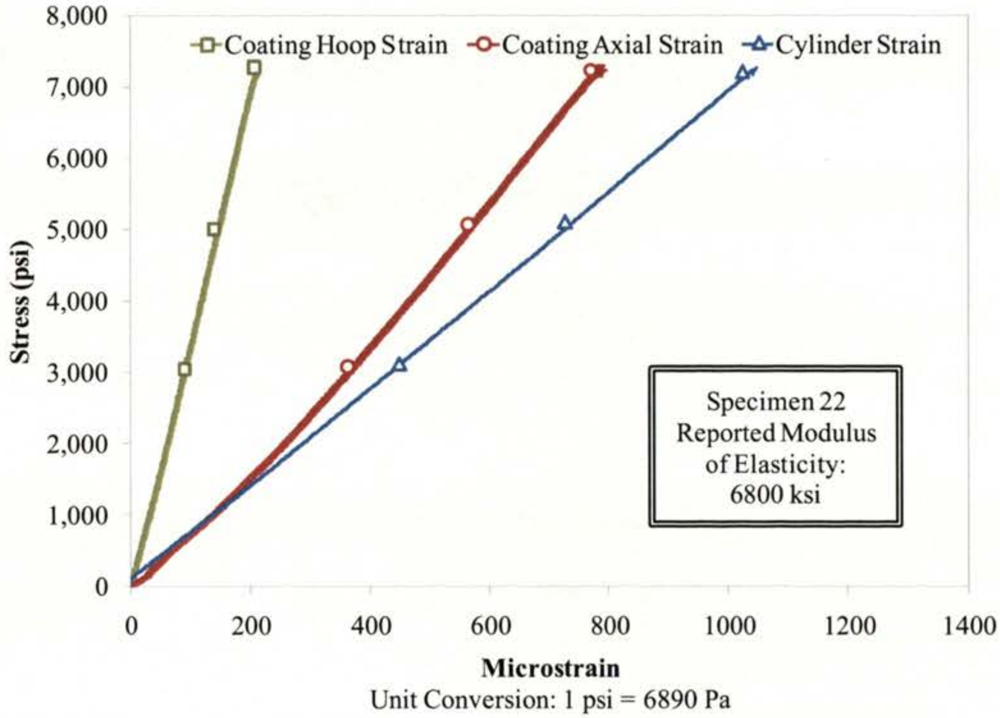


Figure B69. MOE Test for Higher-Strength Concrete, Polyurea B, Lower Fiber

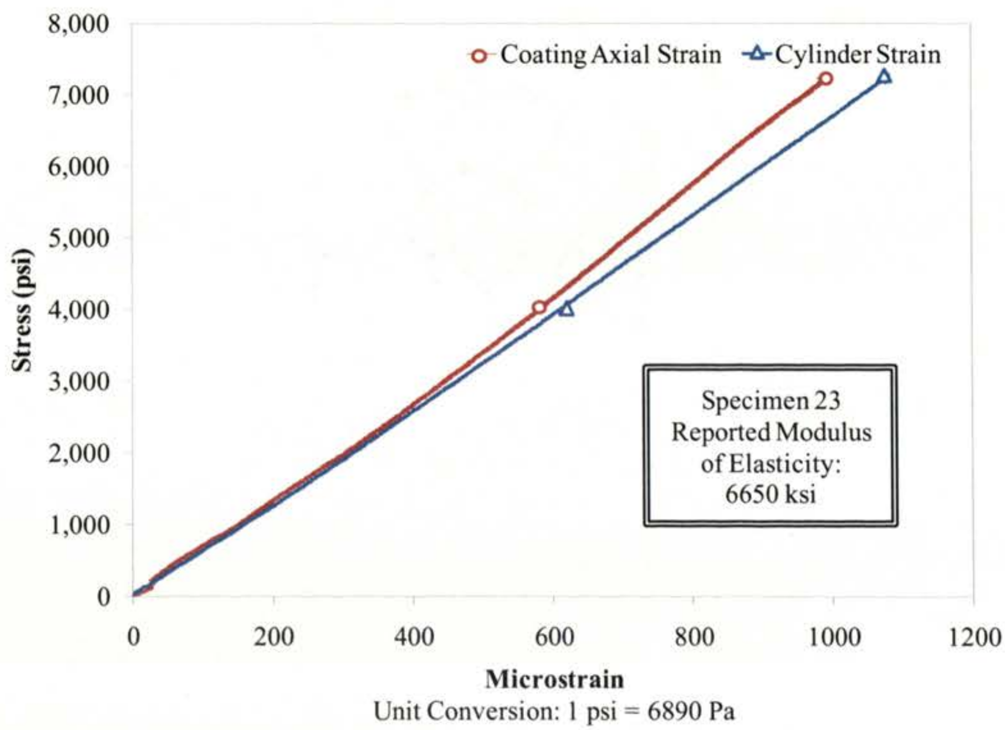


Figure B70. MOE Test for Higher-Strength Concrete, Polyurea B, Lower Fiber

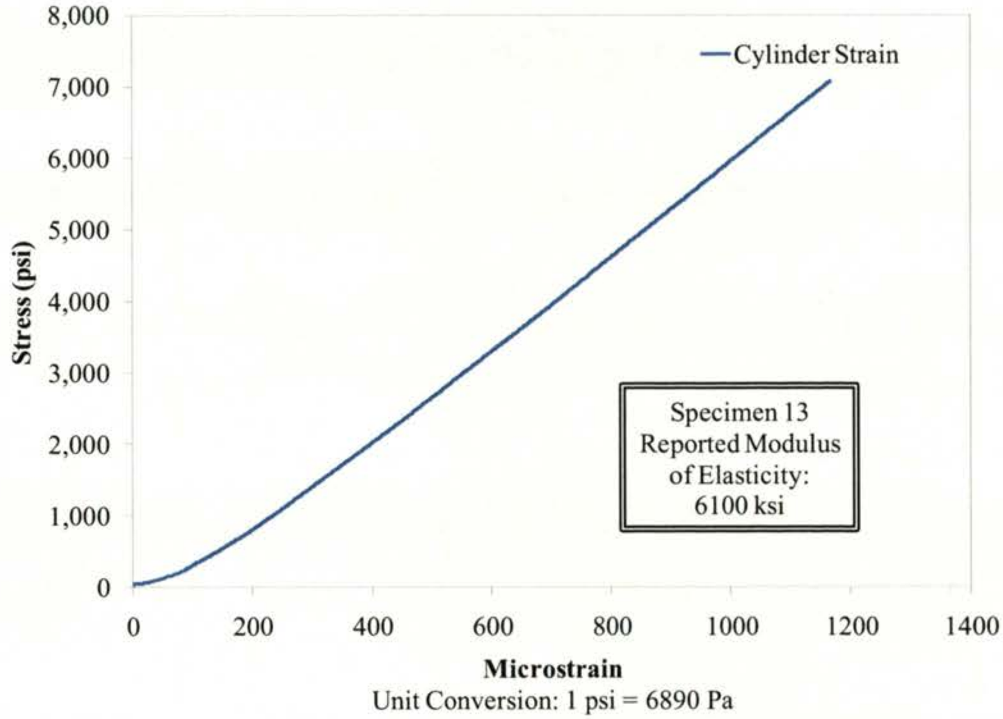


Figure B71. MOE Test for Higher-Strength Concrete, Polyurea B, Lower Fiber

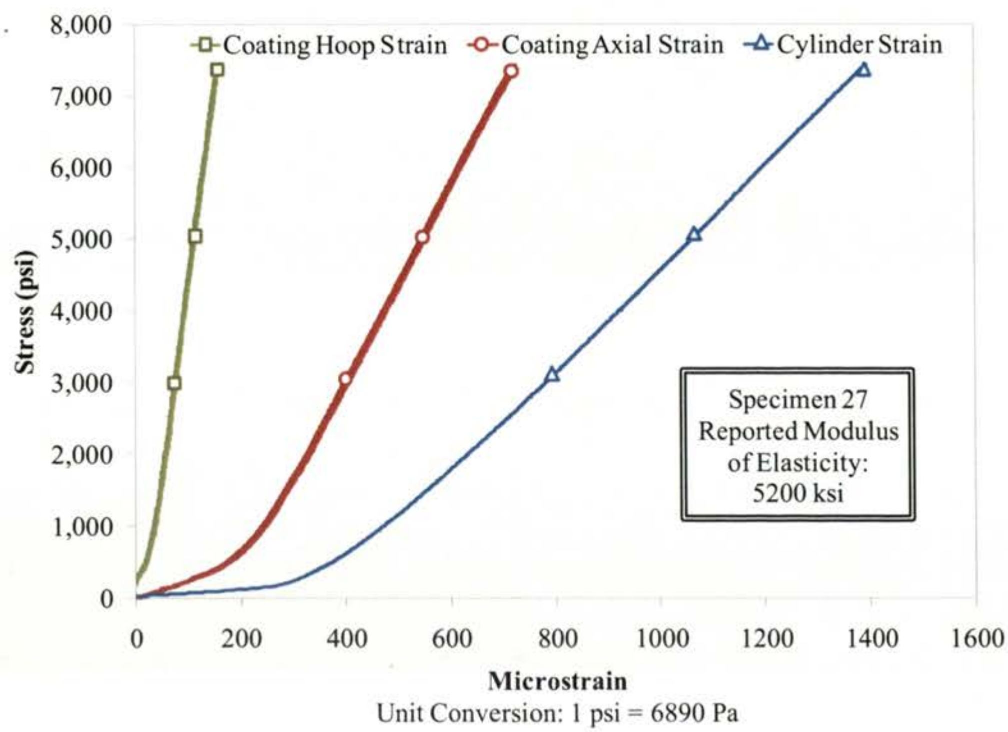


Figure B72. MOE Test for Higher-Strength Concrete, Polyurea B, Higher Fiber

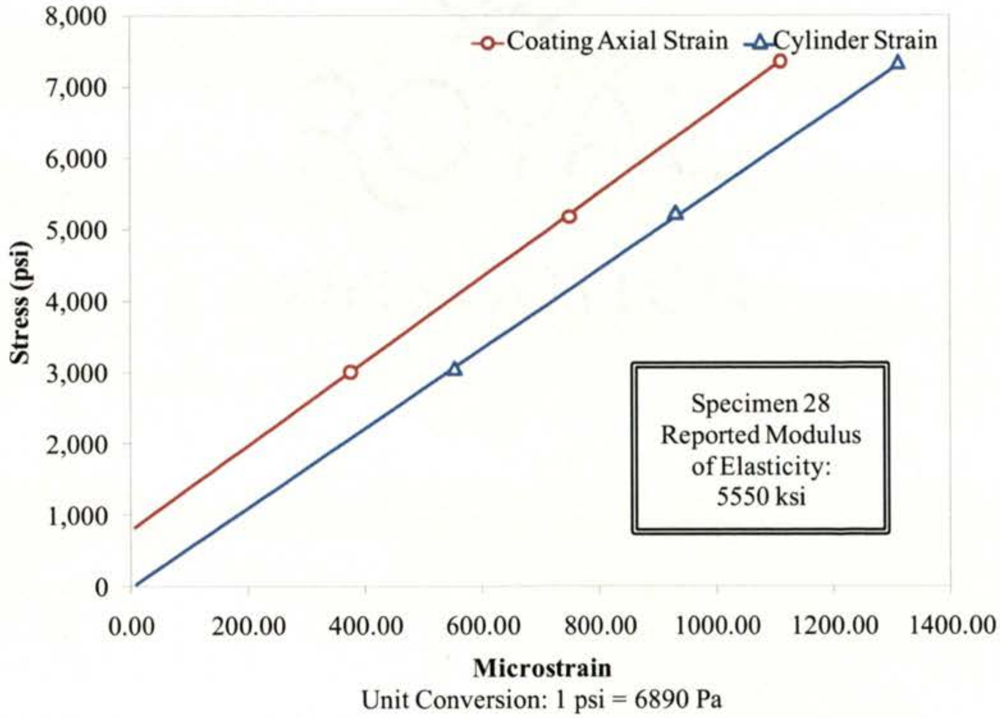


Figure B73. MOE Test for Higher-Strength Concrete, Polyurea B, Higher Fiber

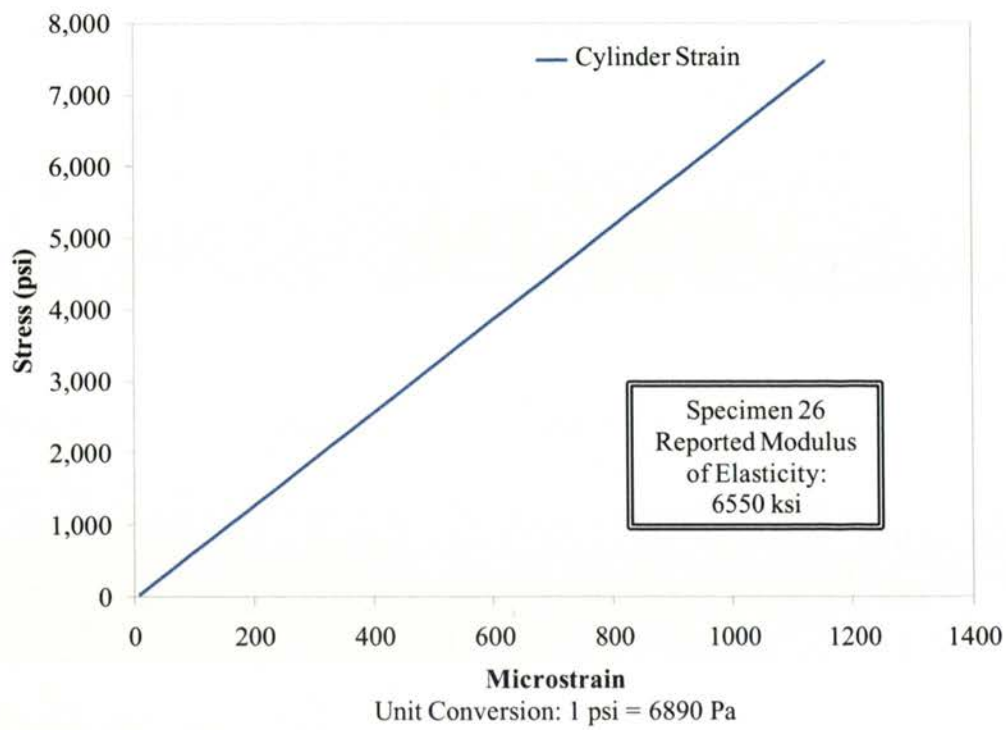


Figure B74. MOE Test for Higher-Strength Concrete, Polyurea B, Higher Fiber

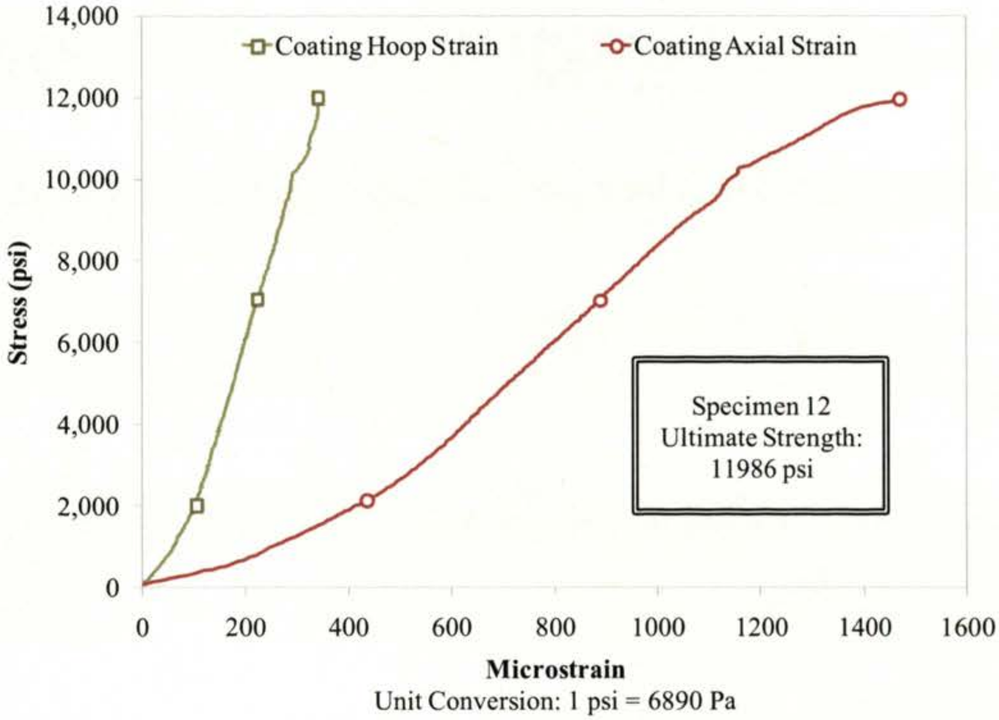


Figure B75. Strength Test for Higher-Strength Concrete, Polyurea A, No Fiber

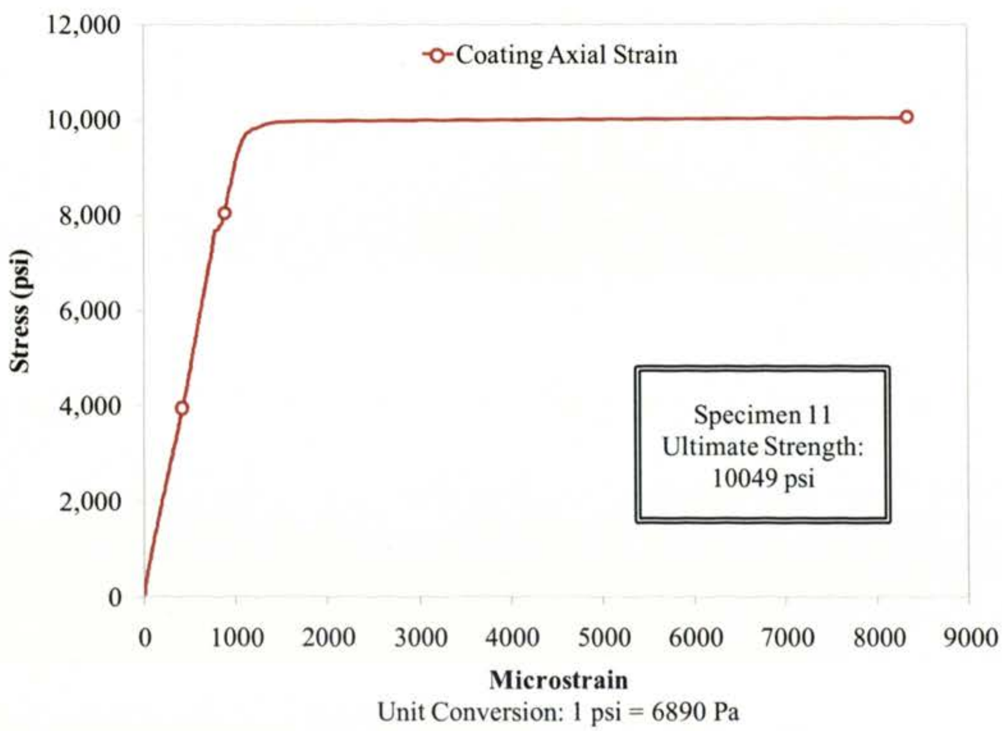


Figure B76. Strength Test for Higher-Strength Concrete, Polyurea A, No Fiber

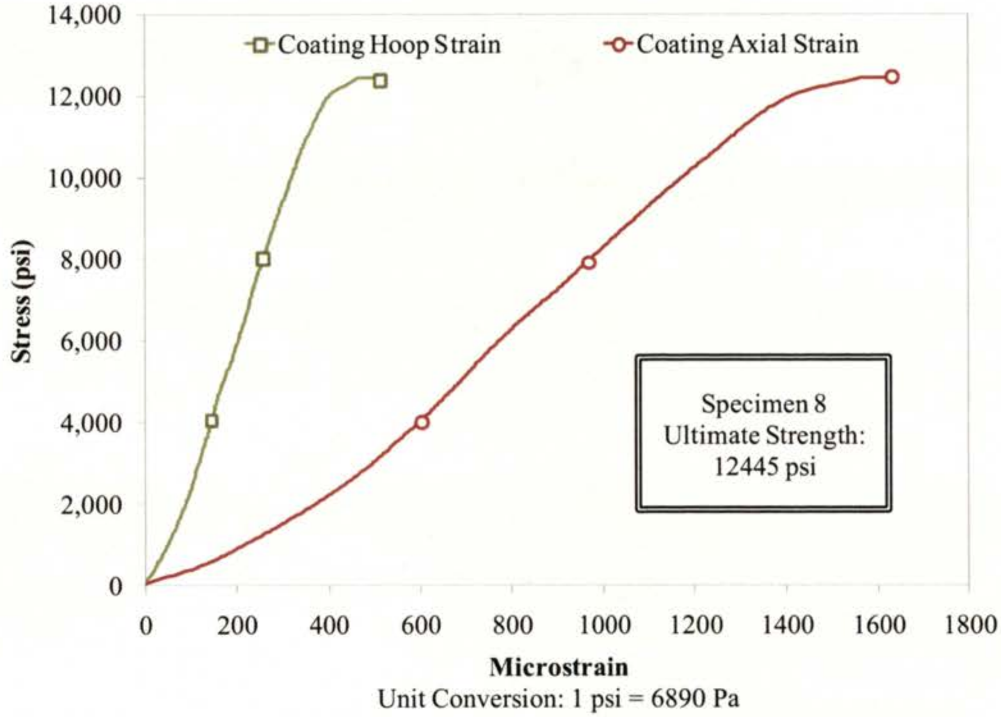


Figure B77. Strength Test for Higher-Strength Concrete, Polyurea A, Lower Fiber

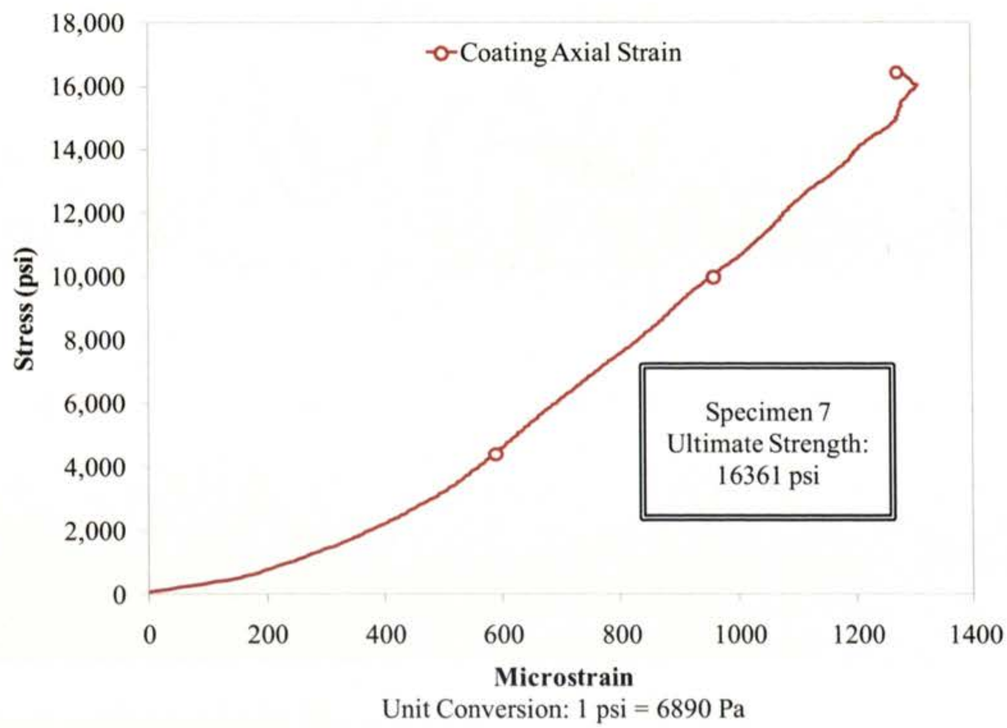
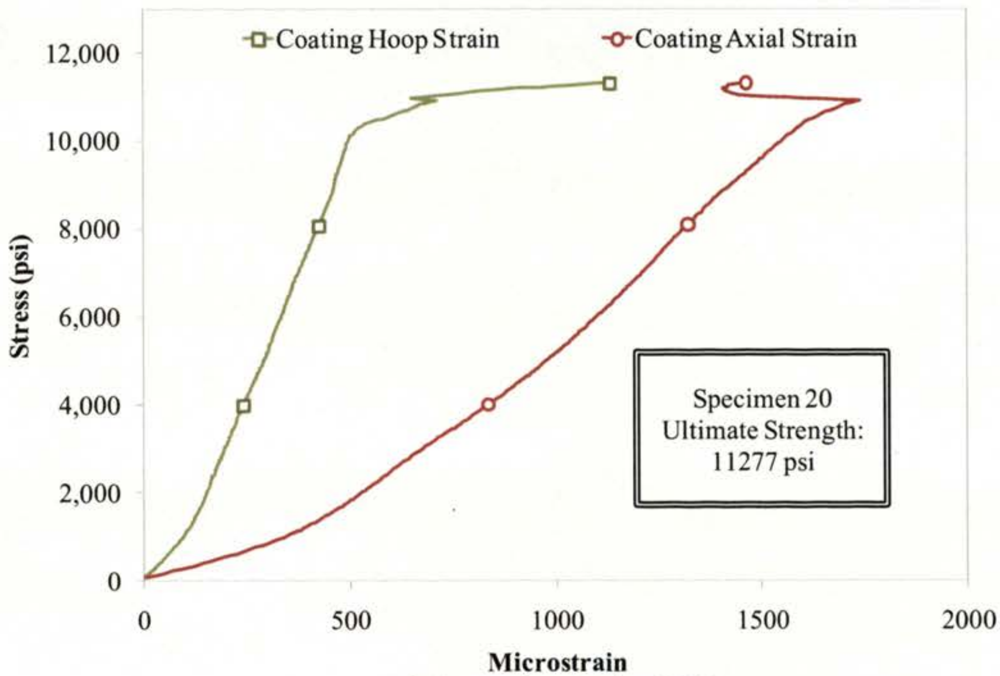
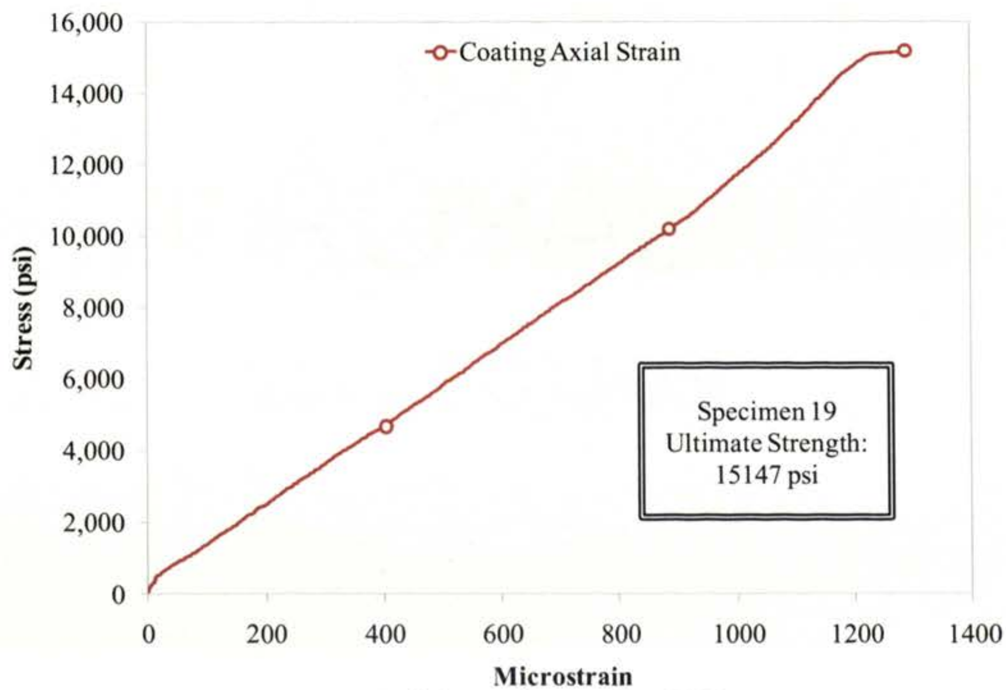


Figure B78. Strength Test for Higher-Strength Concrete, Polyurea A, Lower Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B79. Strength Test for Higher-Strength Concrete, Polyurea B, No Fiber



Unit Conversion: 1 psi = 6890 Pa

Figure B80. Strength Test for Higher-Strength Concrete, Polyurea B, No Fiber

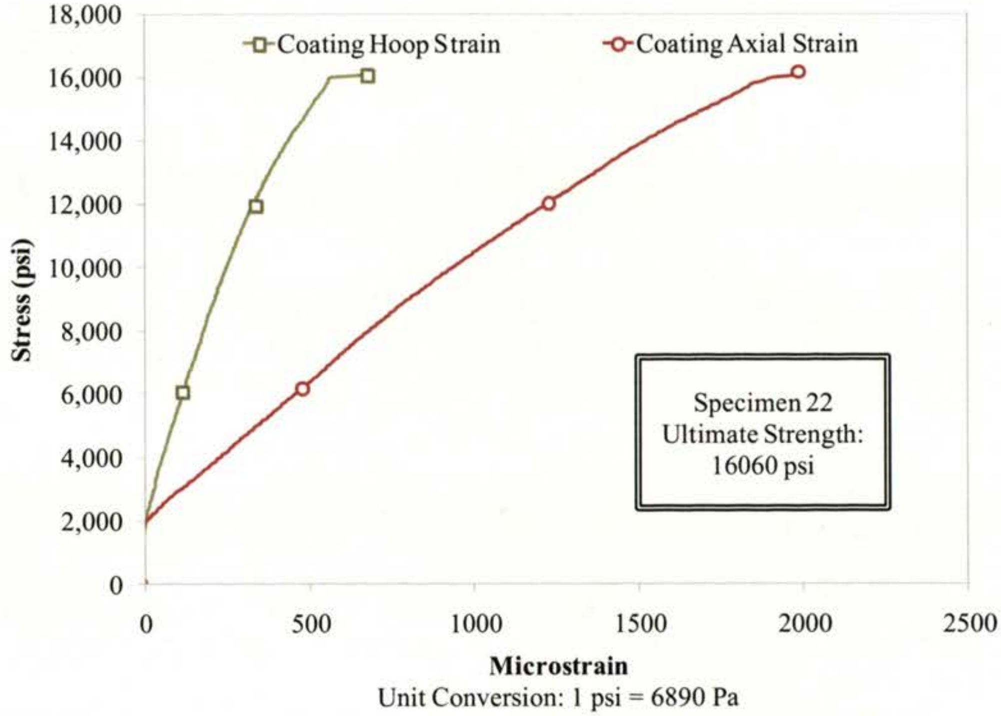


Figure B81. Strength Test for Higher-Strength Concrete, Polyurea B, Lower Fiber

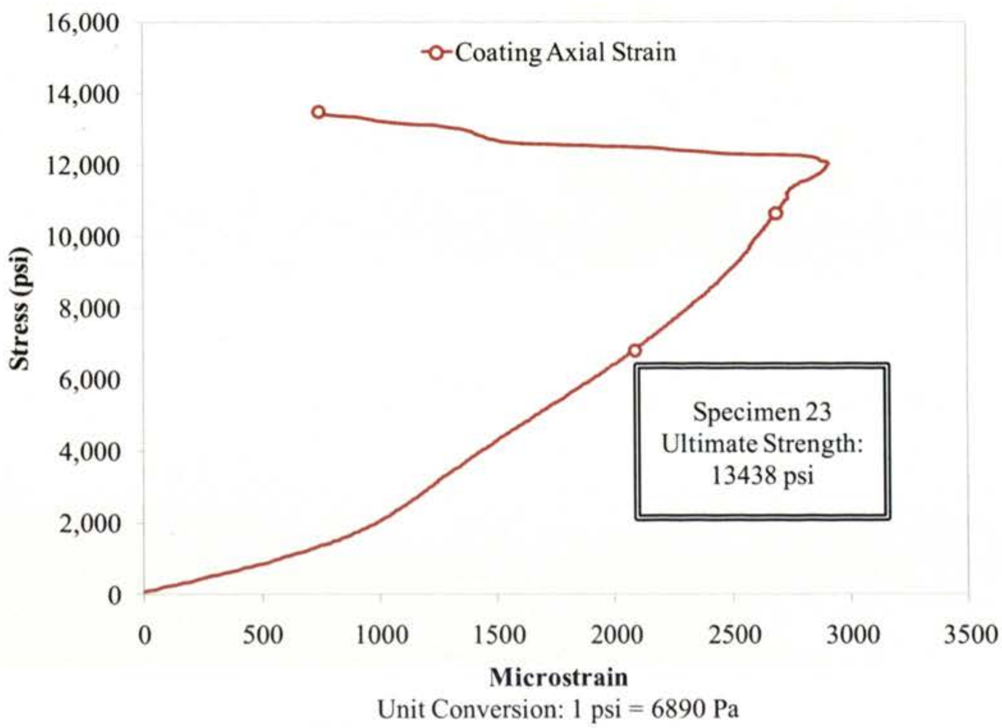


Figure B82. Strength Test for Higher-Strength Concrete, Polyurea B, Lower Fiber

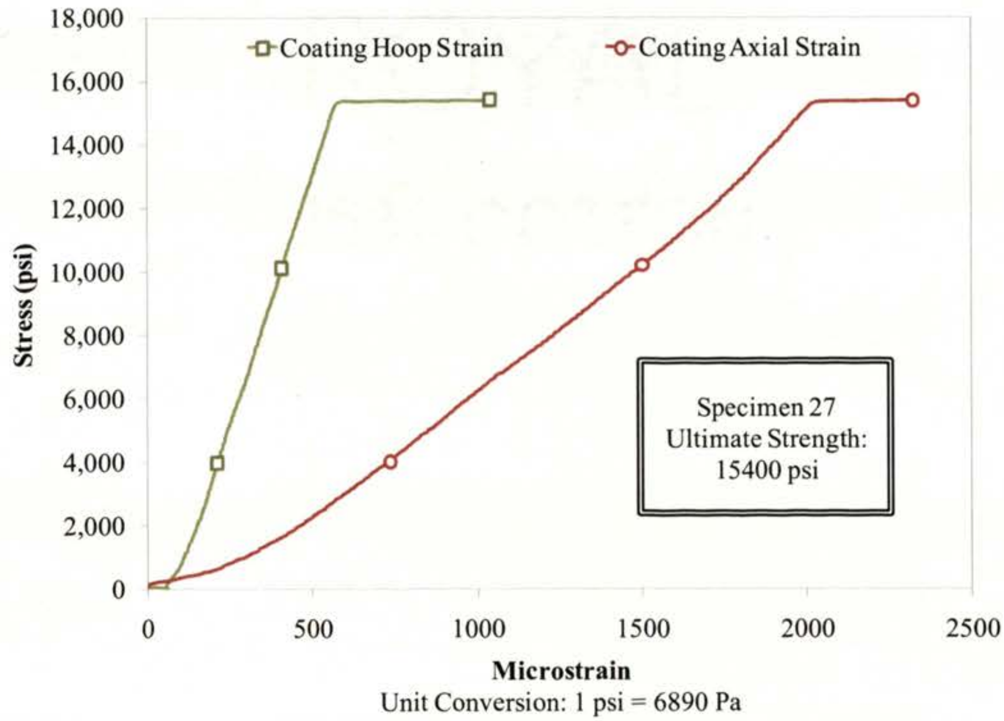


Figure B83. Strength Test for Higher-Strength Concrete, Polyurea B, Higher Fiber

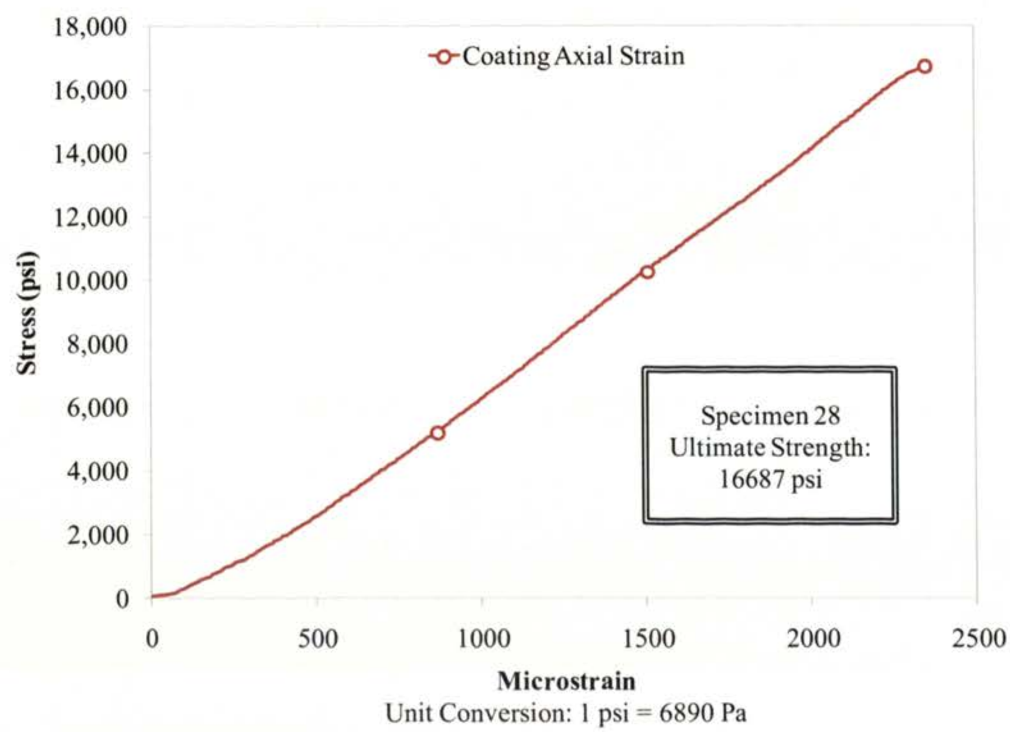


Figure B84. Strength Test for Higher-Strength Concrete, Polyurea B, Higher Fiber

APPENDIX C

BEAM TESTING LOAD VERSUS DEFLECTION DATA

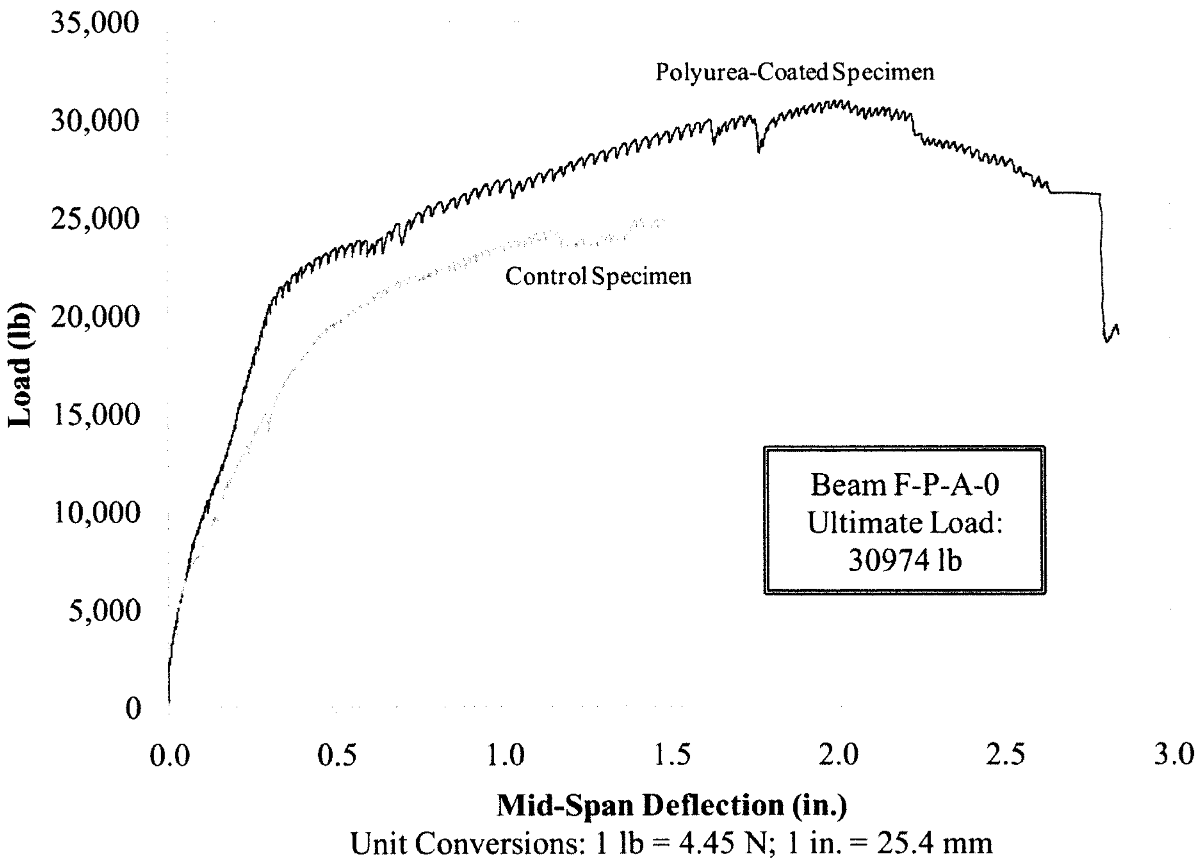


Figure C1. Flexural Test Beam, Polyurea A, No Fiber

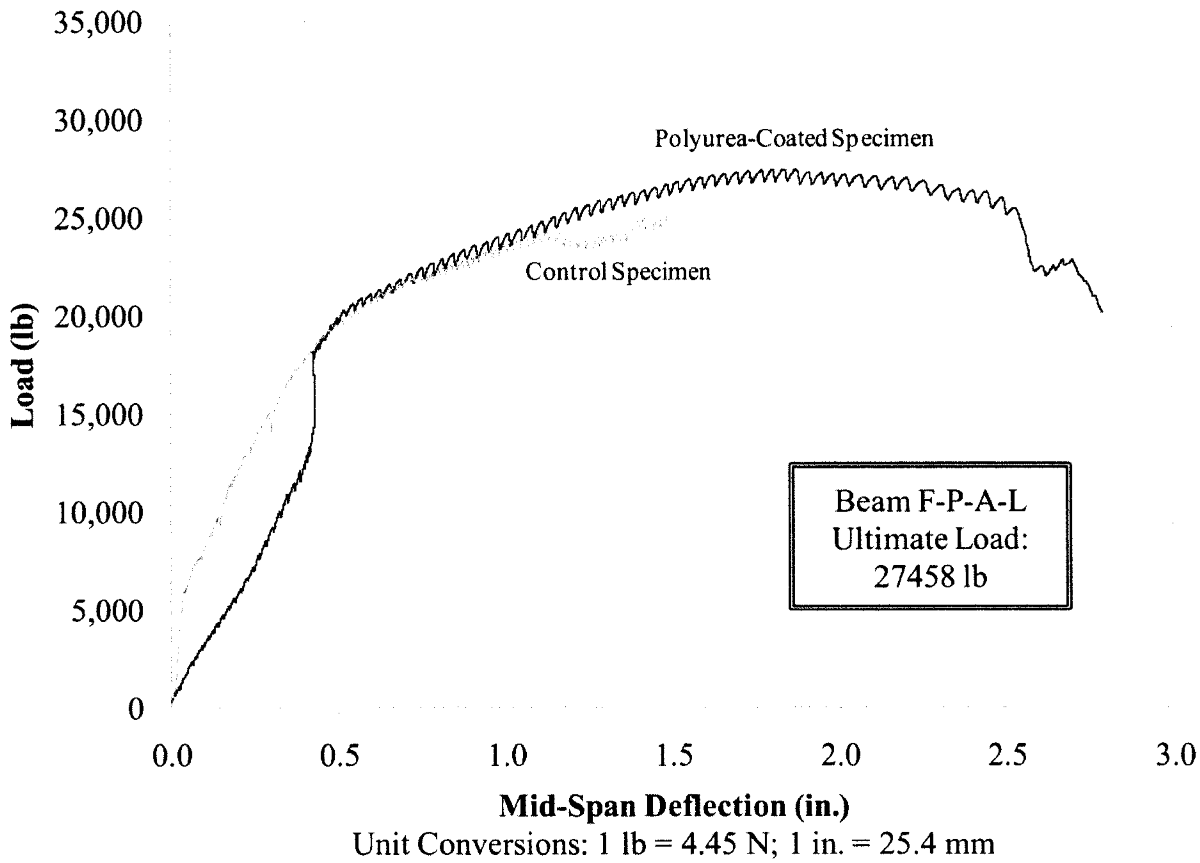


Figure C2. Flexural Test Beam, Polyurea A with Fiber

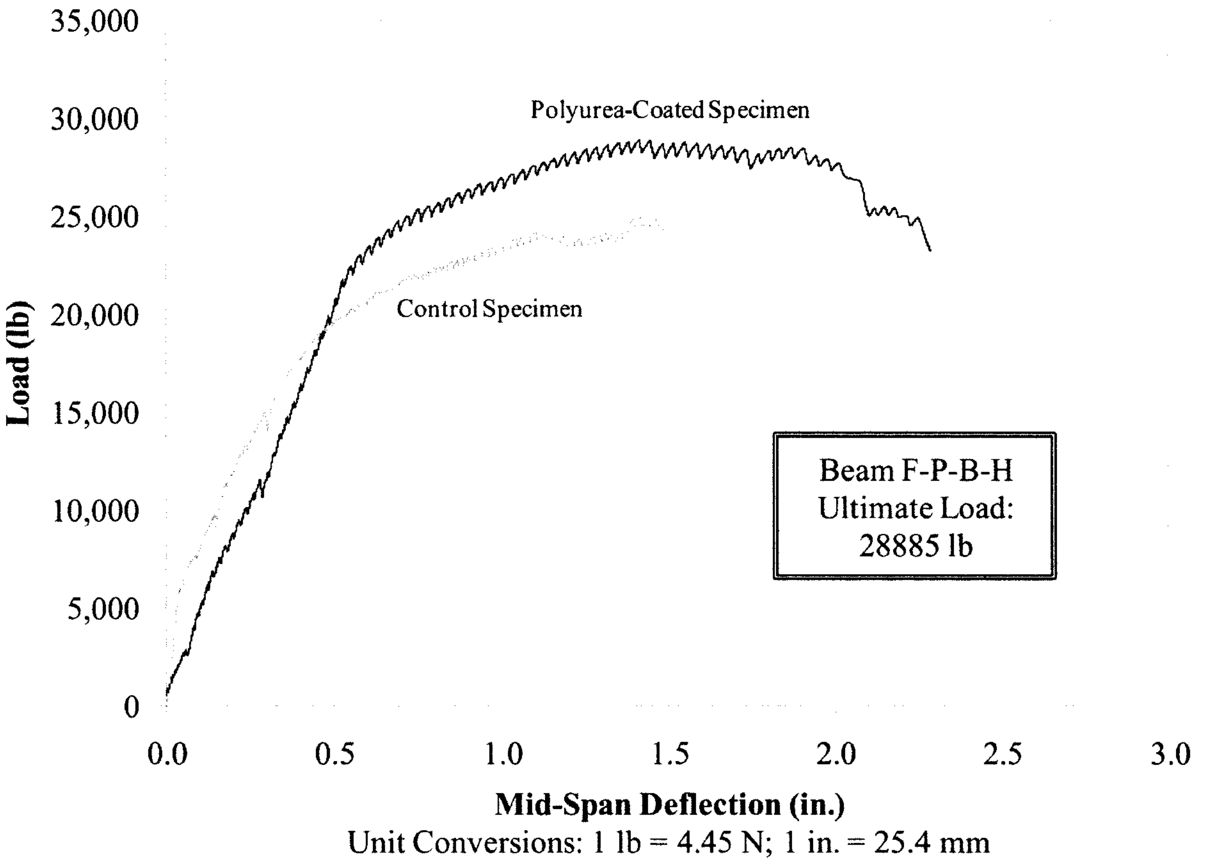


Figure C3. Flexural Test Beam, Polyurea B with Fiber

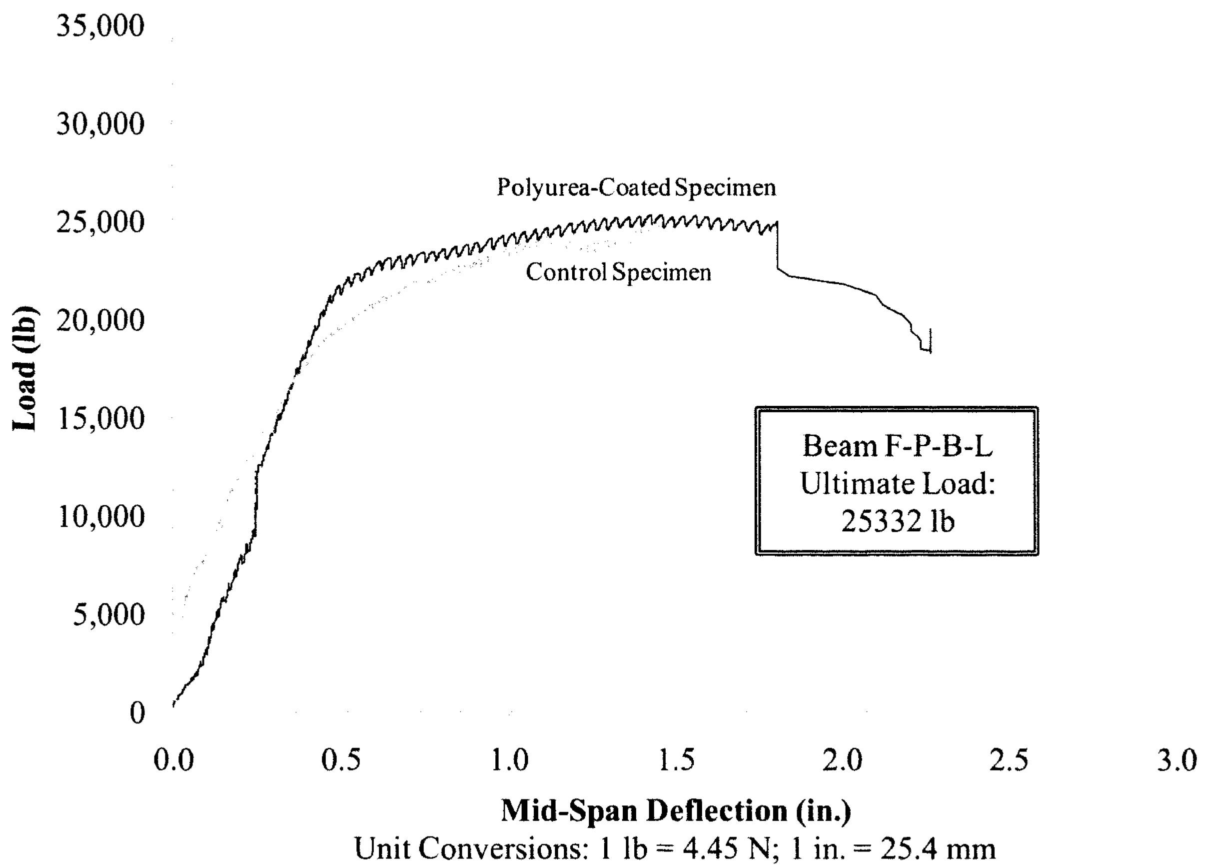


Figure C4. Flexural Test Beam, Polyurea B with Fiber

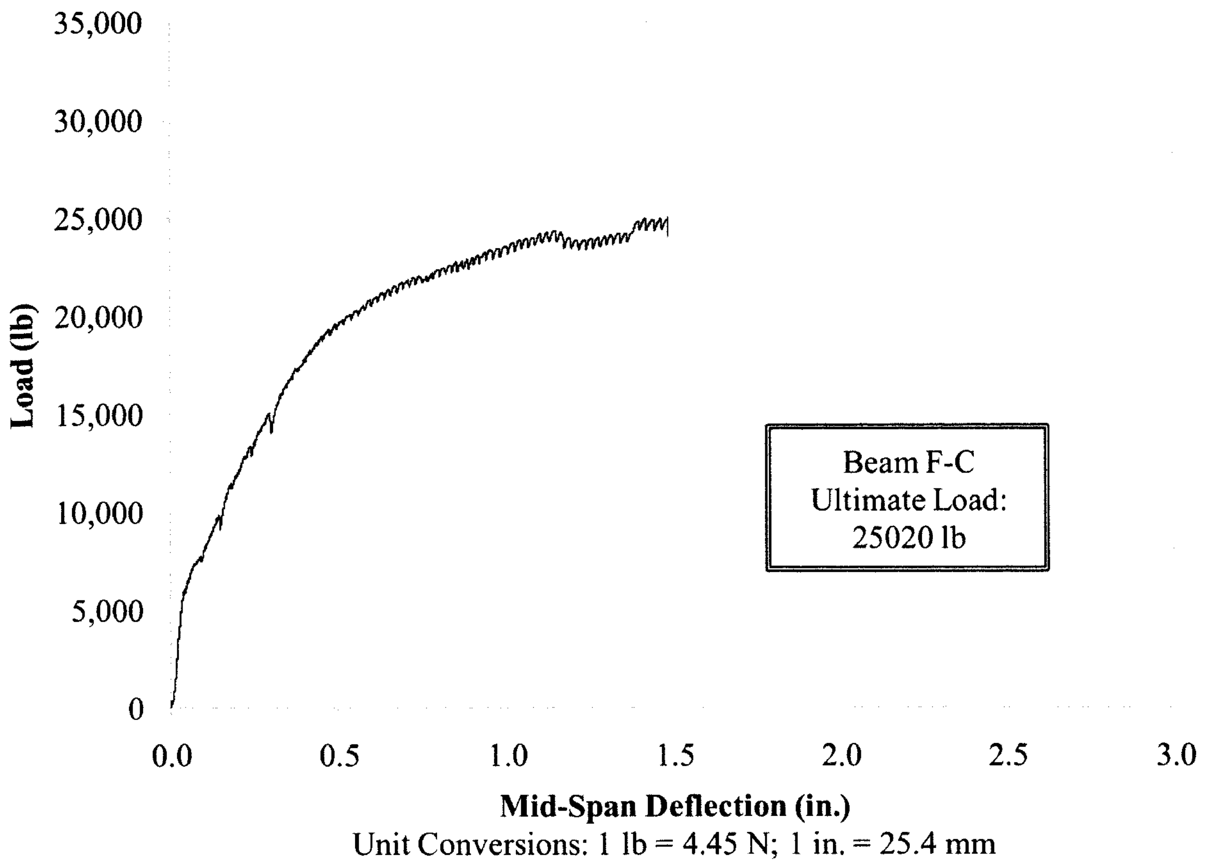


Figure C5. Flexural Test Beam, No Coating

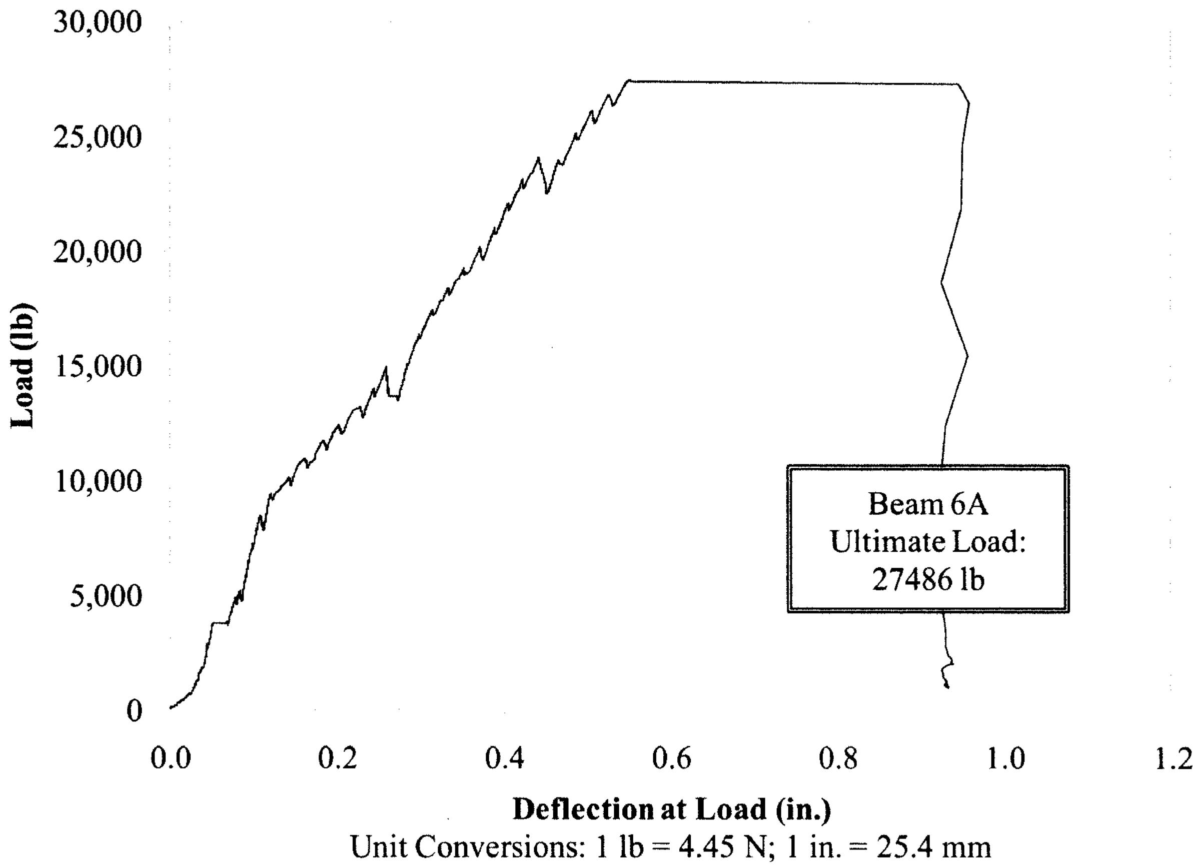
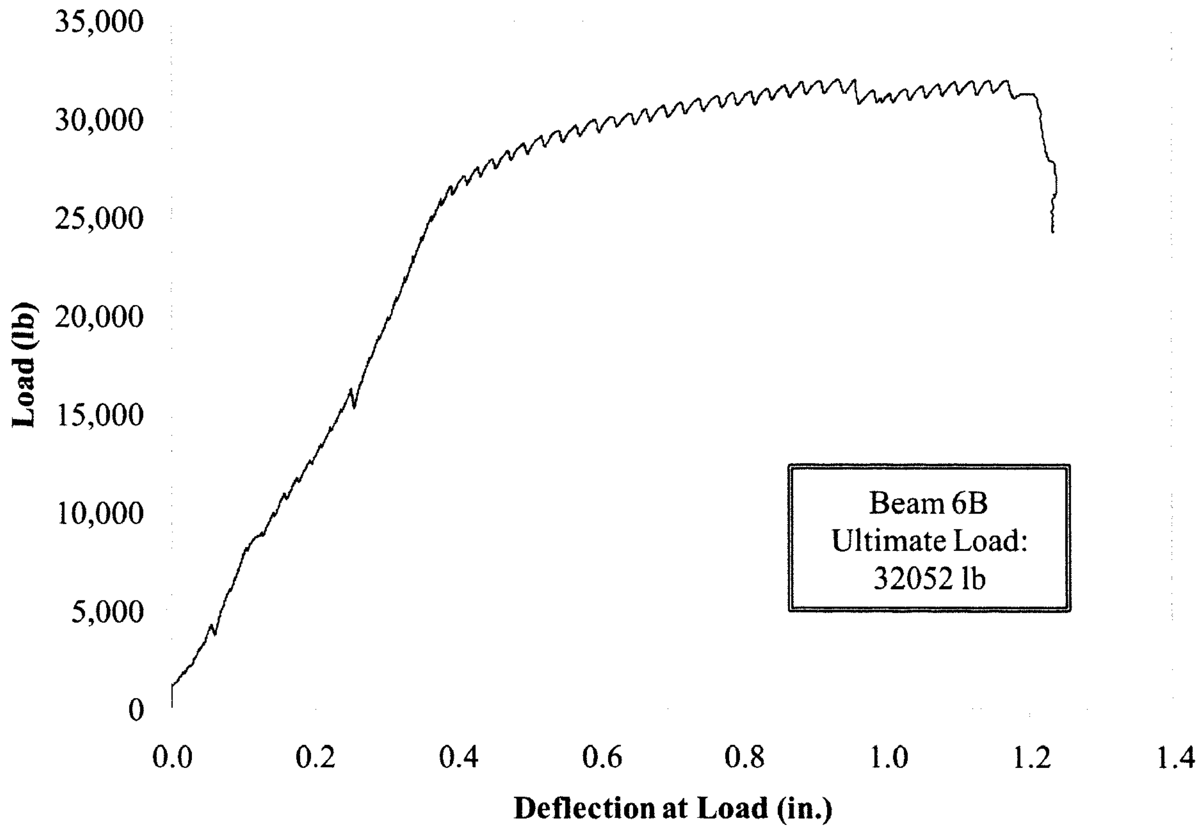
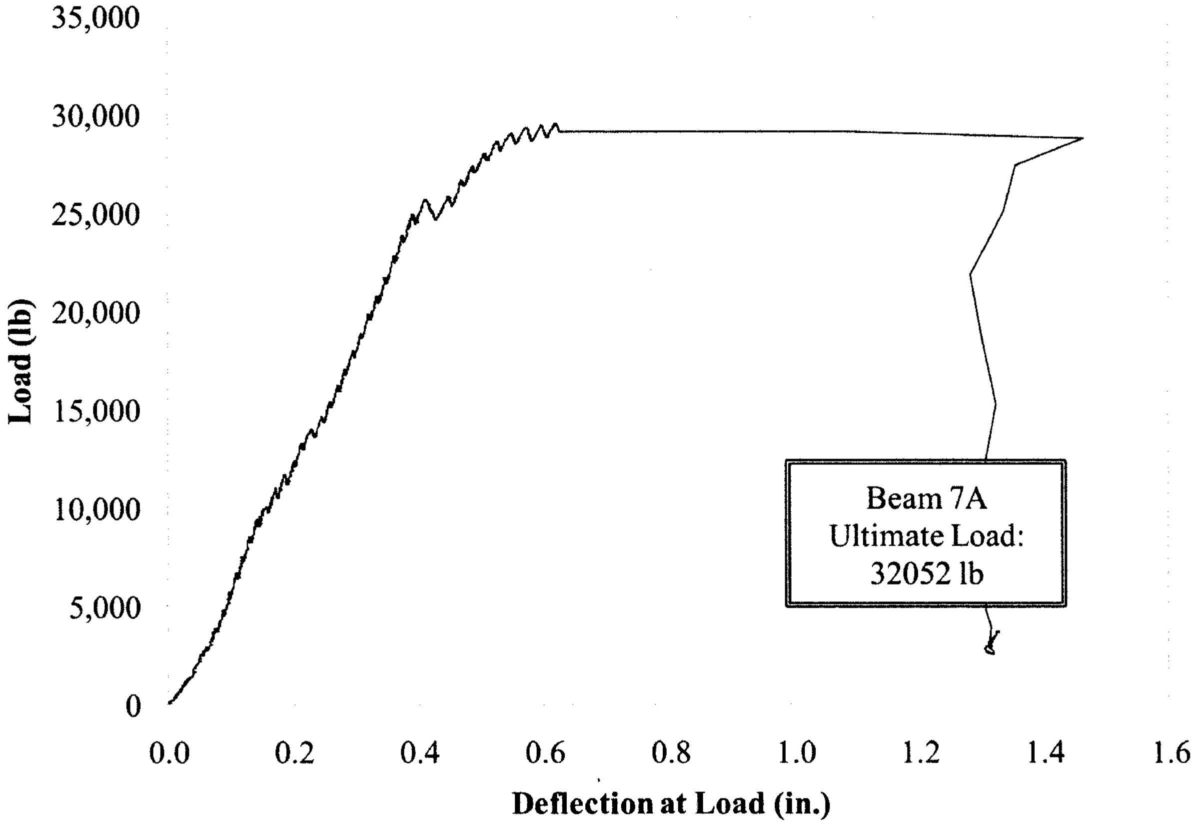


Figure C6. Shear Test Beam, No Coating, No Shear Reinforcement



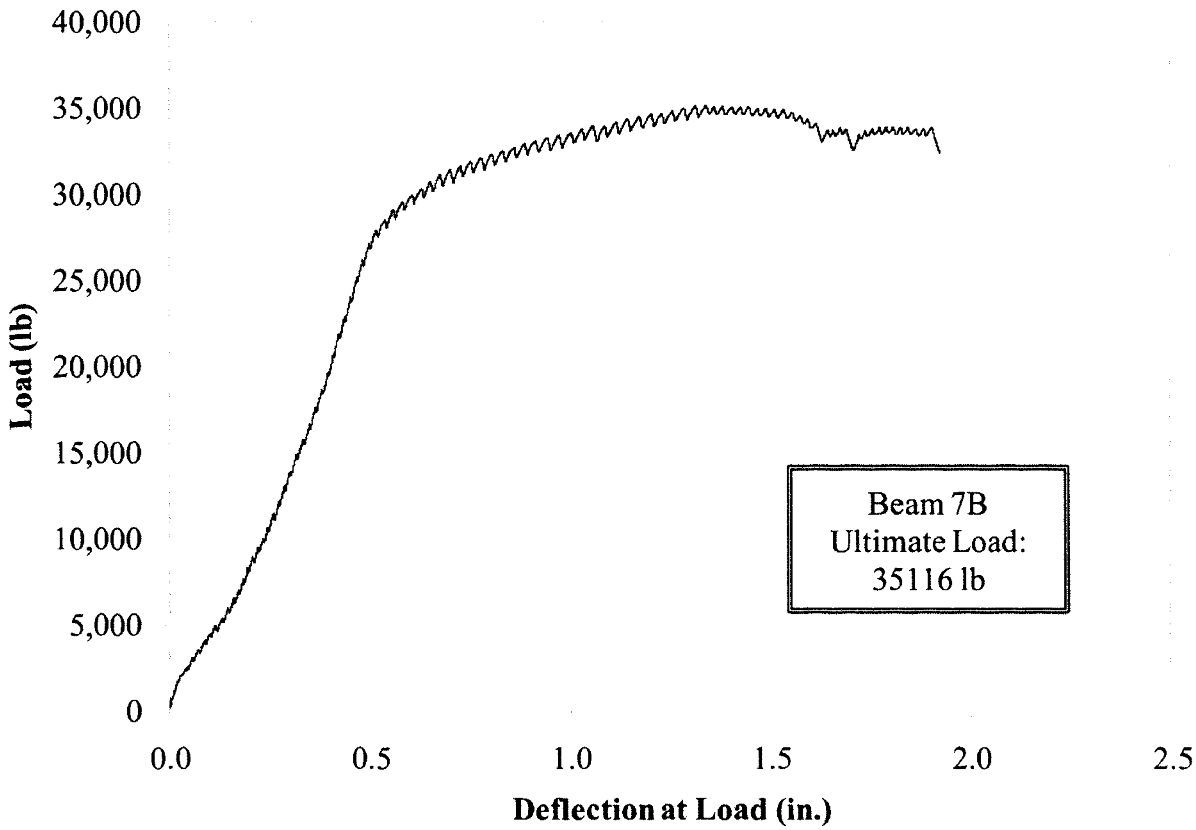
Unit Conversions: 1 lb = 4.45 N; 1 in. = 25.4 mm

Figure C7. Shear Test Beam, No Coating, Shear-Reinforced



Unit Conversions: 1 lb = 4.45 N; 1 in. = 25.4 mm

Figure C8. Shear Test Beam, Polyurea A with Fiber, No Shear Reinforcement



Unit Conversions: 1 lb = 4.45 N; 1 in. = 25.4 mm

Figure C9. Shear Test Beam, Polyurea A with Fiber, Shear-Reinforced

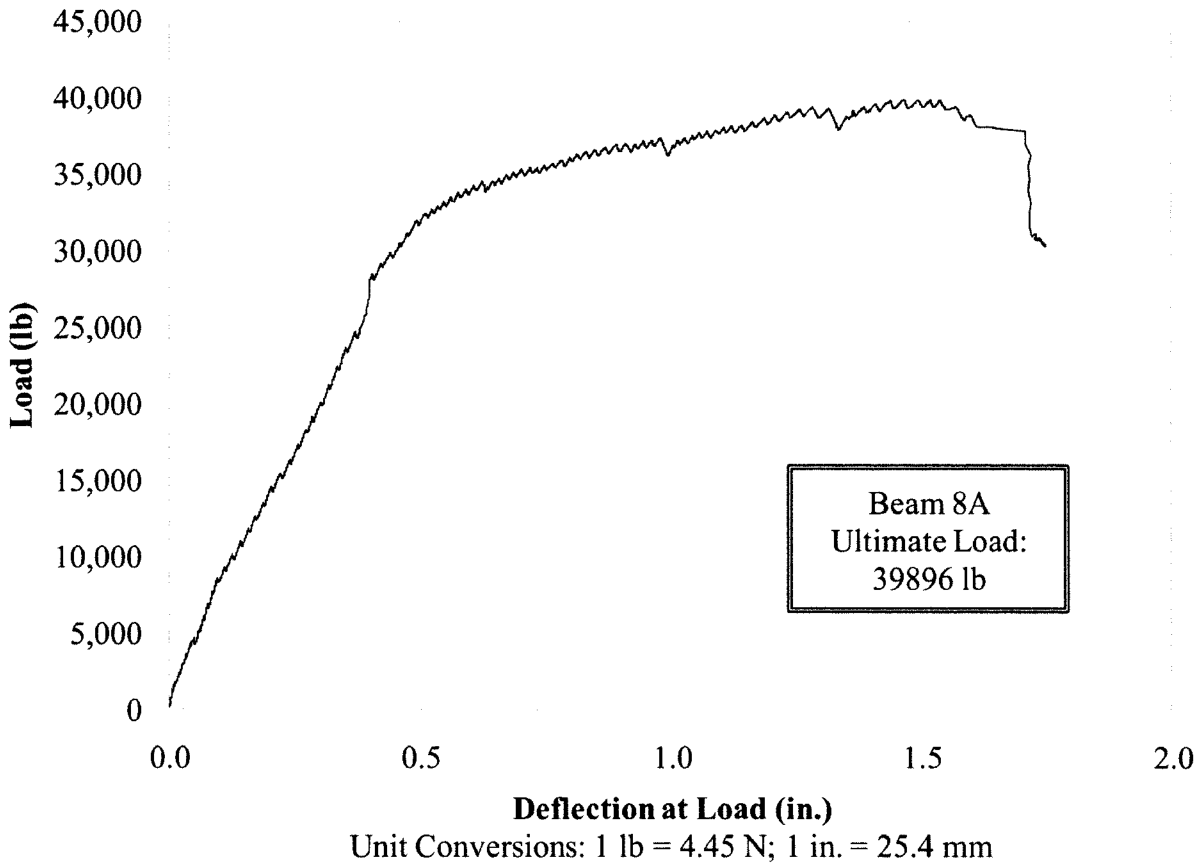


Figure C10. Shear Test Beam, Polyurea B with Fiber, No Shear Reinforcement

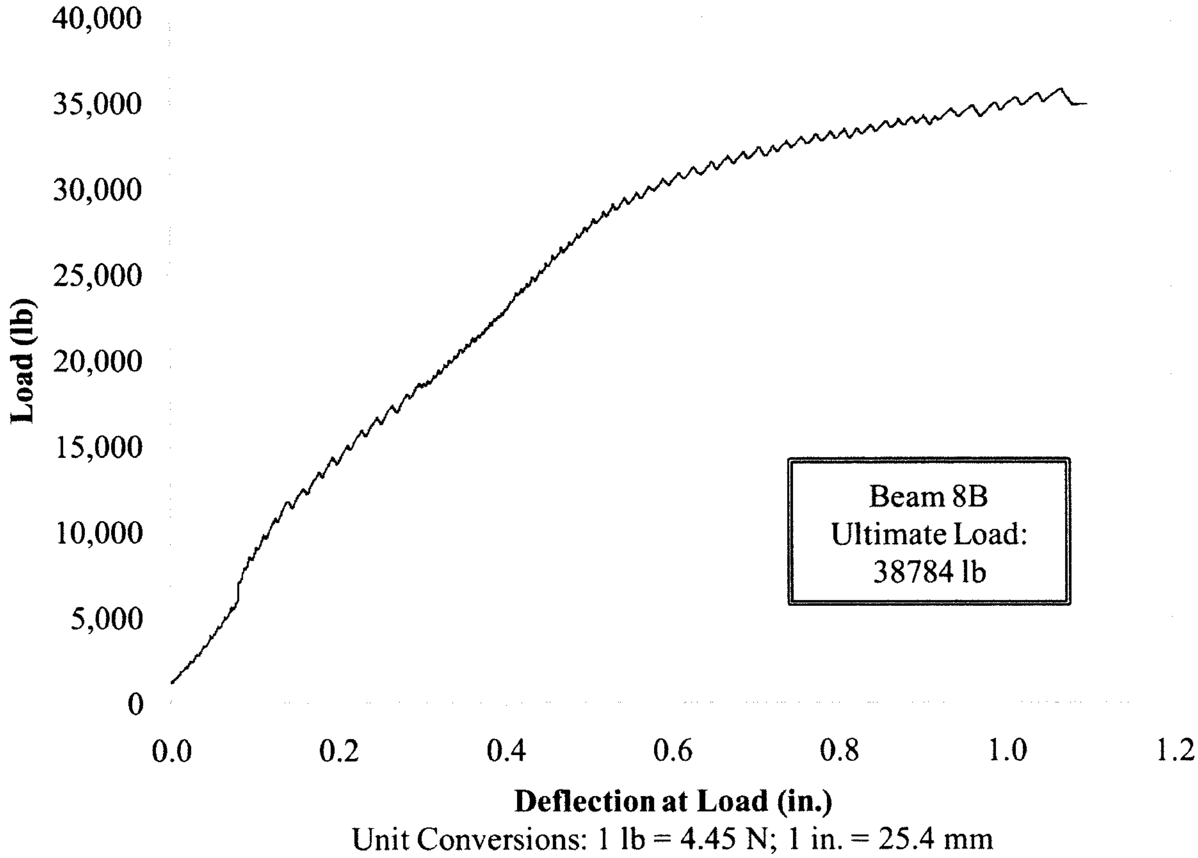


Figure C11. Shear Test Beam, Polyurea B with Fiber, Shear-Reinforced

APPENDIX D

PARAMETRIC STUDY WORKSHEETS

Parametric Study Beam Design Worksheet

Beam Designation: Test Beam #5

Coating System: No Coating (Control)

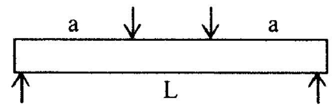
[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions		*Material Properties*		*Reinforcement Details*	
b (in)	8.00	f'_c (psi)	8049	n (bars)	3
b (ft)	0.67	f'_c (ksi)	8.049	Bar Size (#)	4
h (in)	12.00	f_y (psi)	71000	A_s (in^2)	0.600
h (ft)	1.00	f_y (ksi)	71	A_s (ft^2)	0.004
g (in)	2.13			ρ_S	0.76%
d (in)	9.88				
d (ft)	0.82				

Test Setup

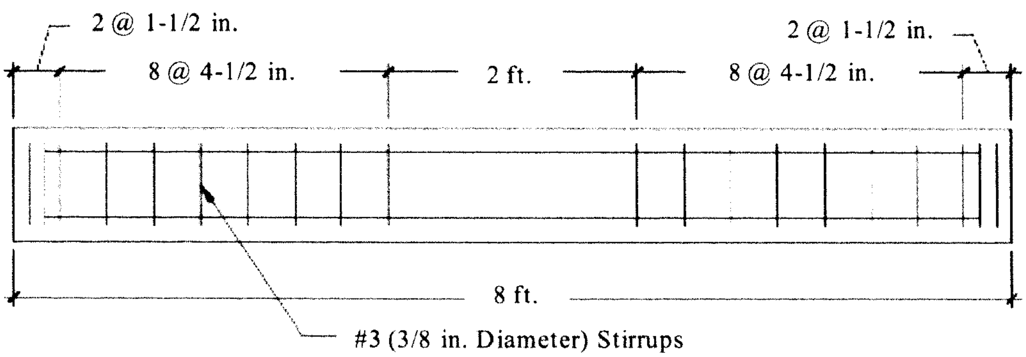
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.78	[10.2.7]
c (in) =	1.20	
M_n (k-in) =	404.1	
M_n (k-ft) =	**33.7**	
c/d_t =	0.121	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	363.7	
M_u (k-ft) =	30.3	
P_u (k) =	**11.02**	

Predicted Total Capacity (k):
24.5



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

MISSOURI S&T
University of Science & Technology

Parametric Study Beam Design Worksheet

Beam Designation: Test Beam #1

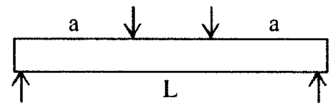
Coating System: Polyurea A, No Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.225	f_f (psi)	2147	n (bars)	3
b (in)	8.00	f_f (ksi)	2.147	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	8049	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	8.049	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	71000	ρ_s	0.76%
g (in)	2.13	f_y (ksi)	71	A_f (in^2)	6.386
d (in)	9.88			y_f (in)	3.853
d (ft)	0.82				

Test Setup

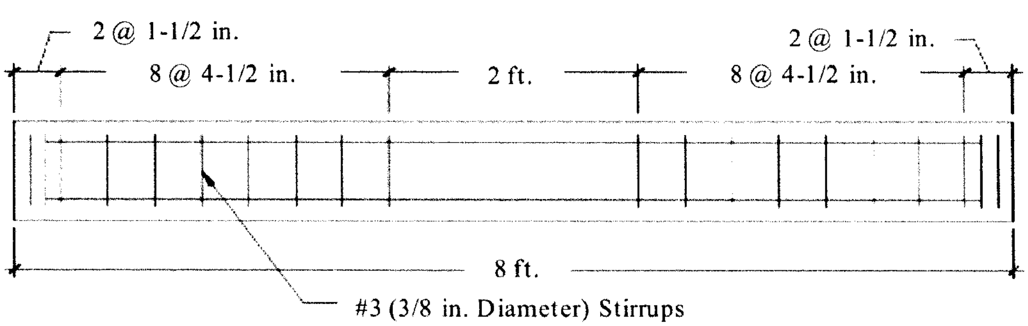
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	1.03	[10.2.7]
c (in) =	1.58	
M_n (k-in) =	503.4	
M_n (k-ft) =	**42.0**	
c/d_t =	0.160	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	453.1	
M_u (k-ft) =	37.8	
P_u (k) =	**13.73**	

Predicted Total Capacity (k):
30.5



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Test Beam #2

Coating System: Polyurea A with Fiber

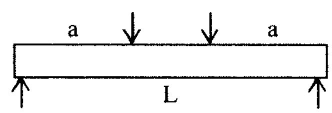
[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.127	f_f (psi)	1004	n (bars)	3
b (in)	8.00	f_f (ksi)	1.004	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	8049	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	8.049	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	71000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	71	A_f (in^2)	3.701
d (in)	9.88			y_f (in)	3.944
d (ft)	0.82				

Test Setup

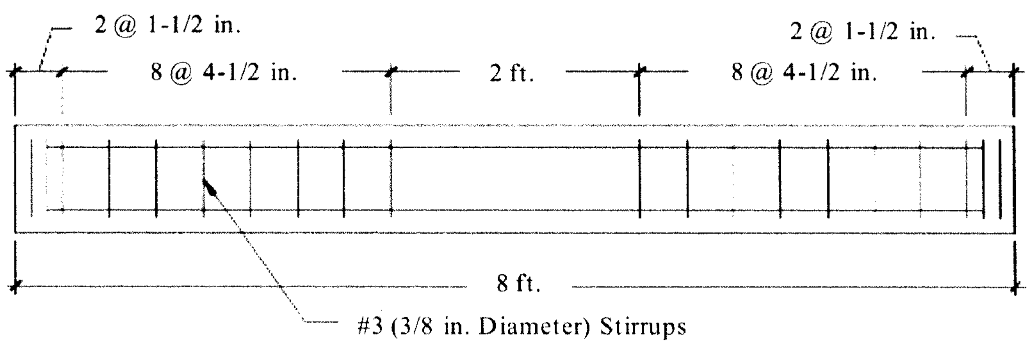
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.85	[10.2.7]
c (in) =	1.30	
M_n (k-in) =	431.0	
M_n (k-ft) =	**35.9**	
c/d_t =	0.132	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	387.9	
M_u (k-ft) =	32.3	
P_u (k) =	**11.75**	

Predicted Total Capacity (k):
26.1



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Test Beam #3

Coating System: Polyurea B with High Fiber

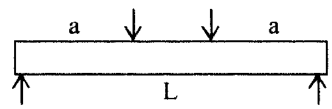
[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.139	f_f (psi)	1859	n (bars)	3
b (in)	8.00	f_f (ksi)	1.859	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	8049	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	8.049	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	71000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	71	A_f (in^2)	4.018
d (in)	9.88			y_f (in)	3.900
d (ft)	0.82				

Test Setup

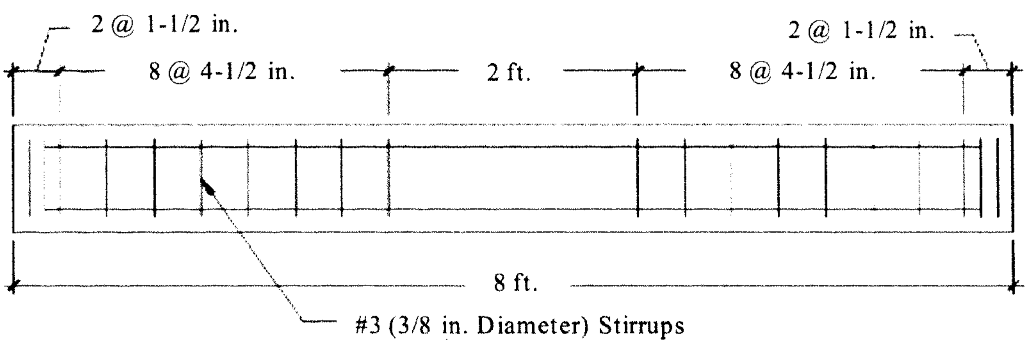
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.91	[10.2.7]
c (in) =	1.41	
M_n (k-in) =	458.3	
M_n (k-ft) =	**38.2**	
c/d_t =	0.143	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	412.4	
M_u (k-ft) =	34.4	
P_u (k) =	**12.50**	

Predicted Total Capacity (k):
27.8



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Test Beam #4

Coating System: Polyurea B with Low Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions

t_f (in)	0.115
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

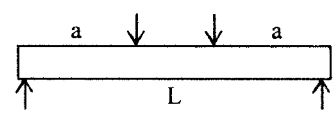
f_f (psi)	1379
f_f (ksi)	1.379
f'_c (psi)	8049
f'_c (ksi)	8.049
f_y (psi)	71000
f_y (ksi)	71

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	3.348
y_f (in)	3.928

Test Setup

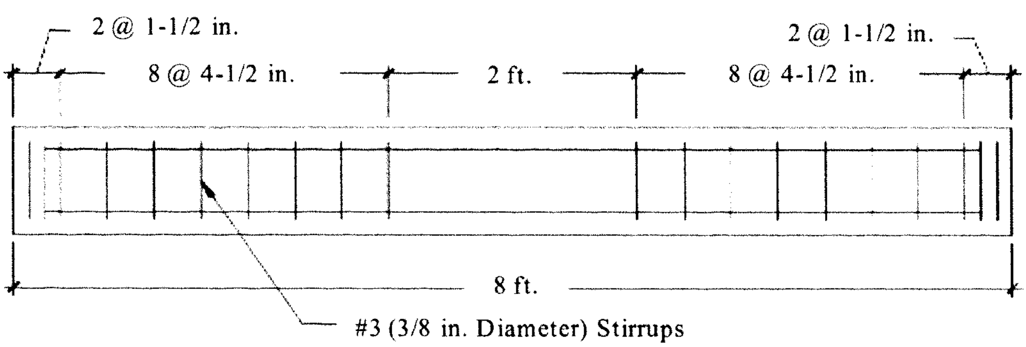
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.86	[10.2.7]
c (in) =	1.33	
M_n (k-in) =	437.6	
M_n (k-ft) =	**36.5**	
c/d_t =	0.134	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	393.8	
M_u (k-ft) =	32.8	
P_u (k) =	**11.93**	

Predicted Total Capacity (k):
26.5



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #1, 4000 psi

Coating System: None

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions

b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

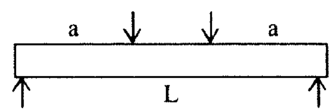
f'_c (psi)	4000
f'_c (ksi)	4
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%

Test Setup

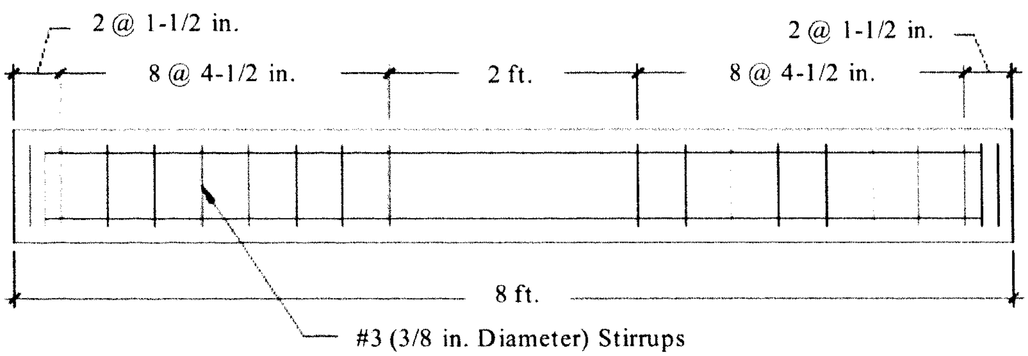
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.85	[10.2.7.3]
a (in) =	1.32	[10.2.7]
c (in) =	1.56	
M_n (k-in) =	331.7	
M_n (k-ft) =	**27.6**	
c/d_t =	0.158	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	298.5	
M_u (k-ft) =	24.9	
P_u (k) =	**9.05**	

Predicted Total Capacity (k):
20.1



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #2, 4000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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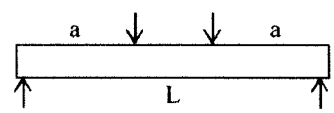
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.125	f_f (psi)	1859	n (bars)	3
b (in)	8.00	f_f (ksi)	1.859	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	4000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	4	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_s	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	3.509
d (in)	9.88			y_f (in)	3.695
d (ft)	0.82				

Test Setup

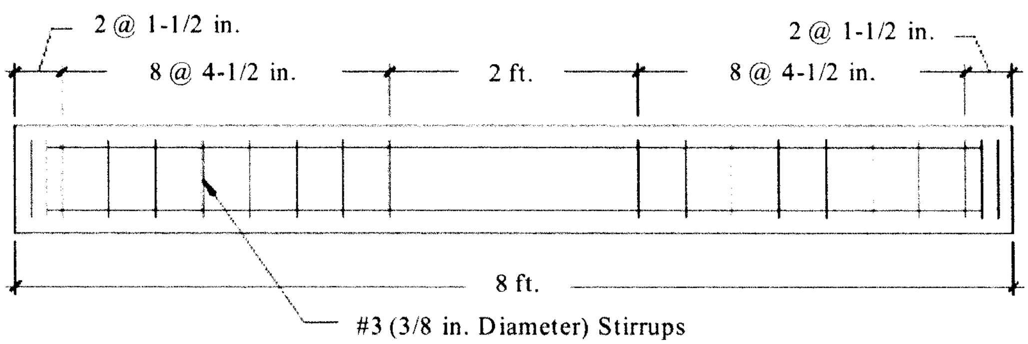
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.85	[10.2.7.3]
a (in) =	1.56	[10.2.7]
c (in) =	1.84	
M_n (k-in) =	376.4	
M_n (k-ft) =	**31.4**	
c/d_t =	0.186	[9.3.2]
	Tension-Controlled	
Φ =	0.9	
M_u (k-in) =	338.8	
M_u (k-ft) =	28.2	
P_u (k) =	**10.27**	

Predicted Total Capacity (k):
22.8



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #3, 5000 psi

Coating System: No Coating

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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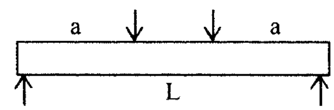
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
b (in)	8.00	f'_c (psi)	5000	n (bars)	3
b (ft)	0.67	f'_c (ksi)	5	Bar Size (#)	4
h (in)	12.00	f_y (psi)	60000	A_s (in^2)	0.600
h (ft)	1.00	f_y (ksi)	60	A_s (ft^2)	0.004
g (in)	2.13			ρ_s	0.76%
d (in)	9.88				
d (ft)	0.82				

Test Setup

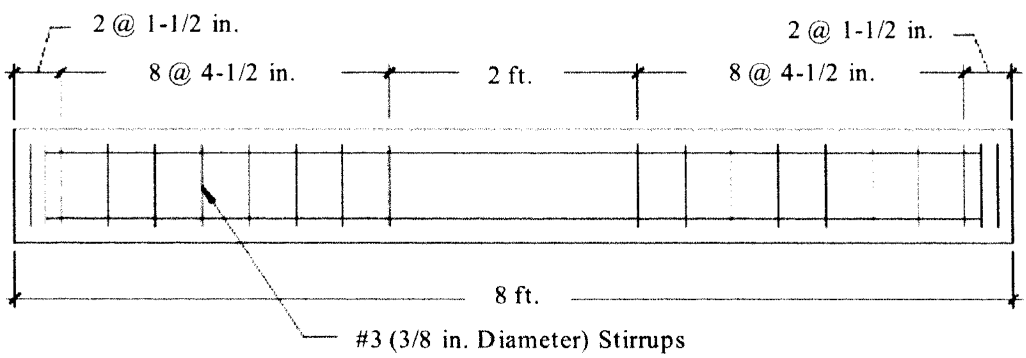
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.8	[10.2.7.3]
a (in) =	1.06	[10.2.7]
c (in) =	1.32	
M_n (k-in) =	336.4	
M_n (k-ft) =	**28.0**	
c/d_t =	0.134	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	302.8	
M_u (k-ft) =	25.2	
P_u (k) =	**9.18**	

Predicted Total Capacity (k):
20.4



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #4, 5000 psi
Coating System: Polyurea B with 10% Glass Fiber
[Brackets denote references to ACI 318-08 Building Code and Commentary]

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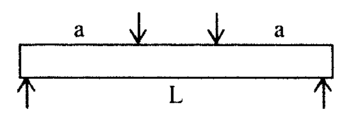
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.125	f_f (psi)	1859	n (bars)	3
b (in)	8.00	f_f (ksi)	1.859	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	5000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	5	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_s	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	3.577
d (in)	9.88			y_f (in)	3.820
d (ft)	0.82				

Test Setup

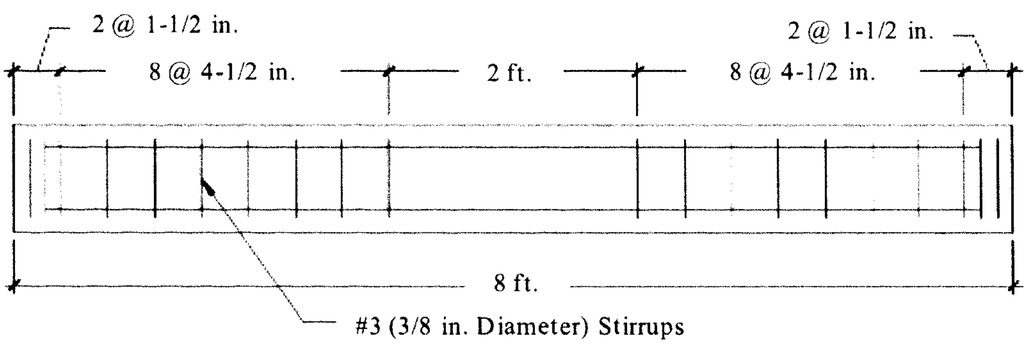
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.8	[10.2.7.3]
a (in) =	1.25	[10.2.7]
c (in) =	1.57	
M_n (k-in) =	383.1	
M_n (k-ft) =	**31.9**	
c/d_t =	0.159	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	344.8	
M_u (k-ft) =	28.7	
P_u (k) =	**10.45**	

Predicted Total Capacity (k):
23.2



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #5, 6000 psi

Coating System: No Coating

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Science & Technology

Beam Dimensions

b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

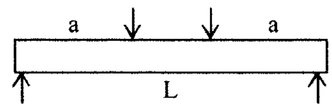
f'_c (psi)	6000
f'_c (ksi)	6
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%

Test Setup

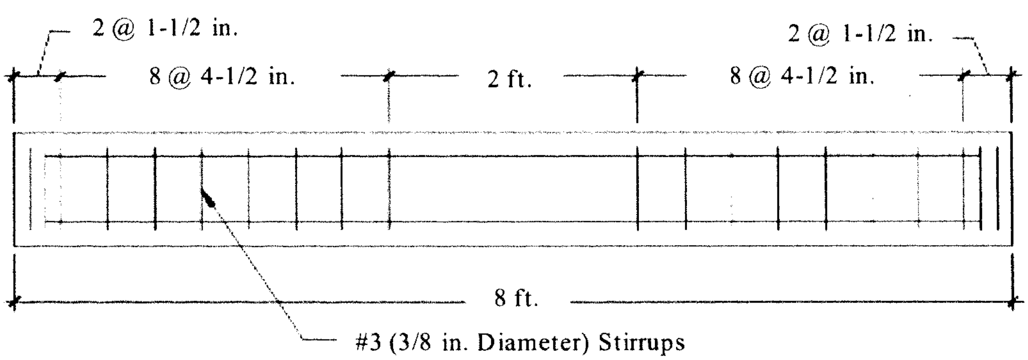
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.75	[10.2.7.3]
a (in) =	0.88	[10.2.7]
c (in) =	1.18	
M_n (k-in) =	339.6	
M_n (k-ft) =	**28.3**	
c/d_t =	0.119	[9.3.2]
	Tension-Controlled	
Φ =	0.9	
M_u (k-in) =	305.7	
M_u (k-ft) =	25.5	
P_u (k) =	**9.26**	

Predicted Total Capacity (k):
20.6



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #6, 6000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

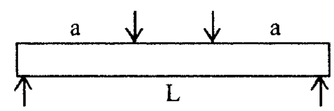
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	6000
f'_c (ksi)	6
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	3.620
y_f (in)	3.900

Test Setup

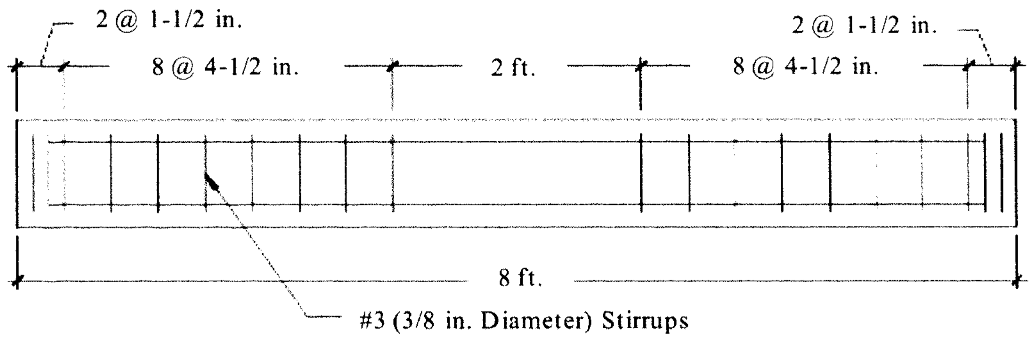
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.75	[10.2.7.3]
a (in) =	1.05	[10.2.7]
c (in) =	1.40	
M_n (k-in) =	387.6	
M_n (k-ft) =	**32.3**	
c/d_t =	0.141	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	348.9	
M_u (k-ft) =	29.1	
P_u (k) =	**10.57**	

Predicted Total Capacity (k):
23.5



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #7, 7000 psi

Coating System: No Coating

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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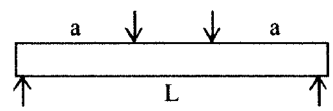
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
b (in)	8.00	f'_c (psi)	7000	n (bars)	3
b (ft)	0.67	f'_c (ksi)	7	Bar Size (#)	4
h (in)	12.00	f_y (psi)	60000	A_s (in^2)	0.600
h (ft)	1.00	f_y (ksi)	60	A_s (ft^2)	0.004
g (in)	2.13			ρ_S	0.76%
d (in)	9.88				
d (ft)	0.82				

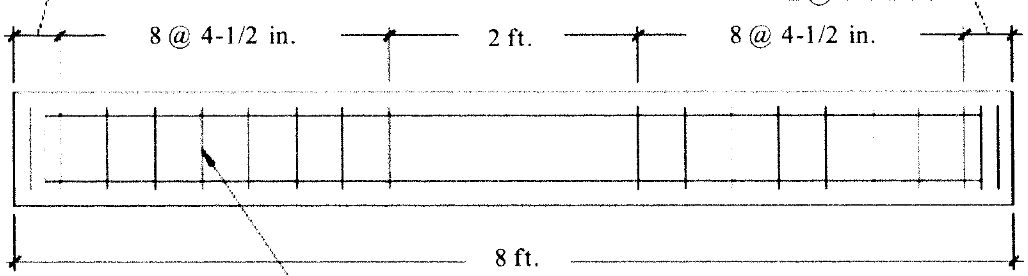
Test Setup			
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.7	[10.2.7.3]
a (in) =	0.76	[10.2.7]
c (in) =	1.08	
M_n (k-in) =	341.9	
M_n (k-ft) =	**28.5**	
c/d_t =	0.109	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	307.7	
M_u (k-ft) =	25.6	
P_u (k) =	**9.32**	

Predicted Total Capacity (k):
20.7



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #8, 7000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

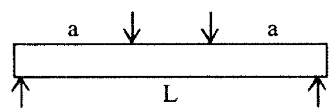
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	7000
f'_c (ksi)	7
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	3.648
y_f (in)	3.952

Test Setup

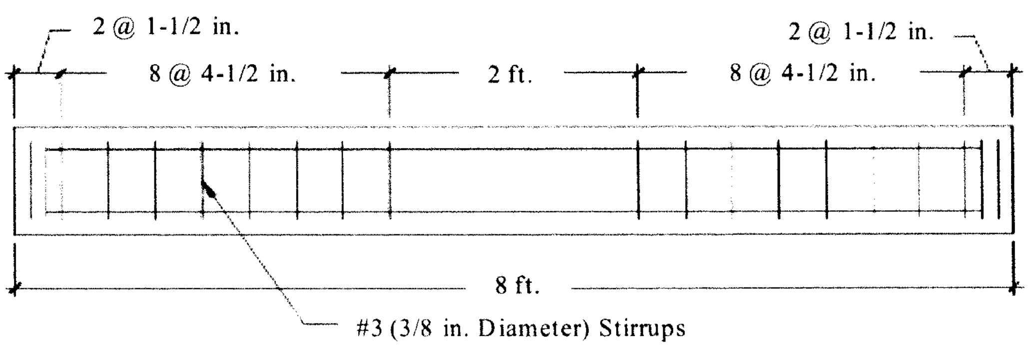
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.7	[10.2.7.3]
a (in) =	0.90	[10.2.7]
c (in) =	1.28	
M_n (k-in) =	390.9	
M_n (k-ft) =	**32.6**	
c/d_t =	0.130	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	351.8	
M_u (k-ft) =	29.3	
P_u (k) =	**10.66**	

Predicted Total Capacity (k):
23.7



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #9, 8000 psi

Coating System: No Coating

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

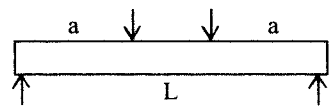
Beam Dimensions	
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties	
f'_c (psi)	8000
f'_c (ksi)	8
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details	
n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%

Test Setup

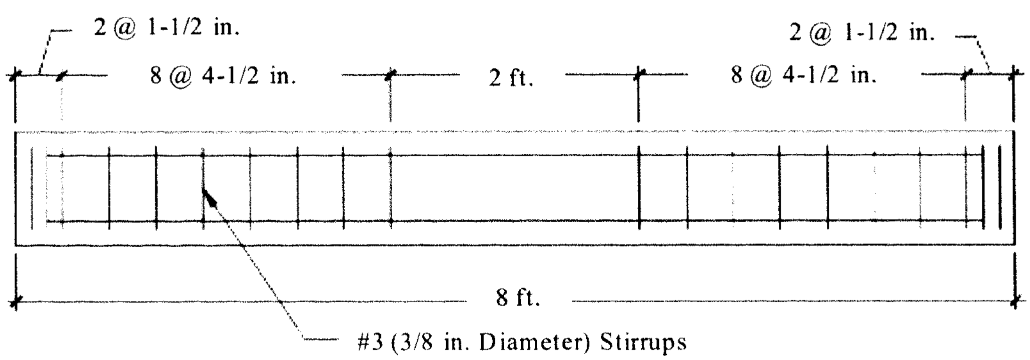
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.66	[10.2.7]
c (in) =	1.02	
M_n (k-in) =	343.6	
M_n (k-ft) =	**28.6**	
c/d_t =	0.103	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	309.2	
M_u (k-ft) =	25.8	
P_u (k) =	**9.37**	

Predicted Total Capacity (k):
20.8



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #10, 8000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions

t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

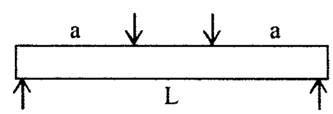
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	8000
f'_c (ksi)	8
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	3.666
y_f (in)	3.986

Test Setup

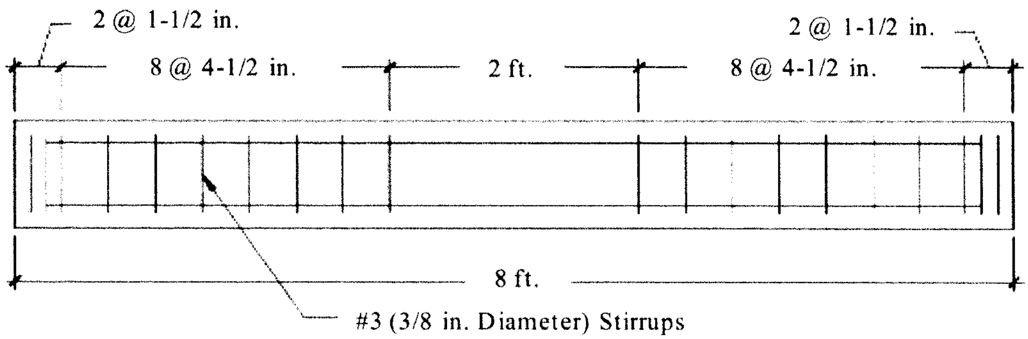
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.79	[10.2.7]
c (in) =	1.21	
M_n (k-in) =	393.3	
M_n (k-ft) =	**32.8**	
c/d_t =	0.123	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	353.9	
M_u (k-ft) =	29.5	
P_u (k) =	**10.73**	

Predicted Total Capacity (k):
23.8



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #11, 9000 psi

Coating System: No Coating

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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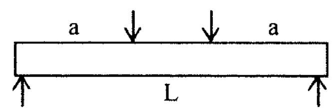
Beam Dimensions	
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties	
f'_c (psi)	9000
f'_c (ksi)	9
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details	
n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%

Test Setup

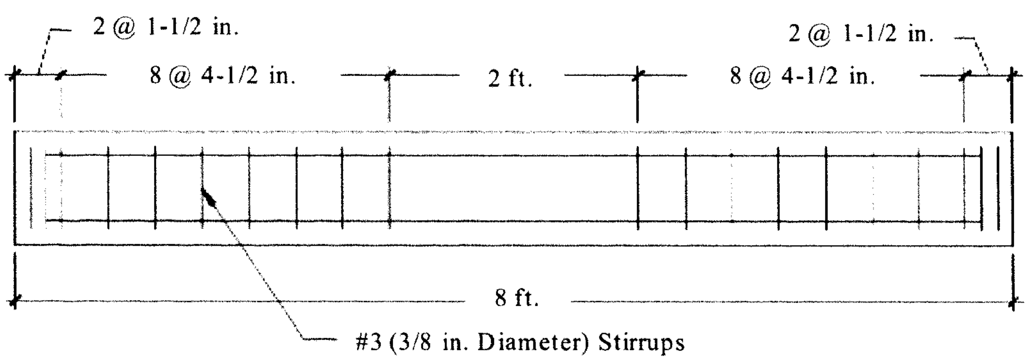
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.59	[10.2.7]
c (in) =	0.90	
M_n (k-in) =	344.9	
M_n (k-ft) =	**28.7**	
c/d_t =	0.092	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	310.4	
M_u (k-ft) =	25.9	
P_u (k) =	**9.41**	

Predicted Total Capacity (k):
20.9



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #12, 9000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

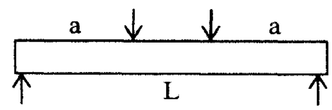
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	9000
f'_c (ksi)	9
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρs	0.76%
A_f (in^2)	3.699
y_f (in)	4.047

Test Setup

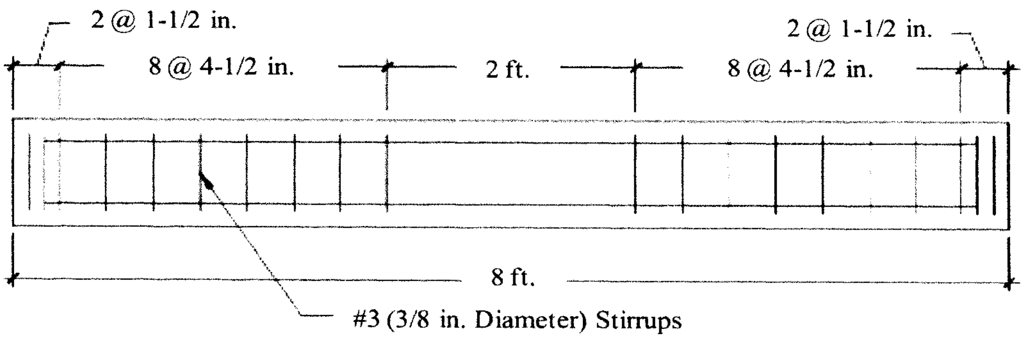
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65 [10.2.7.3]
a (in) =	0.70 [10.2.7]
c (in) =	1.08
M_n (k-in) =	395.2
M_n (k-ft) =	**32.9**
c/d_t =	0.109 [9.3.2]
Tension-Controlled	
Φ =	0.9
M_u (k-in) =	355.7
M_u (k-ft) =	29.6
P_u (k) =	**10.78**

Predicted Total Capacity (k):
23.9



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #13, 10000 psi

Coating System: No Coating

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

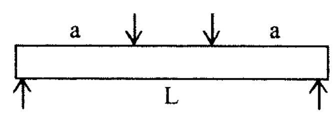
f'_c (psi)	10000
f'_c (ksi)	10
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%

Test Setup

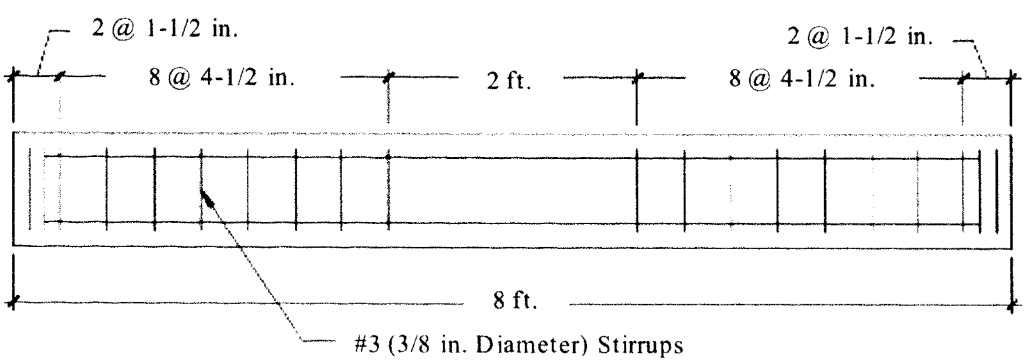
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.53	[10.2.7]
c (in) =	0.81	
M_n (k-in) =	346.0	
M_n (k-ft) =	**28.8**	
c/d_t =	0.082	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	311.4	
M_u (k-ft) =	25.9	
P_u (k) =	**9.44**	

Predicted Total Capacity (k):
21.0



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #14, 10000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

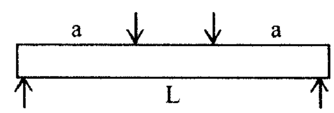
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	10000
f'_c (ksi)	10
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	3.726
y_f (in)	4.097

Test Setup

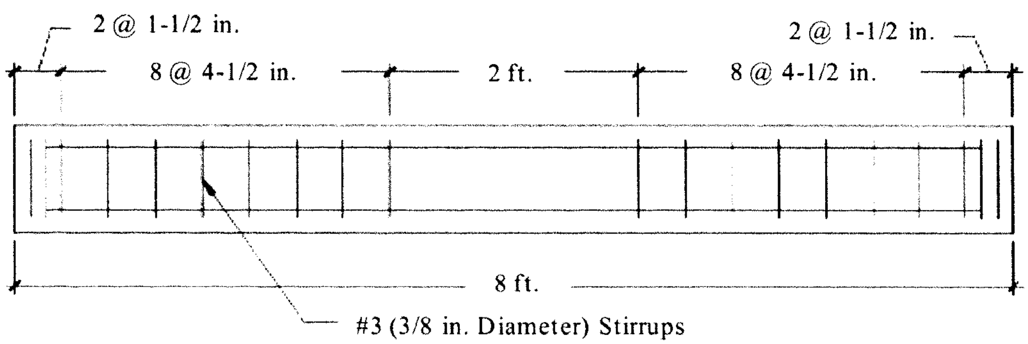
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.63	[10.2.7]
c (in) =	0.97	
M_n (k-in) =	396.7	
M_n (k-ft) =	**33.1**	
c/d_t =	0.098	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	357.0	
M_u (k-ft) =	29.8	
P_u (k) =	**10.82**	

Predicted Total Capacity (k):
24.0



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #15, 11000 psi

Coating System: No Coating

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

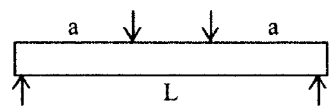
f'_c (psi)	11000
f'_c (ksi)	11
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%

Test Setup

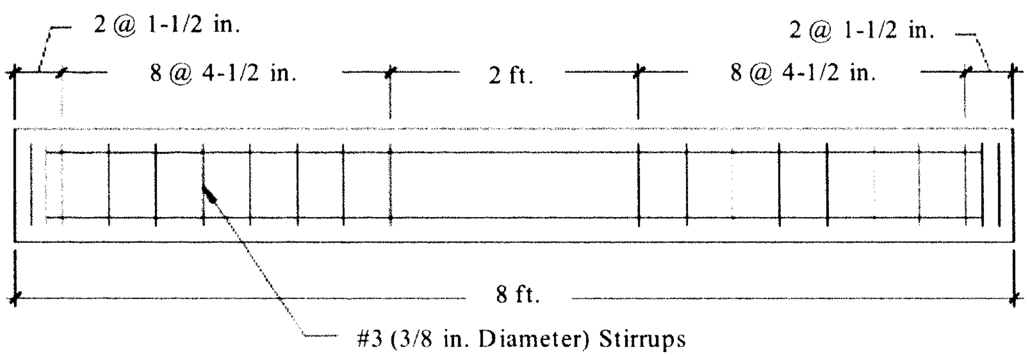
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.48	[10.2.7]
c (in) =	0.74	
M_n (k-in) =	346.8	
M_n (k-ft) =	**28.9**	
c/d_t =	0.075	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	312.2	
M_u (k-ft) =	26.0	
P_u (k) =	**9.46**	

Predicted Total Capacity (k):
21.0



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #16, 11000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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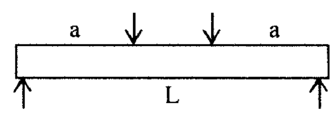
Beam Dimensions	
t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties	
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	11000
f'_c (ksi)	11
f_y (psi)	60000
f_y (ksi)	60

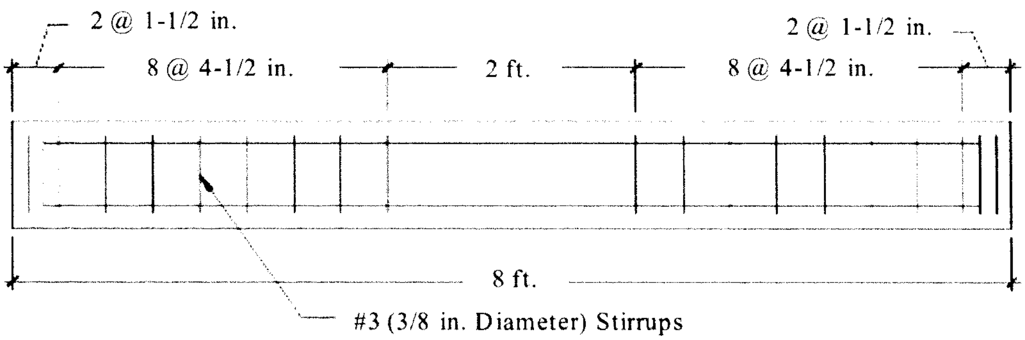
Reinforcement Details	
n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	3.748
y_f (in)	4.138

Test Setup			
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations		
β_1 =	0.65	[10.2.7.3]
a (in) =	0.57	[10.2.7]
c (in) =	0.88	
M_n (k-in) =	397.9	
M_n (k-ft) =	**33.2**	
c/d_t =	0.089	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	358.1	
M_u (k-ft) =	29.8	
P_u (k) =	**10.85**	

Predicted Total Capacity (k):
24.1



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #17, 12000 psi

Coating System: No Coating

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

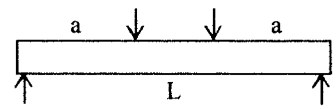
f'_c (psi)	12000
f'_c (ksi)	12
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%

Test Setup

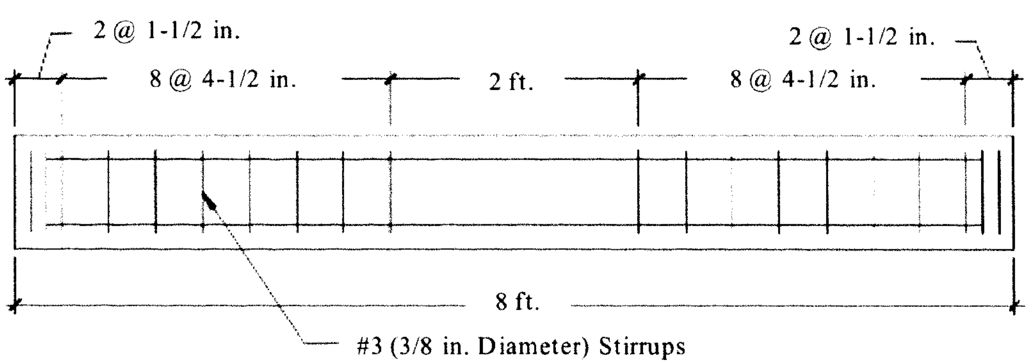
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.44	[10.2.7]
c (in) =	0.68	
M_n (k-in) =	347.6	
M_n (k-ft) =	**29.0**	
c/d_t =	0.069	[9.3.2]
	Tension-Controlled	
Φ =	0.9	
M_u (k-in) =	312.8	
M_u (k-ft) =	26.1	
P_u (k) =	**9.48**	

Predicted Total Capacity (k):
21.1



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #18, 12000 psi
Coating System: Polyurea B with 10% Glass Fiber
[Brackets denote references to ACI 318-08 Building Code and Commentary]

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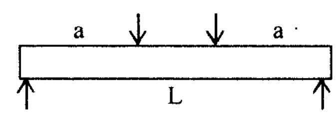
Beam Dimensions	
t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties	
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	12000
f'_c (ksi)	12
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details	
n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	3.766
y_f (in)	4.172

Test Setup

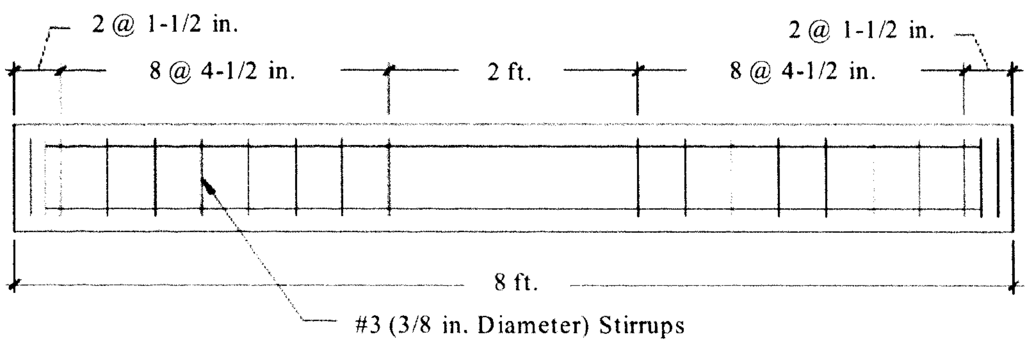
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.53	[10.2.7]
c (in) =	0.81	
M_n (k-in) =	399.0	
M_n (k-ft) =	**33.2**	
c/d_t =	0.082	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	359.1	
M_u (k-ft) =	29.9	
P_u (k) =	**10.88**	

Predicted Total Capacity (k):
24.2



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #19, 13000 psi

Coating System: No Coating

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

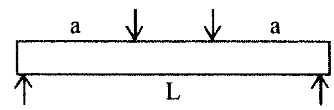
f'_c (psi)	13000
f'_c (ksi)	13
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%

Test Setup

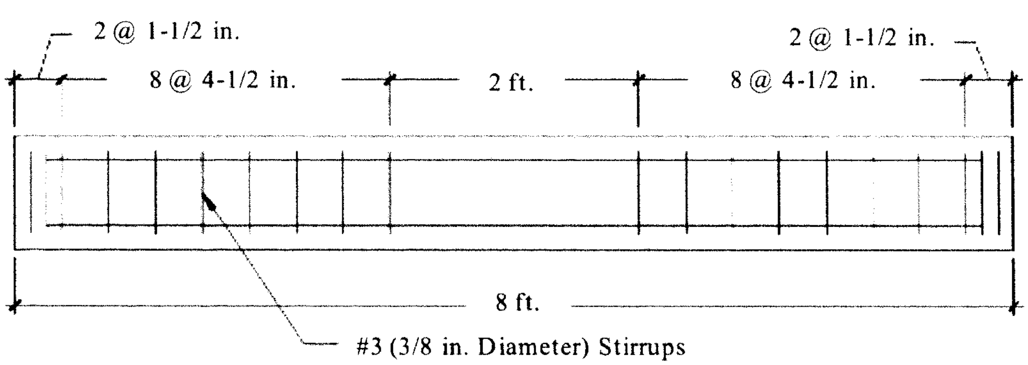
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.41	[10.2.7]
c (in) =	0.63	
M_n (k-in) =	348.2	
M_n (k-ft) =	**29.0**	
c/d_t =	0.063	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	313.4	
M_u (k-ft) =	26.1	
P_u (k) =	**9.50**	

Predicted Total Capacity (k):
21.1



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #20, 13000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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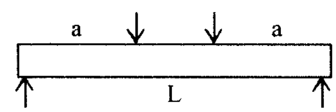
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.125	f_f (psi)	1859	n (bars)	3
b (in)	8.00	f_f (ksi)	1.859	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	13000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	13	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	3.782
d (in)	9.88			y_f (in)	4.200
d (ft)	0.82				

Test Setup

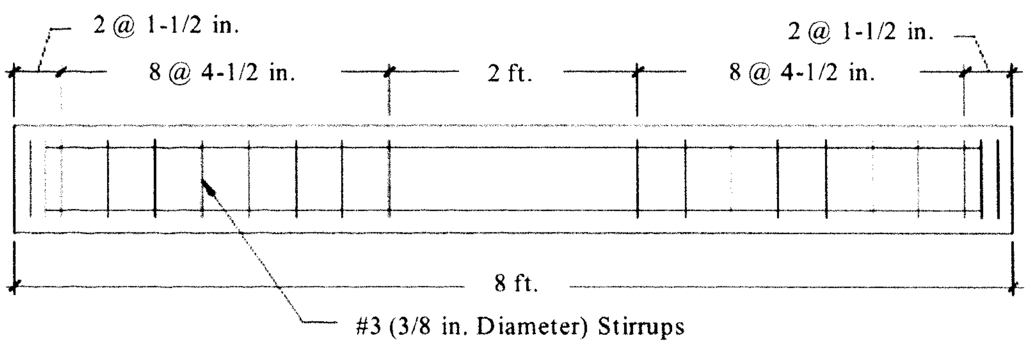
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.49	[10.2.7]
c (in) =	0.75	
M_n (k-in) =	399.9	
M_n (k-ft) =	**33.3**	
c/d_t =	0.076	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	359.9	
M_u (k-ft) =	30.0	
P_u (k) =	**10.91**	

Predicted Total Capacity (k):
24.2



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #21, 14000 psi

Coating System: No Coating

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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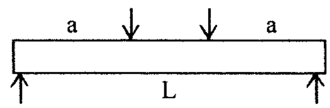
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
b (in)	8.00	f'_c (psi)	14000	n (bars)	3
b (ft)	0.67	f'_c (ksi)	14	Bar Size (#)	4
h (in)	12.00	f_y (psi)	60000	A_s (in^2)	0.600
h (ft)	1.00	f_y (ksi)	60	A_s (ft^2)	0.004
g (in)	2.13			ρ_s	0.76%
d (in)	9.88				
d (ft)	0.82				

Test Setup

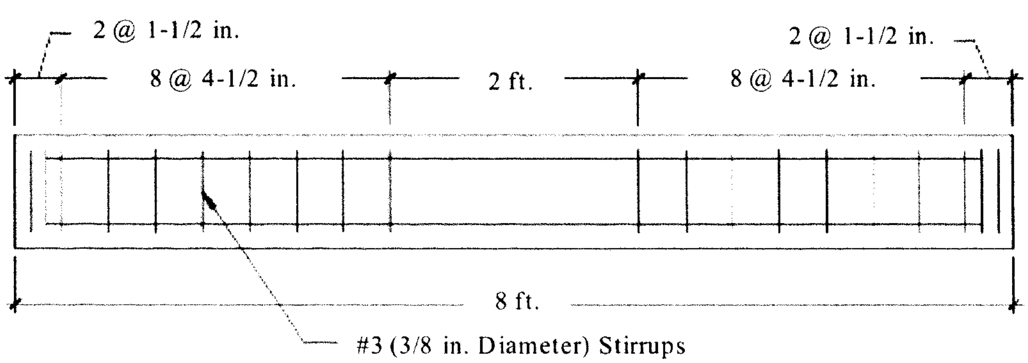
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.38	[10.2.7]
c (in) =	0.58	
M_n (k-in) =	348.7	
M_n (k-ft) =	**29.1**	
c/d_t =	0.059	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	313.8	
M_u (k-ft) =	26.2	
P_u (k) =	**9.51**	

Predicted Total Capacity (k):
21.1



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #22, 14000 psi
Coating System: Polyurea B with 10% Glass Fiber
[Brackets denote references to ACI 318-08 Building Code and Commentary]

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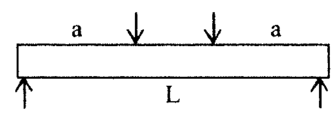
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.125	f_f (psi)	1859	n (bars)	3
b (in)	8.00	f_f (ksi)	1.859	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	14000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	14	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	3.795
d (in)	9.88			y_f (in)	4.225
d (ft)	0.82				

Test Setup

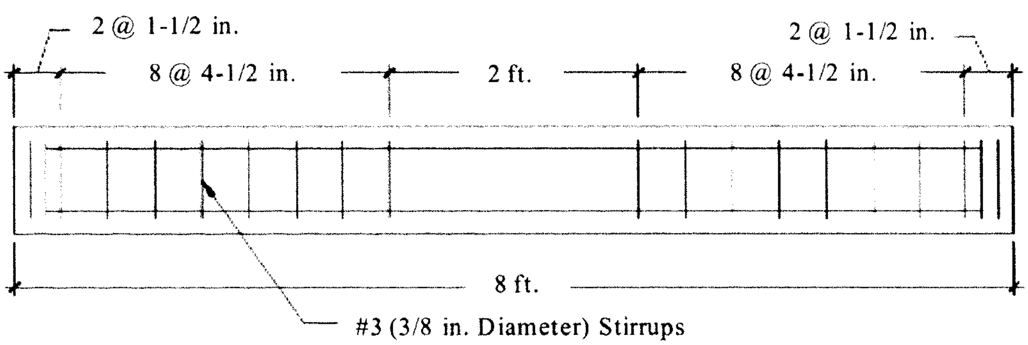
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65 [10.2.7.3]
a (in) =	0.45 [10.2.7]
c (in) =	0.70
M_n (k-in) =	400.6
M_n (k-ft) =	**33.4**
c/d_t =	0.070 [9.3.2]
Tension-Controlled	
Φ =	0.9
M_u (k-in) =	360.6
M_u (k-ft) =	30.0
P_u (k) =	**10.93**

Predicted Total Capacity (k):
24.3



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #23, 4000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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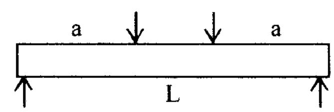
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.125	f_f (psi)	2147	n (bars)	3
b (in)	8.00	f_f (ksi)	2.147	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	4000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	4	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_s	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	3.498
d (in)	9.88			y_f (in)	3.675
d (ft)	0.82				

Test Setup

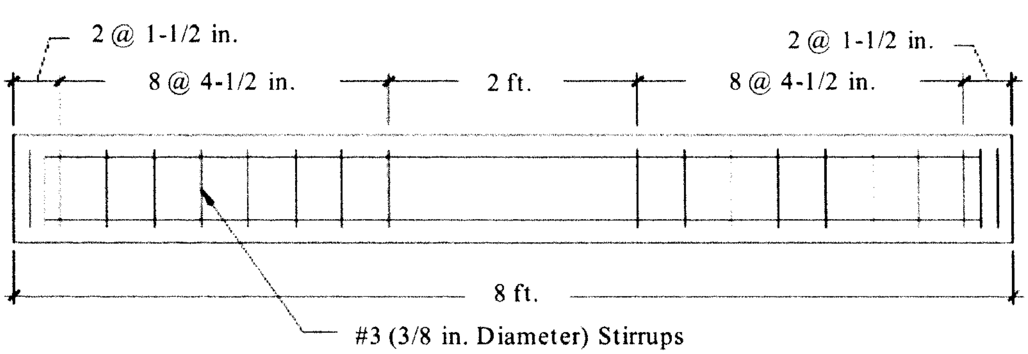
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.85	[10.2.7.3]
a (in) =	1.60	[10.2.7]
c (in) =	1.88	
M_n (k-in) =	383.2	
M_n (k-ft) =	**31.9**	
c/d_t =	0.191	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	344.9	
M_u (k-ft) =	28.7	
P_u (k) =	**10.45**	

Predicted Total Capacity (k):
23.2



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #24, 5000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

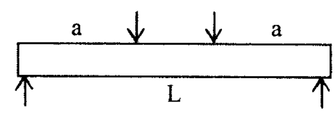
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	5000
f'_c (ksi)	5
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	3.567
y_f (in)	3.803

Test Setup

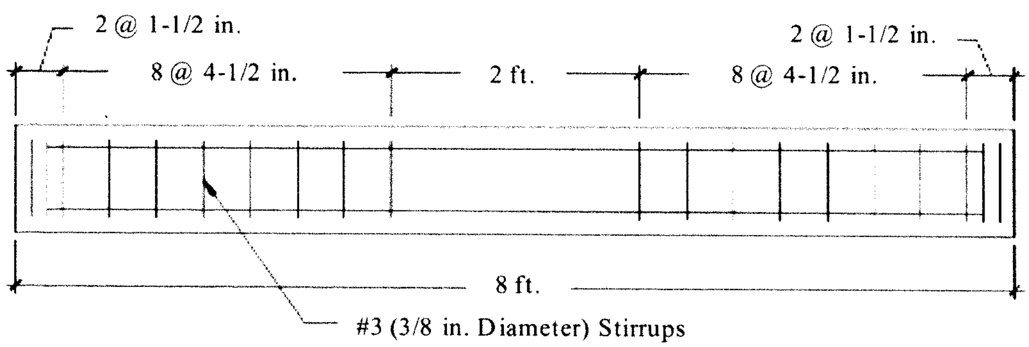
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.8	[10.2.7.3]
a (in) =	1.28	[10.2.7]
c (in) =	1.61	
M_n (k-in) =	390.3	
M_n (k-ft) =	**32.5**	
c/d_t =	0.163	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	351.2	
M_u (k-ft) =	29.3	
P_u (k) =	**10.64**	

Predicted Total Capacity (k):
23.7



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #25, 6000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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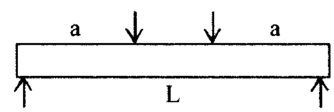
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.125	f_f (psi)	2147	n (bars)	3
b (in)	8.00	f_f (ksi)	2.147	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	6000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	6	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	3.611
d (in)	9.88			y_f (in)	3.884
d (ft)	0.82				

Test Setup

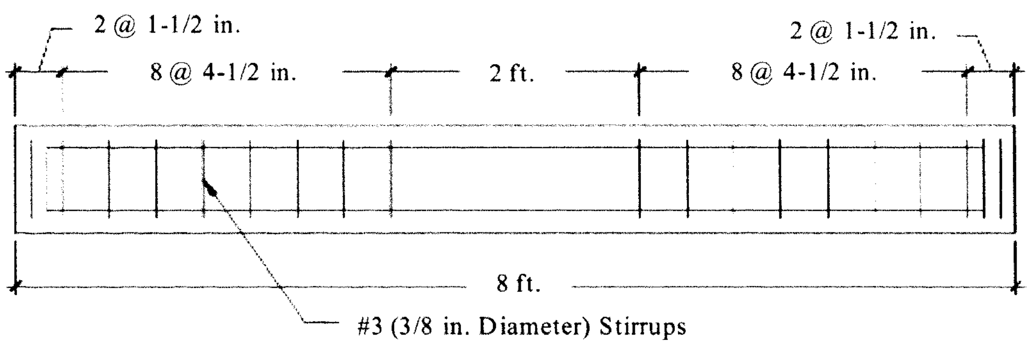
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.75	[10.2.7.3]
a (in) =	1.07	[10.2.7]
c (in) =	1.43	
M_n (k-in) =	395.0	
M_n (k-ft) =	**32.9**	
c/d_t =	0.145	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	355.5	
M_u (k-ft) =	29.6	
P_u (k) =	**10.77**	

Predicted Total Capacity (k):
23.9



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #26, 7000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

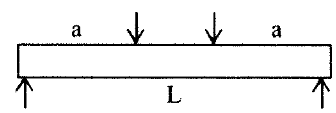
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	7000
f'_c (ksi)	7
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	3.640
y_f (in)	3.937

Test Setup

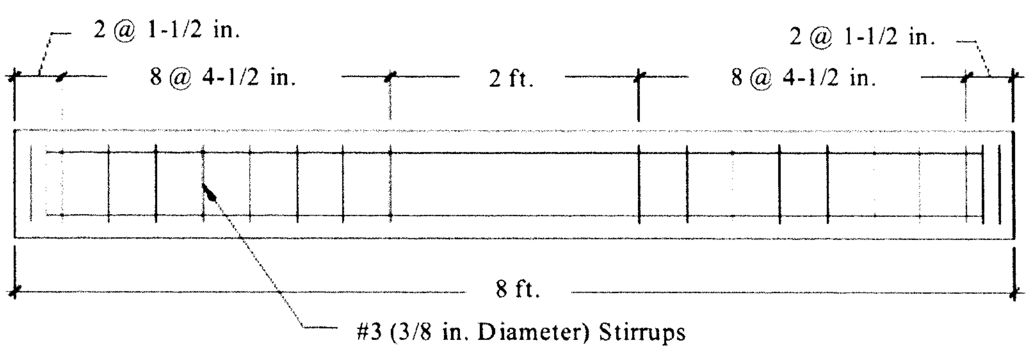
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.7	[10.2.7.3]
a (in) =	0.92	[10.2.7]
c (in) =	1.31	
M_n (k-in) =	398.3	
M_n (k-ft) =	**33.2**	
c/d_t =	0.133	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	358.5	
M_u (k-ft) =	29.9	
P_u (k) =	**10.86**	

Predicted Total Capacity (k):
24.1



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #27, 8000 psi

Coating System: Polyurea A, No Glass Fiber

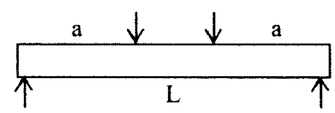
[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.125	f_f (psi)	2147	n (bars)	3
b (in)	8.00	f_f (ksi)	2.147	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	8000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	8	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	3.659
d (in)	9.88			y_f (in)	3.972
d (ft)	0.82				

Test Setup

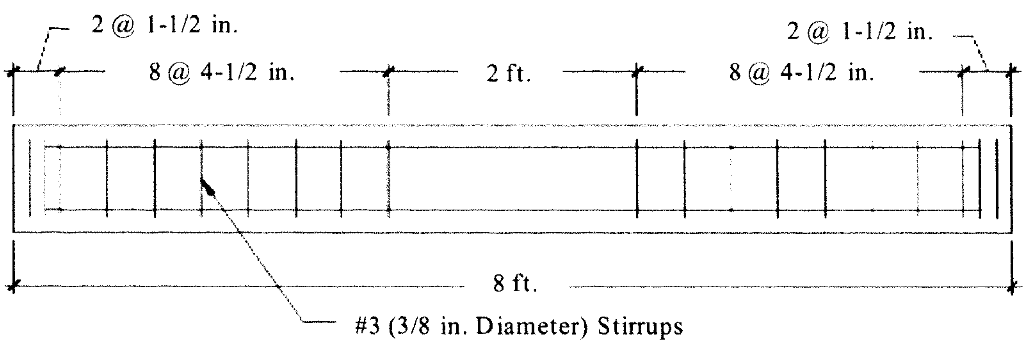
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.81	[10.2.7]
c (in) =	1.24	
M_n (k-in) =	400.9	
M_n (k-ft) =	**33.4**	
c/d_t =	0.126	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	360.8	
M_u (k-ft) =	30.1	
P_u (k) =	**10.93**	

Predicted Total Capacity (k):
24.3



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #28, 9000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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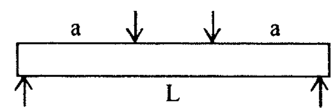
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.125	f_f (psi)	2147	n (bars)	3
b (in)	8.00	f_f (ksi)	2.147	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	9000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	9	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_s	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	3.693
d (in)	9.88			y_f (in)	4.035
d (ft)	0.82				

Test Setup

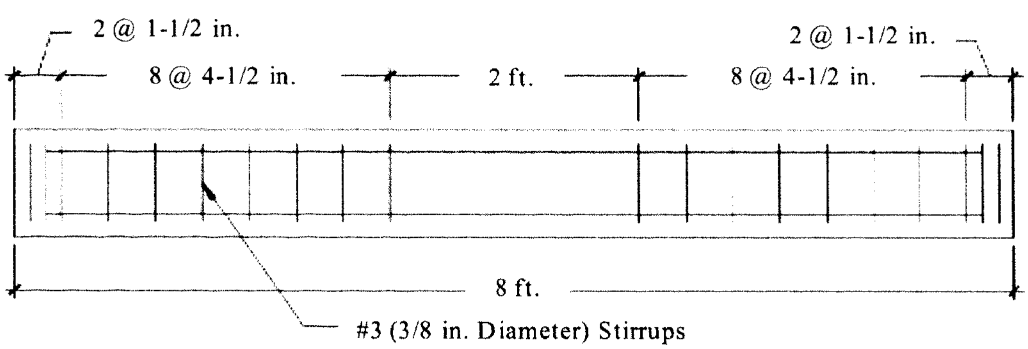
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.72	[10.2.7]
c (in) =	1.10	
M_n (k-in) =	402.9	
M_n (k-ft) =	**33.6**	
c/d_t =	0.112	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	362.6	
M_u (k-ft) =	30.2	
P_u (k) =	**10.99**	

Predicted Total Capacity (k):
24.4



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #29, 10000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

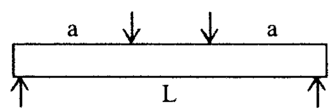
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	10000
f'_c (ksi)	10
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	3.720
y_f (in)	4.086

Test Setup

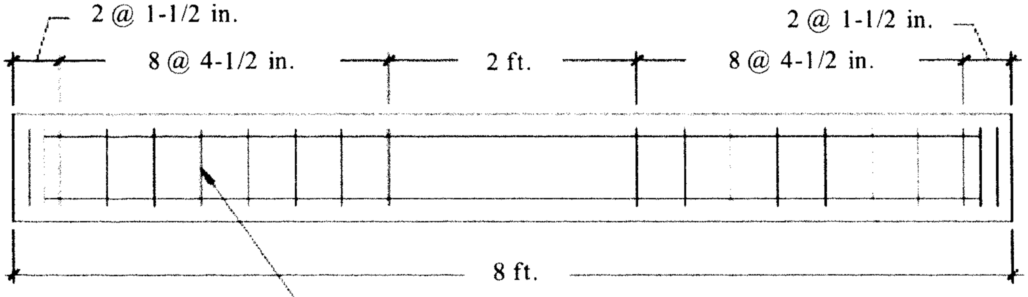
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65 [10.2.7.3]
a (in) =	0.65 [10.2.7]
c (in) =	1.00
M_n (k-in) =	404.5
M_n (k-ft) =	**33.7**
c/d_t =	0.101 [9.3.2]
Tension-Controlled	
Φ =	0.9
M_u (k-in) =	364.0
M_u (k-ft) =	30.3
P_u (k) =	**11.03**

Predicted Total Capacity (k):
24.5



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #30, 11000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

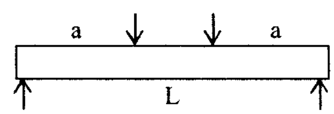
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	11000
f'_c (ksi)	11
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	3.742
y_f (in)	4.127

Test Setup

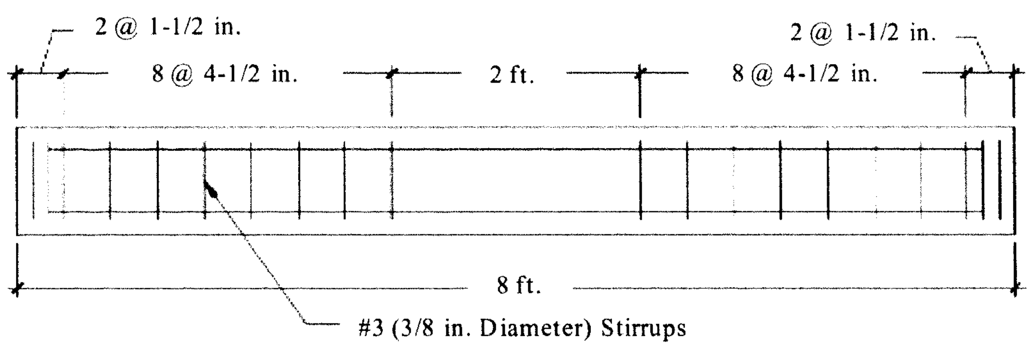
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.59	[10.2.7]
c (in) =	0.91	
M_n (k-in) =	405.8	
M_n (k-ft) =	**33.8**	
c/d_t =	0.092	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	365.2	
M_u (k-ft) =	30.4	
P_u (k) =	**11.07**	

Predicted Total Capacity (k):
24.6



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #31, 12000 psi
Coating System: Polyurea A, No Glass Fiber
[Brackets denote references to ACI 318-08 Building Code and Commentary]

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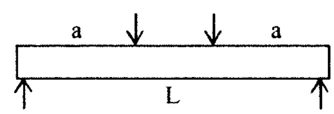
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.125	f_f (psi)	2147	n (bars)	3
b (in)	8.00	f_f (ksi)	2.147	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	12000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	12	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_s	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	3.761
d (in)	9.88			y_f (in)	4.162
d (ft)	0.82				

Test Setup

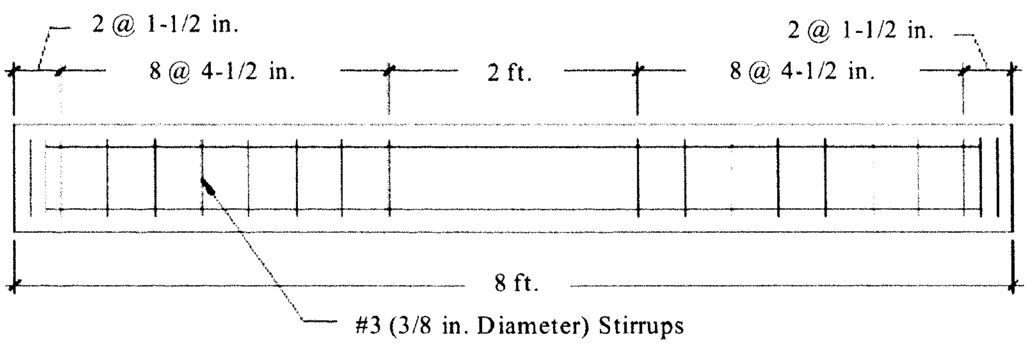
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.54	[10.2.7]
c (in) =	0.83	
M_n (k-in) =	406.9	
M_n (k-ft) =	**33.9**	
c/d_t =	0.084	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	366.2	
M_u (k-ft) =	30.5	
P_u (k) =	**11.10**	

Predicted Total Capacity (k):
24.7



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #32, 13000 psi

Coating System: Polyurea A, No Glass Fiber

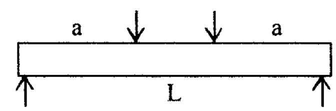
[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.125	f_f (psi)	2147	n (bars)	3
b (in)	8.00	f_f (ksi)	2.147	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	13000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	13	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_s	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	3.777
d (in)	9.88			y_f (in)	4.192
d (ft)	0.82				

Test Setup

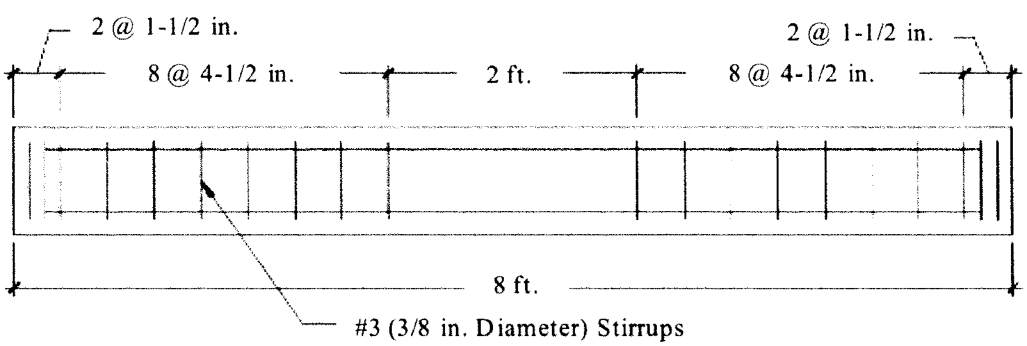
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.50	[10.2.7]
c (in) =	0.77	
M_n (k-in) =	407.8	
M_n (k-ft) =	**34.0**	
c/d_t =	0.078	[9.3.2]
	Tension-Controlled	
Φ =	0.9	
M_u (k-in) =	367.0	
M_u (k-ft) =	30.6	
P_u (k) =	**11.12**	

Predicted Total Capacity (k):
24.7



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #33, 14000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.125
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

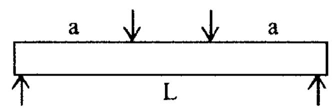
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	14000
f'_c (ksi)	14
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	3.790
y_f (in)	4.217

Test Setup

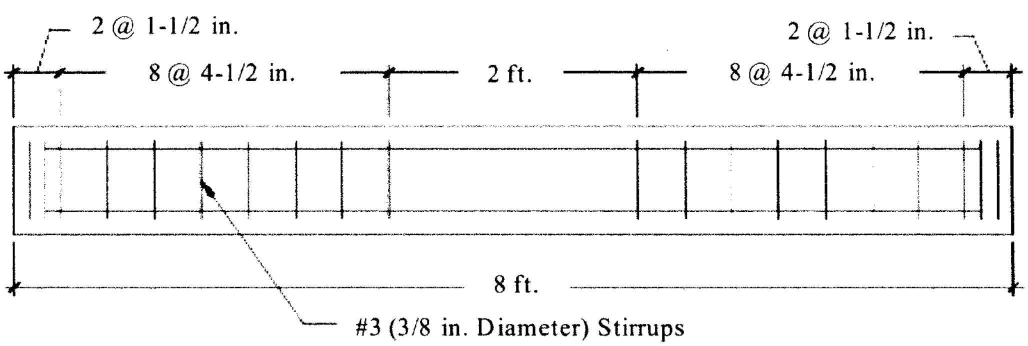
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.46	[10.2.7]
c (in) =	0.71	
M_n (k-in) =	408.6	
M_n (k-ft) =	**34.1**	
c/d_t =	0.072	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	367.7	
M_u (k-ft) =	30.6	
P_u (k) =	**11.14**	

Predicted Total Capacity (k):
24.8



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #34, 4000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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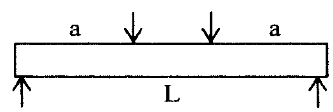
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.0625	f_f (psi)	1859	n (bars)	3
b (in)	8.00	f_f (ksi)	1.859	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	4000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	4	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	1.780
d (in)	9.88			y_f (in)	3.734
d (ft)	0.82				

Test Setup

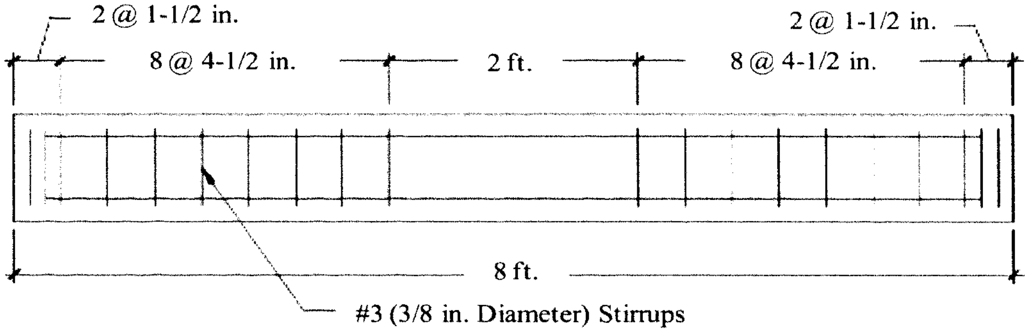
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.85	[10.2.7.3]
a (in) =	1.45	[10.2.7]
c (in) =	1.70	
M_n (k-in) =	354.4	
M_n (k-ft) =	**29.5**	
c/d_t =	0.172	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	319.0	
M_u (k-ft) =	26.6	
P_u (k) =	**9.67**	

Predicted Total Capacity (k):
21.5



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #35, 5000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

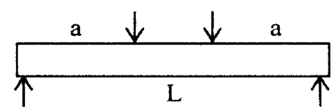
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	5000
f'_c (ksi)	5
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	1.811
y_f (in)	3.851

Test Setup

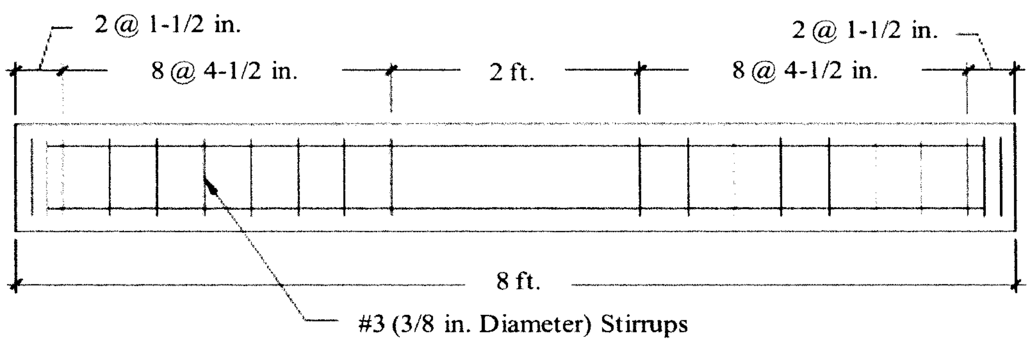
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.8	[10.2.7.3]
a (in) =	1.16	[10.2.7]
c (in) =	1.45	
M_n (k-in) =	360.1	
M_n (k-ft) =	**30.0**	
c/d_t =	0.147	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	324.1	
M_u (k-ft) =	27.0	
P_u (k) =	**9.82**	

Predicted Total Capacity (k):
21.8



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

MISSOURI S&T
University of Science & Technology

Beam Designation: Study Beam #36, 6000 psi

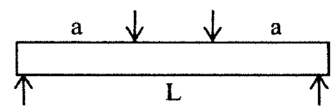
Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.0625	f_f (psi)	1859	n (bars)	3
b (in)	8.00	f_f (ksi)	1.859	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	6000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	6	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	1.831
d (in)	9.88			y_f (in)	3.925
d (ft)	0.82				

Test Setup

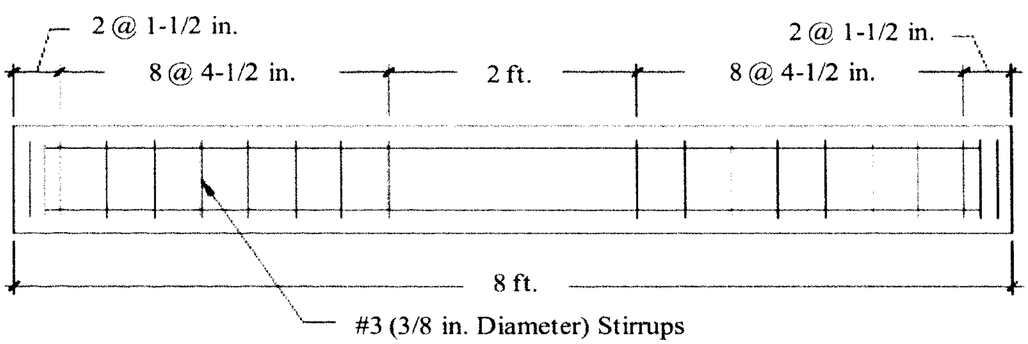
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.75	[10.2.7.3]
a (in) =	0.97	[10.2.7]
c (in) =	1.29	
M_n (k-in) =	364.0	
M_n (k-ft) =	**30.3**	
c/d_t =	0.130	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	327.6	
M_u (k-ft) =	27.3	
P_u (k) =	**9.93**	

Predicted Total Capacity (k):
22.1



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #37, 7000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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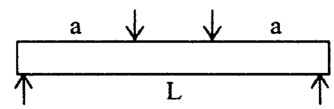
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.0625	f_f (psi)	1859	n (bars)	3
b (in)	8.00	f_f (ksi)	1.859	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	7000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	7	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	1.844
d (in)	9.88			y_f (in)	3.973
d (ft)	0.82				

Test Setup

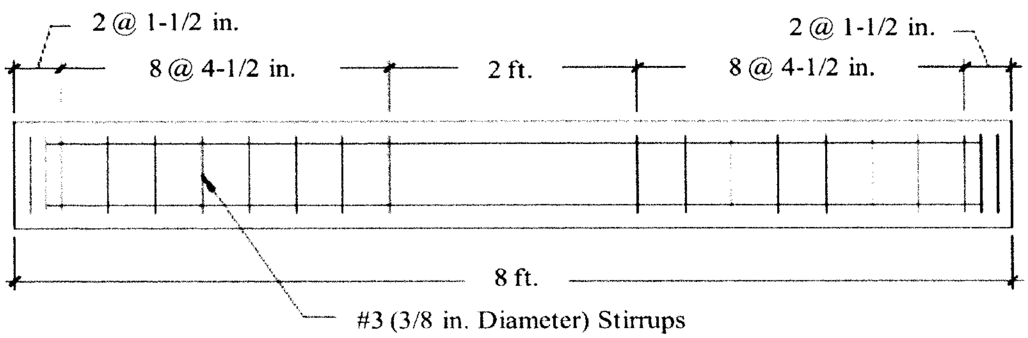
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.7	[10.2.7.3]
a (in) =	0.83	[10.2.7]
c (in) =	1.18	
M_n (k-in) =	366.7	
M_n (k-ft) =	**30.6**	
c/d_t =	0.120	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	330.0	
M_u (k-ft) =	27.5	
P_u (k) =	**10.00**	

Predicted Total Capacity (k):
22.2



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #38, 8000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

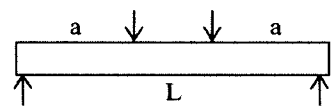
MISSOURI S&T
University of Science & Technology

Beam Dimensions	
t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties	
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	8000
f'_c (ksi)	8
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details	
n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	1.853
y_f (in)	4.005

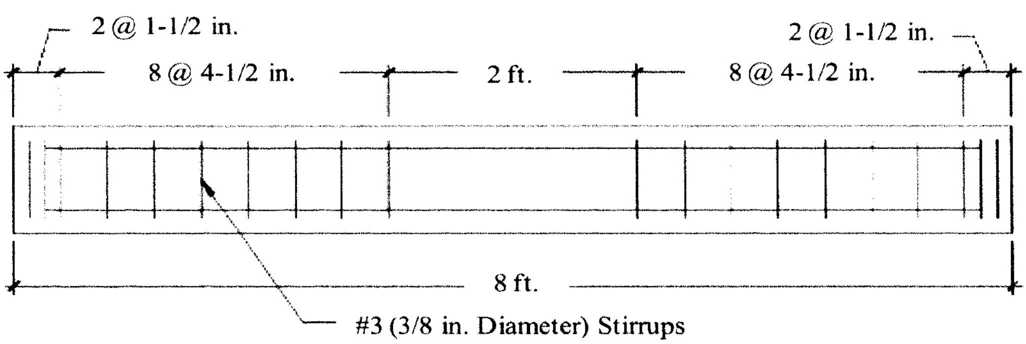
Test Setup			
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.73	[10.2.7]
c (in) =	1.12	
M_n (k-in) =	368.7	
M_n (k-ft) =	**30.7**	
c/d_t =	0.113	[9.3.2]
	Tension-Controlled	
Φ =	0.9	
M_u (k-in) =	331.9	
M_u (k-ft) =	27.7	
P_u (k) =	**10.06**	

Predicted Total Capacity (k):
22.3



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #39, 9000 psi
Coating System: Polyurea B with 10% Glass Fiber
[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T
University of Science & Technology

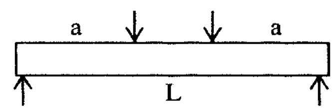
Beam Dimensions	
t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties	
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	9000
f'_c (ksi)	9
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details	
n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	1.868
y_f (in)	4.062

Test Setup

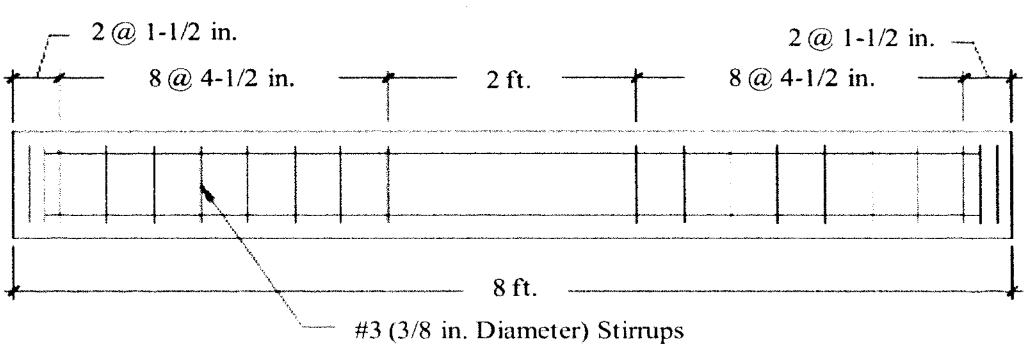
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65 [10.2.7.3]
a (in) =	0.64 [10.2.7]
c (in) =	0.99
M_n (k-in) =	370.3
M_n (k-ft) =	**30.9**
c/d_t =	0.100 [9.3.2]
Tension-Controlled	
Φ =	0.9
M_u (k-in) =	333.3
M_u (k-ft) =	27.8
P_u (k) =	**10.10**

Predicted Total Capacity (k):
22.4



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #40, 10000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

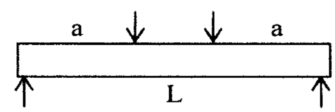
MISSOURI S&T University of Science & Technology

Beam Dimensions	
t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties	
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	10000
f'_c (ksi)	10
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details	
n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	1.880
y_f (in)	4.108

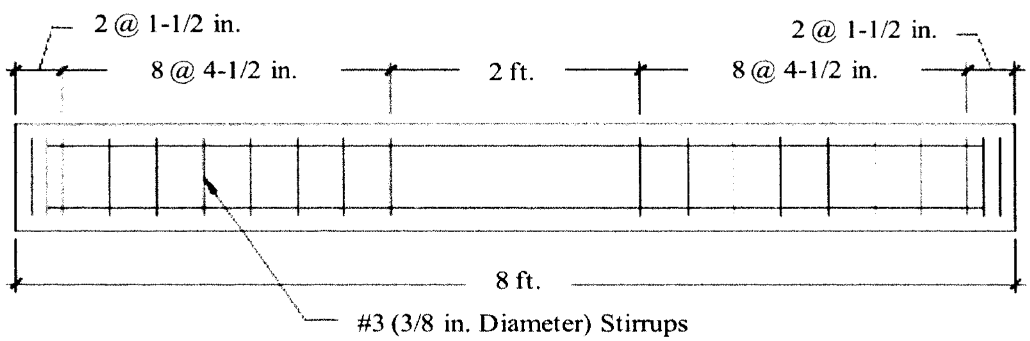
Test Setup			
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.58	[10.2.7]
c (in) =	0.89	
M_n (k-in) =	371.6	
M_n (k-ft) =	**31.0**	
c/d_t =	0.090	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	334.5	
M_u (k-ft) =	27.9	
P_u (k) =	**10.14**	

Predicted Total Capacity (k):
22.5



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #41, 11000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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Beam Dimensions

t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

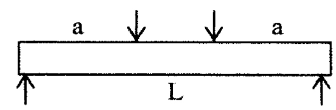
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	11000
f'_c (ksi)	11
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	1.891
y_f (in)	4.146

Test Setup

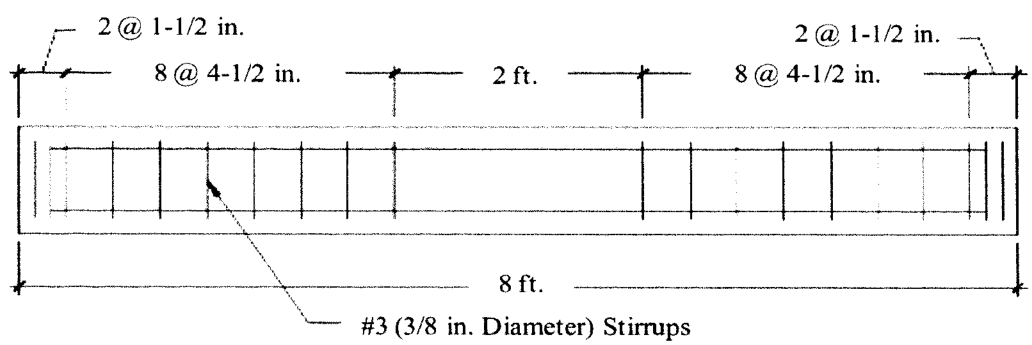
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.53	[10.2.7]
c (in) =	0.81	
M_n (k-in) =	372.7	
M_n (k-ft) =	**31.1**	
c/d_t =	0.082	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	335.4	
M_u (k-ft) =	28.0	
P_u (k) =	**10.16**	

Predicted Total Capacity (k):
22.6



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #42, 12000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

University of Science & Technology

Beam Dimensions

t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

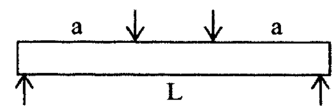
f_f (psi)	1859
f_f (ksi)	1.859
f'_c (psi)	12000
f'_c (ksi)	12
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	1.899
y_f (in)	4.177

Test Setup

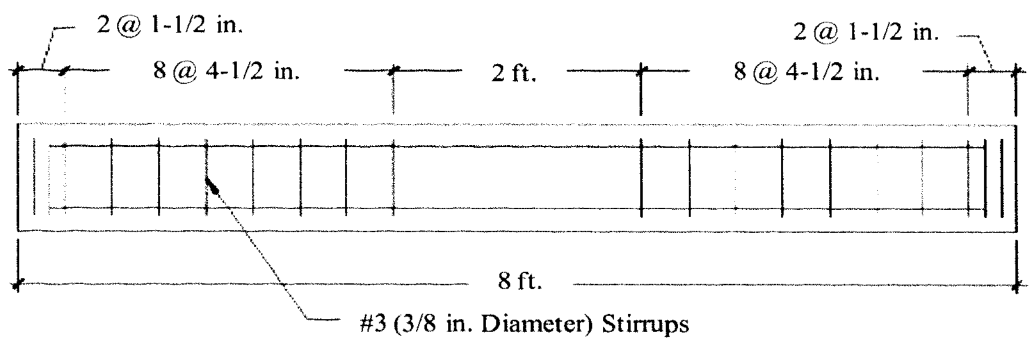
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.48	[10.2.7]
c (in) =	0.75	
M_n (k-in) =	373.5	
M_n (k-ft) =	**31.1**	
c/d_t =	0.075	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	336.2	
M_u (k-ft) =	28.0	
P_u (k) =	**10.19**	

Predicted Total Capacity (k):
22.6



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #43, 13000 psi

Coating System: Polyurea B with 10% Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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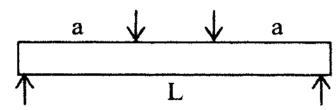
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.0625	f_f (psi)	1859	n (bars)	3
b (in)	8.00	f_f (ksi)	1.859	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	13000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	13	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	1.906
d (in)	9.88			y_f (in)	4.204
d (ft)	0.82				

Test Setup

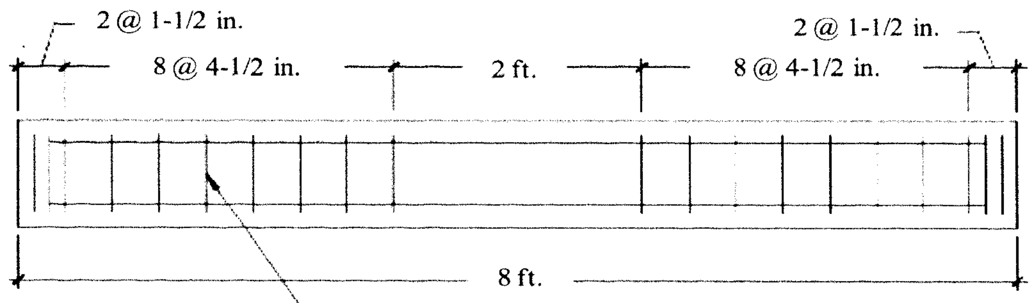
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.45	[10.2.7]
c (in) =	0.69	
M_n (k-in) =	374.3	
M_n (k-ft) =	**31.2**	
c/d_t =	0.070	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	336.9	
M_u (k-ft) =	28.1	
P_u (k) =	**10.21**	

Predicted Total Capacity (k):
22.7



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #44, 14000 psi

Coating System: Polyurea B with 10% Glass Fiber

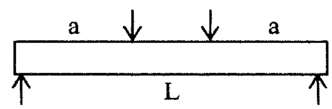
[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.0625	f_f (psi)	1859	n (bars)	3
b (in)	8.00	f_f (ksi)	1.859	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	14000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	14	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	1.912
d (in)	9.88			y_f (in)	4.226
d (ft)	0.82				

Test Setup

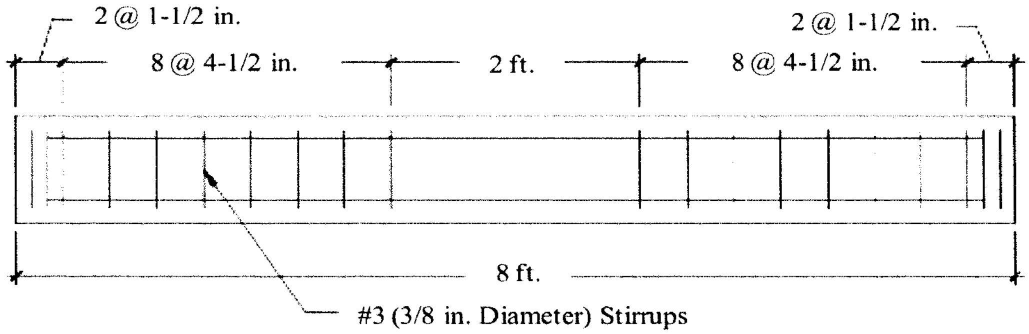
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.42	[10.2.7]
c (in) =	0.64	
M_n (k-in) =	374.9	
M_n (k-ft) =	**31.2**	
c/d_t =	0.065	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	337.4	
M_u (k-ft) =	28.1	
P_u (k) =	**10.23**	

Predicted Total Capacity (k):
22.7



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #45, 4000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions

t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

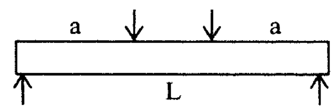
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	4000
f'_c (ksi)	4
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	1.777
y_f (in)	3.724

Test Setup

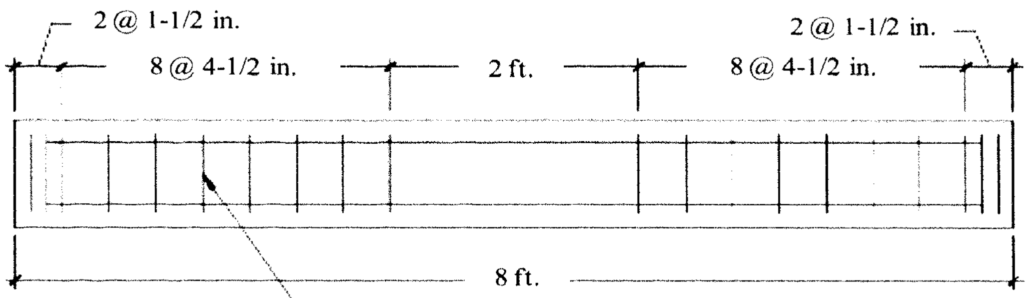
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.85	[10.2.7.3]
a (in) =	1.46	[10.2.7]
c (in) =	1.72	
M_n (k-in) =	357.9	
M_n (k-ft) =	**29.8**	
c/d_t =	0.174	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	322.1	
M_u (k-ft) =	26.8	
P_u (k) =	**9.76**	

Predicted Total Capacity (k):
21.7



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #46, 5000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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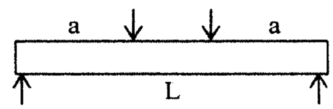
University of Science & Technology

Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.0625	f_f (psi)	2147	n (bars)	3
b (in)	8.00	f_f (ksi)	2.147	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	5000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	5	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_s	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	1.809
d (in)	9.88			y_f (in)	3.842
d (ft)	0.82				

Test Setup

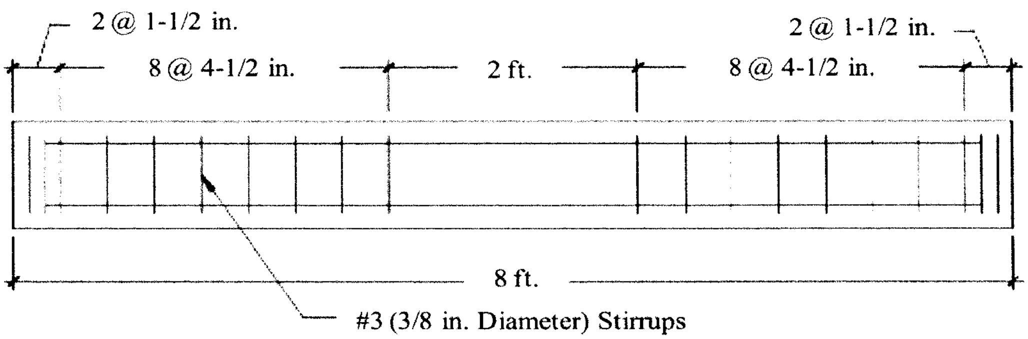
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.8	[10.2.7.3]
a (in) =	1.17	[10.2.7]
c (in) =	1.47	
M_n (k-in) =	363.8	
M_n (k-ft) =	**30.3**	
c/d_t =	0.148	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	327.4	
M_u (k-ft) =	27.3	
P_u (k) =	**9.92**	

Predicted Total Capacity (k):
22.0



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #47, 6000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions

t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

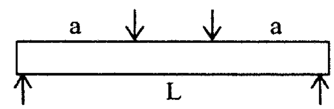
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	6000
f'_c (ksi)	6
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	1.829
y_f (in)	3.917

Test Setup

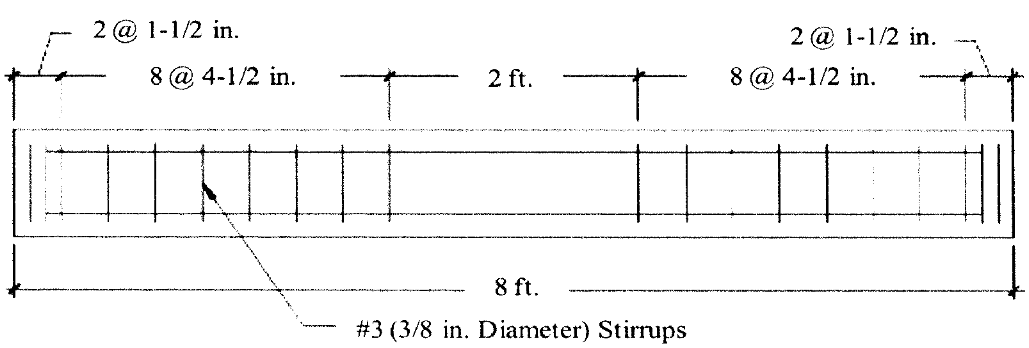
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.75	[10.2.7.3]
a (in) =	0.98	[10.2.7]
c (in) =	1.30	
M_n (k-in) =	367.7	
M_n (k-ft) =	**30.6**	
c/d_t =	0.132	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	330.9	
M_u (k-ft) =	27.6	
P_u (k) =	**10.03**	

Predicted Total Capacity (k):
22.3



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #48, 7000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

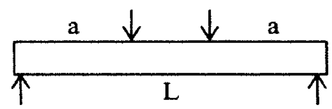
Beam Dimensions	
t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties	
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	7000
f'_c (ksi)	7
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details	
n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	1.842
y_f (in)	3.966

Test Setup

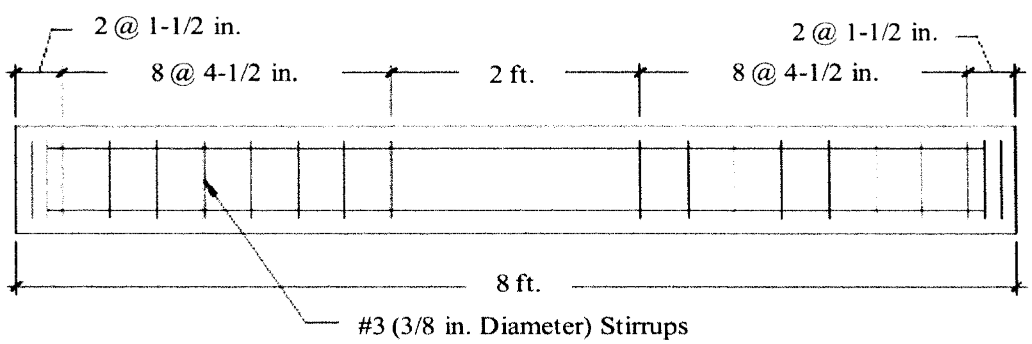
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.7	[10.2.7.3]
a (in) =	0.84	[10.2.7]
c (in) =	1.20	
M_n (k-in) =	370.5	
M_n (k-ft) =	**30.9**	
c/d_t =	0.121	[9.3.2]
	Tension-Controlled	
Φ =	0.9	
M_u (k-in) =	333.5	
M_u (k-ft) =	27.8	
P_u (k) =	**10.10**	

Predicted Total Capacity (k):
22.5



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #49, 8000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions

t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

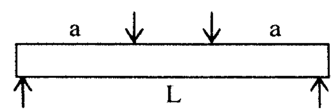
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	8000
f'_c (ksi)	8
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	1.851
y_f (in)	3.998

Test Setup

L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		

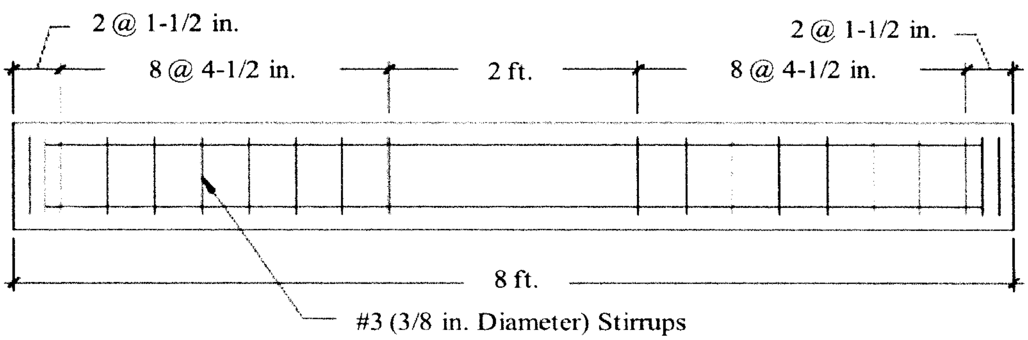


Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.73	[10.2.7]
c (in) =	1.13	
M_n (k-in) =	372.6	
M_n (k-ft) =	**31.1**	
c/d_t =	0.114	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	335.4	
M_u (k-ft) =	27.9	
P_u (k) =	**10.16**	

Predicted Total Capacity (k):

22.6



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #50, 9000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

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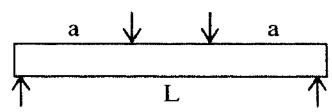
Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.0625	f_f (psi)	2147	n (bars)	3
b (in)	8.00	f_f (ksi)	2.147	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	9000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	9	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_s	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	1.866
d (in)	9.88			y_f (in)	4.056
d (ft)	0.82				

Test Setup

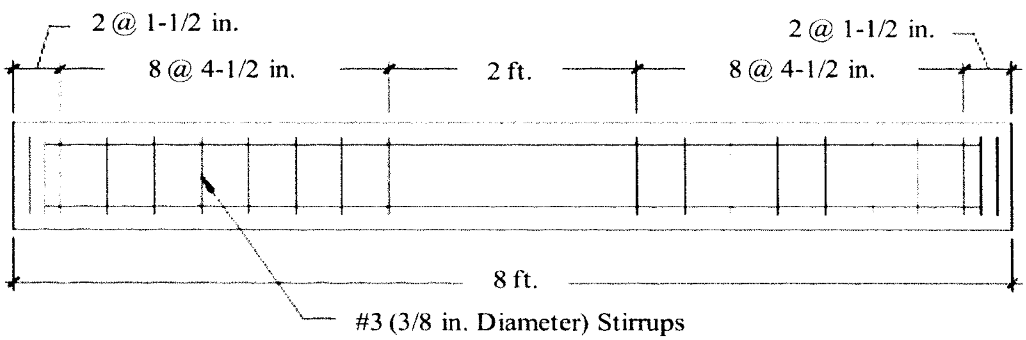
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.65	[10.2.7]
c (in) =	1.01	
M_n (k-in) =	374.3	
M_n (k-ft) =	**31.2**	
c/d_t =	0.102	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	336.8	
M_u (k-ft) =	28.1	
P_u (k) =	**10.21**	

Predicted Total Capacity (k):
22.7



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #51, 10000 psi

Coating System: Polyurea A, No Glass Fiber

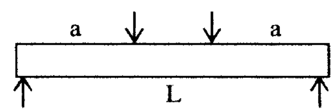
[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions		*Material Properties*		*Reinforcement Details*	
t_f (in)	0.0625	f_f (psi)	2147	n (bars)	3
b (in)	8.00	f_f (ksi)	2.147	Bar Size (#)	4
b (ft)	0.67	f'_c (psi)	10000	A_s (in^2)	0.600
h (in)	12.00	f'_c (ksi)	10	A_s (ft^2)	0.004
h (ft)	1.00	f_y (psi)	60000	ρ_S	0.76%
g (in)	2.13	f_y (ksi)	60	A_f (in^2)	1.879
d (in)	9.88			y_f (in)	4.102
d (ft)	0.82				

Test Setup

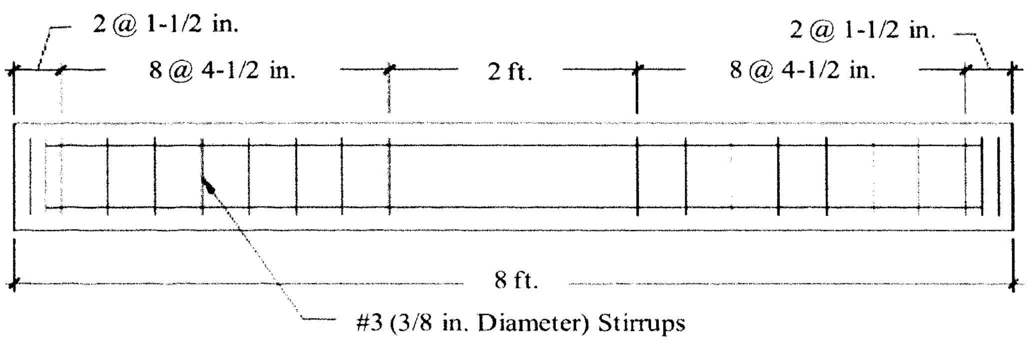
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.59	[10.2.7]
c (in) =	0.91	
M_n (k-in) =	375.6	
M_n (k-ft) =	**31.3**	
c/d_t =	0.092	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	338.0	
M_u (k-ft) =	28.2	
P_u (k) =	**10.24**	

Predicted Total Capacity (k):
22.8



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #52, 11000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

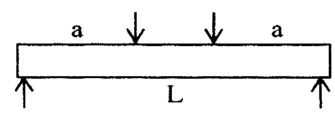
Beam Dimensions	
t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties	
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	11000
f'_c (ksi)	11
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details	
n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	1.889
y_f (in)	4.140

Test Setup

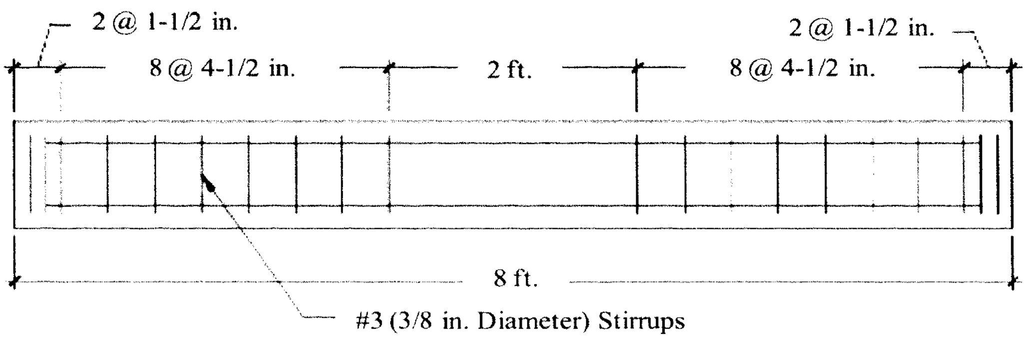
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.54	[10.2.7]
c (in) =	0.82	
M_n (k-in) =	376.7	
M_n (k-ft) =	**31.4**	
c/d_t =	0.083	[9.3.2]
	Tension-Controlled	
Φ =	0.9	
M_u (k-in) =	339.0	
M_u (k-ft) =	28.2	
P_u (k) =	**10.27**	

Predicted Total Capacity (k):
22.8



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #53, 12000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T
University of Science & Technology

Beam Dimensions

t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

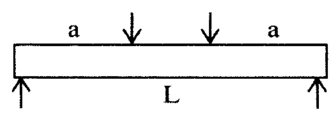
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	12000
f'_c (ksi)	12
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_s	0.76%
A_f (in^2)	1.898
y_f (in)	4.172

Test Setup

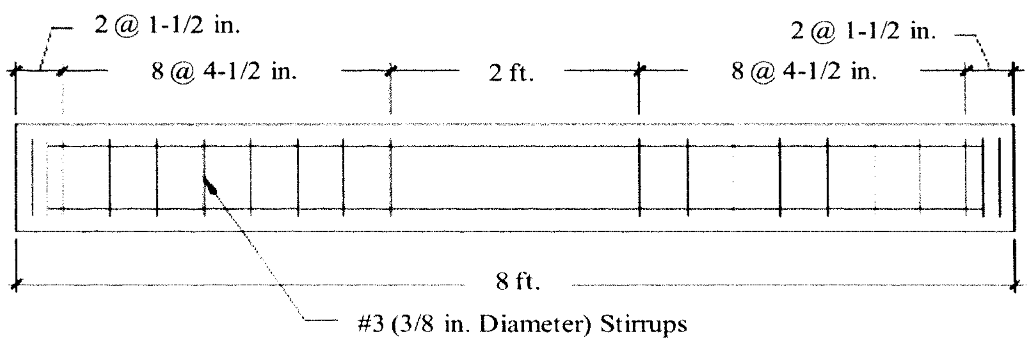
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.49	[10.2.7]
c (in) =	0.76	
M_n (k-in) =	377.6	
M_n (k-ft) =	**31.5**	
c/d_t =	0.077	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	339.8	
M_u (k-ft) =	28.3	
P_u (k) =	**10.30**	

Predicted Total Capacity (k):
22.9



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #54, 13000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions

t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

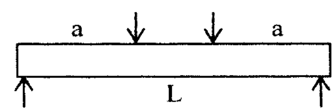
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	13000
f'_c (ksi)	13
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	1.905
y_f (in)	4.199

Test Setup

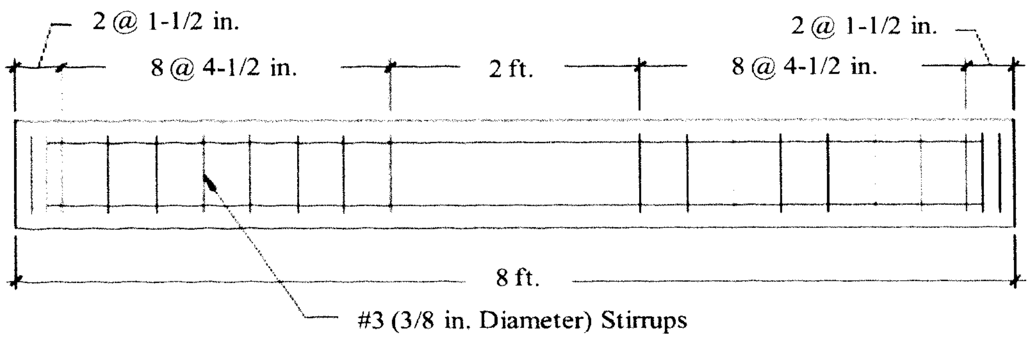
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.45	[10.2.7]
c (in) =	0.70	
M_n (k-in) =	378.3	
M_n (k-ft) =	**31.5**	
c/d_t =	0.071	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	340.5	
M_u (k-ft) =	28.4	
P_u (k) =	**10.32**	

Predicted Total Capacity (k):
22.9



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

Parametric Study Beam Design Worksheet

Beam Designation: Study Beam #55, 14000 psi

Coating System: Polyurea A, No Glass Fiber

[Brackets denote references to ACI 318-08 Building Code and Commentary]

MISSOURI S&T University of Science & Technology

Beam Dimensions

t_f (in)	0.0625
b (in)	8.00
b (ft)	0.67
h (in)	12.00
h (ft)	1.00
g (in)	2.13
d (in)	9.88
d (ft)	0.82

Material Properties

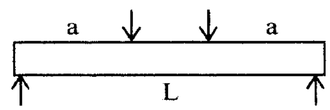
f_f (psi)	2147
f_f (ksi)	2.147
f'_c (psi)	14000
f'_c (ksi)	14
f_y (psi)	60000
f_y (ksi)	60

Reinforcement Details

n (bars)	3
Bar Size (#)	4
A_s (in^2)	0.600
A_s (ft^2)	0.004
ρ_S	0.76%
A_f (in^2)	1.911
y_f (in)	4.222

Test Setup

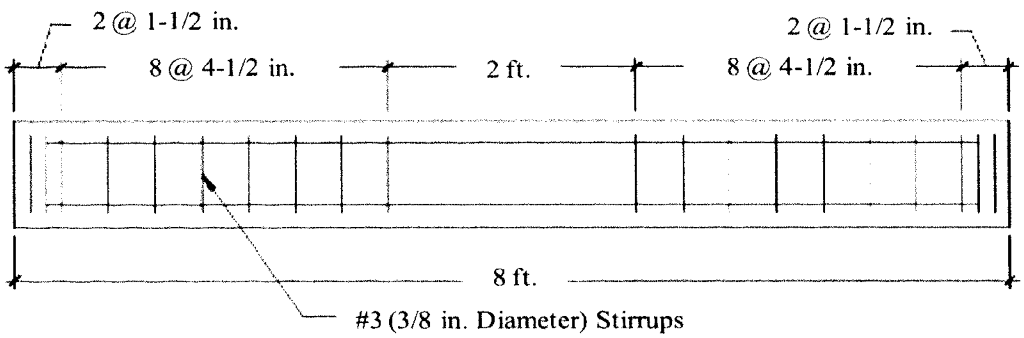
L (in)	90.00	a/d	3.34
L (ft)	7.50	L-2a (in)	24.00
a (in)	33.00	L-2a (in)	2.00
a (ft)	2.75		



Moment Capacity Calcualations

β_1 =	0.65	[10.2.7.3]
a (in) =	0.42	[10.2.7]
c (in) =	0.65	
M_n (k-in) =	379.0	
M_n (k-ft) =	**31.6**	
c/d_t =	0.066	[9.3.2]
Tension-Controlled		
Φ =	0.9	
M_u (k-in) =	341.1	
M_u (k-ft) =	28.4	
P_u (k) =	**10.34**	

Predicted Total Capacity (k):
23.0



Unit Conversions: 1 in = 25.4 mm; 1 ft = 305 mm; 1 psi = 6890 Pa; 1 ksi = 6.9 MPa; 1 lb = 4.45 N

VITA

Courtney Elizabeth Greene, born on September 6, 1985 in Poplar Bluff, Missouri grew up in Fremont and graduated as valedictorian of her high school class at Winona R-III High School in 2004. She then moved to Rolla, Missouri where she pursued a Bachelor of Science degree in Architectural Engineering at Missouri University of Science and Technology (Missouri S&T), graduating summa cum laude in December 2008. She began pursuit of her Master of Science degree in Civil Engineering at Missouri S&T in January 2009 working with Dr. John J. Myers. During her master's degree work, she has studied fiber-reinforced polyurea strengthening systems for concrete applications. Her work was developed to provide seismic, blast, and general strengthening for repair and retrofit situations. She will earn her Master's Degree in December 2010.