

EVALUATION OF THE PERFORMANCE OF STEEL
FIBER REINFORCED CONCRETE PIPES
PRODUCED BY PACKERHEAD
METHOD

by

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April 21, 2014

Abstract

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The University of Texas at Arlington, 2014

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This research aimed at evaluating the use of Dramix RC 65/35 CN steel fiber as an alternative to the conventional reinforcement in concrete pipes. The performance of steel fiber reinforced concrete pipes produced by Packerhead pipe production machine was evaluated through an experimental testing of steel fiber reinforced concrete pipes with diameters from 18 to 36 in. and different steel fiber dosages. Three-edge bearing tests were carried out according to the ASTM C497 to determine the strength class of each case of pipes. For more detailed image of the tested pipes' performance, load-deflection data were acquired and plots were made to determine the residual strength of the tested pipes after reaching the peak strength. Material evaluation was done through experimental testing of compressive cylinder and flexural beam specimens casted using the same concrete batch and at the same time of the production of steel fiber reinforced concrete pipes. Material testing was done according to the ASTM C39 and ASTM C1609.

The three-edge bearing test results and data showed that the steel fiber is considered a proper alternative to the conventional steel reinforcement in concrete pipes.

Most of the tested cases passed the ASTM C76 class III ultimate strength requirements, as well as, the significant post ultimate strength residual strength when increasing the steel fiber dosage.

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Chapter 1

Introduction and Literature Review

Introduction

Concrete pipes have been used to convey sewage water and storm water as a gravity flow conduits and to convey low pressure irrigation water since 1800s. Before concrete pipes were introduced to the competition, clay pipes and steel pipes were been used for sewage water transport.

In 1980s, flexible plastic pipes, mainly Poly Vinyl Chloride PVC and High Density Poly Ethylene HDPE, were introduced to the sewage water pipes market as a cheaper alternative to precast concrete pipes. However, price has never been the unique pivotal factor when other factors that have a direct effect on the performance of a product are involved in comparison like strength, durability, constructability, dependability, and etc.

When concrete pipe strength is mentioned, it doesn't only mean that it is stronger, but it is designed and plant tested to resist the load by itself with a minimal reliance on the installation conditions, unlike flexible pipe that relies mainly on the installation conditions to support load. Being a rigid pipe system, concrete pipe strength is more than 85% dependent on the pipe itself and only 15% on the burying soil developed strength. The self-strength of concrete pipe enables it of withstanding construction flaws and higher fill heights. On the other hand, flexible pipe is at least 95% dependent on the surrounding soil's support; hence, a backfill should be done as a pre-engineered process with continuous measurements and monitoring to assure high compaction levels required to provide the designed strength. In addition, when the soil properties aren't achieving the required design strength, imported backfill should be used. The difference in backfilling process while installing flexible and concrete pipes not only increases the installation costs, but extending the installation duration.

Beside the self-gaining strength and the ease of constructability, concrete pipe is distinguished by durability that exceeds, in most cases, a design life time of 70-100 years. Local availability of concrete pipes, non-flammability, design flexibility, hydraulic efficiency, and sustainability are among the features that distinguish the concrete pipes from flexible pipes.

Hence, various research has been carried out regarding improving the performance of concrete pipes, as well as, lowering the cost of concrete pipes to add another competing factor that expands the pipe concrete market more. Improving the performance of concrete pipes involves the enhancing of the used concrete properties, the reinforcement steel, and the geometry of the pipes.

The concrete pipe system uses the gravity flow to convey the sewage and storm water; hence, there is no pressure force acting on the internal surface of the pipes unlike other pressurized pipe systems. Being buried in almost all of cases, concrete pipes experience earth loads due to both the weight of the soil and the masses over the pipe, as well, as the live loads due to the moving masses over the earth surface, Figure 1-1.

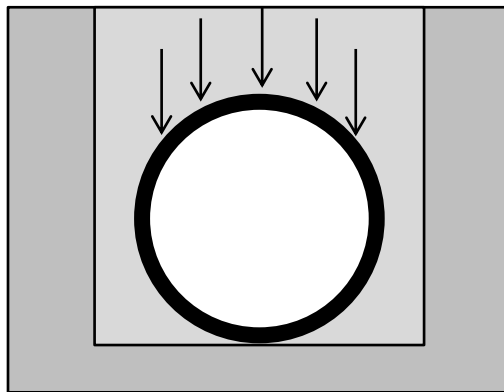


Figure 1-1 Earth Load on a Buried Pipe

Earth Load on a Buried Pipe

The load acting on a buried pipe generates a combination of flexural and shear stresses in the pipe walls. Plain concrete pipes have been used for long time mainly with small pipe sizes. Due to the concern with non-reinforced pipe not having any reserve deformation capacity after it cracks, its use has declined in recent years. Concrete pipes steel reinforcement is a circumferential helix shaped steel wire cage, Figure 1-2, that is put and aligned inside the pipe's casting form then concrete is casted over the reinforcement. The steel cage is fabricated using steel wire rolls by special machine that forms the steel wire to the required size in a helical path while welding it to the longitudinal steel wires that provide a uniform spacing. For small diameter pipes, it's almost impossible to reinforce them with steel cage properly since adjusting steel cage reinforcement at the middle of the wall becomes a precise operation. A small displacement of the designed position of the reinforcement in the wall during casting leads to a significant decrease in the ultimate strength of the pipe.

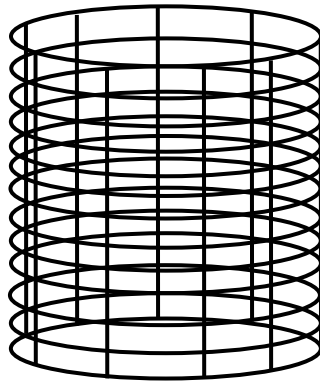


Figure 1-2 Steel Cage

As shown in Figure 1-3, the steel cage reinforcement mainly resists flexural loads and slightly shear forces. When the load on a concrete pipe is high or not uniformly

distributed along the surface of the pipe, the shear load portion increases, hence, the increase of the steel cage reinforcement is not a proper solution and an additional shear stirrups are required to resist the shear forces, which becomes a more sophisticated process that consumes time, labor and material leading to an increase in the cost of producing the pipe. Another factor, that was expected from previous research and observed during this research, which leads to the domination of the shear failure, is the pipe diameter. The larger the diameter of the pipe, the higher the loads to be carried and the more the shear failure dominates.

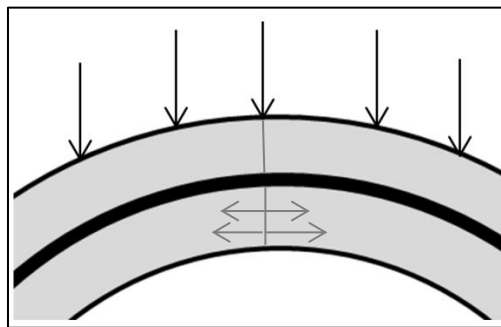


Figure 1-3 Steel Cage Load Carrying

Concrete pipes reinforced using conventional steel reinforcement, either only circumferential reinforcement or with shear reinforcement, has been used and showed a capability of standing high imposed loads, in addition to the availability of standard specifications and design guidelines. However, the production process of conventional reinforcement concrete pipes is time, labor, and material consuming. Time is consumed during the fabrication of the steel cages and a steel cage fabricating machine with an assigned operator is required and any problem with the machine leads to the delay of the whole production process and affecting the production rate.

Using steel fibers in the concrete mix used to produce concrete pipes provides an alternative to the conventional steel cage reinforced pipes with a comparable strength

and enhanced properties. Steel fiber network in the concrete mix provides a higher load transfer than using conventional steel reinforcement. This load transfer mechanism provides higher shear resistance than conventional reinforced concrete. In addition, steel fiber reinforcement improves the crack resistance and increases the crack surface, thereby improves the watertightness and durability of the pipe. Also, steel fibers in concrete pipes don't need any position adjustment unlike the conventional steel reinforcement that needs precise position adjustment within the pipe walls to get the designed strength.

In addition, using steel fiber for concrete pipes reinforcement improves the production rates by excluding the steel cage fabrication from the production process and incorporating the fibers into automated batching process used for concrete mixing. Recently, automated reinforcement fiber dosing equipment have been available in the market which provide accurate dosing and uniform distribution of steel fibers in the concrete mix, reducing the labor cost and increasing the dosing and mixing quality.

Literature Review

Steel fiber reinforced concrete pipes have been used in Europe for over two decades now. Performance-based guidelines have been developed allowing an efficient design and use of steel fiber reinforced concrete pipes as competing alternative to the conventional reinforced concrete pipes. The current European Standard Specifications are mainly based upon the EN 1916:2002 "Concrete pipes and fittings, unreinforced, steel fibre and reinforced". Some of the European Standards that deals with fiber reinforced concrete pipes are the French NF P16-345-2:2003, Belgium NBN -B21-106:2004, Italian UNI EN 1916:2004, Netherlands NEN 7126:2004, Spain UNE 127916:2004, and the Turkish TS-821-EN-1916. A recent American Standard

Specification, ASTM C1765 – 13 “Standard Specification for Steel Fiber Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe”, that establishes the requirements for steel fiber reinforced pipes of internal diameters from 12 to 48 in. to be used in the conveyance of sewage and storm water as well as industrial wastes.

Research studying the performance of steel fiber concrete in general and steel fiber reinforced concrete pipes specifically have been carried out in the last decades.

An intensive experimental research was carried out by Mikhaylova (2013) to evaluate the performance of steel fiber reinforced concrete pipes. A total of 116 pipes of sizes from 15 in. to 48 in. diameters and with fiber dosages from 0.17% to 0.83% by volume were tested according to ASTM C497 using three-edge bearing test. Steel fiber reinforced concrete pipes showed adequate ultimate strength, residual strength, toughness and watertightness. A significant crack size control was observed, were a hairline crack was maintained till the ultimate load. Optimum fiber dosages of 0.25% and 0.5% by volume were recommended for 24 in. and 36 in. diameter pipes respectively.

Haktanir et al. (2007) investigated the performance of steel fiber reinforced concrete pipes compared to those of plain concrete and conventionally reinforced pipes under three-edge-bearing test. Dramix RC-80/60-BN of 2.36 in. (60 mm) length and ZP 308 with 1.18 in. (30 mm) length steel fibers were used in this study with dosages of 42 lb/yd³ and 67 lb/yd³ for each type of fibers. The study showed that the three-edge-bearing strength of RC-80/60-BN steel fiber reinforced concrete pipes was 82% greater than the plain concrete pipes and 6% greater than the conventionally reinforced pipes. Also, the crack size was 47% smaller than the plain concrete pipes and 15% smaller than conventionally reinforced pipes. In addition, the pipes with dosage of 67 lb/yd³ didn't show a significant excess strength than the 42 lb/yd³ when taking into consideration the 60% increase in steel fiber dosage in the case of the 67 lb/yd³.

A study carried out by Thomas and Ramaswamy investigating the mechanical properties of steel fiber reinforced concrete through 60 tests with varying the concrete strength and the steel fiber dosage. The concrete strengths used were 35, 65, and 85 MPa with steel fiber volume fractions of 0, 0.5, 1.0, and 1.5% (approximately: 0, 66, 132, and 198 lb/yd³). The average increase in the 1.5% volume fraction steel fibers compression cube specimens' strength due to the addition of steel fibers was significantly low and didn't exceed 3.65%. The average increase in the cylinder compressive strength was slightly higher than that of the cube compressive strength and ranged from 4.6 to 8.33%. On the other hand, the addition of steel fibers significantly increased the split tensile strength with an average of 40%, the modulus of fracture by an average of 42%. The increase in the split tensile strength and the modulus of rupture was explained to be due to the fibers across the cracks in the concrete matrix that carried higher loads after crack than the strength of the matrix. The study showed an increase in the stiffness due to the addition of steel fibers where the modulus of elasticity increased by an average of 8.6%.

Even though adding steel fibers doesn't have a significant effect on the compressive strength of concrete, it has a significant effect on the impact resistance of the concrete. Impact resistance of steel fiber reinforced concrete has been studied by many researchers. Nataraja et al. (2005) carried out an experimental study to investigate the behavior of the steel fiber reinforced concrete under impact loads. Drop weight tests performed on specimens with steel fiber dosages volume fractions of 0, 0.5, 1.0, and 1.5% (approximately: 0, 66, 132, and 198 lb/yd³) showed a significant increase the impact resistance which increased by 25 times compared to the plain concrete. In addition, a study by Bindiganavile and Banthia using a contoured double cantilevered

beam showed that the steel fiber reinforced concrete showed greater crack growth resistance under impact loading than polypropylene fiber reinforced concrete.

The watertightness of concrete plays a crucial role in the durability of precast concrete products. The effect of adding steel fiber to the concrete water permeability was studied by Singh and Singhal (2011). An extensive experimental investigation using steel fibers with various weight fractions of 1, 2, and 4% and with different aspect ratios of 65, 85, and 105 was carried out. The decrease in the water permeability of concrete after adding steel fibers was significant and had an average of 75% less than the plain concrete.

Production of Pipes

Production of pipes was carried out in Hanson Pipe & Precast Inc. production plant in Grand Prairie, Texas. The plant produces different types of precast products including precast concrete pipes, culverts, manholes, junction boxes, and other precast products as well as large diameter steel pipes. The pipes were produced using Packerhead machine that utilized the spinning technique for concrete consolidation. The Packerhead casting machine, shown in Figure 1-4, involved a main rotor with the required pipe internal diameter and a group of small rotors with their axes fixed to the main rotor that were rotating with high speeds. The rotors utilized the centrifugal force generated as concrete was being poured over to perform the consolidation. Steel forms of required pipe outside diameter were placed in the Packerhead and the rotor started moving inside the forms from the base of the pipe upward while the concrete was being poured from the top to form the pipe internal diameter.



Figure 1-4 Packerhead Machine Rotors

The steel fiber was added to the concrete mix and mixed well before being poured into the form over the rotor. Extra water was added during the casting directly over the rotor with an amount decided by the machine operator based upon his experience while avoiding extra water that might lead to the pipe failure after removing the steel form. The steel form having the recently casted was then moved to the curing zone where the steel form was removed. Plastic curtains enclosing the curing zone were then moved down and steam nozzles were switched on provided saturated air with almost 100% humidity. The pipes were left for curing till the next day before they were moved to the storing zone outside the production plant.

Steel Fiber Used

Dramix RC 65/35 CN steel fiber was used throughout this research as the concrete pipes reinforcement. It's a cold drawn steel wire fiber with hooked ends to ensure optimum anchorage. Dramix steel fiber was manufactured by Bekaert, a global leader in fiber reinforced concrete products. The steel fibers are 35mm [1.4 in.] in length with a 0.55 mm [0.022 in] diameter. The tensile strength of the steel fibers is 1,345 N/mm² [195 ksi] while the Young's Modulus is 210,000 N/mm² [30.5 x 10³ ksi]. The Dramix RC65/35BN conforms to the ASTM A820.

Goals and Objectives

The aim of this research is to continue the evaluation of the performance of Bekaert Dramix RC 65/35 CN steel fibers in various dosages as an alternative to the conventional steel reinforcement in dry-cast concrete pipes with diameters from 18 to 36 in. produced using Packerhead pipe production machine. The performance is evaluated based upon the three-edge bearing test results involving the determination of the ultimate capacity of the pipes and the load-deflection plots. The results are to be compared to the ASTM C76 “Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe” to determine the corresponding ultimate strength class. Also, the material properties of concrete with different dosages of steel fiber reinforcement are to be determined including the flexural behavior and the ultimate compressive strength.

Chapter 2

Material Experimental Testing

Introduction

Material testing description and results of the steel fiber reinforced concrete, used in producing the pipes for this research, are presented in this chapter. The material tests performed during this research were flexural beam test, compressive cylinder strength test and direct tension test. The flexural beam tests were performed in accordance with the ASTM C1609 “Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)”, the compressive cylinder tests were done according to the ASTM C36 “Standard Test Method for Compressive Strength of Cylinder Concrete Specimens” and the direct tension tests were performed according to the ASTM. The specimens were casted with dimensions according to the ASTM C31 “Standard Practice for Making and Curing Test Specimens in the Field”. The specimens were casted using the same mix used for producing each case of pipes at the same time of the pipes’ production. The specimens then were left at the same curing spot of the corresponding produced pipes at the production plant.

Dry cast concrete production method was used in producing the tested pipes. In practice, either dry cast concrete or wet cast concrete production can be used in pre-cast concrete products. The dry cast concrete mixes, known as no-slump mixes, use low water to cement ratio to produce a zero slump concrete mix. The main advantage of using dry cast production is the ability of the removal of the casting form immediately after casting since the dry cast mix allows the pre-casted product to stand by itself allowing the use of the same form in producing more than one pipe daily which significantly increases production volume and lower both tools and labor costs. The presence of a steel cage reinforcement in the traditional pipes helps the recently casted

pipes to stand after removing the forms which allows some increase in the water to cement ratio, however, the pipes produced for this research used steel fiber as a full alternative to the traditional cage reinforcement which required the an even lower water to cement ratio.

The use of the low water to cement ratio results in a harsh hardly workable mixes shown in Figure 2-1. However, the dry cast mixes become usable through using specialized consolidation techniques including heavy-duty vibration, packing, pressing and spinning. In the case of this research, where Packerhead method was used, spinning was consolidation technique used in casting the pipes as discussed in chapter 1.



Figure 2-1 Dry Mix Harsh Looking

Concrete mix

In addition to the low workability of the dry mix used, the low water to cement ration significantly affects the strength of the matrix. The water to cement effect becomes more significant when the pipe production is done during hot weather days. Every pipe production plant has its own mixes that have been developed based upon their practice and experience to satisfy the required strength of different types of pipes. In this research, the concrete mix kept the same for all of the pipes produced which was the mix that is used by Hanson for producing class III pipes. However, the water to cement ratio varied based upon the size of the pipe to a ratio that keeps pipes standing after removing the forms.

Flexural Beam Test

Flexural beam test, known as “Third-Point Loading Test”, was performed to evaluate the flexural performance of the steel fiber-reinforced concrete, used in producing the research tested pipes, through using some parameters from the load deflection curves obtained during the test. The tests were carried on according to the ASTM C1609 “Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)”. This test determines the first-peak and peak load and their corresponding stresses using the modulus of rupture formula shown below . It also determines the residual loads at a specified deflection which can be used to determine the residual strength at this deflection. The area under the load-deflection curve can be used to determine the toughness of the tested specimen which is an indication of the energy absorption capability of the specimen shown in Figure 2-2.

$$f = \frac{PL}{bd^2}$$

where:

f = the strength, psi [MPa]

P = the load, lbf [N]

L = the span length, in. [mm]

b = the average width of the specimen at the fracture, in. [mm]

d = the average depth of the specimen at the fracture, in. [mm]

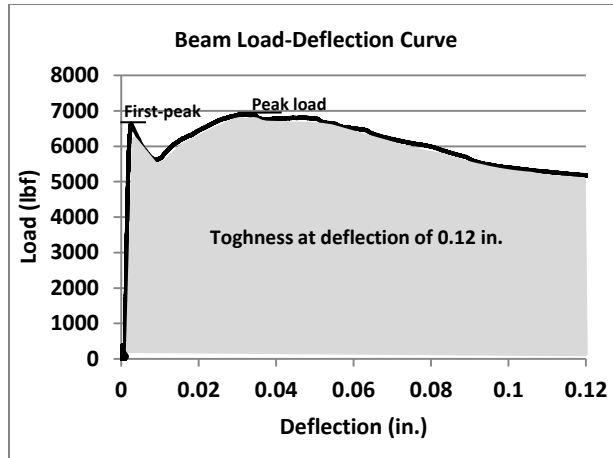


Figure 2-2 Load-Deflection Plot Showing the First-Peak Load, Peak Load and Toughness

The beam specimens tested were casted in the pipe production plant at the same time of the casting of each group of pipes using the same steel fiber reinforced concrete mix. Steel molds with a standard size of 6 by 6 by 20 in. according to the ASTM C1609 and ASTM C31 were used for casting the specimens. The casting involved using a vibration table on which each mold was put and even thickness layers of concrete were added and compacted. Due to the low workability of the dry mix, the vibrating table didn't provide enough compaction, hence, an additional compaction was done using a tamping rod providing high amplitude impact and pressing compaction Figure 2-3.



Figure 2-3 Beam and Cylinder Mold on the Vibrating Table

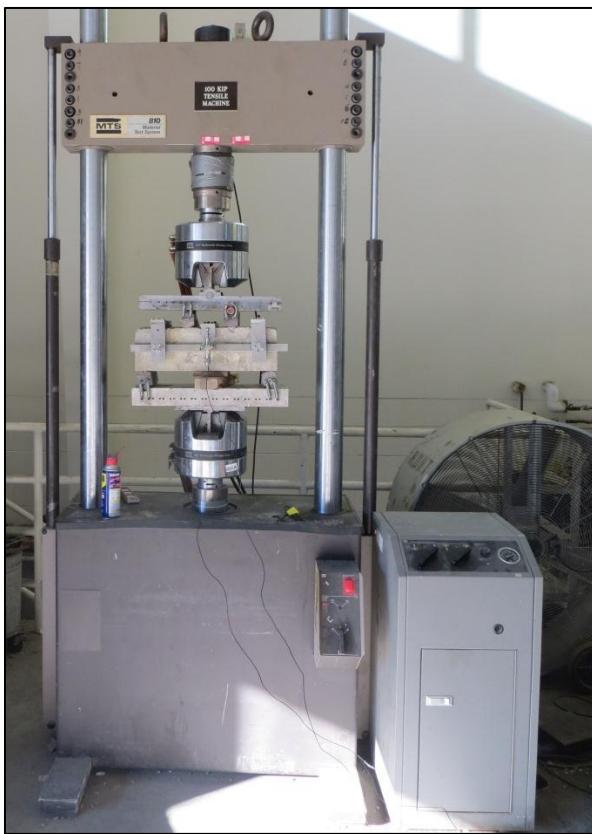
After fully casting the molds, they were put in the curing zone with the corresponding pipes to experience the same conditions of the pipes. A practical observation while casting the beam specimens was the effect of the temperature on the workability of the mix to be used to cast the molds. During high temperature days, the mix to be used for casting the beam specimens started solidification in a short period of less than an hour after mixing the concrete mix, as shown in Figure 2-4, and hence, a limited number of specimens could be casted for each concrete batch.



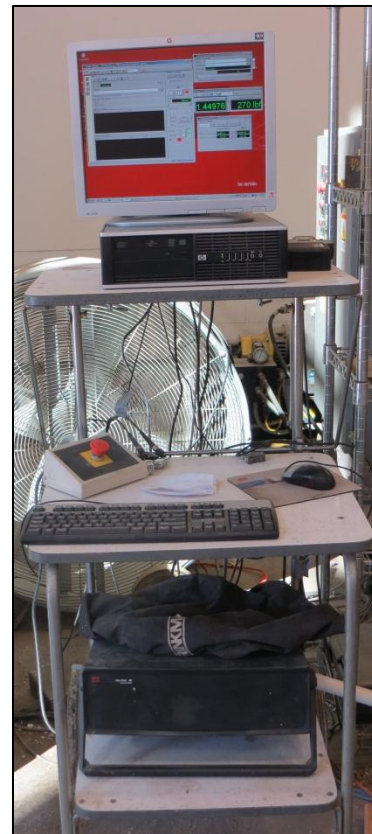
Figure 2-4 Solidified Dry Mix

The Testing Machine

The MTS 100 kips machine was used to perform this test, Figure 2-5. It is a displacement control testing machine used to provide both tensile and compressive loads through a hydraulic cylinder powered by a set of hydraulic pumps. The machine is controlled by a computer that has testing software that allows specifying a displacement rate to be applied for the test. A support and loading attachments were used to provide a simple beam support and loading case were the supporting steel pads, as well as, the loading steel pads were free to rotate around their axes, Figure 2-6.



(a)



(b)

Figure 2-5 Beam Testing Machine (a) MTS Machine (b) Controlling Computer.

The beams were placed on the supports and their positions were adjusted to an 18 in. span between the two supports and a distance of 6 in. between the two loading points with the center of the loading points coinciding the center of the beam. A beam surface full contact with the supports and the loading pads should be satisfied to avoid a non-uniform distributed load along the line of contact which would generate a very high stresses on one side of the beam leading to an early crack development and lower measured strength of the beam.



Figure 2-6 Support and Loading Steel Pads Arrangement

The Measuring Devices

The main output of this test was the load-deflection curves for different fiber dosages concrete beams. The MTS machine is equipped by a load cell that gives the total load exerted by the hydraulic cylinder. The load cell is connected to the MTS machine scanner from which the load cell data was acquired by connecting this scanner to the data acquisition system used that is discussed in the next sections. The beam deflection was measured using a Linear Displacement Sensor, known as Linear Variable Differential Transformer (LVDT), with an accuracy of $\pm 1.75 \times 10^{-3}$ in. and a displacement

range of 0.5 in, Figure 2-7. Two LVDTs were used in both sides of the tested beam to get more reliable data and observe any abnormal behavior or noise during the test. An arrangement similar to the one shown in the ASTM C1609 was used where the LVDTs were fixed on an aluminum frame that was fixed to the tested beam surface at the horizontal centerline of the beam, 3 in. from the top and the bottom of the 6 in. beam as shown in Figure 2-8.



Figure 2-7 Linear Displacement Sensor (LVDT)

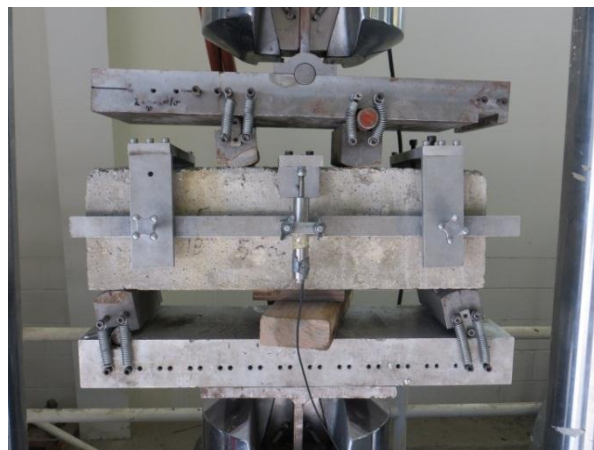


Figure 2-8 LVDT Fixation Frame

The MTS machine load cell connection and the hydraulic cylinder displacement from the MTS scanner, as well as, the LVDTs were connected to a data acquisition system consisted of a scanner connected to a portable computer equipped with data acquisition software Figure 2-9. The data acquisition rate was adjusted to 10 readings per seconds, which was pretty enough to get smooth load-deflection curves.



Figure 2-9 Data Acquisition System



Figure 2-10 Sensors Connections to the Data Acquisition System

According to the ASTM C1609, the displacement rate for a 6 by 6 by 20 in. beam specimen up to a net deflection of L/900 (0.02 in.) should be from 0.0015 to 0.004 in./min and from 0.002 to 0.012 in./min for a net deflection beyond L/900. Also, the data acquisition of load and deflection should be carried out till a net deflection of at least L/150 (0.12 in.). The displacement rate was defined in the MTS machine software to be applied as a predefined testing procedure every time a test was carried out. FIG shows a typical displacement history acquired from one of the tests performed.

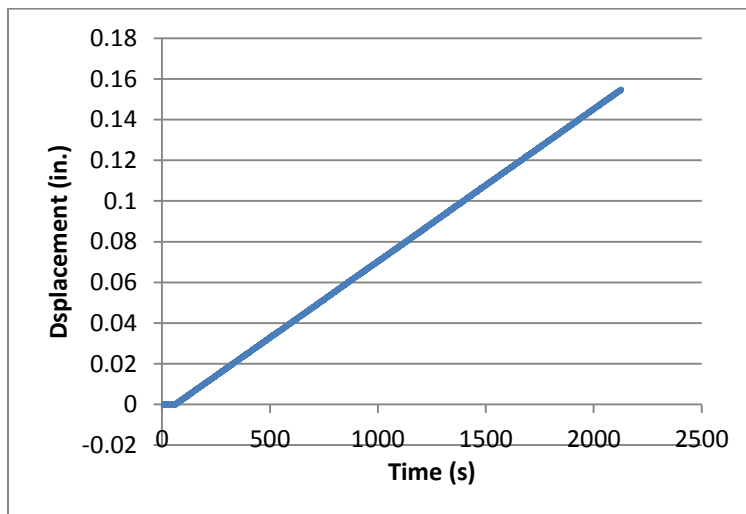


Figure 2-11 Beam Flexural Test Displacement Rate

Test Results

During the research, a total of 29 steel fiber reinforced concrete beams were casted at the pipe production plant and tested at the UT Arlington civil engineering lab at least seven days after the production date. Table shows the details of the different beams produced, the steel fiber dosage and the corresponding pipe group that was produced using the same concrete mix. Knowing the corresponding pipe group helps to relate the flexural beam test results to the corresponding pipe three edge bearing test results highlighting the effect of the water to cement ratio that differs from one pipe size than the other, the effect of the weather temperature, and the human driven machine variation effect.

Table 2-1 Flexural Beam Test Cases

Pipe Diameter (in.)	Steel Fiber Amount lb/yd ³ (% Vol.)	Number of Beams Produced
18 in.	5 (0.04)	2
	11 (0.08)	2
	16 (0.12)	2
	22 (0.17)	2
18 in. (with steel cage)	5 (0.04)	1
	11 (0.08)	1
	16 (0.12)	1
24 in.	11 (0.08)	2
	16 (0.12)	2
	22 (0.17)	2
	44 (0.33)	1
	66 (0.5)	1
	16 (0.12)	1
	22 (0.17)	1
30 in.	33 (0.25)	1
33 in.	44 (0.33)	2
	66 (0.5)	2
36 in.	44 (0.33)	1
	88 (0.67)	2

Flexural beam test results led to some important observations. There was a significant variation in the results of the test of beams with same steel fiber dosages and even those that were casted using the same concrete batch. Variation in results of beams casted from using the same concrete batch is mainly due to two main reasons; first, the consolidation level, which depended on the person performing the consolidation, and the second reason was the time of casting the beams, which became a significant factor during high temperature multi-dosage casting days during which the concrete to be used to cast the late beam start solidification quickly during casting other beams. The effect of casting time appeared significantly in the results of the beams corresponding to the 18 in. pipes which were produced during summer where the 5 lb/yd³ beams were casted first then the 11 and 16 lb/yd³ which showed a significant low ultimate strength.

The very low steel fiber dosage beams of 5 and 11 lb/yd³ showed a pure brittle behavior as it experienced total failure as soon as the peak load was reached and crack occurred as shown in Figures 2-12 and 2-13. Beams of 16 and 22 lb/yd³ showed a significant drop in strength after the peak load but kept a low residual strength of about 10% of the peak strength that prevented sudden collapse of beams as shown in Figure 2-14. Higher steel fiber dosages of 33 lb/yd³ and higher showed a significant post ultimate residual strength. A hypothesis of the relation between the steel fiber dosage and the post ultimate residual strength couldn't be proved to be true due to the significant variation in the results due to the lack of homogeneity of the dry mix when casted in beam molds, an example of this variation is shown in Figure 2-15.

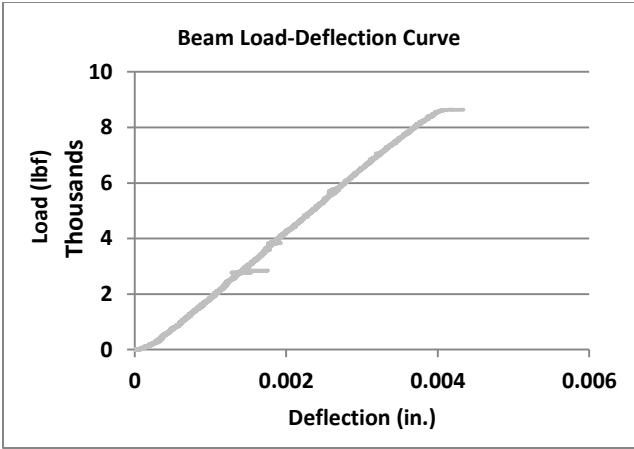


Figure 2-12 Load Deflection Plot of 5 lb/yd³ Beam Showing the Brittle Behavior



Figure 2-13 Brittle Failure of 5 lb/yd³ steel fiber beam

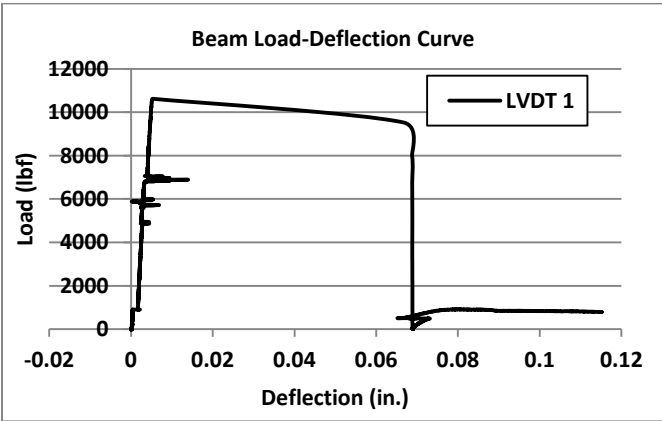
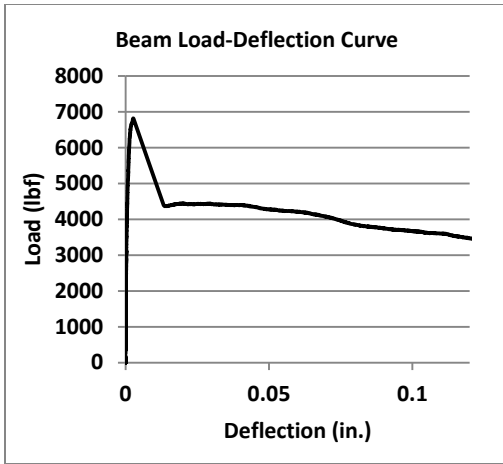
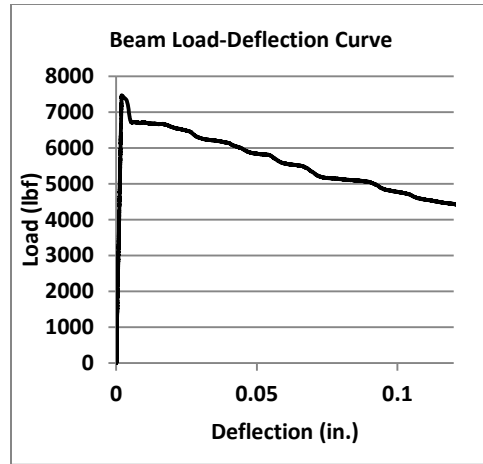


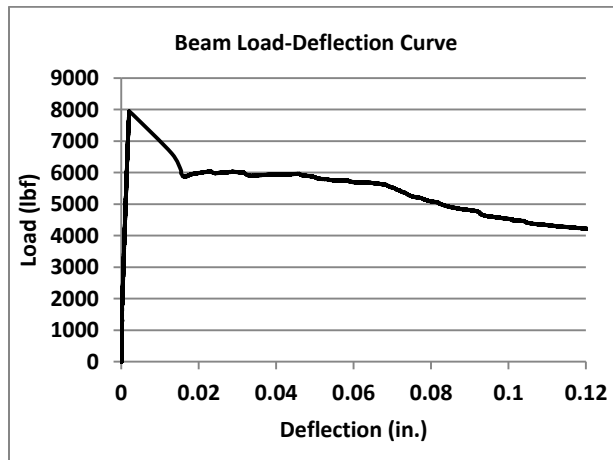
Figure 2-14 Load-Deflection Plot of beams with 16 lb/yd³ of fiber



(a)



(b)



(c)

Figure 2-15 Load-Deflection Plots of 44 lb/yd³ beams corresponding to pipes with diameters of: (a) 24 in. (b) 33 in. (c) 36 in.

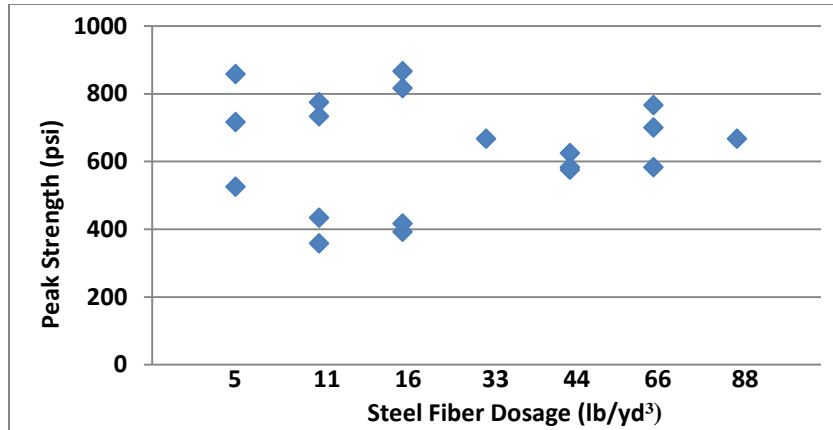


Figure 2-16 Peak Strength of Flexural Beam Specimens

Figure 2-16 shows the peak strength of the tested beams for different steel fiber dosages. The variation in the test results for the same fiber dosage specimens was obvious; however, there were some close results in some cases. For the 11 and 16 lb/yd³, the beams corresponding to the 24 in. pipes showed close results, the upper two results for each case, and were significantly higher than those for the beams corresponding to the 18 in. pipes, the lower two results for each case. Also, the 44 lb/yd³ beams corresponding to different pipes showed a significant close peak loads. The average peak load for the whole group of beams was 7580 lbf which is corresponding to peak strength of 630 psi.

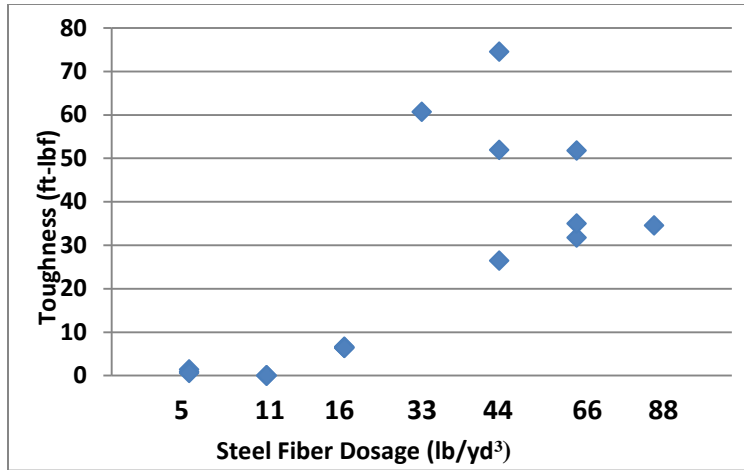


Figure 2-17 Post First-Peak Load Residual Strength

Figure 2-17 shows the toughness of flexural beams with different fiber dosages. Beams with low steel fiber dosages of 5, 11 and 16 lb/yd³ showed a significantly low toughness. Beams with fiber dosage of 33 lb/yd³ and higher showed a significantly higher toughness with an average of 50 ft-lbf.

Compressive Cylinder Strength Test

Steel fiber reinforced concrete cylinders were casted at the production plant for compressive strength testing. Specimens were casted using the same concrete mix used in producing each group of pipes at the same time of pipes production. The cylinders were made according to the ASTM C31 “Standard Practice for Making and Curing Concrete Test Specimens in the Field”. Standard size plastic cylinders of 4 in. diameter 8 in. height were used as casting molds in making the cylindrical specimens. The casting involved using a vibrating table, as well as, a tamping rod for consolidation. Then the cylinders were filled with even layers with approximately equal depth of concrete and compaction using the tamping rod was done for each layer. According to the ASTM C31, two layers of concrete and 25 roddings per layer are recommended, but due to the low workability of the dry mix, from 3 to 4 layers were put to assure well consolidation. After casting, the cylinders were put at the curing zone with the corresponding pipes. In some cases when the mix was significantly dry, the different layers of the casted cylinder were so obvious, shown in Figure 2-18. Lack of fiber interference between two adjacent layers would be expected due to the compaction of each layer before putting the next layer.



Figure 2-18 Layers of Concrete in a Compressive Cylinder Test Specimen due to Dry Mix

After curing, the cylinders were prepared and tested according to the ASTM C36 “Standard Test Method for Compressive Strength of Cylinder Concrete Specimens” at the UT Arlington civil engineering lab. The test involved applying compressive axial load to the concrete cylinders at a specified loading rate range till failure. It was used to determine the ultimate compressive strength of different steel fiber concrete cases. The values obtained from this test were expected to have significant variation since those values depends upon the mixing procedures, methods of sampling, molding, consolidation, temperature and other factors. For the dry mix case in this research, consolidation level and temperature during casting varied significantly from one specimen to the other. However, the test was done to get an averaged image of the compressive behavior of different dosage concrete mixes, as well as, to find a link between the pipe behavior under three edge bearing test, discussed in chapter 3, and the compressive behavior of the compression cylinders, as well as the flexural behavior, in case of an unusual three edge bearing behavior to decide if the problem was a material problem or a production problem.

After de-molding the specimens, the concrete cylinders were capped with a capping compound that meets the ASTM C617 providing a uniform distribution of load and ensuring that neither end of the tested cylinder was inclined to the perpendicular to the cylinder axis with more than 0.5° according to the ASTM C39. The capping material was melt and poured in a capping fixture that provided capped surfaces perpendicular to the axis of the cylinder shown in Figure 2-19. The capping quality was a crucial factor that affected the test results. A slightly inclined surface results in a side failure of cylinder at a significant lower load than the expected ultimate load, shown in Figure 2-20. Hard rubber pads were been allowed to use instead of capping, but according to previous experience, rubber pads caused damage to the testing machine when used.



Figure 2-19 Capping Fixture



Figure 2-20 One Side Failure due to Poor Capping

The Testing Machine

The testing machine used was a 500 kips compression machine, Figure 2-21, in which the load was applied through a hydraulic cylinder powered by a hydraulic pump. The testing machine complied with the ASTM C39. The hydraulic cylinder allowed a continuous applying of load without shock at a specified loading rate that can be controlled using a hydraulic valve attached to the oil supply line after the pump shown in Figure 2-22. The testing machine was equipped by a hardened face steel upper spherically seated bearing block, which provided a tolerance for very low inclinations of the capped surfaces, and a lower cylinder bearing. The testing machine had a built-in load cell to measure the instant load, as well as, the loading rate which were displayed on the equipped display.



Figure 2-21 Compression Testing Machine



Figure 2-22 Load Display and Control Valve

The loading rate was increased gradually, using the control valve, to avoid the occurrence of a shock and then kept within 440 ± 90 lb/s during the test, which corresponded to 35 ± 7 psi/s stress rate specified by the ASTM C39, until failure occurred.

Test Results

During this research, a total of 35 steel fiber reinforced concrete cylinders with different steel fiber dosages were tested. Tests were carried out at 3, 7 and 28 days after casting. In some cases, the 28 day specimen was tested later in about 90 days. In cases of 2 or 1 cylinders only, the cylinders were tested after 27 days of casting. Table 2-2 shows the detailed numbers of cylinders tested.

Table 2-2 Compressive Cylinder Strength Test Specimens

Pipe Diameter (in.)	Steel Fiber Amount lb/yd ³ (% Vol.)	Number of Cylinders Tested
18 in.	5 (0.04)	3
	11 (0.08)	3
	16 (0.12)	3
	22 (0.17)	3
24 in.	11 (0.08)	3
	16 (0.12)	3
	22 (0.17)	3
	44 (0.33)	3
	66 (0.5)	3
30 in.	33 (0.25)	4
33 in.	44 (0.33)	2
	66 (0.5)	2
36 in.	44 (0.33)	1
	88 (0.67)	1

Various crack pattern appeared when the cylinder specimens where tested. The crack pattern mainly depended on the steel fiber dosage, the appropriate consolidations, and the water to cement ratio that had a significant effect. The low water to cement ratio lead to a dry mix which became drier during casting the cylinders. The very dry caused segregation of concrete when vibrated for consolidation, consequently, decreased the cylinder expected strength. Figure 2-23 shows a case of concrete segregation. In few cases, crack pattern appeared to be a cross-sectional crushing, as shown in Figure 2-24. Typical crack patterns are shown in Figure 2-25.



Figure 2-23 Segregation due to Dry Mix and High Frequency Vibration Consolidation



Figure 2-24 Crushing Failure

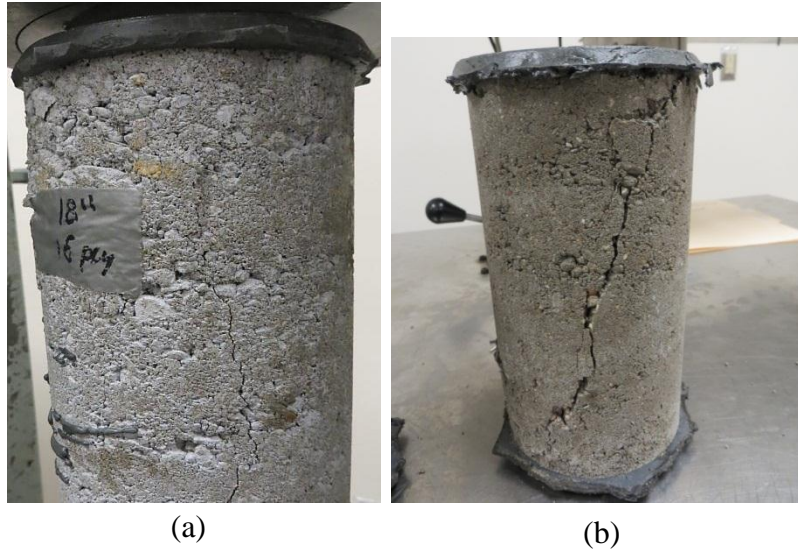


Figure 2-25 Typical Crack Patterns for (a) 16 lb/yd³ (b) 44 lb/yd³

Test results showed a significant variation in the strength of tested cylinders. This variation was due to the variation in sampling and casting times, the lack of a proper compaction due the low workability of the dry mix and the human factor which depended on the person performing the compaction. A relation between the amount of steel fibers in the concrete and the ultimate compressive strength couldn't be observed.

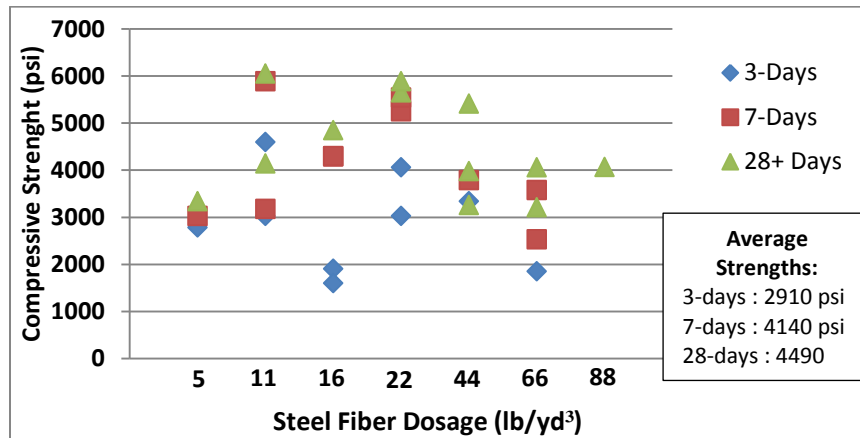


Figure 2-26 Ultimate Compressive Strength of Concrete Cylinders

Figure 2-26 shows a plot of the compressive strength of cylinders with different steel fiber dosages. The overall average of the concrete cylinders strength was found to be 3,900 psi. The average compressive strength for each steel fiber dosage group of cylinders was plotted in Figure 2-27

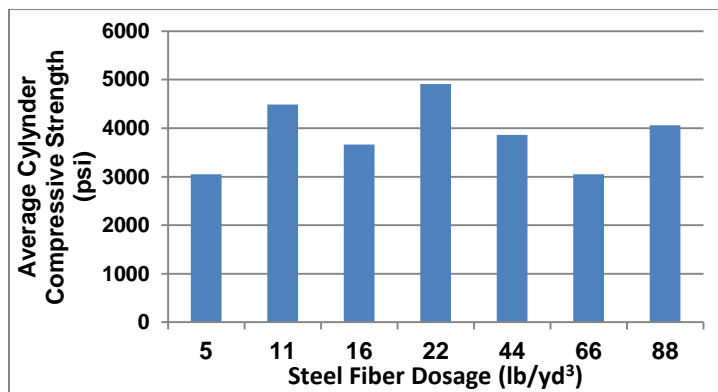


Figure 2-27 Average Ultimate Compressive Strength of Concrete Cylinders

Chapter 3

Pipes' Structural Testing

Introduction

Pipes' structural testing description and results are presented in this chapter. Several types of concrete pipes' structural tests are specified per international standard specifications such as BS EN 1916:2002 "Concrete Pipes And Fittings, Unreinforced, Steel Fibre And Reinforced" that specifies the performance requirements and describes the test procedures for both steel reinforced concrete pipes and steel fiber reinforced concrete pipes. In this research, the ASTM C497 – 05 "Standard Test Methods for Concrete Pipe, manhole Sections, or Tile" that describes various methods of concrete pipes' testing that are used in production quality control and design acceptance testing.

The ASTM C497 – 05 presents four main methods of testing the structural strength and performance of concrete pipes through either concrete pipe's loading tests or material tests. Material tests include both Core Strength Test and Cylinder Strength Test. Core Strength Tests are compressive crushing tests on concrete cores cut from the concrete pipe's wall. Concrete cylinders are casted from the same concrete mix used for the pipes at the same day of pipe production and tested in accordance with ASTM C31 and ASTM C39 as described in the previous chapter. Concrete pipe's loading tests include Flat Slap Test, that is used to test the longitudinal strength of concrete pipes, and External Load Crushing Strength Test by Three Edge Bearing Test Method, which is known by the "Dload Test" and the Dload is defined as the test load in pounds-force per linear foot of the pipe per foot of pipe diameter.

$$Dload = \frac{Load \text{ (pounds – force)}}{Length \text{ of pipe (foot)} \times Diameter \text{ of pipe (foot)}}$$

The three edge bearing test method, which will be described in details in the next sections, was used in this research, in addition to, the ASTM C76 – 10 “Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe”. The ASTM C76 – 10 classifies concrete pipes into five classes; Class I, Class II, Class III, Class IV and Class V, as well as, defining the Dload strength test requirements, wall thicknesses and design reinforcement required for traditional reinforced concrete pipes. Beside the previous specifications stated by the ASTM C76 – 10, some permissible variations in the physical dimensions of the produced pipes are defined as a tolerance limits not to be violated during production which was checked every time before performing the Dload test. The internal diameter variation of 12-in. to 24-in. pipes should not exceed 2% of the design diameter of 12-in. pipe and 1.5% for 24-in. pipe with linear variations for intermediate pipe sizes. For 27-in. pipes and larger, a maximum variation should not exceed the greater of 1% of the design diameter and 3/8 in. The wall thickness variation should not exceed the greater of 5% of the design diameter and 3/16 in. For pipes of internal diameter up to 24-in., the variation in the length of two opposite sides of pipe shouldn't exceed 1/4 in. and 1/8 in. for larger diameters with 5/8 in.

Even though ASTM C497 and ASTM C76 do not include mentioning to steel fiber reinforced concrete pipes but traditional reinforcement concrete pipes, they were used in this research so that to compare the performance of steel fiber reinforced concrete pipes to the traditional reinforced concrete pipe of class III.

The D-Load test provided two main information; the ultimate load carried by the pipe and the load-deflection plot. The ultimate load is used to get the D-Load value, which is the load per linear foot of pipe per foot of diameter. The D-Load value is used to eliminate the effect of pipe diameter and length to get a common base of comparing the behavior of different sizes of pipes. The D-Load is considered as the criterion that shows

if the pipe meets the C76-10 class specified capacity. While the load-deflection plot, where values of vertical and horizontal deflection are plotted against the load, shows the ductility and post crack capacity of the pipe when experiencing three edge bearing loading as shown in Figure 3-3..

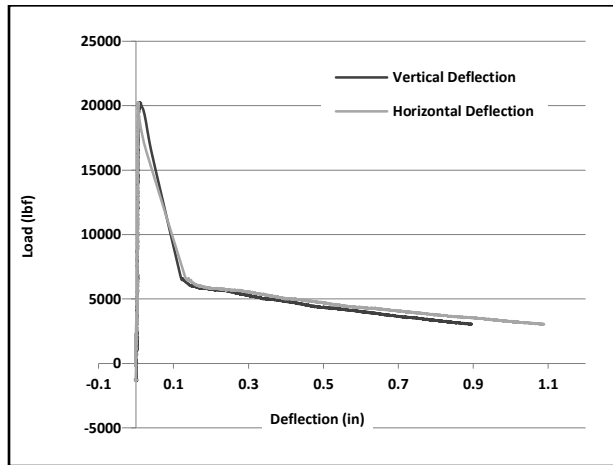


Figure 3-1 Load-Deflection Curve of Low fiber dosage Pipes (24"- 16 lb/yd³)

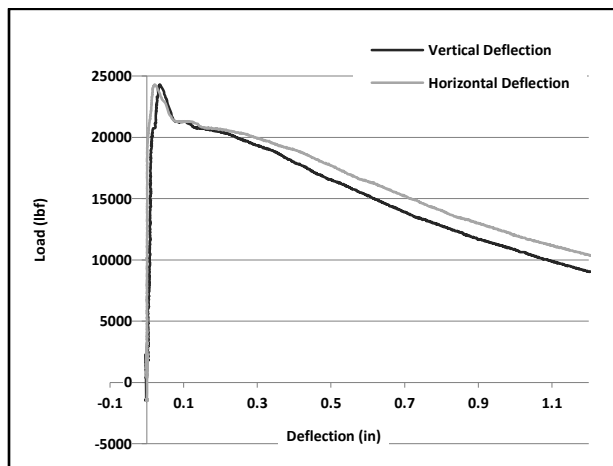


Figure 3-2 Load-Deflection Curve of High fiber dosage Pipes (24"- 44 lb/yd³)

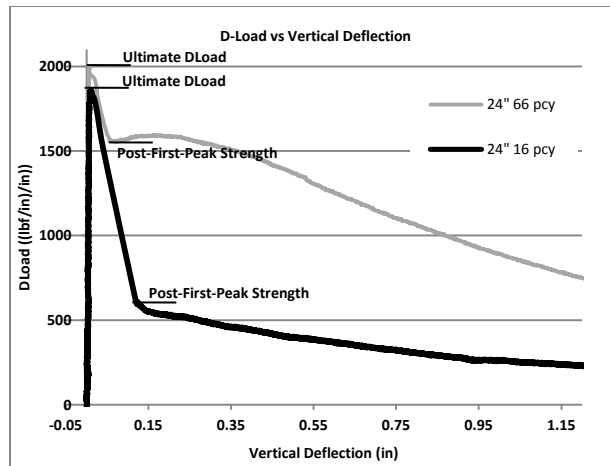


Figure 3-3 Load Deflection Plot Showing First Post Ultimate Strength

Three Edge Bearing Test

The three edge bearing test, which is known as Dload test, is a concrete pipe testing method, described in ASTM C497 – 05, in which a crushing force is applied on the plan parallel to the vertical axis of the pipe and extending along the length of the pipe. The test is used for either quality control of the produced pipes by the manufacturer or as a proof of design adequacy, which is the case in this research.

According to the ASTM C497, the machine used in the test should be of a sufficient capacity that exceeds the ultimate load of the greatest strength of the pipes to be tested. In addition, the machine should be capable of providing a way to control the loading rate. Also, the machine should be rigid enough so that the load distribution is not significantly affected by the deflection of any part of the machine. The pipe to be tested should be supported by a lower bearing of two parallel strips while the load being applied through an upper bearing strip and the three bearing strips should be parallel to the axis of the tested pipe, as well as, having a length greater than or equal to that of the tested pipe. The lower bearing strips should be made of either straight wood strips, with a

cross section of width greater than or equal to 2 in. and a height within 1 in. and 1 ½ in., or rectangular hard rubber strips, with a width more than or equal to 2 in., a thickness within 1 in. and 1 ½ in. and a round radius of ½ in. The lower bearing strips should be fastened to a beam of either wood or steel or directly to the concrete base to provide rigidity of bearings to avoid significant deflection of lower bearings. The two lower bearing strips should be spaced apart by a distance not more than 1 in./ft of pipe diameter and not less than 1 in. The upper bearing should be rigid straight beam made of wood with or without a hard rubber strip attached to the contact face with the tested pipe. The thickness of the hard rubber strip should have a minimum width of 2 in. and a thickness from 1 to 1 ½ in. Figure 3-4 shows schematic drawing for the three-edge bearing test arrangement.

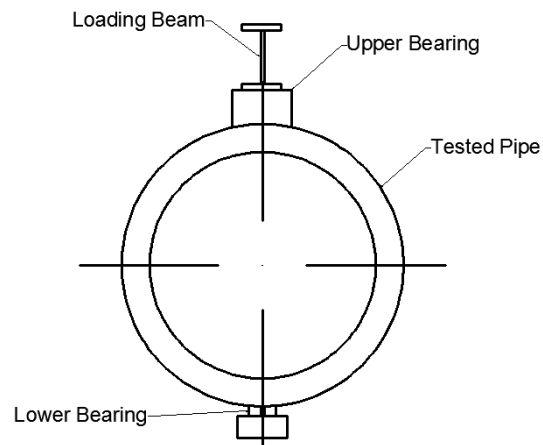


Figure 3-4 Three-Edge Bearing Test

The Testing Machine

A three edge testing machine located in Hanson's Grand Prairie production plant was used to perform all of the pipes' tests, Figure 3-5. The testing machine used in

testing the pipes meets the C497 specifications. It is formed of a rigid steel frame with variable height adjustment. The loading steel beam is driven by two hydraulic cylinders with common inlet to assure equal loading in both cylinders. The cylinders are driven by a hydraulic pump with a control valve that allows controlling the oil flow rate and hence keeping the loading rate in the range specified by the ASTM C497. Beside controlling the loading rate, controlling the oil flow rate and keeping it constant lead to constant displacement rate loading, which is used as the loading type when the pipes are modeled with finite element analysis software, Figure 3-7 shows a typical displacement history. A 6 in. x 6 in. hard wood beam is bolted to the loading steel beam forming the upper bearing with a 1 in. thickness 6 in. width hard rubber strip fixed to the lower face to be in contact with the tested pipe. The lower bearings are made of a 1 ½ in. hard rubber with round corners and fixed on a rigid adjustable steel supports that allow adjusting the distance between the two bearing according to the tested pipe diameter shown in Figure 3-6.



Figure 3-5 Three-Edge Bearing Test Machine



Figure 3-6 Lower Bearing Adjustment

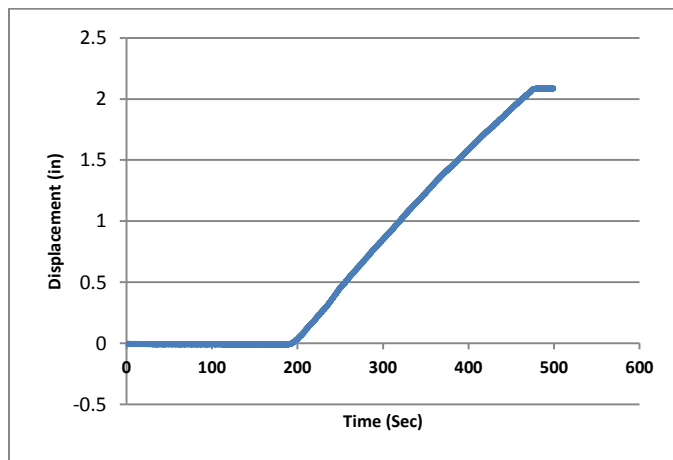


Figure 3-7 Plot of constant vertical deflection rate

Measuring devices

The instant load and deflection were measured during the test to get the load-deflection curves. Two Cable-Extension Displacement Sensors (CDS) with an accuracy of ± 0.015 in. and a measuring range of 10 in., which is enough for a deflection of a maximum of 5% of the diameter of the largest pipe tested (i.e 36 in.), were used to measure the vertical and the horizontal deflections. The two CDSs were fixed to the inner surface of the pipe at a distance of a minimum of 7 in. from the pipe side and the CDS to read the vertical deflection was fixed to the invert with the extended cable fixed to the crown while the other CDS to measure the horizontal deflection was fixed to the springline with the extended cable fixed to the opposite springline shown in Figure 3-8. The instant load was measured through a hydraulic pressure load cell connected to the oil line just after the control valve as shown in Figure 3-9. The control valve keeps the flow rate nearly constant and hence the effect of dynamic pressure on the hydraulic load cell minimized and the load cell reading can be calibrated to get the force applied by the hydraulic cylinders on the tested pipe. The pressure load cell as well as the displacement sensors were connected to data acquisition system consisted of a scanner connected to a portable computer equipped with data acquisition software. The data acquisition rate was from 2 to 5 readings per seconds, which was pretty enough to get smooth load-deflection curves.

According to ASTM C497, the loading rate shouldn't exceed 7500 lbf/linear foot of pipe per minute till 75% of the designed strength of the pipe then a uniform load of 1/3 of the designed strength of the pipe should be applied.



Figure 3-8 Cable Displacement Sensors (CDS) Positioning



Figure 3-9 Hydraulic Pump, Control Valve, and Pressure Load Cell

Test Results

During this research, a total of 27 steel fiber reinforced concrete pipes with different sizes and steel fiber dosages were produced and tested at the production plant after at least seven days from the production date. Table 3-1 shows the details of the different pipes sizes and dosages of steel fibers.

Table 3-1 Pipes Produces Details

Pipe Diameter (in.)	Steel Fiber Amount lb/yd³ (% vol.)	Length of Pipe (ft.)	Number of Pipes Produced
18 in.	5 (0.04)	6	2
	11 (0.08)	6	2
	16 (0.12)	6	2
	22 (0.17)	6	2
24 in.	5 (0.04)	6	2
	11 (0.08)	6	2
	16 (0.12)	6	2
	11 (0.08)	6	2
	16 (0.12)	6	2
30 in.	22 (0.17)	6	2
33 in.	44 (0.33)	8	2
	66 (0.5)	8	2
36 in.	16 (0.12)	8	1
	22 (0.17)	8	2

Before performing each test, the loading beam was approached towards the pipe till the upper bearing rubber strip touched the surface of the pipe to avoid an impact or dynamic loading. During this process, pre-test data acquisition was been performed to monitor the contact moment and to record any sudden increase in loading that may affect

the pipe's performance during the test. The three edge bearing tests as well as the data acquisition were performed continuously till the end of the test. To avoid a total and sudden failure of the tested pipe which will cause damage to the measuring devices, a limit of 5% of the tested pipe's diameter was assigned as the maximum vertical deflection at which the loading should be stopped when reached. This limit was proposed by previous research performed on similar kind of pipes. An extra displacement beyond the 5% of vertical deflection was applied to some tested pipes with different fiber dosages after removing the measuring devices to examine the behavior of those pipes with large deflections as a safety indicator.

The ASTM C76-10 defines the class of the pipe by the ultimate Dload that can be carried by the tested pipe. For class I, the minimum ultimate Dload is 1200 lbf/ft/ft, and for class II is 1500 lbf/ft/ft and for class III is 2000 lbf/ft/ft. The ultimate loads that were carried by the tested pipes, as well as, the ultimate Dloads, the class that the tested pipe passed and the post ultimate Dload strength are shown in Table 2-3. As shown in the previous Table 3-1, two pipes of each dosage for each pipe size were produced and tested to get more reliable results. The summary shown in the Table below considers the average of the load values of each of the two pipes

Table 3-2 Ultimate Load, Ultimate Dload, Strength Class, and First Post Ultimate Dload

Pipe Size	Steel Fiber lb/yd ³	Ultimate Load (lbf)	Ultimate Dload (lbf/ft/ft)	Class	First Post Ultimate Dload (lbf/ft/ft)
18"	5	18810	2090	III	0
	11	21681	2409	III	385
	16	21483	2387	III	520
	22	19899	2211	III	1110
24"	11	18744	1562	II	360
	16	21120	1760	II	650

Table 3-2 - Continued

	22	24720	2060	III	1000
	44	24420	2035	III	1700
	66	24120	2010	III	1530
30"	33	32175	2145	III	1150
33"	44	32560	1480	I	1340
	66	33880	1540	II	1420
36"	44	56280	2345	III	2345
	88	65760	2740	III	2740

The ultimate Dload data in the previous table is plotted in the following chart to give a better image of the strength of each group of pipes.

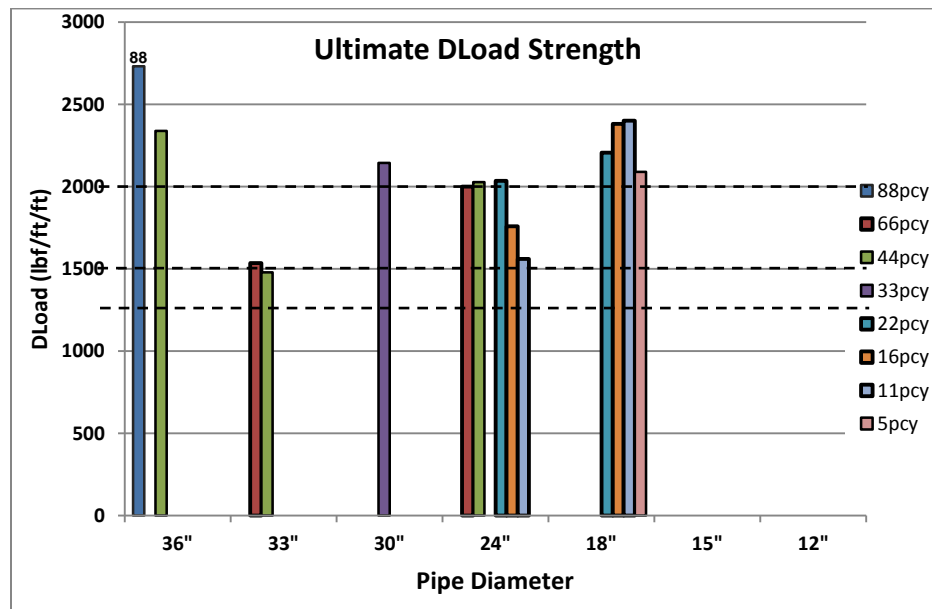


Figure 3-10 Ultimate Dload Strength

As seen in the above chart in Figure 3-10, the 36-in. pipes have the highest ultimate Dload that significantly exceeded the ASTM C76-10 class III acceptance ultimate Dload value, 2000 lb/ft/ft. The 30-in. as well as all of the 18-in. pipes with different dosages also passed the Dload strength required for class III pipes. In the 24-in. case,

higher steel fiber dosages pipes from 22 lb/yd³ and up slightly passed the class III limits, while low steel fiber dosage pipes of 16 lb/yd³ and 11 lb/yd³ didn't show enough strength and passed the class II limits but not class III. The 33-in. showed an unexpected low strength that was hardly close to class II strength requirement that will be discussed in detail in the following sections.

As discussed in the previous sections, the Dload-Deflection curves plotted using the data acquired during the test is used to know the post failure (post ultimate Dload) strength of each pipe that shows that amount of ductility that each pipe carried. The post ultimate Dload data for different sizes and fiber dosages is plotted in the following chart:

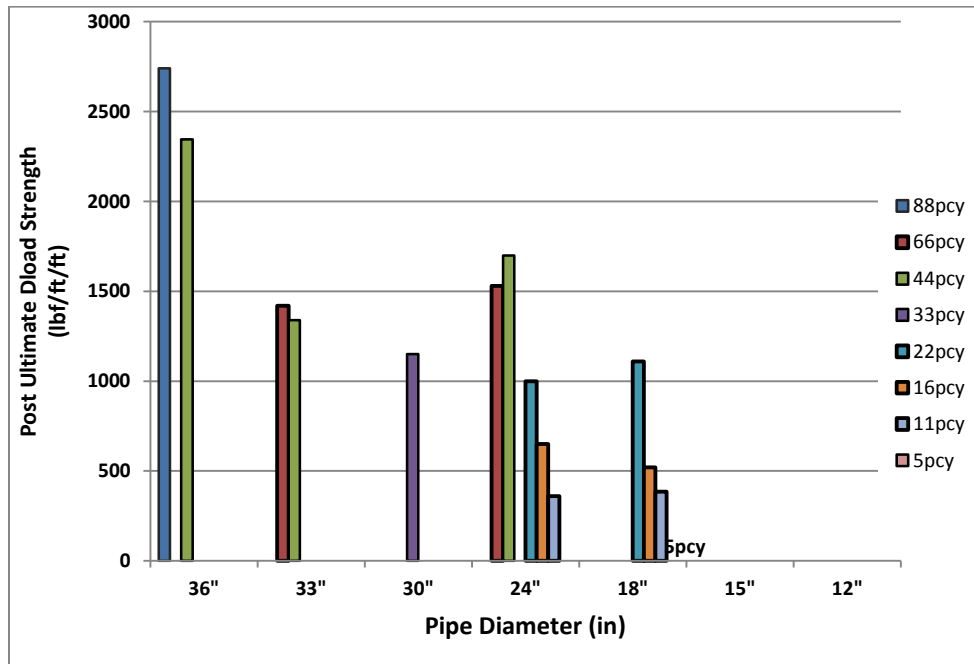


Figure 3-11 First Post Ultimate Dload Strength

The above chart, Figure 3-11, shows a significant increase in post ultimate Dload strength with the increase of the steel fiber dosage which appears significantly in the

smaller pipe sizes of 18-in. and 24-in. except for the 66 lb/yd³ 24-in. that showed a lower post ultimate Dload strength than the 44 lb/yd³ 24-in. Also, pipes with same fiber dosages tend to have close values of post ultimate Dload strength even with different pipe sizes. Another observation is that the large size pipes of 36-in. didn't show any sudden drop in the Dload after the ultimate Dload strength neither for the high dosage of 88 lb/yd³ nor for the 44 lb/yd³ pipes, instead, it had a smooth decrease in the Dload as will be shown in the following sections. On the other hand, the very low dosage of 5 lb/yd³ 18-in. pipes didn't show any post ultimate load strength, instead, they totally failed after reaching the ultimate load and collapsed after removing the CDS and while trying to take it off the testing machine as shown in Figure 3-12.

In the following section, each group of pipes with same size will be discussed in more detail to highlight important observations and notes for each case.

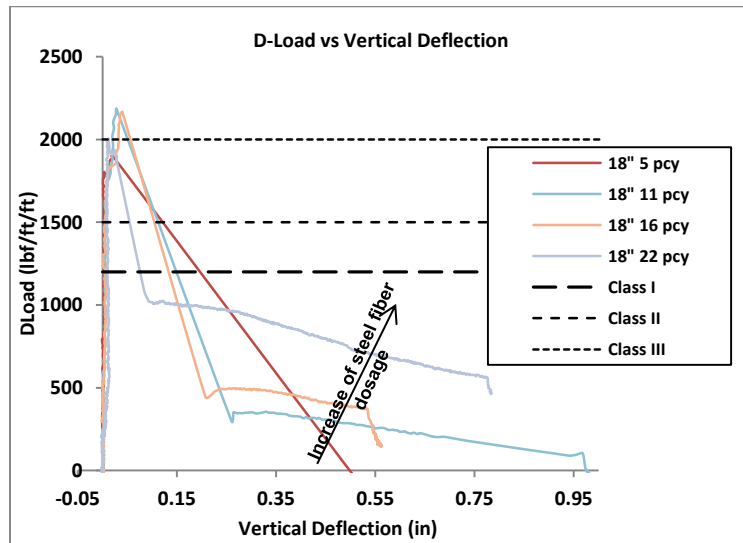


Figure 3-12 Effect of Increasing Fiber Dosage in Post Peak Strength

The above plot shows the Dload against the vertical deflection of the 18-in. pipes. It's obvious that even though the low fiber dosage pipes of 11 lb/yd³ and 16 lb/yd³ showed a higher ultimate Dload than the higher fiber dosage of 22 lb/yd³, the 22 lb/yd³ pipes showed a significant higher post ultimate Dload strength, of about 50% of the ultimate Dload, than those of lower fiber dosages that showed a low post ultimate Dload of less than 20% of the ultimate value.

Another observation was that the very low fiber dosage pipes of 5 lb/yd³ didn't show any post ultimate strength, the strength suddenly vanished and the pipe totally collapsed after removing the measuring devices and while moving the pipe off the testing machine.

Another observation was the occurrence of the crack above the springline in one side of both 11 lb/yd³ and 16 lb/yd³ pipes as shown in Figure 3-13. The crack started at the right side and propagated along the separation line between the two parts of the casting form and extended higher than this separation line at the left side of the pipe which arises a hypothesis of the significance effect of either the pipes surface finish or the pipe production method used on the crack profile. The crack on the other side was a regular crack that occurred around the other springline.



Figure 3-13 Crack Propagation through the Separation Line

Another observation was the diagonal crack, shown in Figure 3-14 and Figure 3-15, that extended from the right side of the springline upward to the left side which was observed on one side of the 22 lb/yd³ pipe. The other side showed a regular crack profile around the springline.



Figure 3-14 Diagonal Crack



Figure 3-15 Diagonal Crack End

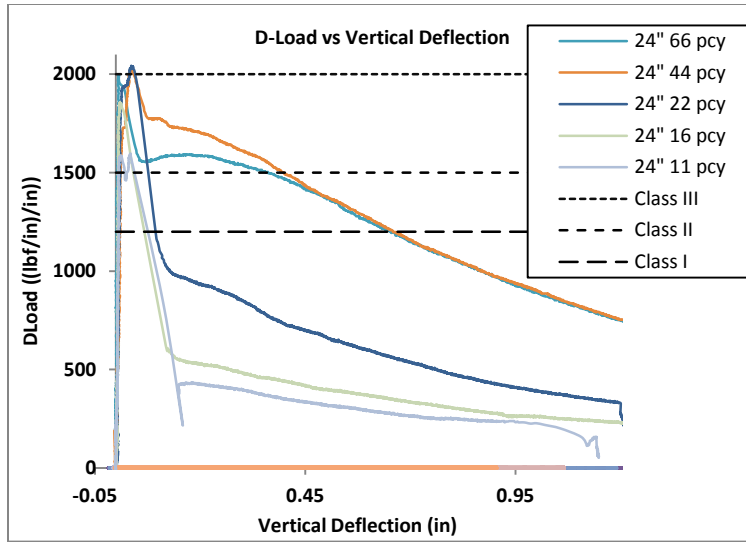


Figure 3-16 Dload-Deflection Plot of 24 in. Diameter Pipes

The above chart, Figure 3-16, shows the Dload versus the vertical deflections of different fiber dosages 24-in. pipes. All the fiber dosages pipes passed the class III ultimate strength requirement except the low dosage pipes of 16 lb/yd³ and 11 lb/yd³. The high fiber dosage pipes showed a significantly high post ultimate Dload strength. The 44 lb/yd³ pipes showed the highest post ultimate Dload strength of 84% of the ultimate strength, while the low dosage pipes of 16 lb/yd³ and 11 lb/yd³ post ultimate strength was only from 23% to 36% of the ultimate strengths which were already lower than the class-III ultimate strength requirement. Also, the 44 lb/yd³ pipes' ultimate Dload strength exceeded that of the higher dosage of 66 lb/yd³ showing the unprofitability of using the 66 lb/yd³ for 24-in. pipes.

An observation that supports the hypothesis of the significance effect of either the pipes surface finish or the pipe production method used on the crack profile was

observed while testing one of the 44 lb/yd³ pipes where the crack initiation and a poor compacted section were noticed at the casting forms separation line as shown in 3-17.



Figure 3-17 Crack Initiation and Propagation through the Separation Line

Another observation was a secondary crack that developed on one side of one of the 22 lb/yd³ pipes shown in Figure 3-18.



Figure 3-18 Secondary Crack Development

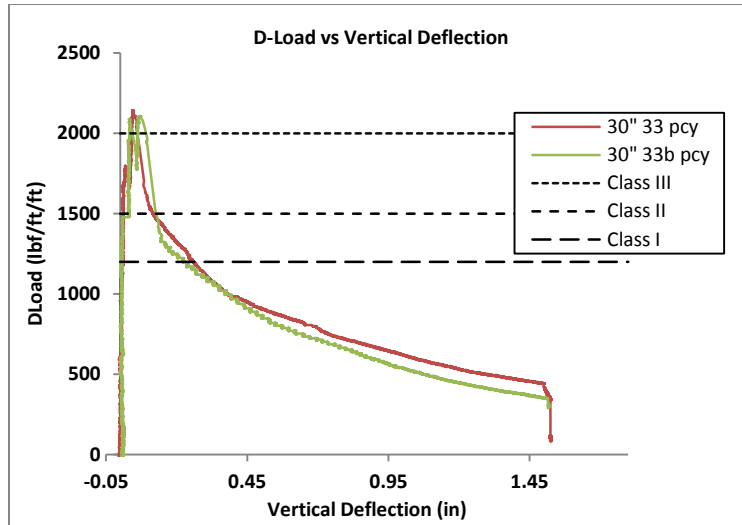


Figure 3-19 Dload-Deflection Plot of 30 in. Diameter Pipes

The Dload versus the vertical deflection of the 30-in. 33 lb/yd³ pipe were plotted on the chart above. Besides exceeding the class III ultimate strength requirement, a decrease in the Dload after the initial crack followed by a makeup increase in Dload can be observed. Other than these observations, there was nothing significant and the crack profiles were regular.

The Dload history was plotted below, Figure 3-20, shows the instant decrease and makeup of the Dload.

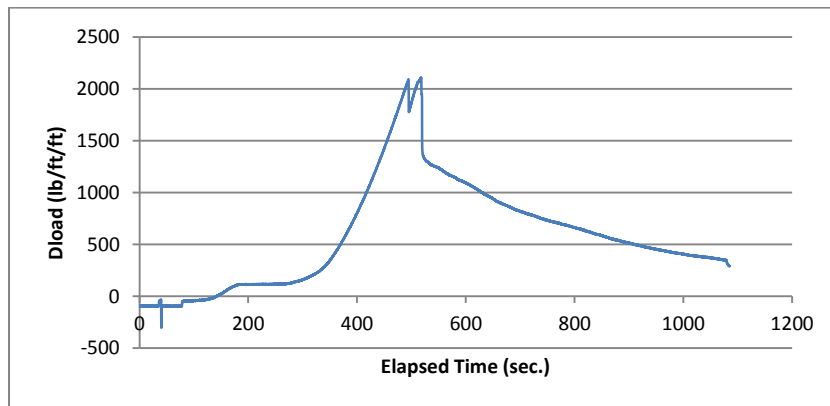


Figure 3-20 Dload History Showing Strength Recovery

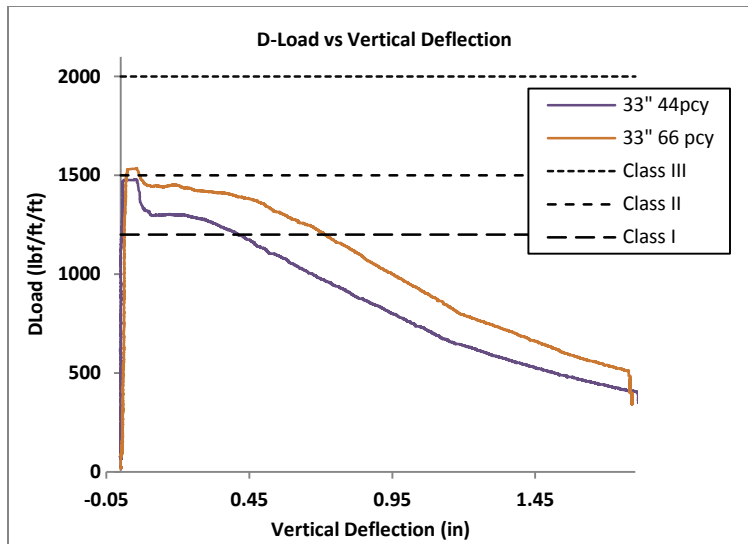


Figure 3-21 Dload-Deflection Plot of 33 in. Diameter Pipes

Both of the 44 lb/yd³ and 66 lb/yd³ 33-in. pipes showed a significantly low ultimate Dload strength that was hardly reached class II ultimate strength requirement. The visual inspection of the tested pipes showed poor compacted regions with significant voids and rough surface. In addition, the steel fibers were visible and highly dense in some spots of the pipes inner part which shows a poor fiber-concrete mixing and distribution. Also, testing this group of pipes showed multi-crack profile on both sides of the 66 lb/yd³ pipes in which secondary cracks extended along the main crack between the two ends of the pipes as shown in Figure 3-22.

At the beginning of the result analysis, an inadequate mix problem was expected till performing the four point load material test, on the beams casted using the same mix used to produce the pipes at the day of production, which showed an ultimate flexural strength values within the average values for the rest of the tested beams (7000kip total MTS load) as mentioned in the previous chapter. Hence, the problem appeared to be a

production problem related to the casting and compaction processes while producing these specific pipes.



Figure 3-22 Multi Crack Development



Figure 3-23 Multi Crack Development

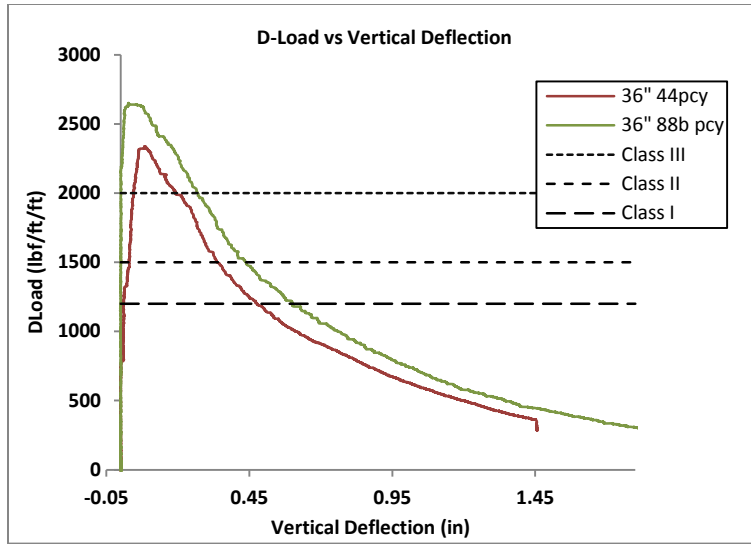


Figure 3-24 Dload-Deflection Plot of 36 in. Diameter Pipes

The Dload versus the vertical deflection of the 36-in. pipes with different fiber dosages was plot in the above chart. Besides exceeding the ultimate Dload strength requirement of Class III, the pipes with both fiber dosages of 44 lb/yd³ and 88 lb/yd³ didn't show any sudden drop in the Dload after the ultimate Dload; instead they showed a smooth decrease in the Dload unlike the rest of the pipes of smaller sizes with the same fiber dosages that showed a sudden drop in the Dload after reaching the ultimate. Another supporting observation that supports the hypothesis of the significance effect of either the pipes surface finish or the pipe production method used on the crack profile was observed that is showed in Figure 3-25 in which the crack extended below the springline and followed the path of the casting mold separation line.

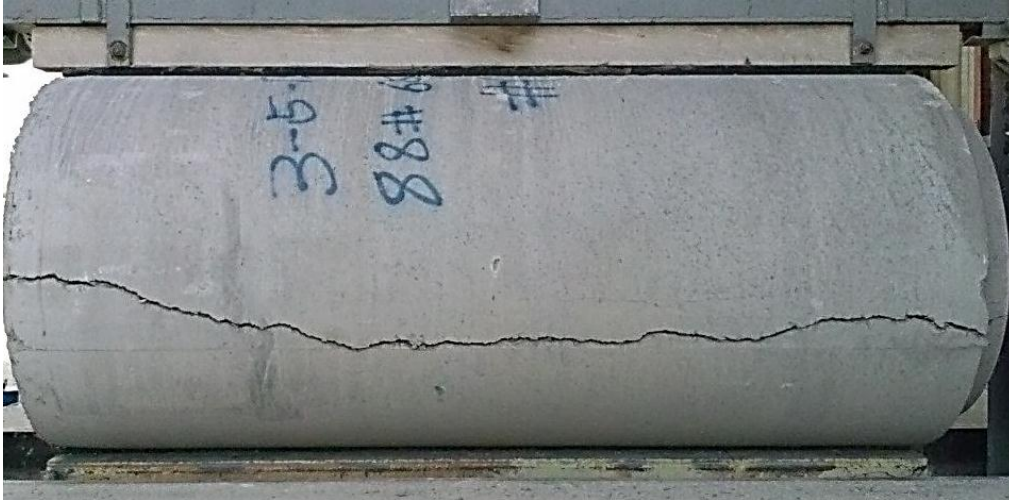


Figure 3-25 Crack Propagation Through the Separation Line

A final observation within the whole group of pipes is the pipes cross section crack profiles shown in Figure 3-26. It was observed that the small diameter pipes showed a flexural cross-section cracks except in the case at which the locations where the crack extended significantly above or below the springline which showed a shear crack. The 36 in. diameter pipes showed a significant shear cross-section cracks either at the springlines, the crown or the invert within the inner and outer layers of the pipes. The 30 in. and 33 in. pipes showed combinations of flexural and shear cross-section cracks where the shear cracks appeared to be at the outer layer of the pipe while the flexural crack was at the inner layer of the pipes.



(a)



(b)



(c)



(d)

Figure 3-26 Cross Sectional Crack Profile for: (a) 18 in. (b) 24 in. (c) 33 in. (d) 36 in.

Chapter 4

Summary, Conclusion, and Recommendations

Summary

This research studied the performance of concrete pipes using steel fibers as an alternative of conventional steel reinforcement. Twenty seven pipes with the same concrete mix but with different sizes and different steel fiber dosages were produced using Packerhead pipes producing machine. The pipes were tested according the ASTM C497 three-edge bearing test and the ultimate Dload values were compared to the ASTM C76 pipe's ultimate Dload requirements for different strength classes. In addition, the instant Dload and deflections were recorded using a data acquisition system then the data was plotted to have a clear image of the post-first-peak strength load carrying ability for different fiber dosages. Furthermore, material properties investigation was conducted through the production and testing of flexural beam and compressive cylinder specimens according to the ASTM C31, ASTM C1609, and ASTM C39.

Conclusion

Based upon the three-edge bearing tests of pipes, the following is concluded:

- Steel fiber reinforced concrete pipe is an alternative to conventionally steel reinforced pipes with comparable strengths and enhanced ductility properties.
- Steel fiber reinforcement provides an effective crack control agent that eliminates the presence of multi micro cracks, instead, few relatively small cracks were observed till the ultimate load reached.
- Strength of small size pipes of 18 in. diameter meets the ASTM C76 class-III even with very low steel fiber dosages, as low as 11 lb/yd³, due

to hoop stresses effect; however, steel fiber is recommended to be added to provide post crack residual strength.

- Low fiber dosages less than 22 lb/yd³ don't have a significant effect on neither the pipe's ultimate strength nor the residual strength after the peak ultimate strength, hence, using fiber dosages less than 22 lb/yd³ is not recommended.
- Fiber dosages from 44 lb/yd³ to 66 lb/yd³ are the optimum dosage range for pipes of diameters up to 36 in. Specific optimum fiber dosage of each pipe size can be evaluated based upon the required performance of the pipe.
- High fiber dosage of 88 lb/yd³ is not recommended from the economical point of view.
- Poor distribution of steel fibers in the concrete mix leads to a significant decrease in the pipe's actual strength, however, the steel fibers used in this research showed a significant mixing-ability in the concrete mix.

Based upon the flexural beam tests, the following is concluded:

- Load deflection curves of steel fiber reinforced concrete beams with fiber dosages up to 66 lb/yd³ showed only one peak load, while those of beams with fiber dosages of 88 lb/yd³ showed two peak loads.
- The increase of steel fiber dosage had a significant effect on increasing the toughness and residual strength of beams after the peak load.
- Very low fiber dosage beams with 5, 11, and 16 lb/yd³ showed a brittle failure immediately as ultimate load reached.

- Brittle crack patterns of low fiber dosage beams were vertical cracks in most cases, while an inclination in the crack was noticed for higher dosages of steel fiber.
- A relation between the fiber dosage and the ultimate strength wasn't observed.

Based upon the flexural beam tests, the following is concluded:

- Sampling and casting time, as well as, consolidation procedures of low workable dry cast mix appeared to be among the main factors that affected the strength of the cylinder specimens.
- Steel fiber dosage in the concrete mix didn't appear to have a significant effect on the compressive strength of the cylinder specimens; however, it showed an effect on the crack pattern and distribution.

Recommendations

The future research recommendations include;

- Developing a standard specification for making steel fiber reinforced dry cast zero slump concrete flexural beam and compressive cylinder test specimens, avoiding the significant variation appeared due to the lack of specimens' making standards for dry cast concrete, and providing a more expressive material properties specimens. The procedures may include high amplitude low frequency compaction and a developed way to ensure steel fiber overlap between successive compacted layers. Another suggested approach is the use of the "Shotcrete" concept in casting the specimens which gives a more simulation to the Packerhead spinning production method.
- Studying the effect of the steel fiber orientation on the flexural and compressive behavior through the use of Computed Tomography (CT) scan and fiber orientation visualization software along with more experimental testing of the scanned specimens. This study can also be used in evaluating the first proposed recommendation.
- Evaluation of the durability of the steel fiber reinforced concrete pipes through a long term testing that involves buried pipes with real earth load along with water permeability investigation of the stressed buried pipes.
- Evaluation of hybrid fiber reinforced concrete pipes using the advantage of the high strength of steel fibers and the advantage of crack control of synthetic fibers.

- Studying the behavior of steel fiber reinforced pipes under impact loading which simulates high amplitude moving loads, as well as, ballast loads over buried concrete pipes.

Appendix A
Flexural Beam Test Plots

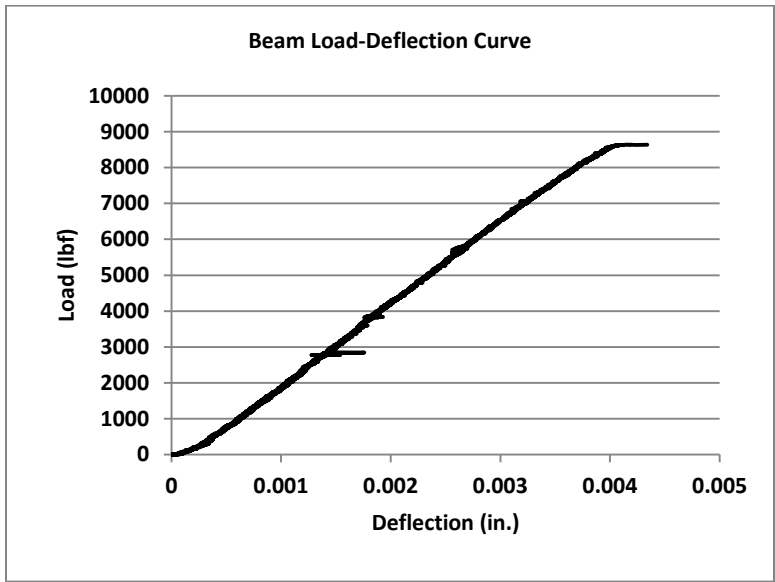


Figure A- 1: Load Deflection Curve of 5 lb/yd³ Steel Fiber Beam – 18 in. pipe – I

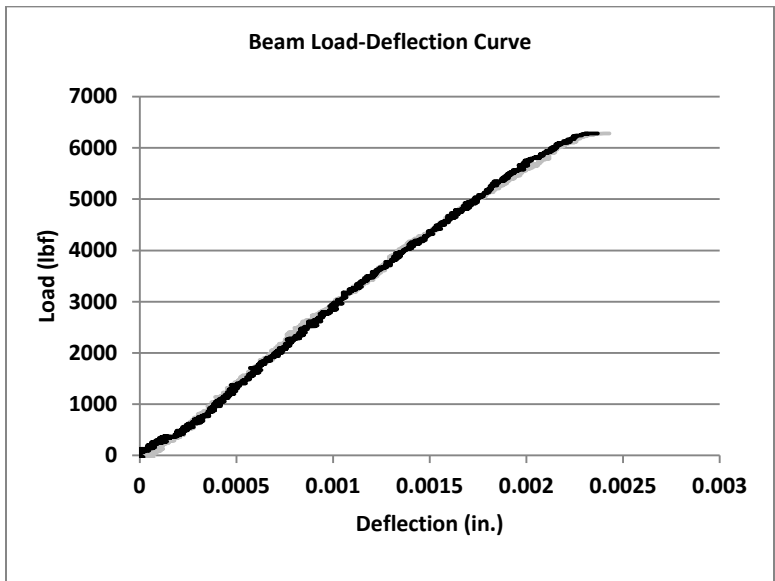


Figure A- 2: Load Deflection Curve of 5 lb/yd³ Steel Fiber Beam – 18 in pipe – II

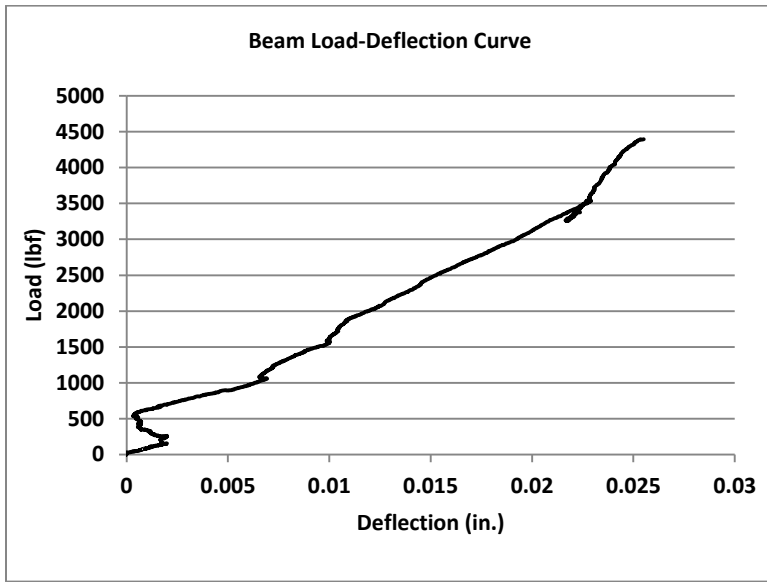


Figure A- 3: Load Deflection Curve of 11 lb/yd³ Steel Fiber Beam – 18 in. pipe – I

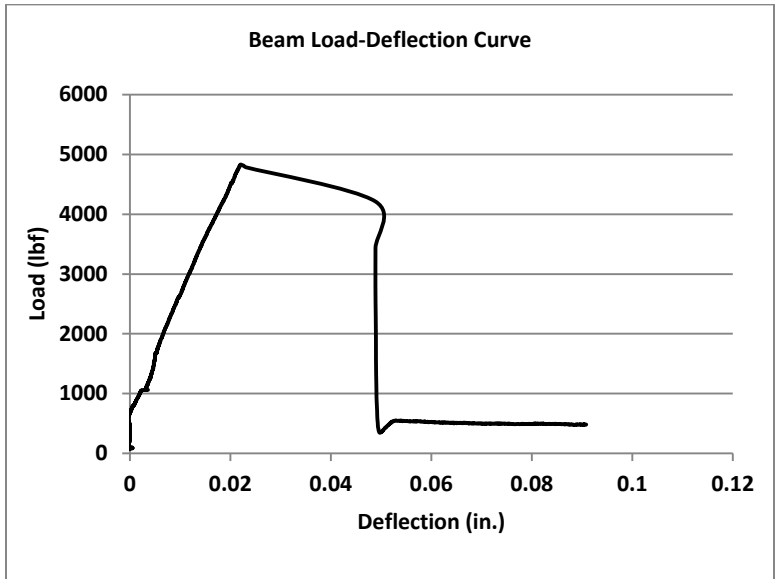


Figure A- 4: Load Deflection Curve of 16 lb/yd³ Steel Fiber Beam – 18 in. pipe – I

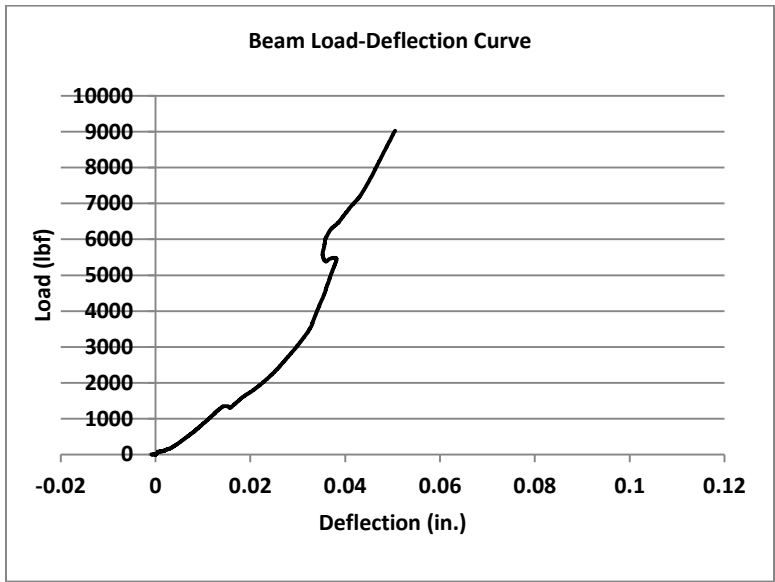


Figure A- 5: Load Deflection Curve of 11 lb/yd³ Steel Fiber Beam – 24 in. pipe – I

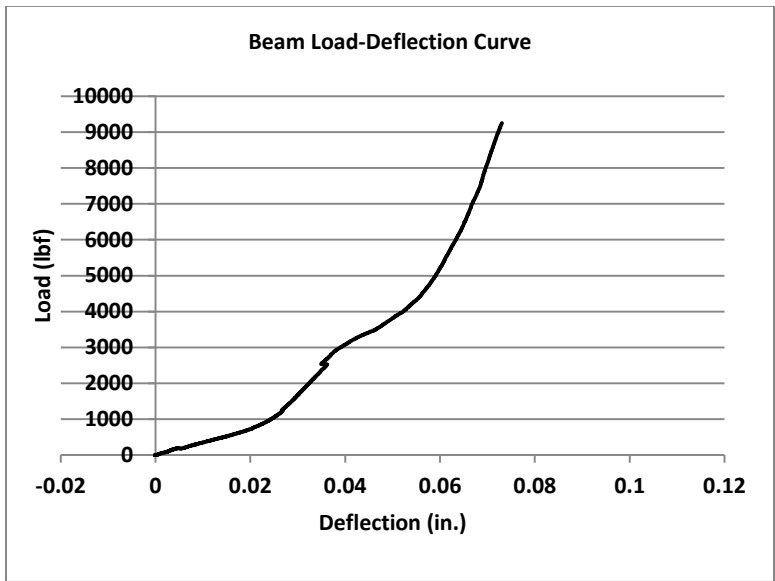


Figure A- 6: Load Deflection Curve of 11 lb/yd³ Steel Fiber Beam – 24 in. pipe – II

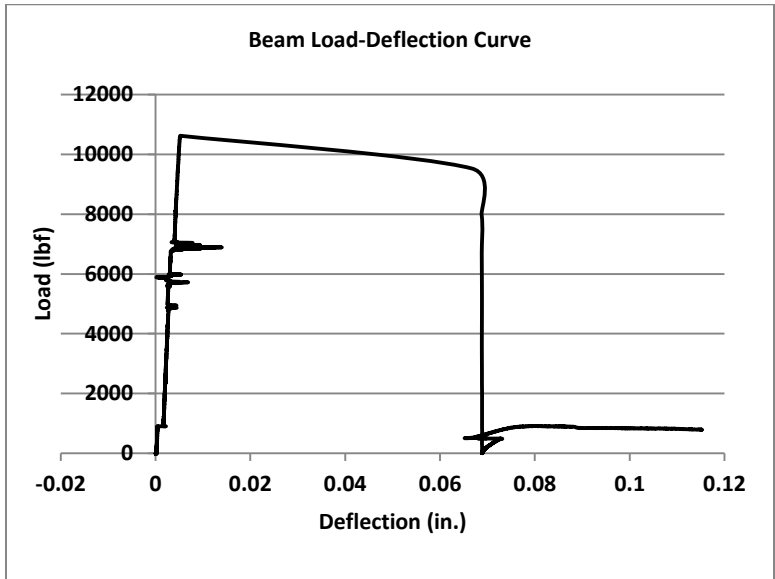


Figure A- 7: Load Deflection Curve of 16 lb/yd³ Steel Fiber Beam – 24 in. pipe – I

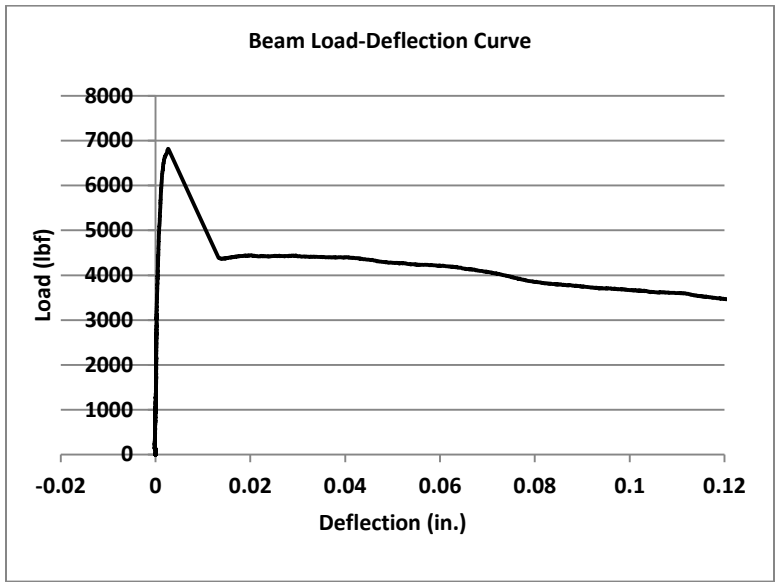


Figure A- 8: Load Deflection Curve of 44 lb/yd³ Steel Fiber Beam – 24 in. pipe

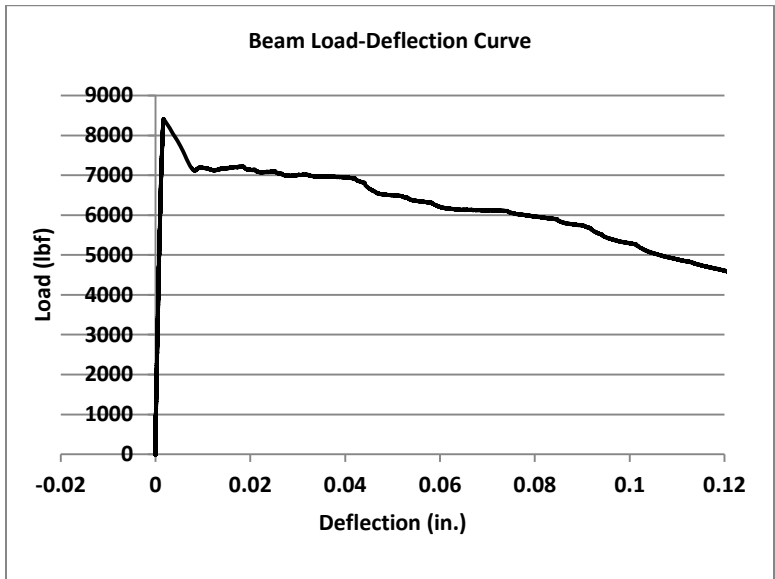


Figure A- 9: Load Deflection Curve of 66 lb/yd³ Steel Fiber Beam – 24 in. pipe

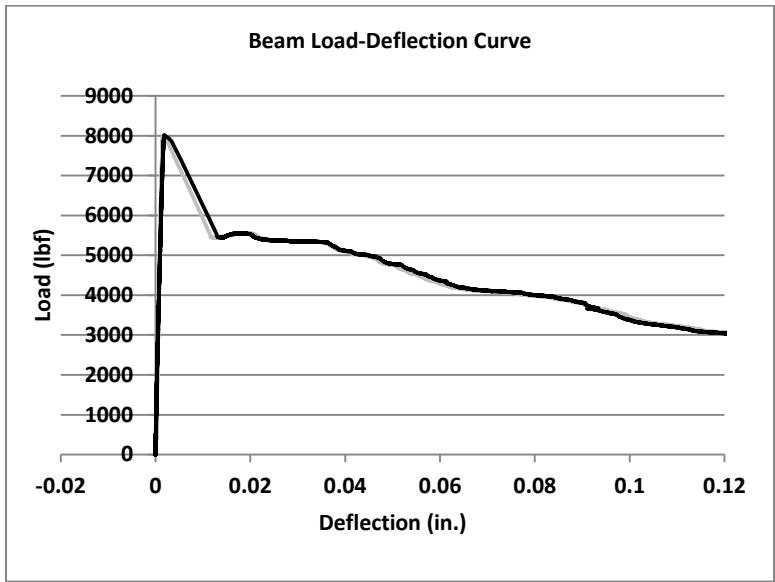


Figure A- 10: Load Deflection Curve of 33 lb/yd³ Steel Fiber Beam – 30 in. pipe

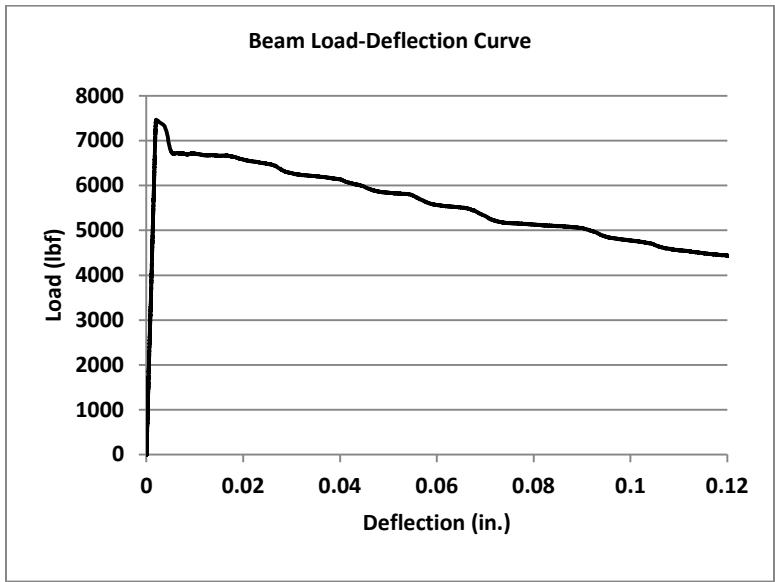


Figure A- 11: Load Deflection Curve of 44 lb/yd³ Steel Fiber Beam – 33 in. pipe – I

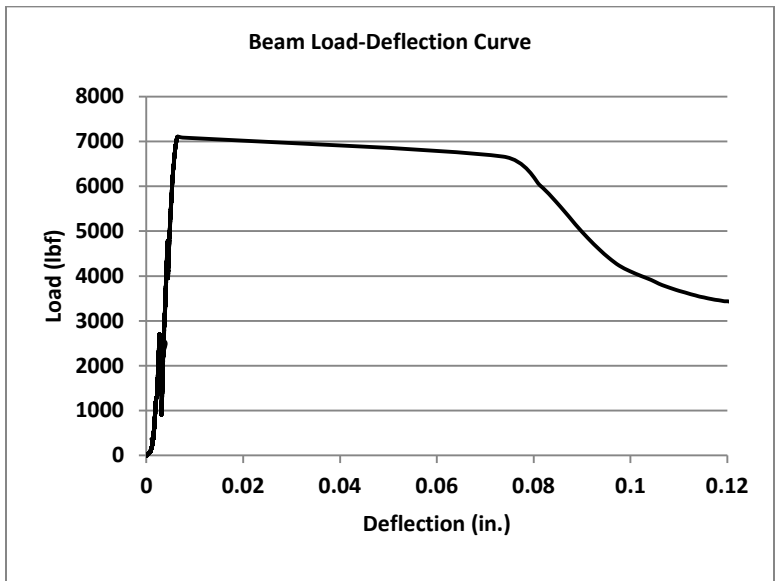


Figure A- 12: Load Deflection Curve of 44 lb/yd³ Steel Fiber Beam – 33 in. pipe – II

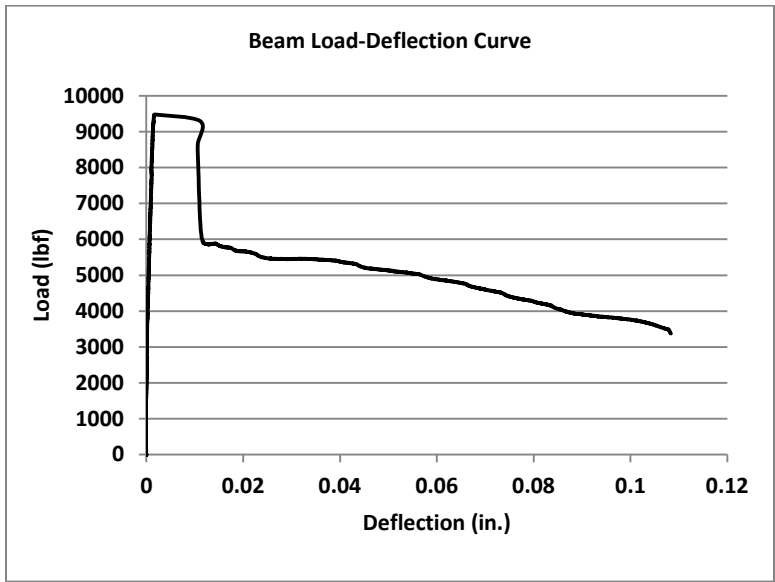


Figure A- 13 Load Deflection Curve of 66 lb/yd³ Steel Fiber Beam – 33 in. pipe – I

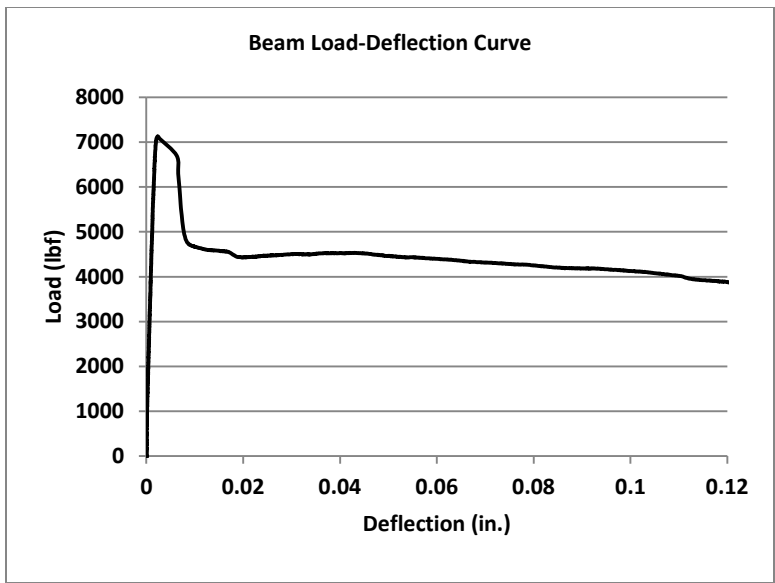


Figure A- 14 Load Deflection Curve of 66 lb/yd³ Steel Fiber Beam – 33 in. pipe – II

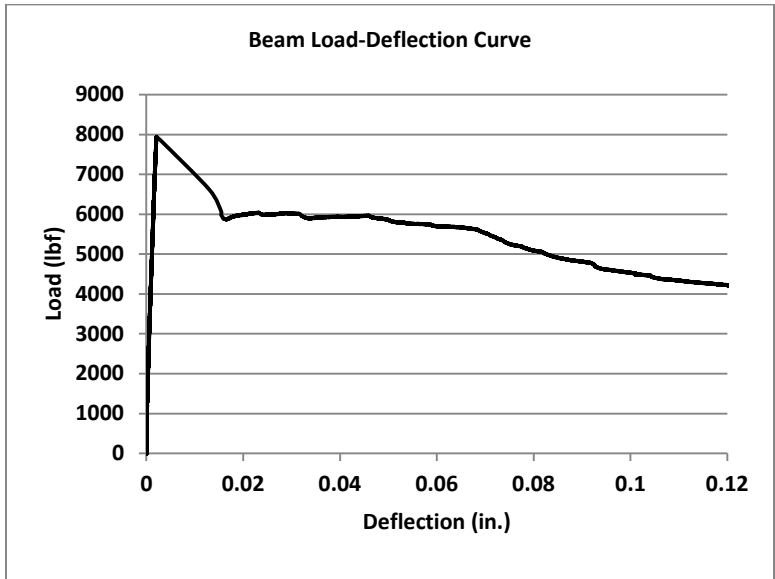


Figure A- 15: Load Deflection Curve of 44 lb/yd³ Steel Fiber Beam – 36 in. pipe – I

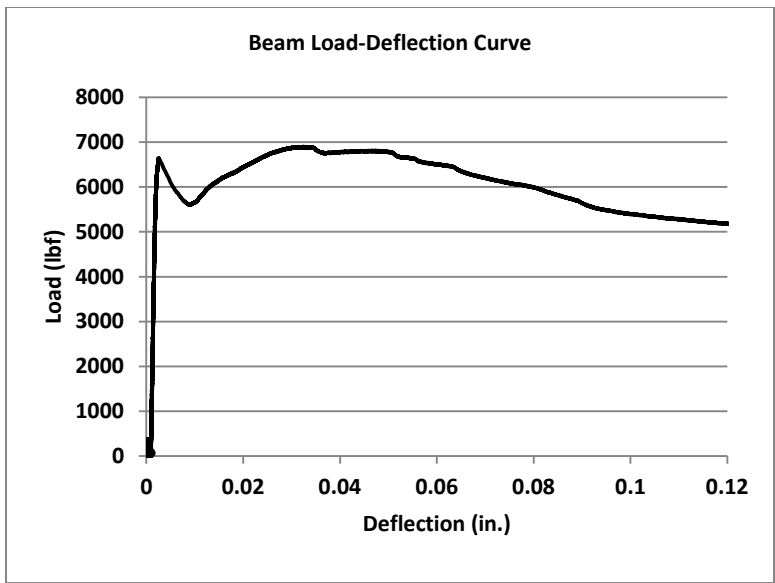


Figure A- 16: Load Deflection Curve of 88 lb/yd³ Steel Fiber Beam – 36 in. pipe – II

Appendix B

Three-Edge Bearing Test Load-Deflection Plots

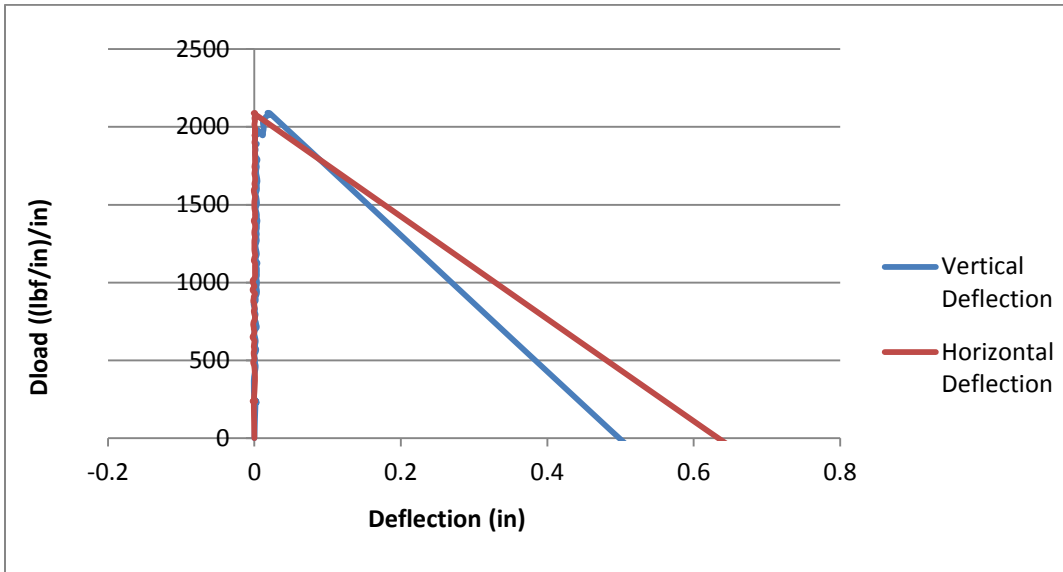


Figure B- 1: Load-Deflection Plot of 18 in. pipe – 5 lb/yd³ Steel Fiber – I

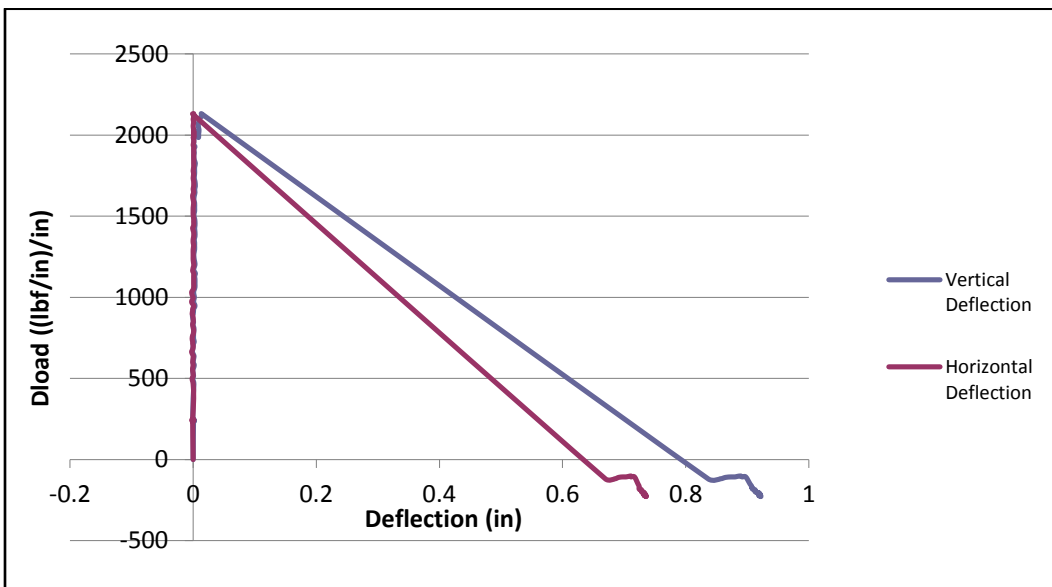


Figure B- 2: Load-Deflection Plot of 18 in. pipe – 5 lb/yd³ Steel Fiber – II

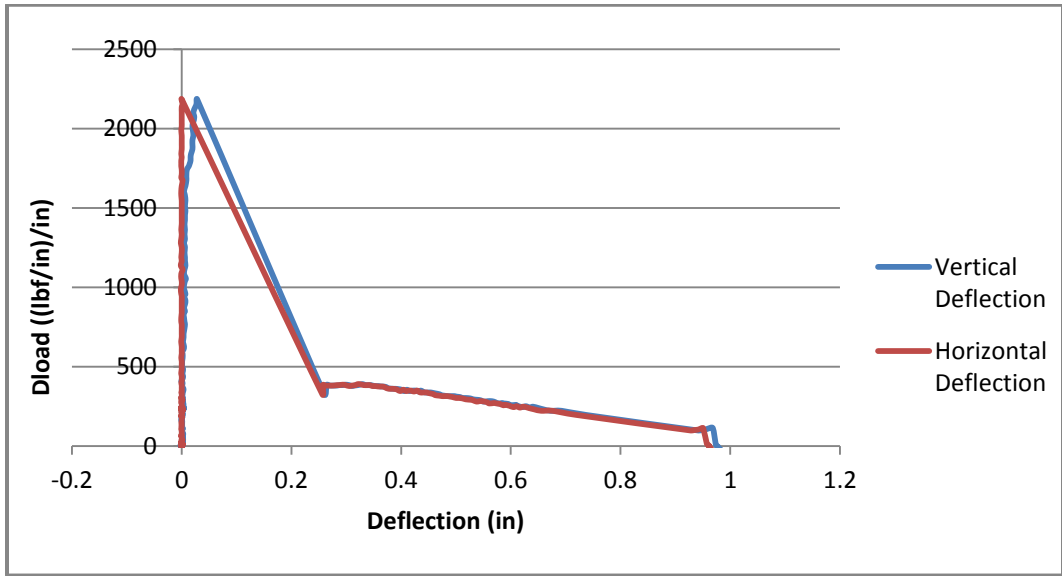


Figure B- 3: Load-Deflection Plot of 18 in. pipe – 11 lb/yd³ Steel Fiber – I

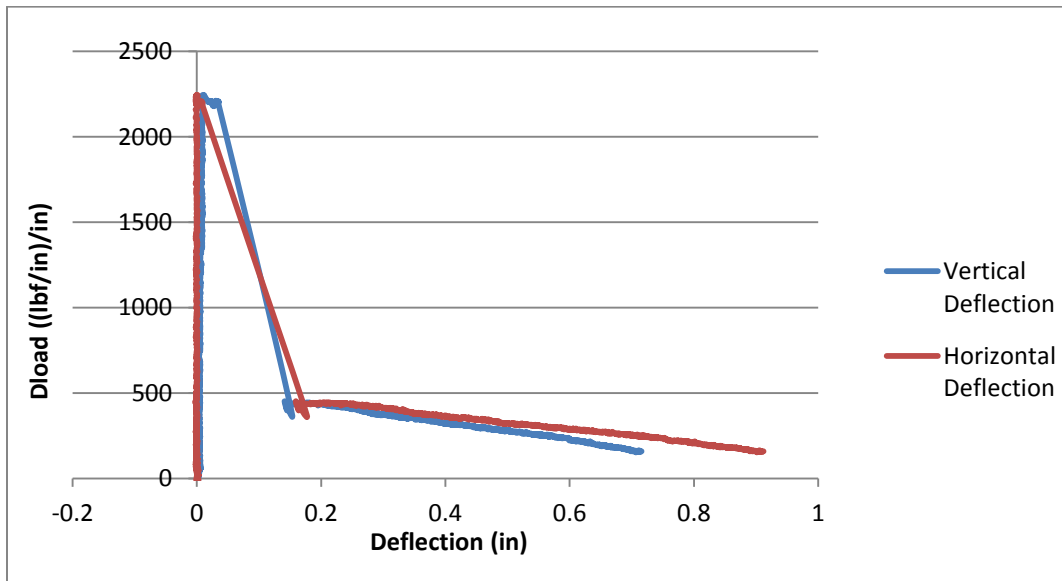


Figure B- 4: Load-Deflection Plot of 18 in. pipe – 11 lb/yd³ Steel Fiber – li

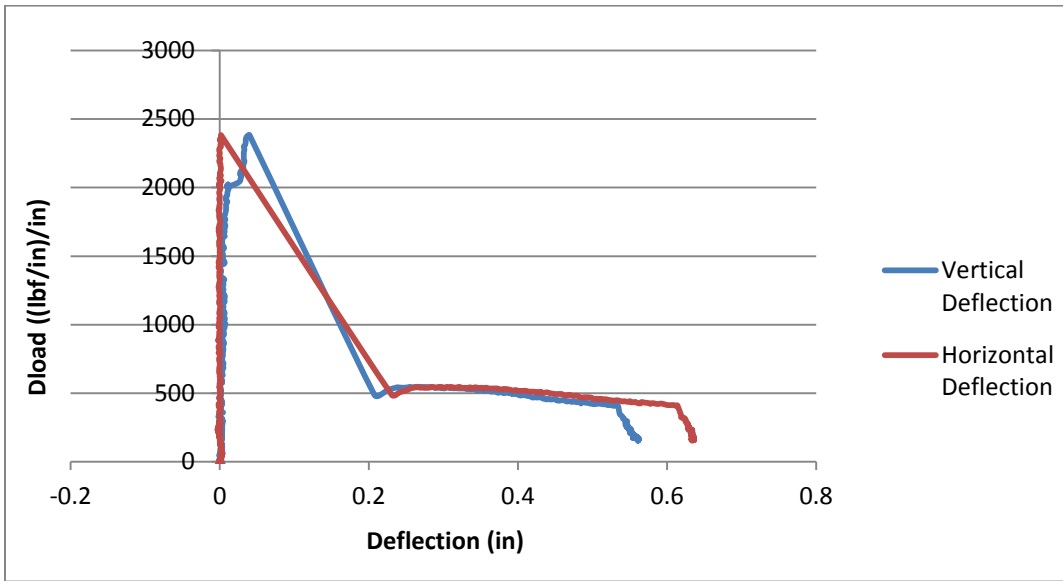


Figure B- 5: Load-Deflection Plot of 18 in. pipe – 16 lb/yd³ Steel Fiber – I

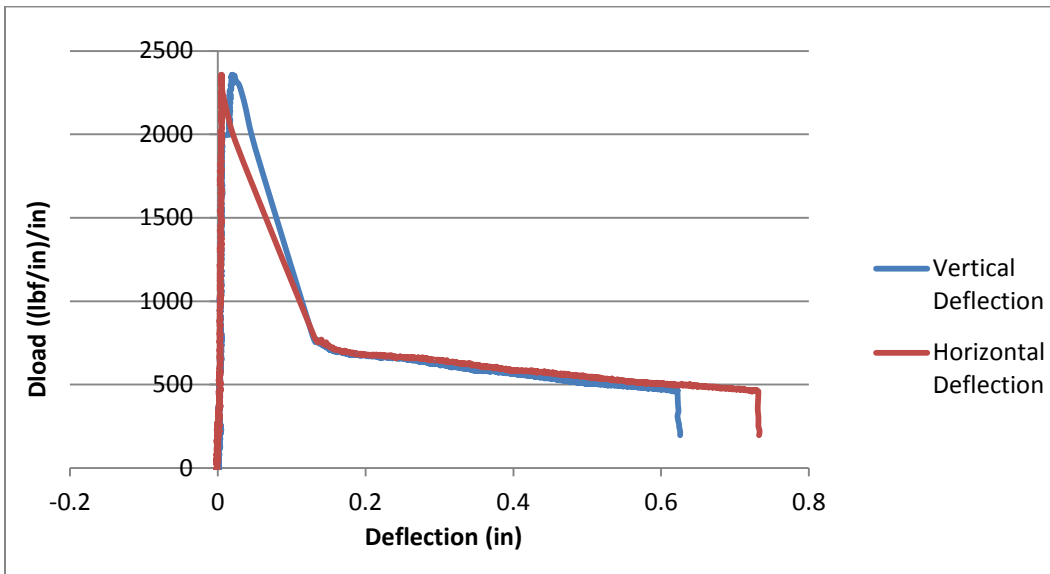


Figure B- 6: Load-Deflection Plot of 18 in. pipe – 16 lb/yd³ Steel Fiber – II

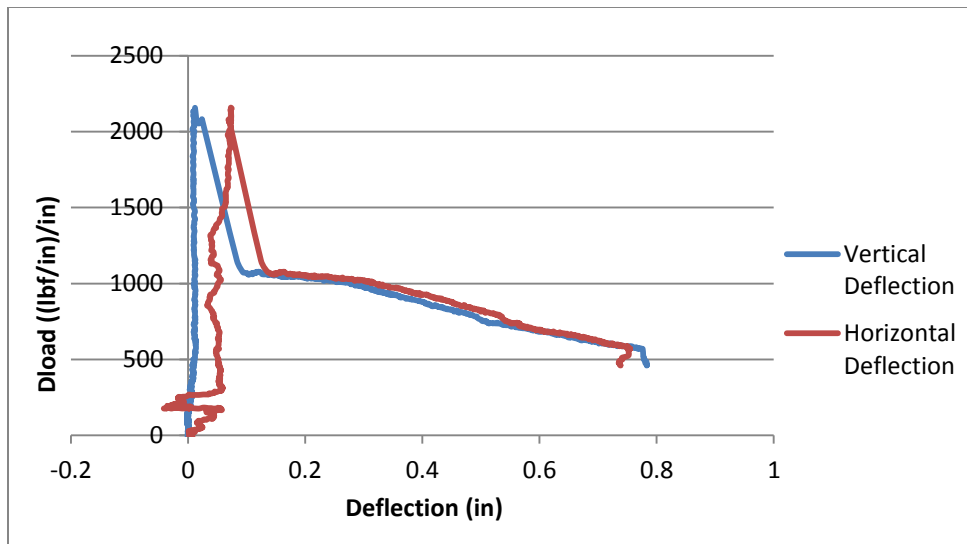


Figure B- 7: Load-Deflection Plot of 18 in. pipe – 22 lb/yd³ Steel Fiber – I

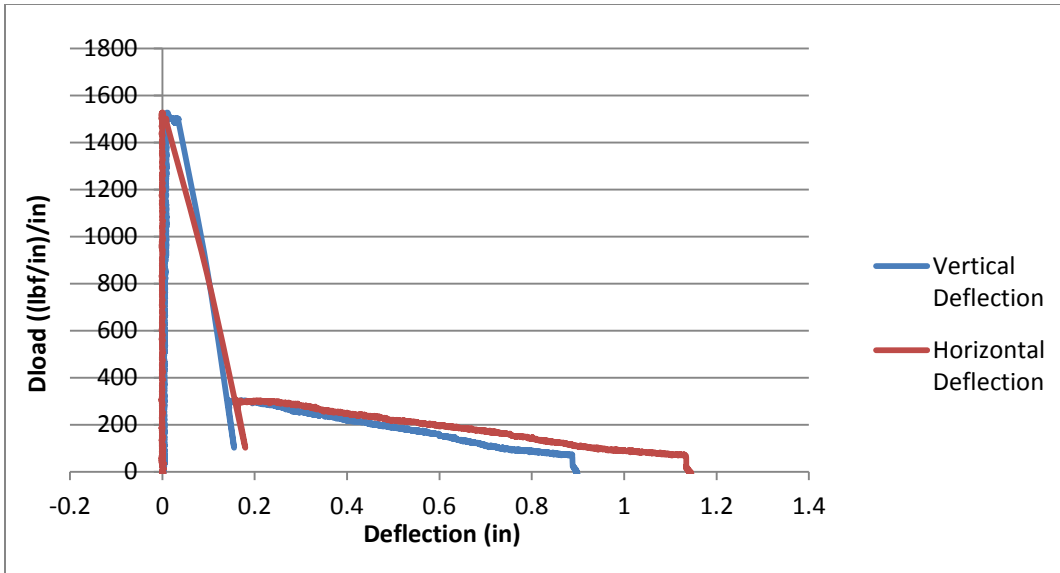


Figure B- 8: Load-Deflection Plot of 24 in. pipe – 11 lb/yd³ Steel Fiber – I

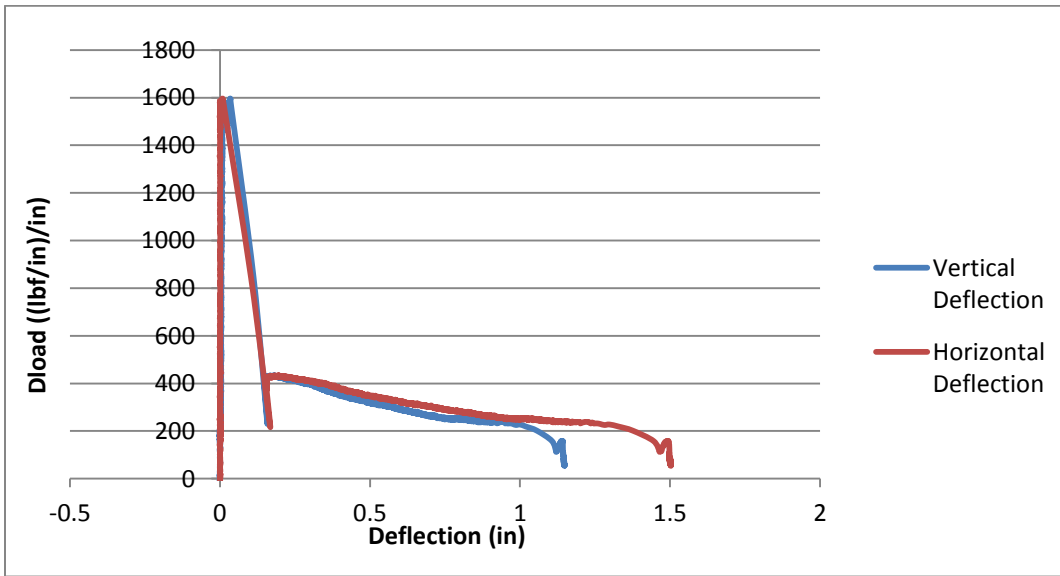


Figure B- 9: Load-Deflection Plot of 24 in. pipe – 11 lb/yd³ Steel Fiber – II

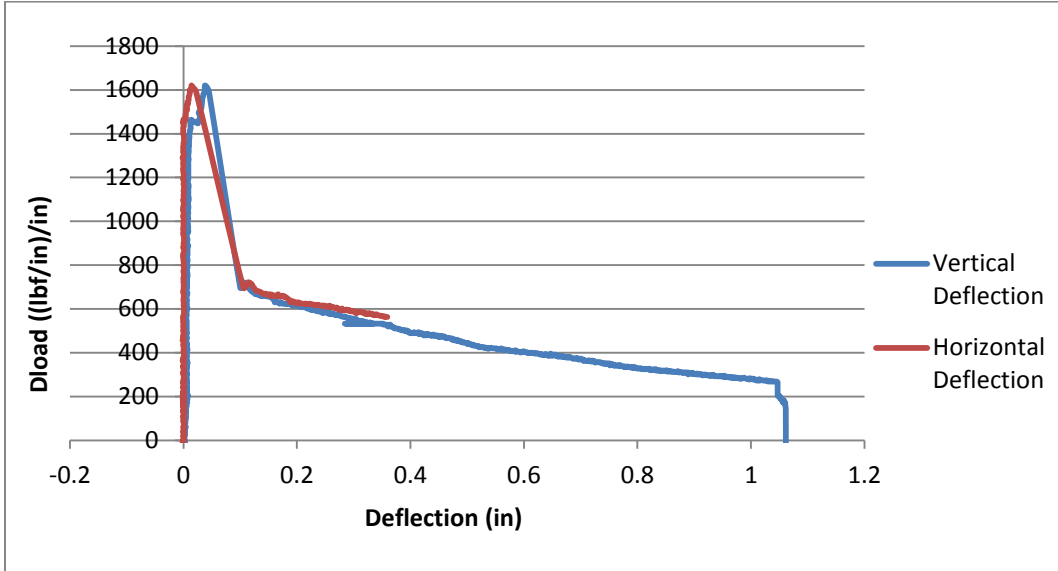


Figure B- 10: Load-Deflection Plot of 24 in. pipe – 16 lb/yd³ Steel Fiber – I

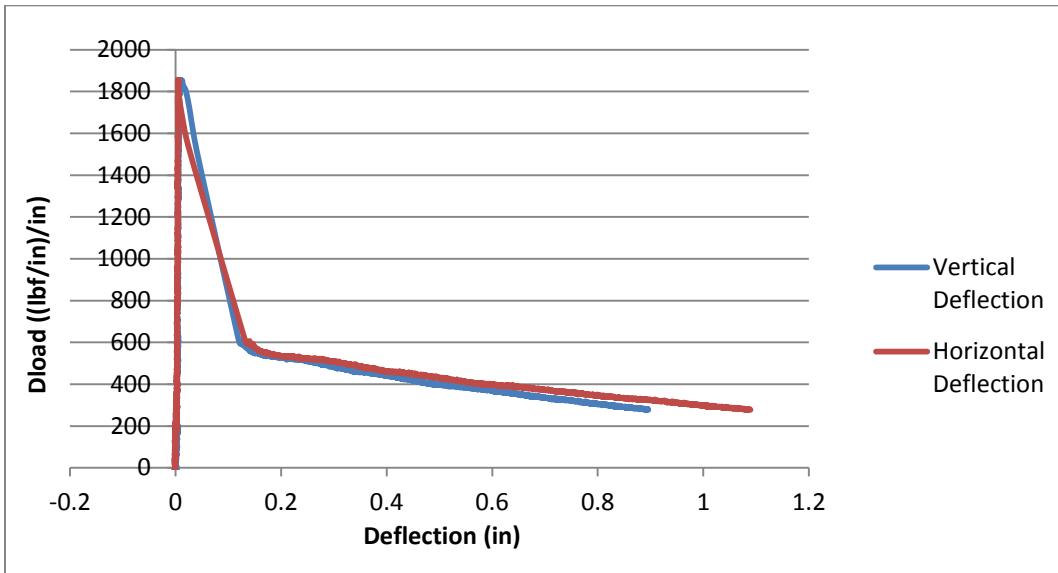


Figure B- 11: Load-Deflection Plot of 24 in. pipe – 16 lb/yd³ Steel Fiber – II

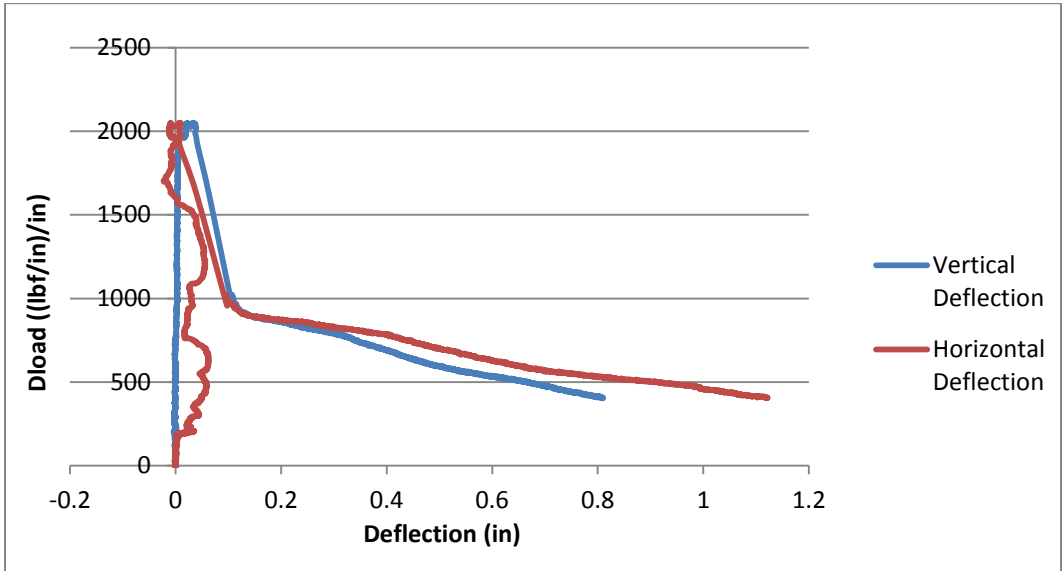


Figure B- 12: Load-Deflection Plot of 24 in. pipe – 22 lb/yd³ Steel Fiber – I

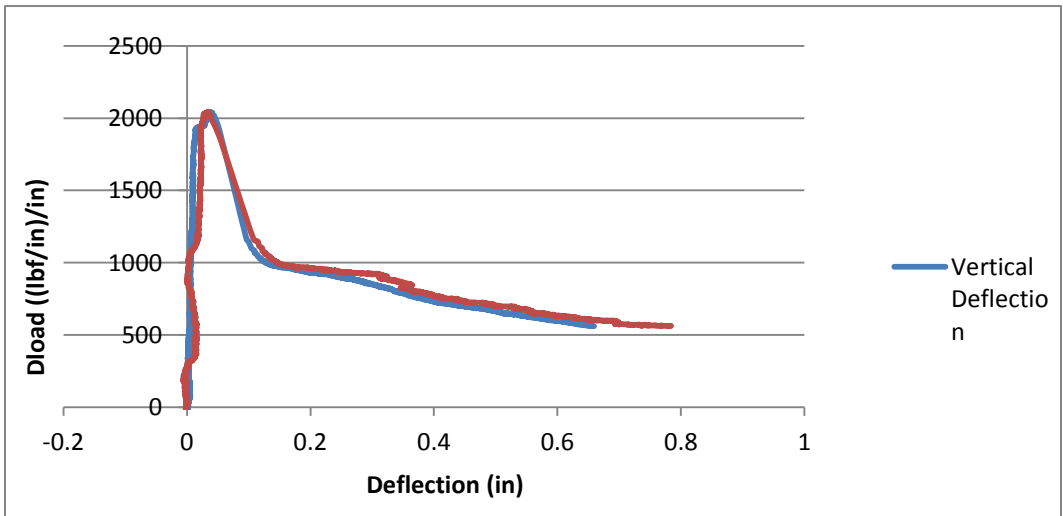


Figure B- 13: Load-Deflection Plot of 24 in. pipe – 22 lb/yd³ Steel Fiber – II

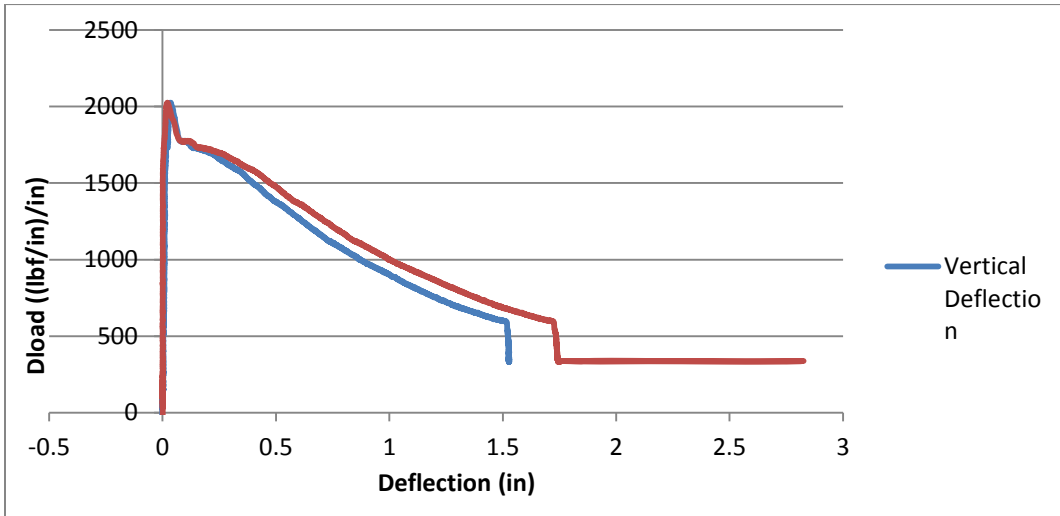


Figure B- 14: Load-Deflection Plot of 24 in. pipe – 44 lb/yd³ Steel Fiber – I

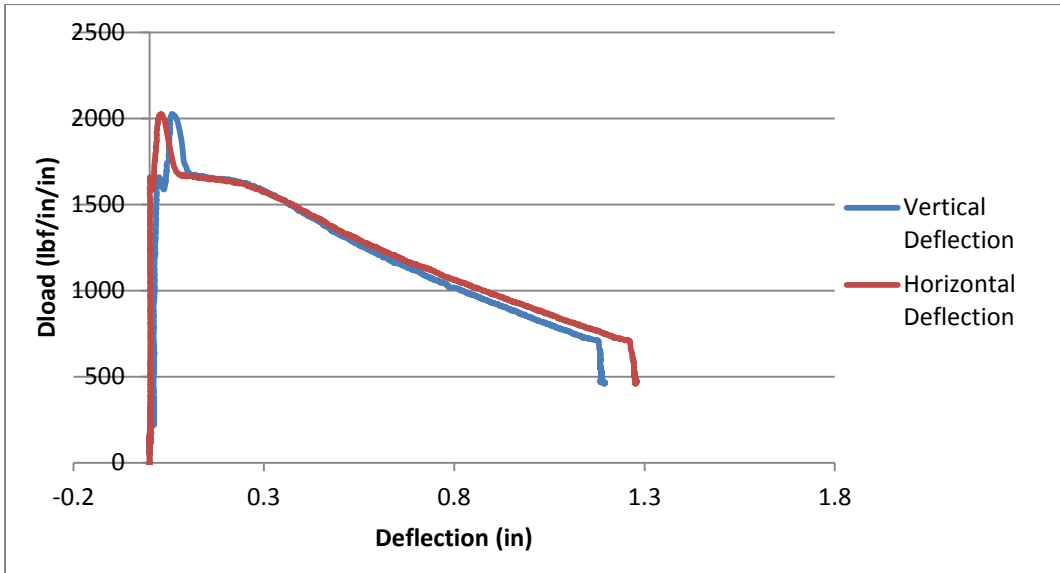


Figure B- 15: Load-Deflection Plot of 24 in. pipe – 44 lb/yd³ Steel Fiber – II

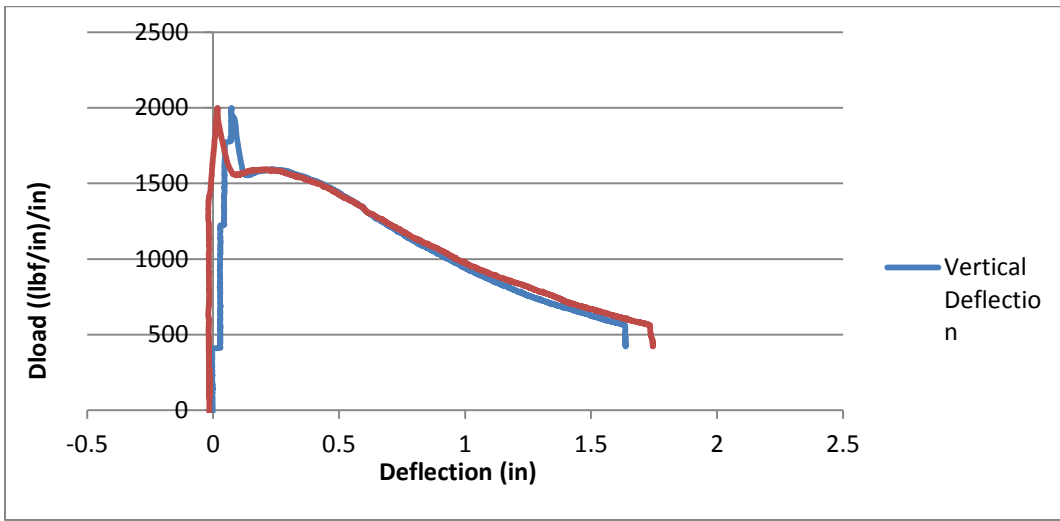


Figure B- 16: Load-Deflection Plot of 24 in. pipe – 66 lb/yd³ Steel Fiber – I

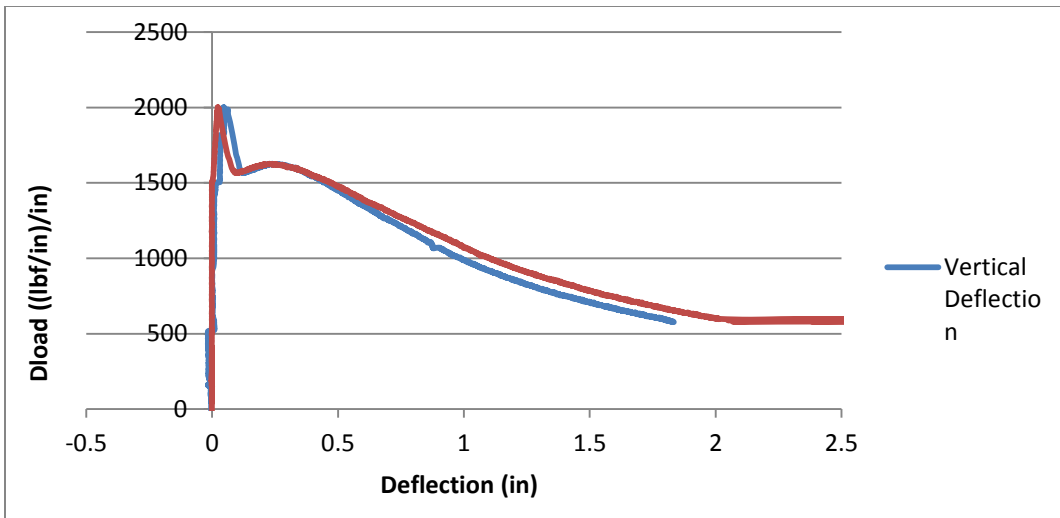


Figure B- 17: Load-Deflection Plot of 24 in. pipe – 66 lb/yd³ Steel Fiber – II

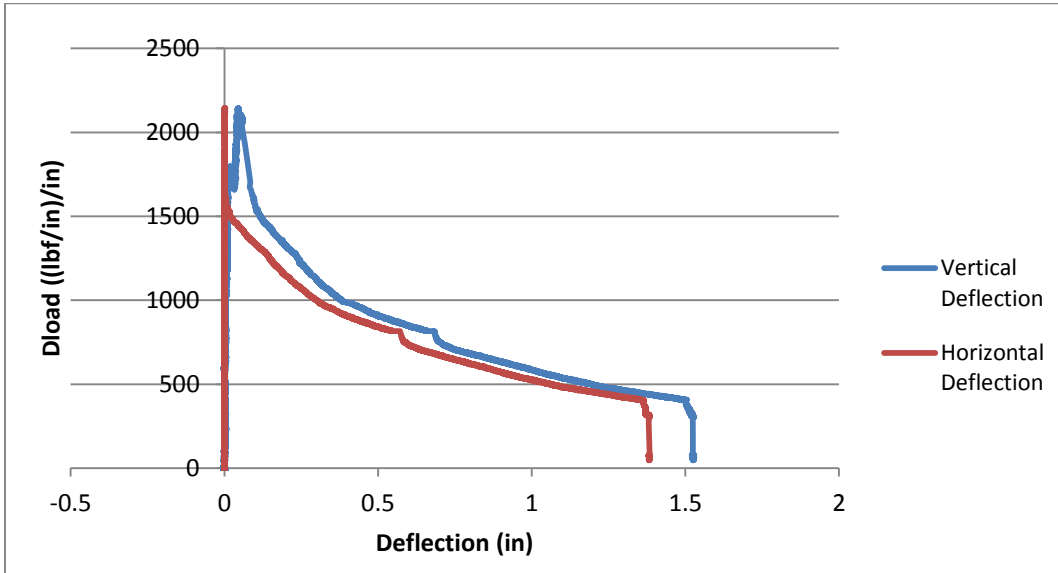


Figure B- 18: Load-Deflection Plot of 30 in. pipe – 33 lb/yd³ Steel Fiber – I

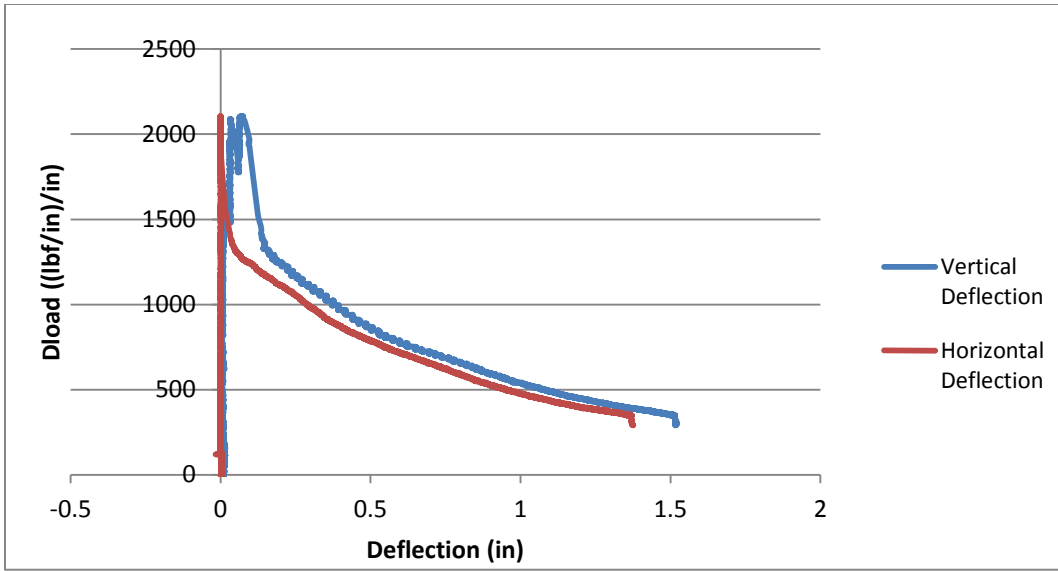


Figure B- 19: Load-Deflection Plot of 30 in. pipe – 33 lb/yd³ Steel Fiber – II

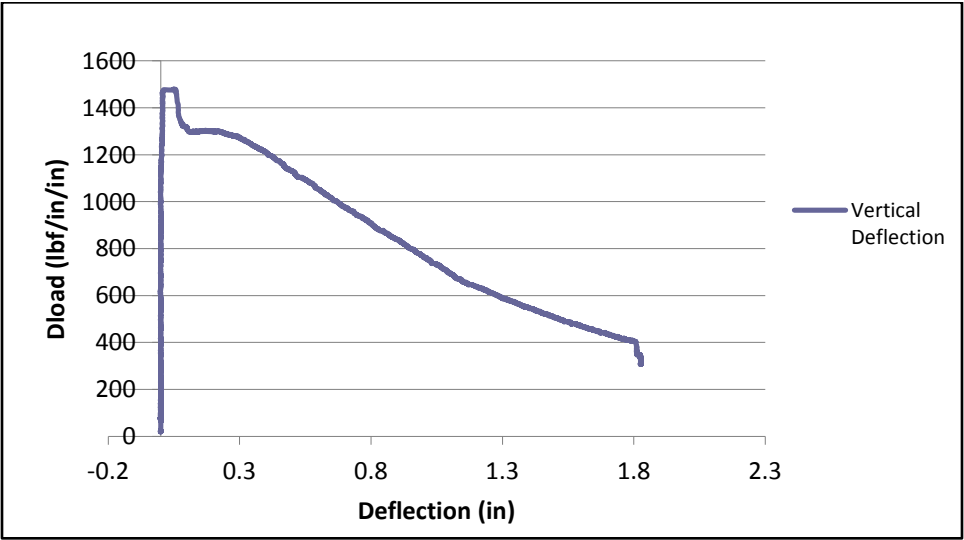


Figure B- 20: Load-Deflection Plot of 33 in. pipe – 44 lb/yd³ Steel Fiber – I

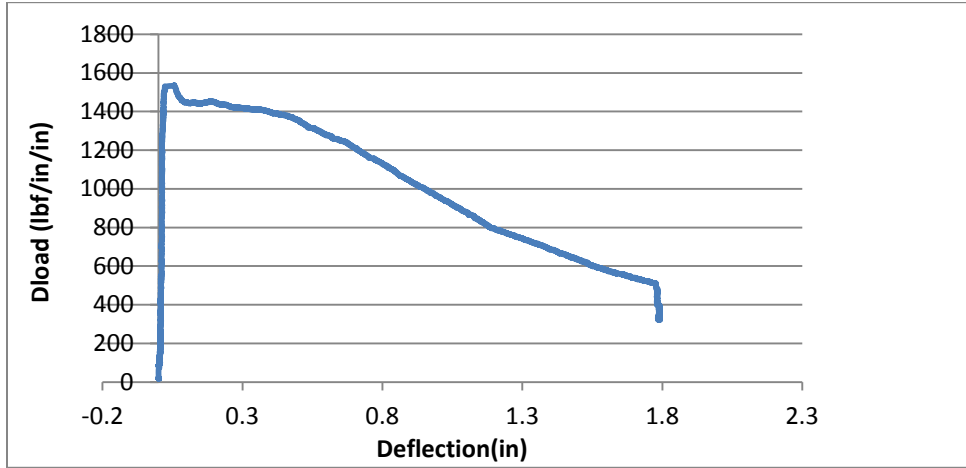


Figure B- 21: Load-Deflection Plot of 33 in. pipe – 66 lb/yd³ Steel Fiber – I

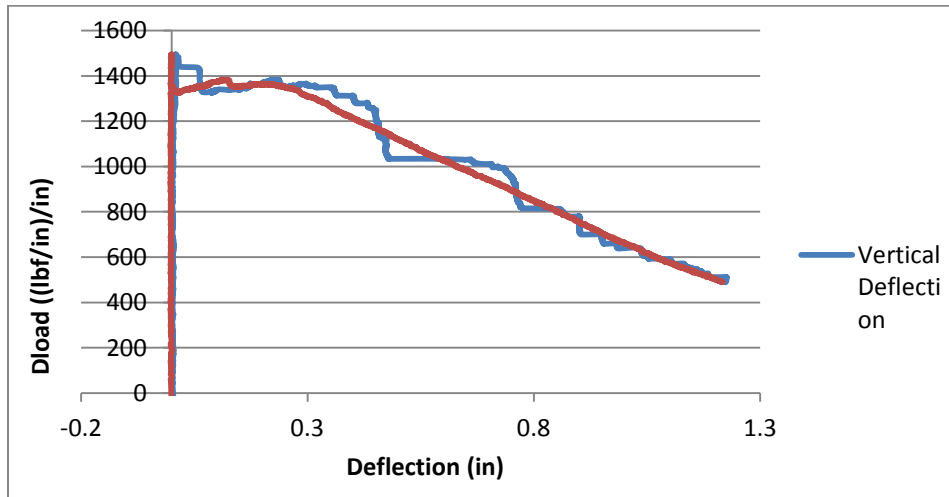


Figure B- 22: Load-Deflection Plot of 33 in. pipe – 66 lb/yd³ Steel Fiber – II

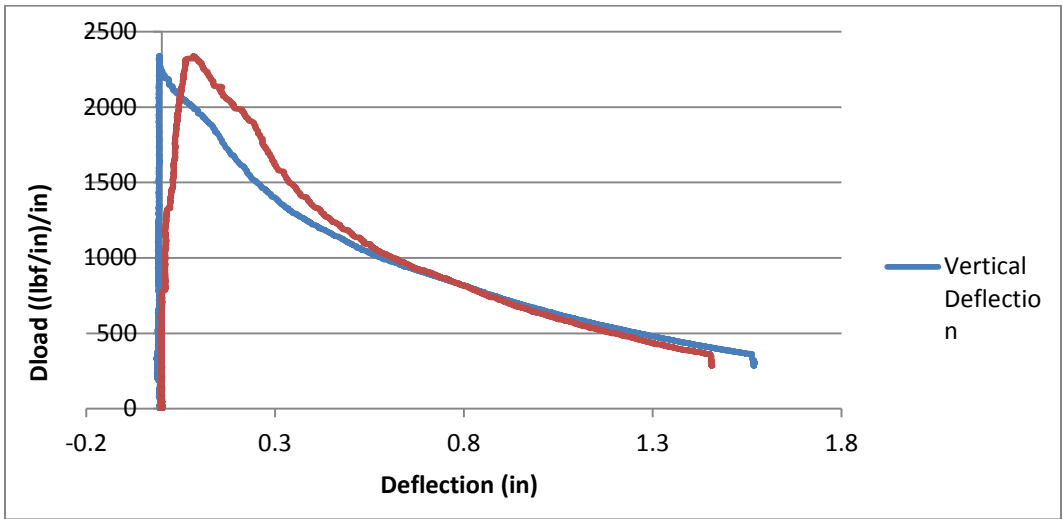


Figure B- 23: Load-Deflection Plot of 36 in. pipe – 44 lb/yd³ Steel Fiber – I

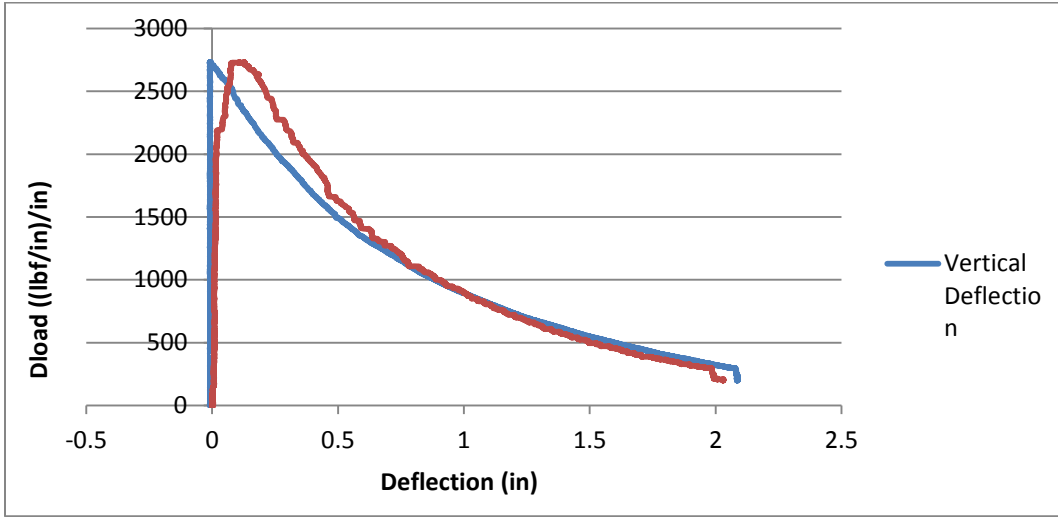


Figure B- 24: Load-Deflection Plot of 36 in. pipe – 88 lb/yd³ Steel Fiber – I

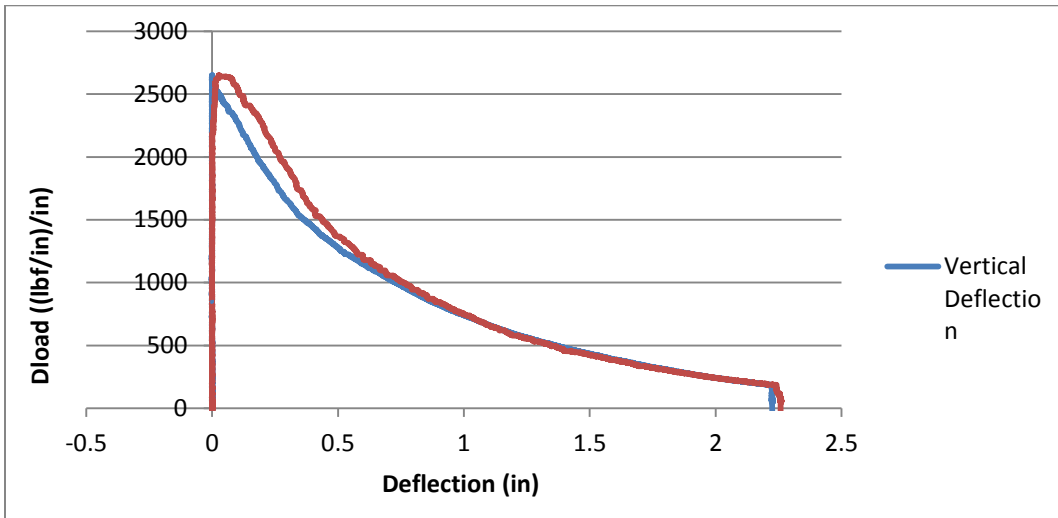


Figure B- 25: Load-Deflection Plot of 36 in. pipe – 88 lb/yd³ Steel Fiber – II

Appendix C
Compressive Cylinders Strength Results

		Compressive Strength (psi)		
		Test Days after Production		
		3 Days	7 Days	28+ Days
Steel Fiber Dosage (lb/yd ³)	5	2780	3025	3340
	11	3025	3180	4140
		4600	5890	6050
	16	1910	4290	-
		1600	4300	4850
	22	3025	5250	5650
		4060	5540	5890
	44	3340	3790	5410
		-	-	3980
		-	-	3260
	66	1850	2530	3208
		-	3580	4060
	88	-	-	4070

Table C- 1: Compressive Cylinders Strength

References

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