FINITE ELEMENT ANALYSIS FOR ASTM C-76 REINFORCED CONCRETE PIPES WITH REDUCED STEEL CAGE

By

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ABSTRACT

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CAGE

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Reinforced concrete pipes (RCP) are composite pipes which have been widely used in the industry for more than ten decades. They are generally used for sewerage, water drainage, and industrial waste water.

There are two methods for designing the RCP so that it will bear the soil weight and the live load on it: Indirect design (ID) and direct design (DD) methods. ASTM C76 (1) classifies pipes into five categories. The five categories of pipes have been classified in order of ascending pipe diameter with their required load

and reinforcement's area. Typically, there are two reinforcement types: circumferential and longitudinal. Circumferential reinforcement is placed in two layers in the thickness of the pipe and the longitudinal reinforcements are placed around the circumferential reinforcements. All these reinforcements are placed in one layer, also known as cages. The task of placing two cages of reinforcement is not only tedious but also time consuming, expensive and sometimes unnecessary, especially for pipe classes III, IV and V.

In this study, a three dimensional non-linear finite element modeling has been generated by using Abacus, Version 6.14-3, a program which is well known for non-linear finite element analysis, to simulate real pipe behavior for implementation of single cage instead of double cages reinforcements. Simulations were generated for classes III, IV and V with pipe diameters of 24, 36, 48, 60 and 72 in. Pipes were modeled by using three different single-cage reinforcement locations, in addition to the original double cage concrete pipe. After which a total of 80 simulations were conducted in order to compare the difference between the single and double cage behavior.

In order to verify the simulations, three ASTM standard Three Edge Bearing tests were performed. Pipes were selected and tested according to ASTM C76 and ASTM C497 standards specifications.

The study showed one cage of reinforcements in some pipes, satisfies all the ASTM requirements. Thereby making it possible for manufacturers to produce reinforced concrete pipes with a smaller amount of steel reinforcements per foot.

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CHAPTER 1

1.1 Introduction

One of the most crucial facilities in every country is the pipeline infrastructures, which are not only costly but also important for maintaining our economy and way of life. One of the most primary functions for the pipe system is to transport waste water and sewage out of the city in order to maintain a clean and sanitized environment. In a time of disaster, Pipelines carry the storm water and runoff to the proper channels or rivers. In arid countries, water management is a very essential and vital part of life. In such cases, the purpose of the pipeline is to collect surface, rain or gray water and convey it for storage. The absence or failure of these pipelines could result in an epidemic, famine, dearth of pure water, inundation, and increased mortality. Furthermore, the proper pipeline is essential for the transportation of gas and oil resulting in the balance of the economy. Therefore, many countries spend billions of dollar every year for construction and development of their pipelines.

With the continuous improvement of technology, there are many types of pipes under production such as reinforced concrete, fiber-reinforced concrete, polypropylene, PVC, and steel pipes. There are a variety of pipes produced with different diameters and shapes, and amongst them reinforced concrete pipes have the highest amount of production in the world for sewerage-drainage networks.

Reinforced concrete pipe (RCP) is a composite pipe which consists of concrete and steel reinforcements. Reinforced concrete pipes have a long history of excellent durability for sewer, storm-water and industrial drainages. They have been produced and have functioned for almost a century. During the past three decades the rapid growth of the industry, technology and production practices of RCP have made them more durable, efficient, and reliable. This is accredited to the rapid growth of the industry, and the innovation in the technology to produce the concrete material. One example of this can be seen in the strengthening of the concrete material by adding admixtures to the traditional concrete mix design.

All new concrete pipes manufactured must be able to resist corrosion such as sulfates and chlorides attack in the soil. Moreover, if designed properly, the expectation is that the reinforced concrete pipes last for hundreds of years due to the high durability and self-healing of concrete in wet environment. Based on this high durability and performance, reinforced concrete pipe is the most viable choice for sewer, storm water, and industrial drainage.

Reinforced concrete pipe structures consist of concrete and wire steel reinforcements. RCP is produced in round, elliptical, arch, elbow, and perforated shapes with various diameters. The reinforcements are manufactured in circular (round) and elliptical shapes. Due to their ease of installation, reinforced concrete with circular reinforcements are one the most popular RCP in the industry. There are two types of steel reinforcements in RCP: circumferential and longitudinal. In order to better understand the reinforcement in concrete pipes, assume that the concrete pipe is a curved beam. The circumferential reinforcements would act similar to how the longitudinal reinforcements act in the beam, by providing strength against the bending moment. The longitudinal reinforcements would act similar to how the stirrups act in the beam by controlling the crack distributions, providing proper spacing and rigidity during manufacturing, and keeping the circumferential reinforcements in a cage.

These round or elliptical reinforcement cages are typically placed in one or two layers inside the pipe thickness relative to the pipe diameter. According to Figure 1-1, there are two different tension zones in the concrete pipe therefore the use of a double cage is required. In order to increase the moment capacity of the section, reinforcements are placed in both tension zones due to the weak strength of concrete against tension.

The RCP has a high demand and massive production in many countries. As shown in Figure 1-3, placing two layers of reinforcement increases the congestion of the steel in the pipe wall thickness. This issue poses a dilemma since the high congestion creates many difficulties during the construction of the pipe. By implementing a single cage, many longitudinal reinforcements and one layer of circumferential reinforcement will be eliminated. This change will make the RCP easier to install, faster to manufacture, and more economical by reducing the total reinforcements used by about 25%. This research will investigate whether the elimination of a single cage in RCP is feasible and determine the optimum location for the reinforcements in order to obtaining the best results.

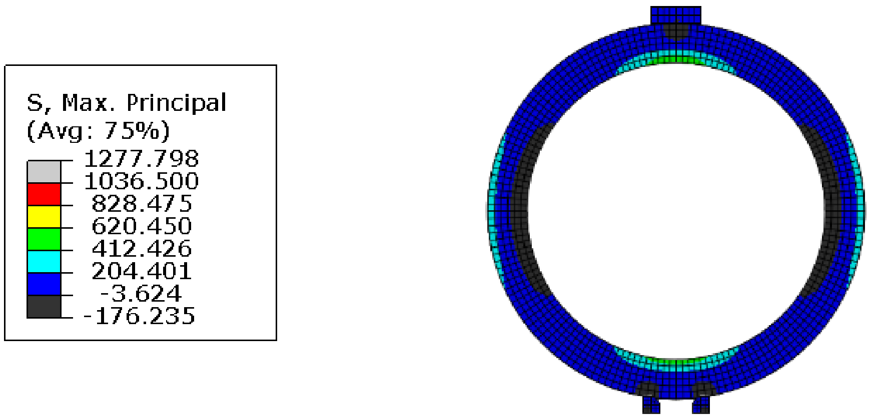


Figure 1-1, The positive numbers indicate tensile stress and the negative numbers indicate compressive stress

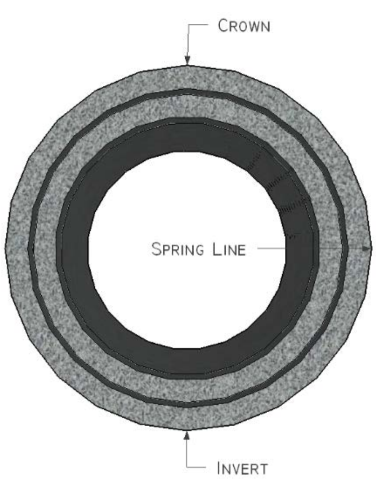


Figure 1-2, Reinforced Concrete Pipe Sections

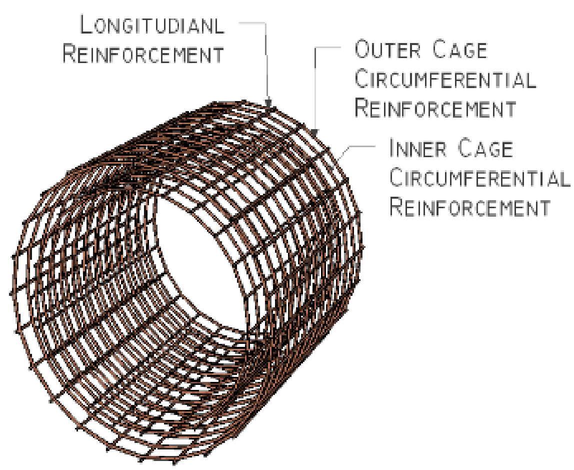


Figure 1-3, Reinforcement Cages

1.1.1 History

The history of the construction underground conduits dates back thousands of years when the first civilizations expanded their cities. By prevalence of many diseases and the importance of accessibly of pure water, they were made to seek a solution to drain the sewage out the cities and bring pure water to the cities from the rivers.

One of the first underground conveyance systems was invented in the Persian Empire in 3000 B.C. The oldest and longest underground water conveyance system, Qanat, belongs to the city Zarch (2) in the center of Iran (44.1 miles and 3020 years old). They were providing their needed agricultural and sanitary water through Qanat.

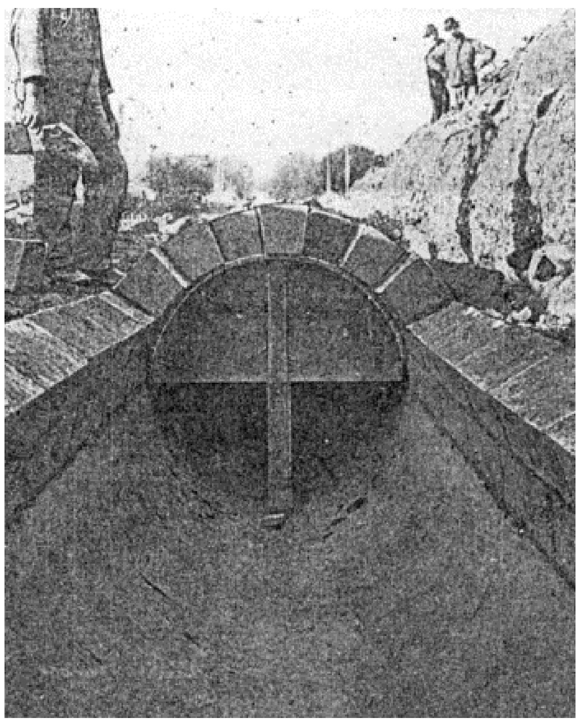
In 180 B.C. the Romans built the sewer system, Cloaca Maxima, in order to drain the sewage, waste water, and effluent to the river. In order to build the Cloaca Maxima, they used pozzolanic ash which they took from a volcano to produce hydraulic cement. They used this hydraulic cement as a paste to make the natural cement concrete. This natural concrete was the best material to expose water, moisture, and harden over time. Some of these pipelines have withstood the test of time and are still functioning today.

Picture 1-1, Oldest Qanat - Iran. (2)

Picture 1-2, Cloacae Maxima - Italy

In the 19th century, London was suffering from an epidemic of cholera and in 1850 more than 10,000 people lost their lives. The high mortality rate led to the public awareness for the need of sanitation systems to control the spread of diseases. In order to solve this predicament, engineers and scientists proposed sewerage network systems. Joseph Bazalgette designed extensive underground sewerage systems which delivered London's sewage to the Thames River. They have used 318 million bricks, 3.5 million cubic feet excavation and 876 thousand cubic yard of concrete. By innovation of Portland cement they could fortify the tunnels and let them to construct this massive underground sewage system.

The modern day concrete pipeline sewer system emerged in 1842 in Mohawk, N.Y. (3) In the late 19th century, other New England cities installed concrete pipes as well. The French were the first who placed steel reinforcement inside concrete pipes in 1896, also known as the Monier patent. Monier was a commercial gardener who experimented steel wire inside concrete tubes and basins. He patented his idea in 1867 and in the same year showed his invention to the public in the Paris Exposition. The concept was brought to America in 1905 and later to Australia. Australia and New Zealand developed more than 186 thousand miles of pipelines, culverts, sewer drainage, and pressure pipe application which are still in use today.



Picture 1-3, Concrete sewer with Arch Blocks, Toledo, O. (34)

1.1.2 Concrete Pipe Design History

In the early 19th century, Talbot (4) began his work on structural analysis of homogeneous concrete pipe. He considered pipe under the vertical distributed uniform load of soil pressure (Figure 1-3). Talbot developed an equation to calculate moment at points A and B;

$$-MA = MB = \frac{1}{16}\omega {D_m}^2 \qquad \text{Eq. 1-1}$$

Where ω is unit load, D_m is the mean diameter of concrete pipe as shown in Figure1-3, the minus sign indicates that the tension zones in points A and B are contrary. Later, Talbot's formula has developed to new form:

$$M = \frac{1}{16} W D_m \qquad \text{Eq. 1-2}$$

Where W is ωD_m, which means total load on a ring of unite length. This equation in combination with Marston's theory, became the first tool for engineers to obtain the theoretical analysis of stresses in concrete pipes. Up to this time the design of reinforced concrete pipe was based on trial and error tests.

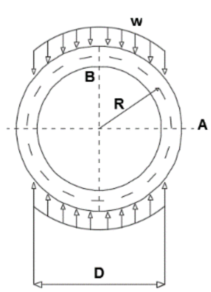


Figure 1-4

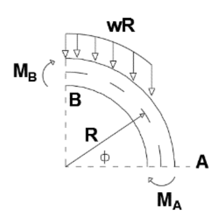


Figure 1-5

In 1926 The Joint Concrete Culvert Pipe Committee (5), consisting of ASTM, AASHTO, ACI, ASCE, ACPA and the Bureau of Public Roads representatives published their reports for determination of steel requirements for pipes based on Talbot's formula. The used formula was:

$$\frac{1}{16}\omega {D_m}^2 = f_s A_s jd \qquad \text{Eq. 1-3}$$

Where A_s is the area of steel cage (in^2), f_s is working stress of steel reinfrocements (psi), j is the ration of lever arm of the resistant couple to d and d is the distance from the compression surface to the tensile reinforcments. This equation was derived from the beam's stresses subjected to the bending moment.

$$M = f_s A_s jd = Pr \qquad \text{Eq. 1-4}$$

Where P is equal to f_sA_s and r is the mean radius concrete pipe.

By using the above equations, many engineers felt that the required amount of steel area was too conservative especially for small size reinforced concrete pipes. Moreover, three inconsistencies were appeared in Talbot's formula. The equation was based on unit distributed load on the top of the concrete, while the only standard test method at the time was the Three Edge Bearing test (TEB). According to the ASTM C-497 specification, TEB exerts a three point load on the pipe. This test was developed at Iowa State University to determine strength condition of pipes by Peckworth and Hendrickson (6). The test is easy, inexpensive and commonly used for concrete pipe quality control. The second inconsistency appeared in equation 1-1 where the ω is load per square foot, while the first D_m of D_m^2 is in feet and the second one is inch in order to obtain the moment in pounds-inch unit. Therefore, later this problem has rectified by developing new equation derived from equation 1-2. The new form of equation was:

$$\frac{0.0625\omega D(D+d)}{12} = f_s A_s jd \qquad \text{Eq. 1-5}$$

And the third inconsistency was the failure to take the effect of the concrete pipe's weight itself into the consideration.

HF Peckworth in 1930, reported the steel areas into the ASTM C-75 and ASTM C76 (7) have determined by modified Talbots formula which were published as ASTM standards. Two layers of equal area of reinforcements were used in each specification for pipes greater than 36 in. for quarter of century, a yielding stress of 27.5 ksi was used for steel area calculations. Neither Talbot's nor modified equation were able to determine the exact amount of steel area required because of the first and third inconsistencies. Therefore, designers used an empirical amount of steel which would pass TEB test required loads.

In 1921, Paris (8) developed a general formula for determination of moment, thrust and shear at any points of concrete pipes. He considered half of the pipe due to the symmetrical structure of pipes with one fixed end, like a cantilever curved beam, and also considered uniform distributed load and supported on a line. Based on the elastic arch theory and Maxwell's theory of reciprocal deflections, moment, thrust and shear coefficients were obtained for all type of loading on concrete pipes. Table1-1 shows the coefficients of moments, thrust and shear under point load (Three Edge Bearing test) condition. These coefficients can be found in Roark's formulas, however with opposite signs for thrust since he used negative signs for tension in his analysis.

Table 1-1, Coefficients of moment, shear and trust under the three edge bearing loading (5) (8)

	Pipe Section	Coefficient	
		Pipe Weight	Test Uniform Line Load
Moment (M)	crown	0.0396	0.159
	spring line	-0.045	-0.0906
	13 degrees from invert	0.067	0.104
	point of support	0.1028	0.1422
	invert	0.1025	0.1423
Thrust (N)	crown	-0.0788	0.0008
	spring line	0.25	0.5
	13 degrees from invert	18	0.112
	point of support	0.1027	0.0341
	invert	0.1137	0.341
Shear (V)	crown	0	0.5
	spring line	0.078888	-0.0008
	13 degrees from invert	-0.434	-0.487
	point of support	-0.4822	-0.4988
	invert	0	0

M = Coefficient x load x D_m, Negative M means tension on outside surface
N or V = Coefficient x load, Negative N means tension, Negative V means upward.

Marston (9) developed a relationship between the in situ situation and three edge bearing load based on trench and embankment condition.

Spangler (10) presented the concept of bedding factor in 1933, to relate the in situ loading condition to the three edge bearing loading condition. He developed three bedding factor configurations. He stated that these bedding factors and consequently, the strength of buried pipes were dependent on the installation conditions. Width, quality of contact, magnitude of lateral pressure and height of the soil over the concretes were the conditions he mentioned in his theory. These studies later became part of the indirect design of reinforced concrete pipes.

In 1956, Babcock (11) published a paper which showed a classified tables of reinforced concrete pipes in order of ultimate D-Load strength (lb/ ft. of length/ ft. of diameter). With this study, the American Concrete Pipe Association (ACPA) (7) published a technical memorandum with tableted RCPs in five classes in order of pipe diameter, steel area requirements and D-loads. This new specification supersede the existing ASTM C75 and C76 (1) in 1957 and remains today with certain changes. The required steel areas were based on the D-Load to produce 0.01 in. crack width and the ultimate failure D-Load. However, in many cases these steel areas were determined by actual TEB test loads but in many cases theoretical calculations were carried out.

The most recent design was developed by Heger 1962 (12). He studied various conditions of loading of reinforced concrete pipes. These developments were based on modern concepts of cracking behavior, ultimate strength, and deformation of reinforced concrete structures. He performed many tests and stated that are three types of failure mode for pipes: Flexural, diagonal tension, and combination of both. Heger developed formulas to determine required steel area in reinforced concrete pipe greater than 60 in. by implementation of welded wire fabrics. These developments were based on design method and analysis of limit load capacity for indeterminate concrete forms, ultimate flexural strength of reinforced concrete components and diagonal tension strength of beams without stirrups. The reason he chose welded-wire fabrics were because of their high ultimate strength, provided proper transverse wire spacing which controlled cracking. Since the ductility was not excessive, the ultimate strength could be obtained without extra distortion at flexural failure mode of the concrete pipe.

Heger's developed formulas were derived for the 0.01in crack width based on moment and crack formation in reinforced concrete due to test loading from an elastic ring analysis:

$$As = \frac{D^2\left[\sqrt{(DL)_{0.01}+0.75\,\frac{W}{D}-\frac{10h\sqrt{f'c}}{D}}\right]}{14000d\Phi_{0.01}\Phi_x} \qquad \text{Eq. 1-6}$$

And for ultimate D-Load capacity:

$$As = \frac{1.65D[(DL)_u D+0.5W]}{f_{su}(d-0.5a)\Phi_f\Phi_x} \qquad \text{Eq. 1-7}$$

Whereas the area of inner cage steel (in^2), D is diameter of pipe (ft), DL stands for D-Load (lb/ft/ft), W is the shell weight of the unite weight of pipe (in), f'_c stands for ultimate compressive stress of concrete (psi), d is pipe wall thickness (in), f_{su} stands for ultimate tensile steel reinforcements (psi), $a = 0.1(\frac{f_{su}}{f'_c})$ and respectively $\Phi_{0.01}$=0.91, Φ_x=0.85 and Φ_f=0.95. For outer reinforcements, area considers 75 percent of the inner steel reinforcement's area.

A similar formula was developed by Heger for determination of deformed welded steel wire fabric. High tensile strength for ultimate load capacity and high bone surface for crack width control are advantages of this type of steel against smooth welded, cold drawn and intermediate grade hot rolled rod. Required steel area for 0.01 in crack width strength can be obtained from:

$$As = \frac{D^2\sqrt{A_{cs}}\left[\sqrt{(DL)_{0.01}+0.75\frac{W}{D}-\frac{10h\sqrt{f'_c}}{D}}\right]}{25000d\Phi_{0.01}\Phi_x} \qquad \text{Eq. 1-8}$$

For ultimate D-load:

$$As = \frac{1.65D[(DL)_u D+0.5W]}{f_{su}(d-0.5a)\Phi_f\Phi_x} \qquad \text{Eq. 1-9}$$

Where A_{cs} is the symmetrical area of concrete surrounding in each circumferential wire (in^2).

Later, these equations were rectified in a form which is available in AASHTO section 12 and in many others RCP design books.

In 1970, the American concrete pipe association (ACPA) (13) began a long range testing in order to find interaction between concrete pipe and soil by Frank Heger (12). Their studies led to development of the SPIDA, a comprehensive finite element computer program for direct design method with soil and pipe interaction analysis. Since the early 1980s SPIDA has been used for many studies including the development of SIDD, the standard Installation for Direct Design method of buried concrete pipe. This studies also replaced the traditional bedding factors with four new standard installations. Later PIPECAR, a program designated for analysis and design of reinforced concrete pipes, was introduced. PIPECAR was written to run on IBM compatible microcomputers which facilitated the direct design procedure based on AASHTO specifications for ultimate flexure radial and diagonal tension design criteria. In addition, PIPECAR considers pipe and soil weight (up to 50 ft. of head), internal gravity fluid weight, live loads, and internal pressures.

In 1993, new standards for installation types and Heger earth pressure distribution, based on Marston and Spangler research, and the direct design method were incorporated by ASCE. Later, all of these researches and practiced methods led to an existing ASSHTO section 12 (14) and ASTM C-76 which remain the engineers design guides for reinforced concrete pipes for engineers.

1.1.3 Finite Element Method History

Finite element is a method for approximation solving of differential equations in a continuum setting. The basic Idea is to break complicated issues to some simpler parts, then by close approximation the answer can be reached. The history of this method back in the date of geometry in Greek in thousands of years ago. Where mathematicians were braking irregular geometries to some regular geometries, such as triangle or rectangular, in order to find whole area with simpler calculations.

Nowadays, Finite Element Method (FEM) is a numerical method of stress analysis that has been used since 1956. Hrennikoff (15) and McHenry (16) were the pioneers in the1940s who used lattice of line for one-dimensional elements like bars and trusses. In the late 1940s Levy (17) developed the flexibility of force method. Later his work was the basis for the stiffness or displacement method, and was used as an alternative to analysis. However, his equations for the stiffness method was hard to solve by hand, but when high-speed computers came into existence, it became popular.

The first treatment of two-dimensional elements was developed by M.J. Turner (18) at the Boeing Company in the 1950s. While other aerospace companies were where using the force method, Turner developed the direct stiffness method. Later the concepts of Isoperimetric models and shape functions were added by B.M Irons (19) to this method of analysis. Wilson (20) was the first one who developed the first open source software for the finite element Analysis.

Hitherto, most of these pioneers were in the aerospace industry which is not a coincidence. The calculation of finite equations demands a digital computation which only giant industrial companies could afford computer during the 1950s. In the meantime, O.C. Zienkiewicz, H.C. Martin, R.W. Clough and J. H. Argyris., were four academics who were largely responsible to link the technology from aerospace industry to the wider range of engineering applications:

Three-dimensional elements were studied by Argyris. He also got credit for being the first to construct the displacement-assume continuum element. Clough and Martin who were faculties of famous universities such as the University of California, Berkeley and the University of Washington, collaborated with Turner during 1952-1953, and that was widely considered the beginning of the present FEM. Clough also got credited for special axisymmetric solids with collaboration of Rashid (21). And Olek Zienkiewicz was the first one who wrote the first FEM textbook in the University of Wales at Swansea.

Since the 1950s, numerous developments have occurred in the application of FEM, and it has become a strong tool in many fields, such as nanotechnology, medical engineering, mechanical engineering, agricultural engineering, etc. In addition, many software were developed in order to find stress, strains, internal and external forces and moments and many other properties that required complicated calculations.

Currently, Abacus is considered the best FEM software in the market. It originated from David Hibbitt's doctoral dissertation in 1972. Later in 1978 he and his associates established the HKS Company and published the first Abacus version. Later in 1991 they added an explicit solver to its numerous features and the first graphical version was released in 1999.

1.2 Reinforced Concrete Pipe Design

There are two methods for designing reinforced concrete pipe: direct and indirect. The direct design method employs modern concepts of reinforced concrete design and structural analysis to find moment, shear and thrust in concrete pipes, while the empirical nature of the indirect design method is with emphasis on bedding factor. The bedding factor is a coefficient which converts strength of pipes in the TEB test to the strength of pipe under an in situ condition. However, the difference is that the loading condition in the pipe wall under the TEB test is much more severe than that of the in situ condition. In the TEB test there is three-point load while buried pipe experiences a distributed soil load. Based on an analysis similar to arch shapes, point loads exert larger stress and deformation on circular pipes in comparison with uniformly distributed loads. Because of this empirical nature of indirect design, although this method requires fewer steps than direct design method procedure, which is an advantage. However the accuracy of this design is lesser than direct design. Based on the Recommendation for Design of Reinforced Concrete Pipe, published by ASCE (22),in the Journal of Pipeline Systems Engineering and Practice (February 2010), “the direct design method is a more flexible, modern, theoretical, and sophisticated practice for the design and installation of RCP taking into account all the important factor that affect RCP behavior.” The author also concluded that: “the direct design method is a superior method for the design of buried RCP installation.”

1.2.1 Indirect Design Method

Design of circular reinforced concrete pipe with indirect design method, according to the ACPA Design manual revised on 2011, is as following steps:

For the required three edge bearing strength of non-reinforced concrete pipe:

$$T.E.B. = \left[\frac{W_E + W_F}{B_{fe}}\right] + \frac{W_L}{B_{FLL}} \times F.S \qquad \text{Eq. 1-10}$$

It should be noted that T.E.B. is not a D-Load and is expressed as pounds per linear foot (lb/ft)

For circular reinforced concrete pipe:

$$D_{0.01} = \left[\frac{W_E+W_F}{B_{fe}}\right] + \frac{W_L}{B_{FLL}} \times \frac{F.S.}{D} \qquad \text{Eq. 1-11}$$

Where: $D_{0.01}$ = the required D-load to produce 0.01 in crack width (lb/ft./ft.).

W_E = earth load on the pipe.

For Positive Project Embankment Soil Load, determined according to Heger earth pressure distribution, with the Standard Installation, this additional load is accounted for by using a Vertical Arching Factor (Table 1-3).

$$W = VAF \times PL \qquad \text{Eq. 1-12}$$

Where: PL is the prism load of soil weight, directly above the pipe

$$PL = \gamma_s \left[H + \frac{D_0(4-\pi)}{8}\right] D_0 \qquad \text{Eq. 1-13}$$

Where γ_s is the soil unite weight (lbs/ft^3)

H: Height of fill, (ft)

D_0 : Outside diameter, (ft)

W_F = “fluid load in the pipe according to the sixteenth edition of the AASHTO Standard Specifications for Highway Bridges states: “The weight of fluid,

W_F, in the pipe shall be considered in design based on a fluid weight, γ_s, of 62.4 lbs/cu ft. unless otherwise specified."

W_L = Live load on top of the pipe (lb/ft)

D = inside diameter of pipe (ft)

B_{fe} = Earth load bedding factor according to (Table 1-2)

B_{FLL} = Live load bedding factor which obtains according to (Table 1-3)

F.S. = Factor of safety. According to the ACPA (13) "The indirect design method for concrete pipe is similar to the common working stress method of steel design, which employs a factor of safety between yield stress and the desired working stress. In the indirect method, the factor of safety is defined as the relationship between the ultimate strength D-load and the 0.01inch crack D-load. This relationship is specified in the ASTM Standards C 76 and C 655 on concrete pipe. The relationship between ultimate D-load and 0.01-inch crack D-load is 1.5 for 0.01-inch crack D-loads of 2,000 or less; 1.25 for 0.01 inch crack D loads of 3,000 or more; and a linear reduction from 1.5 to 1.25 for 0.01 inch crack D-loads between more than 2,000 and less than 3,000. Therefore, a factor of safety of 1.0 should be applied if the 0.01-inch crack strength is used as the design criterion rather than the ultimate strength. The 0.01-inch crack width is an arbitrarily chosen test criterion and not a criteria for field performance or service limit."

Table 1-2, Embankment Condition, B_{fe} (13)

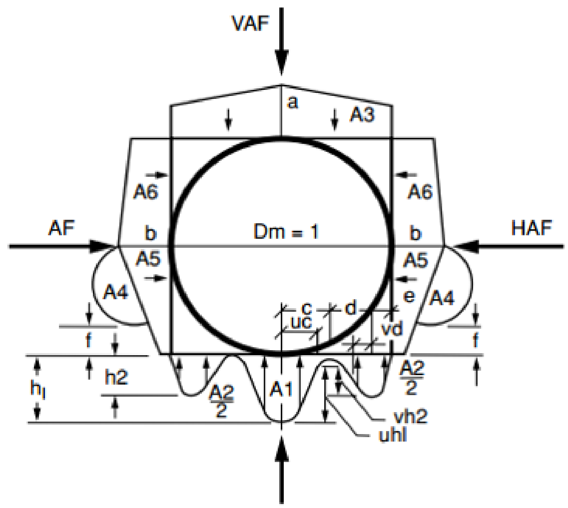
Pipe Diameter	Standard Installation			
	Type 1	Type 2	Type 3	Type 4
12 in.	4.4	3.2	2.5	1.7
24 in.	4.2	3.0	2.4	1.7
36 in.	4.0	2.9	2.3	1.7
72 in.	3.8	2.8	2.2	1.7
144 in.	3.6	2.8	2.2	1.7

Note: For pipe diameter other than listed in table, B_{fe} can be obtained by interpolation.

Table 1-3, Bedding factors, B_{fLL}, for HS20 Live Loading (13)

Fill Height Ft.	Pipe Diameter, Inches										
	12	24	36	48	60	72	84	96	108	120	144
0.5	2.2	1.7	1.4	1.3	1.3	1.1	1.1	1.1	1.1	1.1	1.1
1.0	2.2	2.2	1.7	1.5	1.4	1.3	1.3	1.3	1.1	1.1	1.1
1.5	2.2	2.2	2.1	1.8	1.5	1.4	1.4	1.3	1.3	1.3	1.1
2.0	2.2	2.2	2.2	2.0	1.8	1.5	1.5	1.4	1.4	1.3	1.3
2.5	2.2	2.2	2.2	2.2	2.0	1.8	1.8	1.5	1.4	1.4	1.3
3.0	2.2	2.2	2.2	2.2	2.2	2.2	2.2	1.7	1.5	1.5	1.4
3.5	2.2	2.2	2.2	2.2	2.2	2.2	2.2	1.8	1.7	1.5	1.4
4.0	2.2	2.2	2.2	2.2	2.2	2.2	2.2	1.9	1.8	1.7	1.5
4.5	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	1.9	1.8	1.7
5.0	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	1.9	1.8

Table 1-4 Heger earth pressure distribution (13)



Installation Type	VAF	HAF	A1	A2	A3	A4	A5	A6	a	b	c	e	f	u	v
1	1.35	0.45	0.62	0.73	1.35	0.19	0.08	0.18	1.40	0.40	0.18	0.08	0.05	0.8	0.8
2	1.40	0.40	0.85	0.55	1.40	0.15	0.08	0.17	1.45	0.40	0.19	0.10	0.05	0.82	0.70
3	1.40	0.37	1.05	0.35	1.40	0.10	0.1	0.17	1.45	0.36	0.20	0.12	0.05	0.85	0.60
4	1.40	0.30	1.45	0.00	1.45	0.00	0.11	0.19	1.45	0.30	0.25	0.00	-	0.90	-

Notes: 1. VAF and HAF are vertical and horizontal arching factors. These coefficients represent non-dimensional total vertical and horizontal loads on the pipe, respectively. The actual total vertical and horizontal loads are (VAF) X (PL) and (HAF) X (PL), respectively, where PL is the prism load.

2. Coefficients A1 through A6 represent the integration of non-dimensional vertical and horizontal components of soil pressure under the indicated portions of the component pressure diagrams (i.e. the area under the component pressure diagrams). The pressures are assumed to vary either parabolically or linearly, as shown, with the non-dimensional magnitudes at governing points represented by h1, h2, uh1, vh2, a and b. Non-dimensional horizontal and vertical dimensions of component pressure regions are defined by c, d, e, v_c, v_d, and f coefficients.

3. d is calculated as (0.5-c-e).

h_1 is calculated as (1.5A1) / (c) (1+u).

h_2 is calculated as (1.5A2) / [(d) (1+v) + (2e)]

1.2.2 Direct Design Method

The direct design method was accepted by ASCE in 1993 and is published ASCE 93-15, Standard Practice for Direct Design of Buried Precast Concrete Pipe Using Standard Installation Direct Design (SIDD). As explained before in this method, advanced structural analysis is required in order to find moment, shear and thrust. These data areas of reinforcements can be easily found according to AASHTO, Section 12 equations.

For circular circumferential reinforcements:

$$A_s = \left[g\Phi_f d - N_u - \sqrt{g\left(g\left(\Phi_f d\right)^2\right) - N_u\left(2\Phi_f d - h\right) - 2M_u}\right] \times \frac{1}{f_y} \quad \text{Eq. 1-14}$$

Where g= 0.85 b f'_c

b= 12 in.

d = distance from compression surface to centroid of tension reinforcements (in).

h = overall thickness of member (wall thickness), (in.)

N_U = factored axial thrust acting on cross section of width b, (lb/ft.)

M_U = factored axial moment acting on cross section of width b, (in-lb/ft.)

ϕ_f = resistance factor for flexural 0.9

f_y= specified yielding strength of reinforcing (ksi)

Minimum reinforcement:

For inside face of pipe with two-layer of reinforcements:

$$A_s \geq \left[\frac{(S+h)^2}{1000\, f_y}\right] \geq 0.07 \qquad \text{Eq. 1-15}$$

For outside face of pipe with two-layer of reinforcements:

$$A_s \geq 0.6\left[\frac{(S+h)^2}{1000\, f_y}\right] \geq 0.07 \qquad \text{Eq. 1-16}$$

Where: S= internal diameter or horizontal span of pipe (in).

h= wall thickness of pipe (in)

f_y= yield strength of reinforcement (ksi)

Maximum Flexural Reinforcement without Stirrups:

The flexural reinforcement per ft. of pipe without stirrups shall satisfy:

For inside steel in radial tension:

$$A_s \leq \frac{0.506 r_s F_{rp} \sqrt{f'_c}(R_\Phi) F_{rt}}{f_y} \qquad \text{Eq. 1-17}$$

r_s = radius of the inside reinforcement (in.)

f'_c = compressive strength of concrete (ksi)

f_y = specified yield strength of reinforcement (ksi)

R_Φ = ratio of resistance factors for radial tension and moment

F_{rp} = 1.0 unless a higher value substantiated by test data and approved by the Engineer

In which: For $12\ in. \leq S_i \leq 72\ in.$

$$F_{rt} = 1 + 0.00833\ (72 - S_i)$$

For $72\ in. \leq S_i \leq 144\ in.$

$$F_{rt} = \frac{(72 - S_i)^2}{26000} + 0.8$$

For $144\ in. \leq S_i$.

$$F_{rt} = 0.8$$

For reinforcing steel in compression:

$$A_s \leq \frac{\left[\frac{55g\prime\Phi d}{87+f_y} - 0.75N_u\right]}{f_y} \quad \text{Eq. 1-18}$$

Where:

$$g' = bf'_c[0.85 - 0.05(f'_c - 4)] \quad \text{Eq. 1-19}$$

$$0.85\ b\ f'_c \geq g' \geq 0.65\ b\ f'_c \quad \text{Eq. 1-20}$$

Reinforcement for Crack Width Control:

$$F_{cr} = \frac{B_1}{30\Phi dA_s}\left[\frac{M_s + N_s(d - \frac{h}{2})}{ij} - 0.0316\ C_1 b\ h^2 \sqrt{f'_c}\right] \quad \text{Eq. 1-21}$$

If N_s is tensile, it is taken as negative and:

$$F_{cr} = \frac{B_1}{30\Phi dA_s}\left[1.1M_s - 0.6N_s d - 0.0316\ C_1 b\ h^2 \sqrt{f'_c}\right] \quad \text{Eq. 1-22}$$

Where:

$$j = 0.74 + 0.1\ \frac{e}{d} \leq 0.9 \quad \text{Eq. 1-23}$$

$$i = \frac{1}{(1 - \frac{jd}{e})} \qquad \text{Eq. 1-24}$$

$$e = \frac{M_s}{N_s} + d - \frac{h}{2} \qquad \text{Eq. 1-25}$$

$$B_1 = (\frac{t_b S_l}{2n})^{\frac{1}{3}} \qquad \text{Eq. 1-26}$$

Where:

M_s = flexural moment at service limit state (kip-in/ft)

N_s = axial thrust at service limit state (kip/ft)

d = distance from compression face to centroid of tension reinforcements (in).

h = overall thickness of member (wall thickness), (in).

C_1 = crack control coefficient for various types of reinforcements as specified in table.

n = 1.0 for single cage, 2.0 for double cage or grater

ϕ = resistance factor for flexural (0.9)

It should be noted that, “Crack control is assumed to be 1.0 in. from the closest tension reinforcement, even if the cover over the reinforcement is greater than or less than 1.0 in. The crack control factor, F_{cr} in Eq.1-21 indicates the probability that a crack of a specified maximum width will occur. If the ratio of *e/d* is less than 1.15, crack control will not govern.” (14)

1.2.3 ASTM C-76 Specifications

This specification classifies reinforced concrete pipes into five classes and each classes contains three preferences for designed pipe. These preferences are called wall A, B and C. Wall A presents pipes with more preferences in the steel area and less concrete wall thickness, while wall C has more wall thickness which means more concrete area with a lesser amount of steel area. Wall B is a situation between Wall A and Wall B. ASTM C-76 is also sort with ascending pipe diameters. In this specification the required D-Load, reinforcement steel area, pipe’s geometries and concrete compression strength for each concrete pipe class have been determined. In other words, the reinforced concrete pipes are standardized in this specification based on their diameters. Generally ASTM C-76 is the easiest way to choose the pipes with determined service load and ultimate load capacity.

In this specification steel wires, concrete and test methods for concrete pipes and fiber-reinforced are respectively based on ASTM A82/82M (23), C33 & C150, C497 (24) and C1116.

1.3 Goals and objectives

ASTM C-76 provides a provision which allows manufacturers to use single cages for Class III Wall B and C pipes with 36 in. diameter by increasing the summation of both inner and outer areas of reinforcement by 25%. The implementation of a single cage for a pipe diameter greater than 36 in. has not been attempted to this date. However, all empirical provisions are required to be approved by TEB test through the manufacturer.

By eliminating one cage and one layer of longitudinal reinforcement in the concrete pipe, drastically reduces the cost of steel and manufacturing. Due to the removal of one cage, the cage installation is simplified hence resulting in the reduction of labor work. By implementing a single cage, the location of steel wires changes which gives the designers more space in which to place the reinforcements. Due to this fact, the reinforcement cover increases and the risk of corrosion in steel wires decreases. Because of the corrosive flows inside the pipe and corrosive soil environment, corrosion is one of the most important concerns in reinforced concrete pipe design. For this reason, The D-Load for 0.01 in. crack width is a criteria for pipe integrity. Professor W.J. Schlick (25) of Iowa State University developed the 0.01 in. crack width criteria, in which that corrosion does not occur. By using a single cage, the reinforcement can be placed deeper into the concrete and the risk of corrosion substantially decreases.

In this study, the conventional two cages were eliminated and a single cage was used instead. The total reinforcement area for the single cage was equal to the summation of the inner and outer cage reinforcement areas of the double cage pipe. In a few cases, the total reinforcement area increased by 25% in order to meet ASTM C-76 benchmarks. To find the most optimal location for the placement of the single reinforcement cage, the rebars were placed in three different locations within the pipe thickness. The results were compared with the behavior of double cage reinforcements.

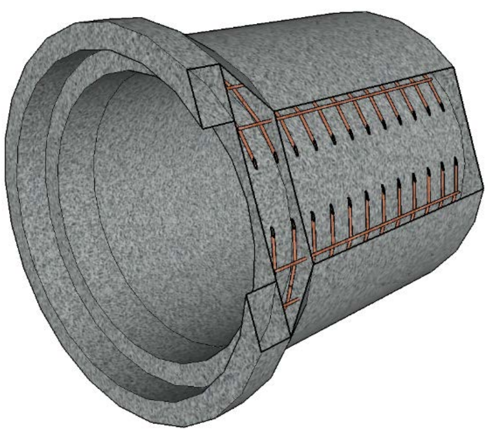


Figure 1-6, Single Reinforced Cage Concrete Pipe

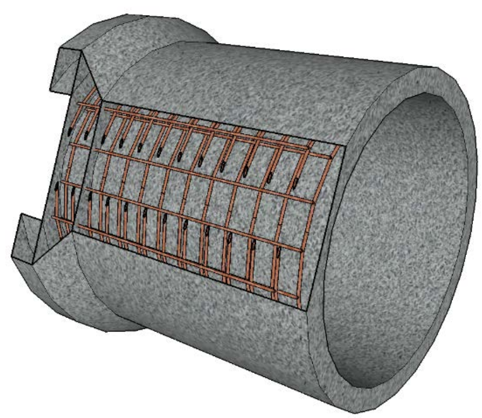


Figure 1-7, Double Reinforced Cage Concrete Pipe

Three standard experimental TEB tests were performed to verify the finite element simulation. The advantage of simulations by finite element modeling render expensive and time consuming tests useless. Furthermore, computer simulation accuracy is higher than tests due to the lack of manufacturing error. In this study 17 different RCPs from three different classes were studied and a total of 80 simulations were performed.

The following chapters further validate how the two cage reinforcement of the concrete pipes can be reduced to a single cage reinforcement. In the next chapter, two different type of experimental test are discussed. The first test is the uniaxial compression cylinder test which is used to verify the material properties. The second test is the TEB test which is used to substantiate the Finite Element Analysis (FEA) simulations. The third chapter will discuss the finite element analysis and correlate the results to the TEB test in order to determine legitimacy of the simulations. The fourth chapter will discuss, in detail, the final results obtained from both the experimental tests and the FEA simulations.

CHAPTER 2

2.1 Experimental Test

In order to verify the credibility of FEM simulations, two different tests were performed: Three Edge Bearing (TEB) test for RCP and Uniaxial Concrete Cylinder Compression test. Both tests were performed by The University of Texas at Arlington, in the Center for Structural Engineering Research (CSER). The purpose of performing the TEB test was to verify the FEM simulations of the whole model and the purpose of the Uniaxial Compression Cylinder test was verifying the FEM material model properties.

2.1.1 Three Edge Bearing Test

The Three Edge Bearing test is a standard test, developed for concrete pipe design (indirect design) and evaluation of structural behavior at Iowa State University in 1960s (22). This is an inexpensive way to determine the ultimate strength and quality control of reinforced concrete pipes. The loading condition for the TEB test is more severe than what it is in field. Due to the point load on the pipe in the TEB test, there is stress concentration at the crown, while the earth load on pipe is distributed.

According to ASTM C497 “Standard Test Methods for Concrete Pipe, Manhole Sections, or Tile” (24), the pipe is tested in a machine, designed to apply crushing load upon the specimen in a vertical direction extending along the length of the pipe. The testing machine must be rigid enough to prevent any deflection or yielding due to loading. Also, must support the three edge bearing method, so that the specimen is placed between the three longitudinal parallel strips in a form of two supports at bottom and one loading strips at the top. The machine which is shown in Figure 2-1, consists of: a rigid plate at the top, frame load and two rigid plate at bottom as a support. In addition to that, a layer of rubber or wood should be placed between the rigid plates and concrete pipe. Measurement instruments should be used to measure the deflection and load value.

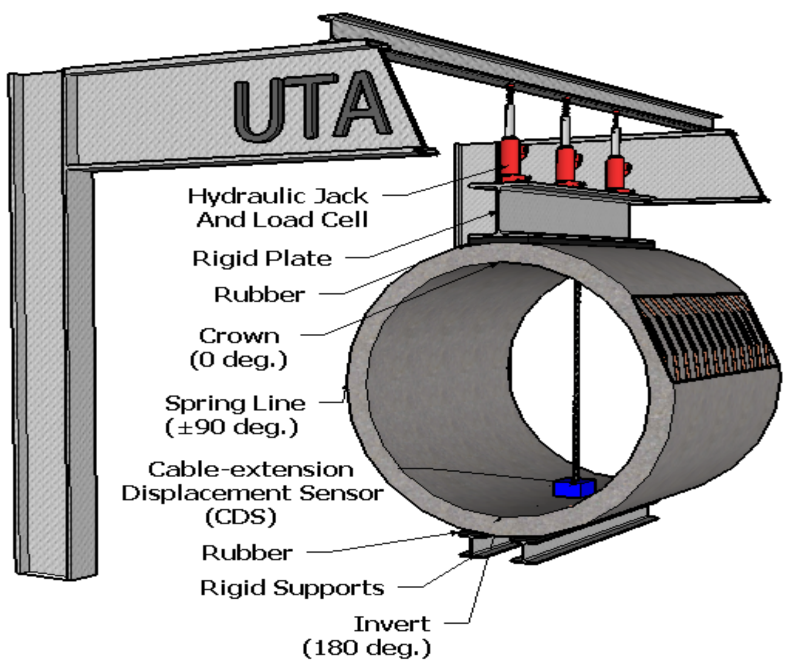


Figure 2-1, Three Edge Bearing Test Setup

According to ASTM C497, The lower bearing shall consist of wood (Figure 2-3) or hard rubber (Figure 2-2) strips, which should provide enough strength. They shall be straight with specified dimensions. The required rigidity for wooden strips is not greater than $1/_{720}$ of the specimen length at maximum load. In case of hard rubber strips, the durometer hardness shall not be less than forty five nor greater than sixty.

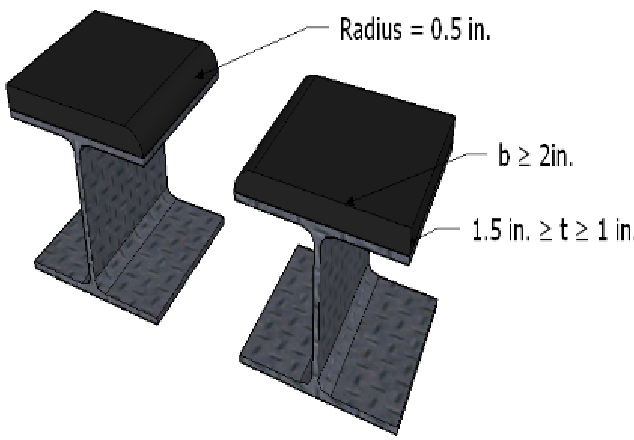


Figure 2-2, Hard Rubber Lower Bearing Strips

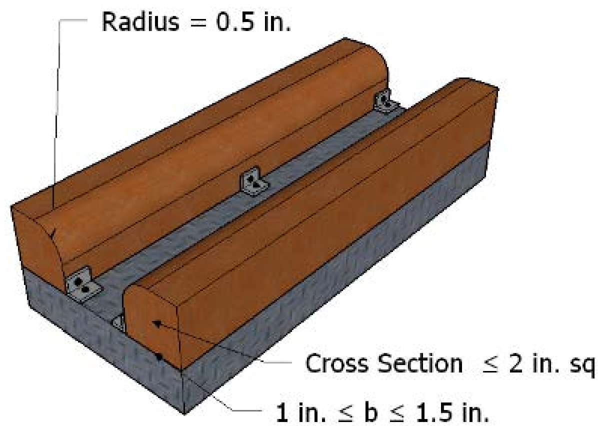


Figure 2-3, Wooden Lower Bearing Strips

The upper bearing shall be a rigid wooden (Figure 2-4) or steel beam with implementation of hard rubber (Figure 2-5). In case of wood beam, hard rubber is not mandatory. It should be sound, straight and free of knots. The maximum allowable deflection is $1/_{720}$ of the specimen length. The bearing face of the upper bearing also, shall not deviate from straight from straight line by more than $1/_{32}$ in./ft. of length. In case of hard rubber, the durometer stiffness shall not be less than forty five and not greater than sixty. Also its width shall be at least 2 in. and the thickness should not be less than 1 in, and nor greater than 1.5 in.

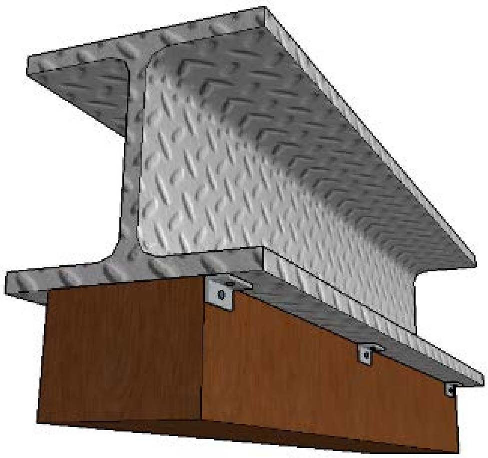


Figure 2-4, Wooden Upper Bearing

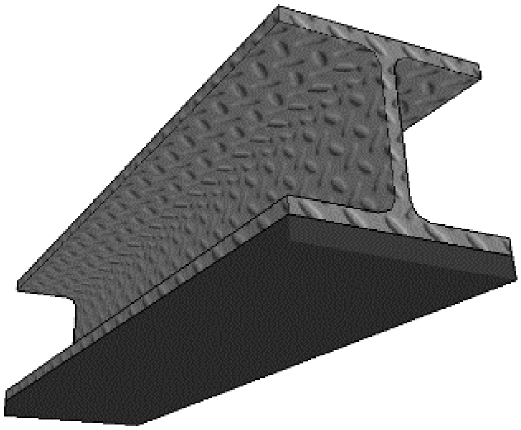


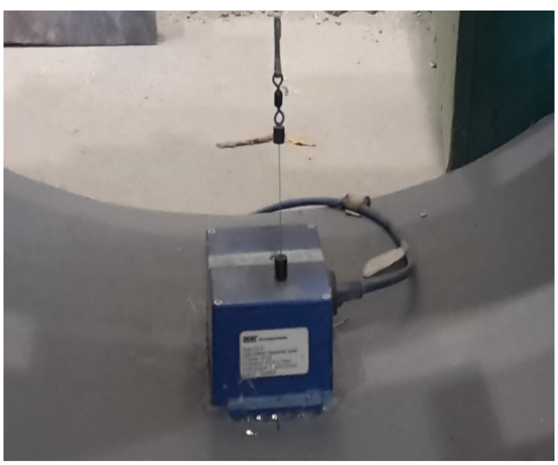
Figure 2-5, Hard Rubber Upper Bearing

For reinforced concrete pipe, the maximum required load rate is up to 7500 pound-force per linear foot (10.2 kN-m/m) per minute. This rate should be used up to 75% of the specified design strength based on elaboration of ASTM C497.

2.1.1.1 Instrumentation

In order to obtain load-deflection of the RCP under the TEB test, two important devices are required: a device to read the deflection of the pipe and a device to read the exerted load amount on the structure. However in order to collect and link the data a third device is required.

For vertical deflection measurement of RCP along the test, Cable extension Displacement Sensor (CDS) have used. CDS is providing a voltage signal linearly along the extension of a retractable nylon-coated stainless steel cable and is used for micro displacement measurements. This device has a full scale usable range from five to fifty inches and its accuracy is 0.1 percent of total displacement. CDS measures any changes on its string location and transfers the data to the Vishay scanner. After installation, the string goes either out or in, and this device can measure the differences. In order to obtain a vertical load-deflection graph for the RCP under the TEB test, CDS was installed at the invert of the pipe and respectively its string was hooked in a straight line to the crown (Picture 2-1).



Picture 2-1, CDS

Picture 2-2, Load Cell

The load cell is the other important device which reads the exerted load from a hydraulic jack and transfers it to the Vishay. It is a type of force sensor that converts the deformation of a material, into an electrical signal. Load cell measures the deformation by a strain gauge installed inside, and as the strain is proportional to the stress, it can convert the deflection to the force.

Vishay scanner (Picture 2-3) synchronizes the data from the CDS and load cell. Which is used for this study. Vishay scanner from Micro-Measurements is a versatile, precision data acquisition instrument system. This scanner has many channels of data acquisition (Picture 2-4). Each channel can be configured, via software (strain-smart) to accept signals from strain-gage-based transducers (CDS) or high level voltage sensors (load cells). For strain gauge's channels this device accept full, half, or quarter-bridge configurations.

Picture 2-3, Vishay Scanner

Picture 2-4, Vishay Scanner's Channels

2.1.1.2 Specimens

The RCPs were designed according to the ASTM C76, from two different classes and diameters, manufactured and tested at Hanson Inc. the properties of these specimens are listed below:

Table 2-1, Specimen No.1 Properties

Reinforced Concrete Pipe #1	
Class	III
Wall	B
Diameter	24 in.
Wall Thickness	3 in.
Concrete Strength	4000 psi
Reinforcement Area per Foot	0.07 in^2
Reinforcement Diameter	0.175 in
Required D-Load for 0.01 in Crack	1350 (lb/ft/ft)
Required D-Load for Ultimate	2000 (lb/ft/ft)

Table 2-2, Specimen No.2 Properties

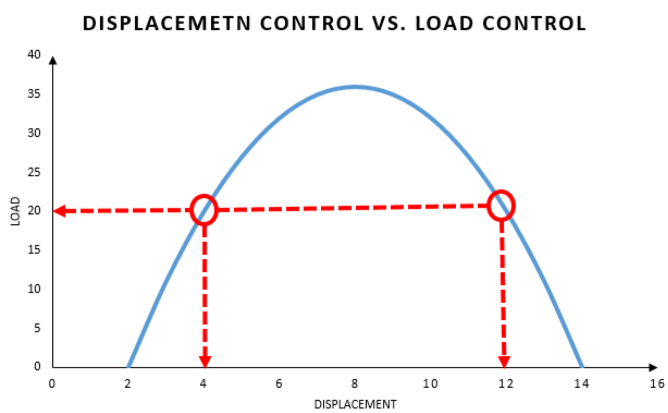
Reinforced Concrete Pipe #2	
Class	III
Wall	C
Diameter	24 in.
Wall Thickness	3.75 in.
Concrete Strength	4000 psi
Reinforcement Area	0.27 in^2
Reinforcement Diameter	0.399 in
Required D-Load for 0.01 in Crack	1350 (lb/ft/ft)
Required D-Load for Ultimate	2000 (lb/ft/ft)

Table 2-3, Specimen No. 3 Properties

Reinforced Concrete Pipe #3	
Class	III
Wall	B
Diameter	36 in.
Wall Thickness	4 in.
Concrete Strength	4000 psi
Inner Reinforcement Area	0.17 in^2
Outer Reinforcement Area	0.10 in^2
Inner Reinforcement Diameter	0.269 in.
Outer Reinforcement Diameter	0.205 in.
Required D-Load for 0.01 in Crack	1350 (lb/ft/ft)
Required D-Load for Ultimate	2000 (lb/ft/ft)

2.1.1.3 Test Experiment and Procedure

For this test the displacement-control method was used. Technically two methods are applicable for any load-deflection test like TEB: displacement-control and load-control. In case of displacement- control, the load can be obtained by imputing displacement. In contrast to that, the input of the load-control method is force. The advantage of displacement-control method is for a non-linear test, where the displacement data is unique along the test, and the whole test can be plotted up to a specified displacement. Because of rises and drops of the load along the test, there can be more than one load at any step (Graph 2-1). Hence through this method, in the instruments and FEM simulations, just up to peak load can be plotted. For better understanding, there is an arbitrary non-linear load-deflection graph which shows the difference. The graph is unique along the X axis (displacement), while more than one data can exist for any load. As a result, the displacement-control method is strongly recommended for non-linear behavior.



Graph 2-1, arbitrary displacement-control vs. load-displacement

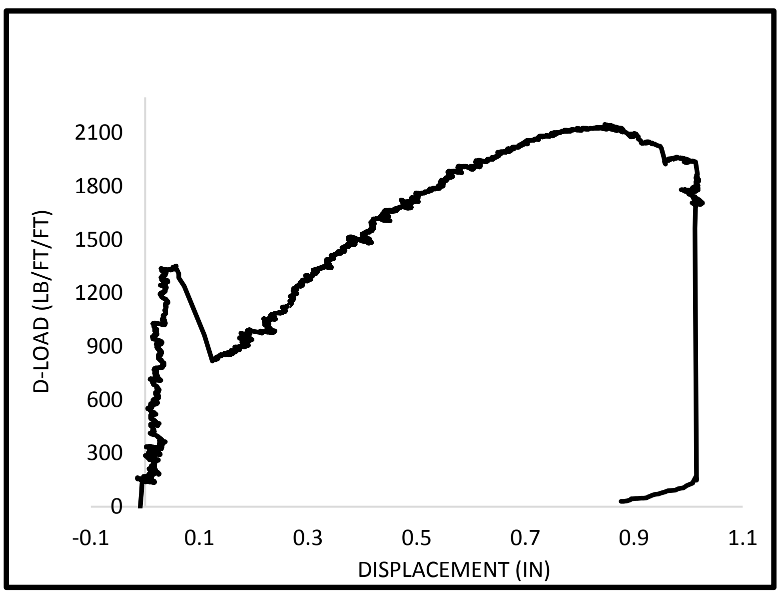
Three RCPs were tested. Pipes were placed on the lower bearings. With the wooden lower bearings selected. After making sure that the pipe was installed in the correct position, the CDS was installed at the Invert, and its string was installed right on top of it at the crown, in order to read the vertical displacements. Then the top bearings were pulled down to touch the pipe's surface.

The CDS and load cell cables were installed in the Vishay scanner. In order to colligate the sensors, by synchronizing them to the strain-smart, the input values were zero.

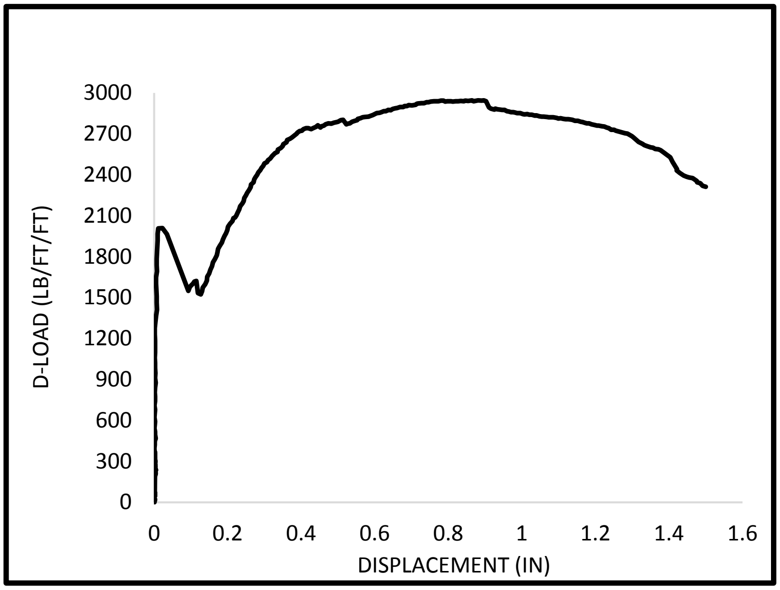
The load were applied to the pipe, by using the CDS and the vertical displacements and by implementation of the load cell, the load values were recorded.

2.1.1.4 Test Results

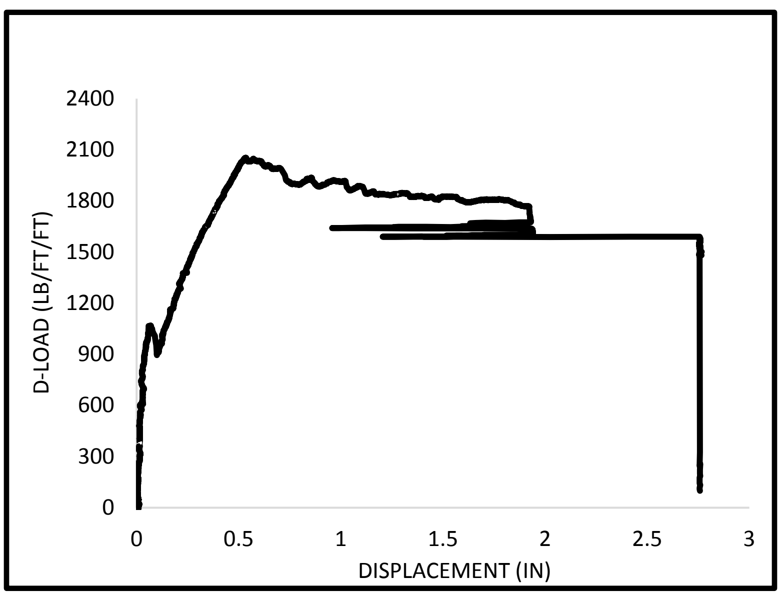
The recorded data was transferred to the computers and they plotted in the conventional method according to the ASTM C76. The load was plotted along the Y axis, and the displacements were plotted respectively, along the X axis. It should be noted that the pipes were tested in lengths of 8 feet.



Graph 2-2, RCP #1 under TEB Test



Graph 2-3, RCP #2 under TEB Test



Graph 2-4, RCP #3 under TEB Test

2.2.1 Uniaxial Cylinder Compression Test

The uniaxial compression cylinder test (UCC) was performed, In order to verify the material properties behavior of FEM simulations. These tests were carried out in the Center for Structural Engineering Research (CSER) at the University of Texas at Arlington. Cylinders were produced and tested according to ASTM C39 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." This testing method obtains the maximum compressive strength of the cylinder specimen. By exerting the force through the axis of cylinder, the breaking force and respectively the equivalent compressive stress were obtained. Cylinders were made according to ASTM C39 with dimensions of 4 in. diameter and 8 in. height (4x8), and were cured for 28 days.

Standard plastic molds were used for this test. Specimens were vibrated on the vibration table according to ASTM C39 specifications. After one day, they were demolded through an air compressor and placed in curing room for 28 days. Before testing they were capped by a sulfur mortar capping compound to ensure that the load would distribute uniformly on the cylinder surface during testing. In order to cap the concrete cylinders, the capping compound was melted and poured inside the steel molds. Specimens were placed perpendicularly inside the molds and kept for one minute. This procedure was performed for both end of the concrete cylinder.

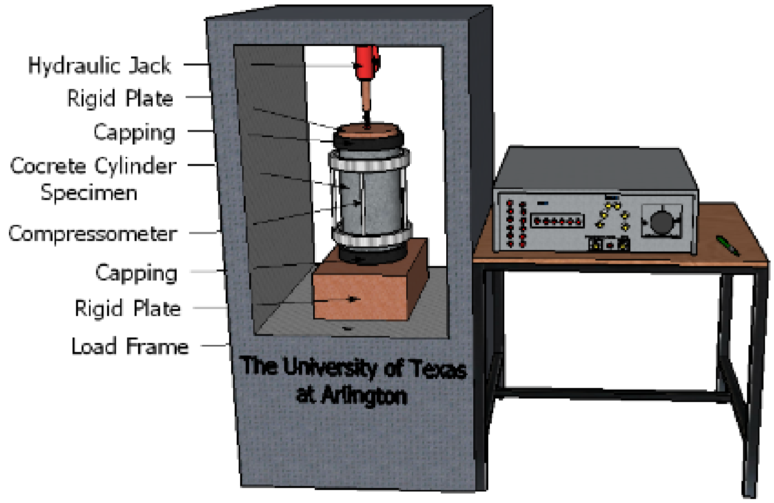


Figure 2-6, Uniaxial Compression Test Machine

2.2.1.1 Test Setup

The model C-1217DC compression machine was used for this test (Figure 2-6). It is located in Small Specimen room in the Civil Engineering Laboratory Building (CELB) at the University of Texas at Arlington. The machine has the ability to exert a uniform continuous prescribed loading rate. Before the placement of the concrete cylinder inside the machine a compressometer was installed around the specimen in order to determine the strain along the concrete cylinder. The compressometer consists of two frames that clamp to the specimen, two spacers to hold the two frames in position and a gauge, fixed to a bracket at the top of the frame for taking deformation measurements. The compressometer and load cell were connected to the Vishay box in order to record the load and deflections. At the final stage the specimen with the compressometer was placed inside the apparatus.

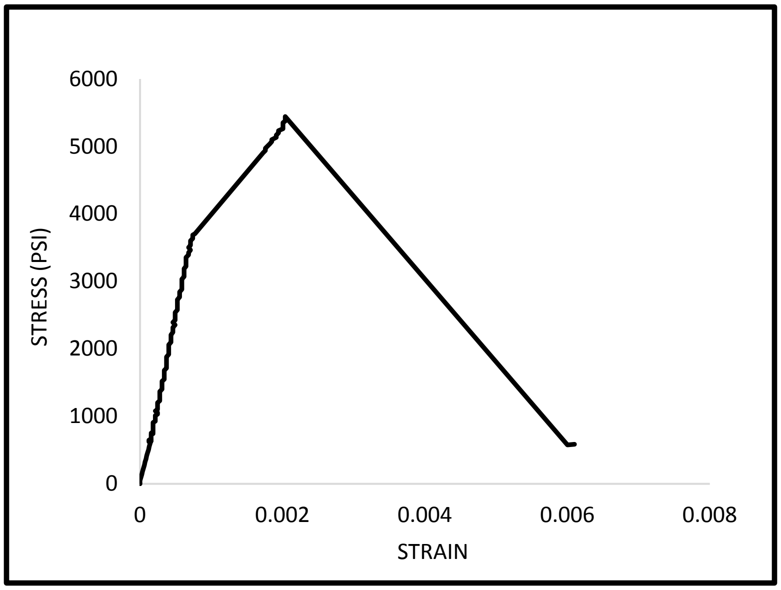
Picture 2-5, Uniaxial Compression Machine (C-1217DC)

2.2.1.2 Test Experiment and Procedure

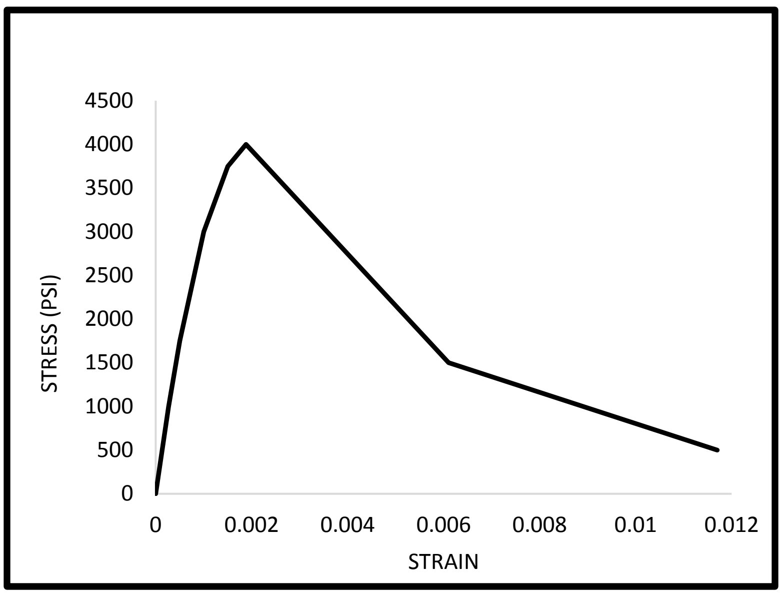
In order to put the specimen inside the compressive machine, a rigid plate with a 3 inch grater, were placed below the specimen. The hydraulic jack was pulled down to touch the specimen for calibration of the indicators. The uniform continuous load was applied without causing any shock to the specimen surface. The loading rate is specified in ASTM C39.

2.2.1.3 Test Results

Specimen #1 was designed for 5000 psi, and reached 5443 psi. Specimen #2 was designed for 4000 psi and it almost reached to that number. All the mix designs were according to ACI specifications.



Graph 2-5, Specimen #1 - Uniaxial Compression Test (37)



Graph 2-6, Specimen #2 - Uniaxial Compression Test (38)

CHAPTER 3

3.1 Three Dimension Finite Element Analysis

The Finite Element Analysis (FEA) is a numerical method for finding approximate solutions for partial differential equations with implementation of boundary values. The concept of the Finite Element Method (FEM) is subdividing the problems to simpler and smaller parts (elements) and investigate the physical behavior of each elements. Quantities such as stress and strain can be calculated by assembling the elements at the nodes to form an approximate system of equations for whole structure and solving the equations. FEM is a power tool for non-linear analysis which includes crack formation, buckling, yielding, fraction and deformations. The philosophy of the FEM simulation is that it prevents to many similar tests. This method is economical, safe, and fast, with high accuracy. By simulation of experimental tests, all the procedures and every single details such as displacements, stresses, strains, forces, etc. can be accurately monitored. Therefore, this method gives an insight to the scientist about what is really happing throughout the tests and it is highly recommended for non-linear analysis.

In this study the three dimensional finite element method was used to simulate RCP behavior under the TEB test for classes III, IV, and V wall C. FEM modeling was performed through Abaqus Version 6.14-3, a powerful FEM software, and was verified with the three actual TEB test. The material properties were also verified with two the UCC tests.

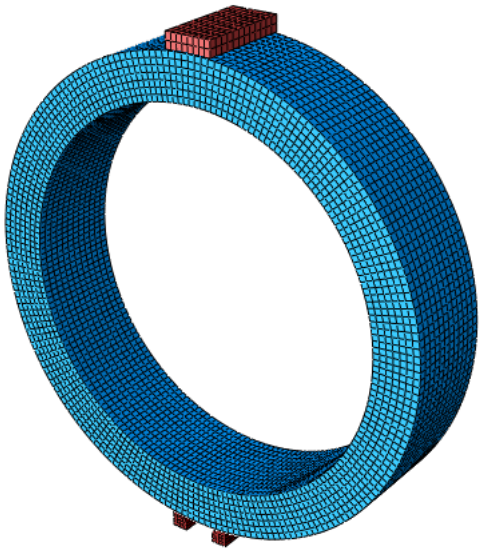


Figure 3-1, Finite Element Simulation

Picture 3-1, Finite Element Analysis

3.1.1 Model's Parts

The RCP simulation consists of a concrete pipe, circumferential steel wire reinforcements, longitudinal steel wire reinforcements and solid bearings (solids) the top and the bottom. For concrete pipe and solids deformable 3D modeling space was chosen. They are also chose to be solid in shape and extrusion type in Base Feature section. Likewise for reinforcement wires, deformable 3D modeling space was chosen, but planar wire was selected for Base Feature. These wires acted as a 2D element, like truss, and they were embedded inside the concrete pipe. This made the modeling easier, prevented the need for the consideration of holes inside the concrete pipe, and rendered the assembly inside the concrete pipe easier.

3.1.2 Material Properties

In the FEM method, material modeling is based on the mathematical relationship between stress (б) and strain (Ɛ). The model is expressed in infinitesimal increments of stress and strain. In RCP three different material were used: concrete, steel and solid. In case of solid, a robust material was needed to prevent any deformation and failure thorough the analysis. Therefore a material with a high modulus of elasticity was assumed. Regular grade sixty steel was used for reinforcements.

3.1.2.1 Concrete material properties

Concrete material properties is one the most controversial and challenging subjects in civil engineering materials, especially for FEM simulations. In contrast with steel, concrete has a nonlinear behavior under compression before it reaches its compressive strength (f'c). Moreover, it has a different behavior under tensile stress and degrades quicker. On the other hand concrete has two modes of failure: crushing under compression and cracking under tension. All this causes difficulties in numerical analysis. In order to resolve this issues, between many models, Concrete Damage Plasticity model has been suggested by Kmiecik (26). Concrete damage plasticity consist of the behavior of concrete under tension and compression for uniaxial and biaxial loading and its degradation.

One of the strength hypothesis most frequently applied to concrete was expressed by Drucker-Prager in 1952. The use of the CDP model in the Abaqus is a modification of the Drucker and Prager hypothesis. According to the modifications, the failure surface in a deviatoric cross section does not need to be a circle due to a governing parameter K_c (ratio of the distance between the hydrostatic axis and compression and tension meridian). CDP recommends assuming $K_c = {}^{2}/_{3}$.

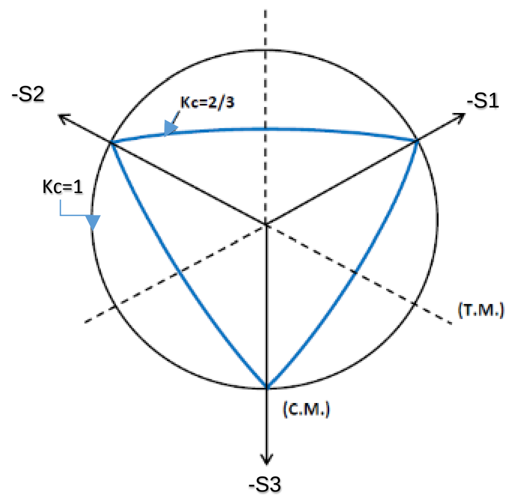


Figure 3-2, Deviatoric Cross Section of Failure Surface in CDP model

Experimental results shows that the meridians are curves. Thus, the plastic potential surface in the meridional plain for the CDP model is considered hyperbola. Due to its eccentricity it can be adjusted (plastic potential eccentricity). This parameter can be expressed as the ratio of tensile strength to compressive strength. The CDP recommends to assume Ɛ=0.1.

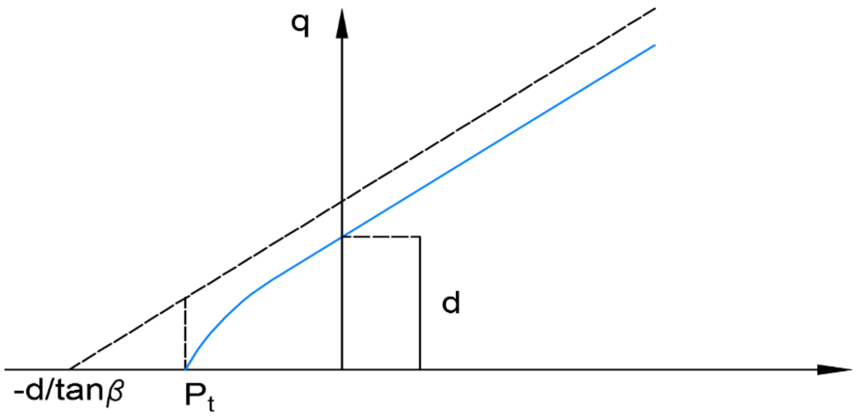


Figure 3-3, Hyperbolic surface of plastic potential in meridional plane (26)

The other important parameter of concrete failure is its behavior under biaxial compression. Kupler in 1969 reported a ratio for biaxial over uniaxial compression and which states biaxial compressive strength of concrete is almost 1.16248 times greater than its strength for uniaxial compression. Abaqus manual (27) also specifies $f_{bo}/f_{co} = 1.16$.

Dilation Angle is another important parameter of concrete performance characteristics. The inclination angle of the failure surface towards the hydrostatic axis, measured in the meridional plane, is called the dilation angle. According to Kmiecik this value can vary from 36 to 40 while other researchers believe it can vary from 30 to 40.

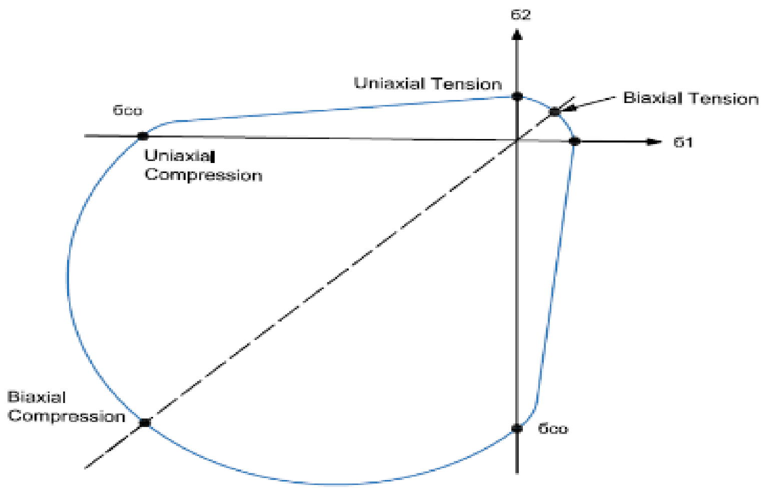
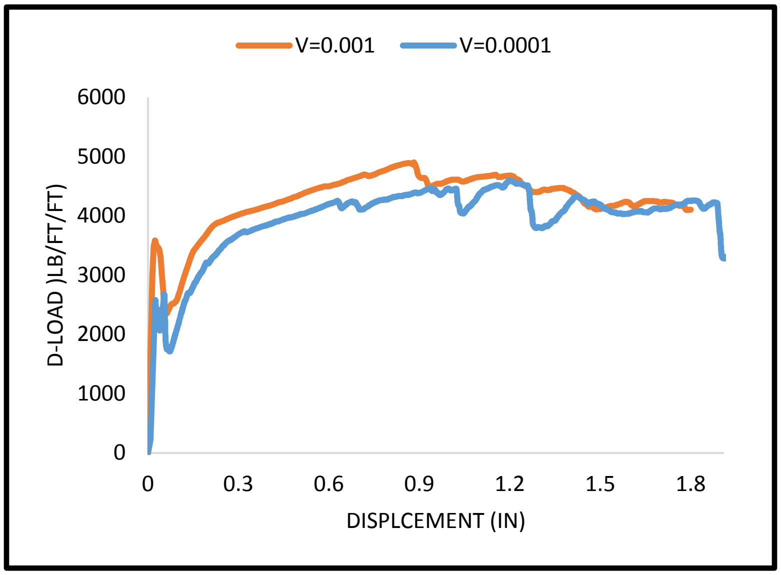


Figure 3-4, Concrete Strength under Biaxial Stress in CDP Model

Viscosity is one the most important factors in the behavior of concrete in Abaqus. According to the Abaqus manual the considered value for velocity is zero. While the Abaqus analysis aborts if put zero for velocity. Therefore velocity should considered a number close to zero. In order to verify the exact number for velocity, an arbitrary RCP was modeled and analyzed three times for three different velocities (0.001, 0.0001 and 0.00001). The difference between 0.001 and 0.0001 was substantial, while there was no difference between 0.0001 and 0.00001.

Table 3-1, Parameters of CDP under Compound Stress

Parameter Name	Value
Dilation Angle	30-40
Eccentricity	0.1
f_{bo}/f_{co}	1.16
k	0.667
Viscosity Parameter	0.0001



Graph 3-1, Comparison of Two Different Values for Velocity and Its Effects on RCP Simulation

3.1.2.1.1 Uniaxial Compression

The stress-strain relationship can be obtained by the uniaxial compression test. Many researchers have developed a numerical equation for the stress strain relationship of non-linear behavior of concrete under uniaxial compression (Table 3-2). According to McGregor (28), the modified Hognestad (29) formula accurately expresses concrete behavior under uniaxial compression which has three stages: linear, non-linear before ultimate strength and linear after ultimate strength (Figure 3-6). Hognestad suggests a second-degree parabola with the apex at strain of $1.8 f''_c/E$ (Figure 3-5), where $f''_c=0.9f'_c$ and becomes linear to $0.85f''_c$ afterwards. The reduced strength (f''_c) considers the difference between specimen strength and the uniaxial compression cylinder strength test due to curing, shrinkage and placing. This effect has been ignored in this study, and f"c= f'c was considered due to the absence of test errors and environmental effects in Abaqus.

Hognestad expresses his equation for stress-strain as follows:

$$f_c = f'_c\left[\frac{2\varepsilon c}{\varepsilon 0} - (\frac{\varepsilon c}{\varepsilon 0})^2\right] \qquad \text{Eq. 3-1}$$

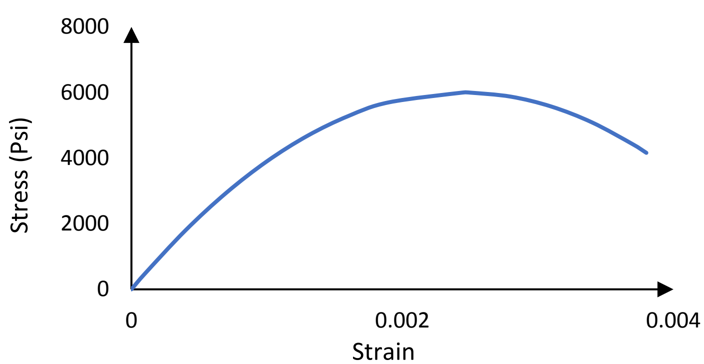
Where $\varepsilon_0 = \frac{1.8\, f'c}{E}$

E = modulus of elasticity obtained from ACI Code Section 8.5.1 for normal weight concrete

$$E = 57000\sqrt{f'_c} \qquad \text{Eq. 3-2}$$

F'_c= ultimate strength of concrete

The Hognestad parabola can be obtained for any strain (ε_c) (Figure 3-5).



Graph 3-2, Modified Hognestad Parabola for Ultimate Strength of 6000 psi

The ultimate stress-strain curve of concrete under uniaxial compression can be obtained by assembling the parabola and preliminary linear part, (Figure 3-6).

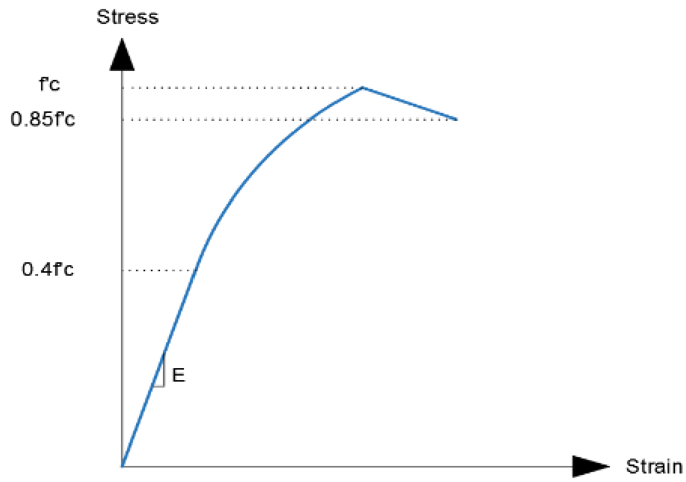


Figure 3-3, Concrete Behavior under Uniaxial Compression

Damage exerted to the models starts right after ultimate strength. In order to find the strain produced after the peak load (inelastic strain ε_c^{in}), elastic strain (ε_c^{el}) should be subtracted (elastic strain corresponds to undamaged material).

$$\varepsilon_c{}^{in} = \varepsilon_c - \varepsilon_c{}^{el} \qquad \text{Eq. 3-3}$$

$$\varepsilon_c{}^{el} = \frac{\sigma_c}{E_0} \qquad \text{Eq. 3-4}$$

In order to find plastic strain, the degradation variable (d_c) should be determined first. It can vary from 0 to 1, where zero value means the material is undamaged and one states the total damage in material. The degradation value can obtained by following equation:

$$d_c = 1 - (\frac{\sigma_c}{f'_c}) \quad \text{Eq. 3-5}$$

$$\varepsilon_c^{\ pl} = \varepsilon_c^{\ in} - \frac{d_c}{1-d_c} \times \frac{\sigma_c}{E_0} \quad \text{Eq. 3-6}$$

Where: E_0 stands for modulus of elasticity for undamaged material.

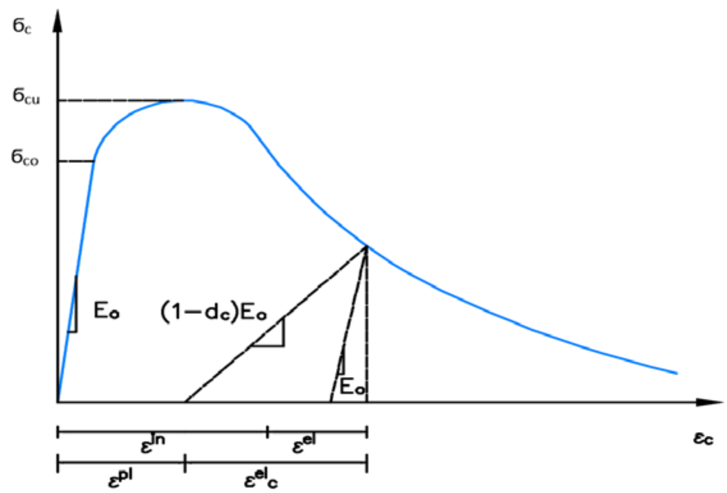


Figure 3-4, Concrete Behavior under Uniaxial Compression (26)

Based on these equations, a spread sheets were developed which represents the uniaxial concrete compression behavior. These spreadsheets demands favorable compressive strength, and based on that it produces the required variable for the Abaqus such as stress, strain, degradation value and plastic strain.

Table 3-2, Stress-Strain Relation for non-linear Behavior of Concrete (26)

Formula Name/ Source	Formula Form	Variables
Madrid Parabola	$\sigma_c = E_c\varepsilon_c\left[1 - \frac{1}{2}\,(\frac{\varepsilon_c}{\varepsilon_{el}})\right]$	$\sigma_c = f(E_c, \varepsilon_{el})$
Desay & Krishnan Formula	$\sigma_c = \frac{E_c\varepsilon_c}{1 + (\frac{\varepsilon_c}{\varepsilon_{el}})^2}$	$\sigma_c = f(E_c, \varepsilon_{el})$
EN 1992-1-1	$\sigma_c = \frac{k\eta - \eta^2}{1 + (k-2)\eta}$ $k = 1.05E_{cm}\frac{\varepsilon_{el}}{f_{cm}}$ $\eta = \frac{\varepsilon_c}{\varepsilon_{el}}$	$\sigma_c = f(E_c, f_{cm}, \varepsilon_{el})$
Majewski Formula	$\sigma_c = E_c\varepsilon_c$ if $\sigma_c \leq e_{lim}f_{cm}$ $\sigma_c = f_{cm}\frac{(e_{lim}-2)^2}{4(e_{lim}-1)}\left(\frac{\varepsilon_c}{\varepsilon_{el}}\right)^2 +$ $\frac{f_{cm}}{\sigma_c}(2 - e_{lim}),$ $-f_{cm}\frac{(e_{lim}-2)^2}{2(e_{lim}-1)}\left(\frac{\varepsilon_c}{\varepsilon_{el}}\right) +$ $f_{cm}\frac{{e_{lim}}^2}{4(e_{lim}-1)}$ $\Bigg]$ $E_c =$ If $\sigma_c \geq e_{lim}f_{cm}$, e_{lim} in formula (3)	$\sigma_c = f(E_c, \varepsilon_{el})$
Wang & Hsu Fromula	$\sigma_c = \varsigma f_{cm}\left[2\left(\frac{\varepsilon_c}{\varsigma\varepsilon_{cl}}\right) - (\frac{\varepsilon_c}{\varsigma\varepsilon_{cl}})^2\right]$ if $\frac{\varepsilon_c}{\varsigma\varepsilon_{cl}} \leq 1$ $\sigma_c = \varsigma f_{cm}\left[1 - \left(\frac{\frac{\varepsilon_c}{\varsigma\varepsilon_{cl}} - 1}{\frac{2}{\varsigma f_{cm}} - 1}\right)^2\right]$ if $\frac{\varepsilon_c}{\varsigma\varepsilon_{cl}} \geq 1$	$\sigma_c = f(E_c, \varepsilon_{el})$
Saenza Formula	$\sigma_e = \frac{\varepsilon_c}{A + B\varepsilon_c + c{\varepsilon_c}^2 + D{\varepsilon_c}^3}$ Symbols in formula (12)	$\sigma_c = f(E_c, f_{cm}, f_{cu}, \varepsilon_{el}, \varepsilon_{cul})$

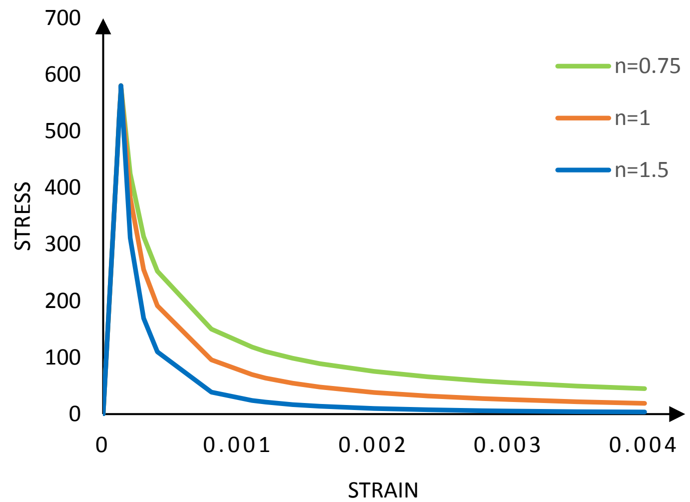
3.1.2.1.2 Uniaxial Tension

In order to define tensile behavior of concrete, Wang and Hsu (30) suggested a function which was developed based on the many tensile tests. Unlike compressive behavior of concrete, before failure, concrete shows linear behavior up to the pick load. Thereafter with downward parabolic function, tensile stress decreases down close to zero. According to Wang and Hsu this graph can be plotted by following equations:

$$\sigma_c = E_c \times \varepsilon_c \qquad \varepsilon_c < \varepsilon_{cr} \qquad \text{Eq. 3-7}$$

$$\sigma_c = f_{cr} \times \left(\frac{\varepsilon_{cr}}{\varepsilon_c}\right)^n \qquad \varepsilon_c > \varepsilon_{cr} \qquad \text{Eq. 3-8}$$

Where E_c is the undamaged modulus of elasticity of concrete, and f_{cr} is the cracking stress of concrete (f'_t) and, n is the rate of weakening and can vary from 0.4 to 1.5.

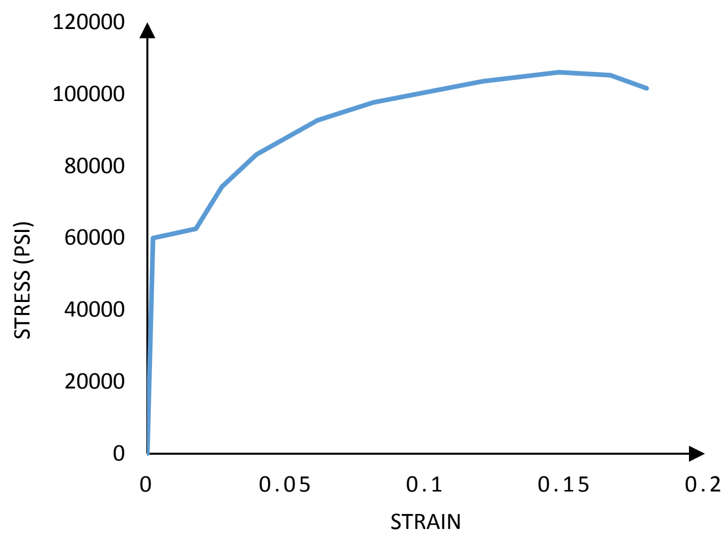


Graph 3-5, Concrete Tensile Stress-Strain Curve

The damage parameters for tensile is similar to compressive and can be obtained by same formulations. Similar to compression, a comprehensive spreadsheet were developed regarded to f'_c which plots tensile. This spreadsheet were synchronize to compression spreadsheet and produced a united excel file which works by single input, f'_c.

3.1.2.2 Steel Material Properties

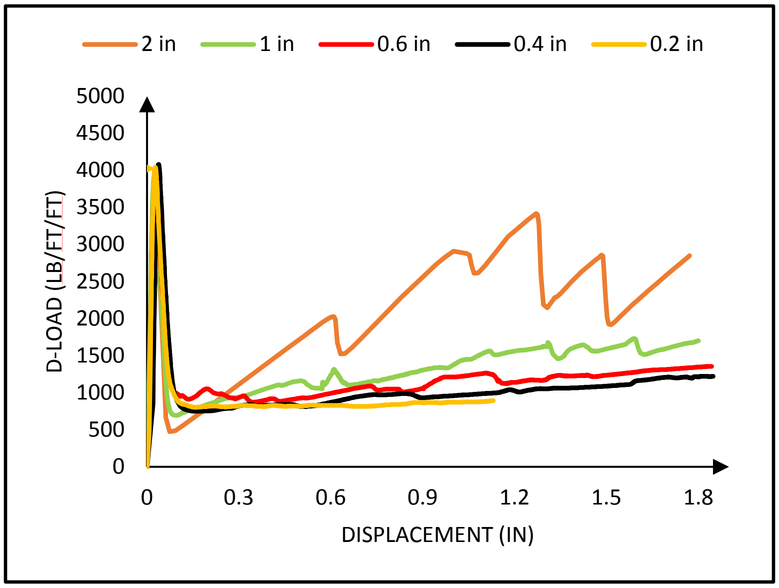
For steel material properties, regular grade sixty steel was used. The stress-strain curve was developed at The University of Texas at Arlington, Center for Structural Engineering Research (CSER). The same material properties were used and verified by many researches such as Hamedani and Esfehani (31).



Graph 3-6, Steel Stress-Strain Curve

3.1.3 Analysis Procedure

According to ASTM C497, a 3-D model was developed assembled and meshed. In order to find the proper mesh size, an arbitrary plain concrete pipe was modeled with different mesh sizes, and the results were compared.



Graph 3-7, Mesh Convergence Analysis

Five different mesh sizes were chose, 2, 1, 0.6, 0.4, and 0.2 in.. As the number of meshes increased (smaller mesh size) the time required for analysis increased as well. For instance 0.2 in. mesh size lasts for 6 consecutive days and at the end, due to the limited capacity of computer's RAM, the analysis remained uncompleted. On the other hand, the larger mesh size led to unreal behavior of concrete pipe (as is indicated in Figure 3-10). Therefor 0.6 in. mesh size or 6 or more elements along the wall thickness had the most optimized mesh size. In this study 0.8 in. mesh size was used, due to the wall thickness dimension. In most of the pipes 0.6 in. mesh size and 0.8 in. mesh size produced equal numbers of elements along the thickness, and as in the Abaqus element numbers along the section were more important than element mesh size (in other words, mesh size is defined in order to determine element numbers along the section), therefore in order to faster analyzes and prevent the full occupation of the computer's RAM 8 in. mesh sizes were selected.

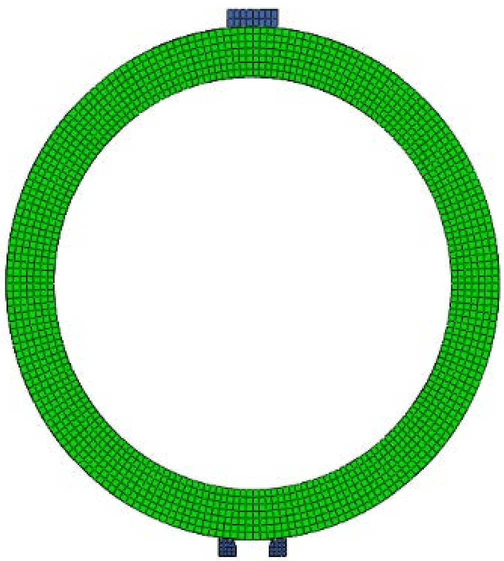


Figure 3-1, Three Edge Bearing Test Simulation According to ASTM C497

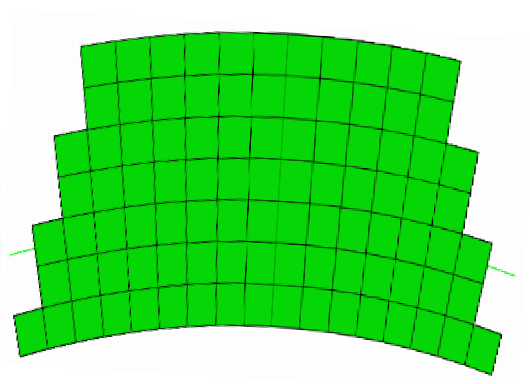


Figure 3-2, Elements Number along the Wall Thickness

The reinforcement's meshes were seat for 0.2 to create a better connection between concrete elements and reinforcements. The lower and upper bearings meshed the same as the pipe itself due to better correlation.

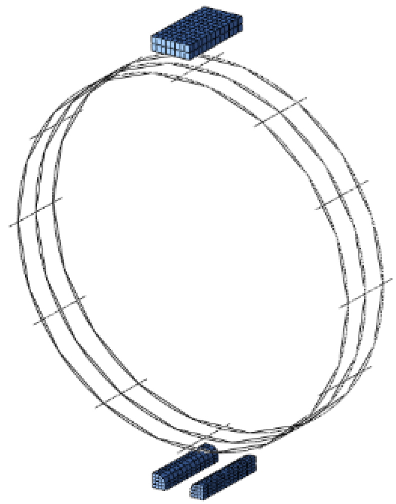


Figure 3-3 Reinforcements Meshing

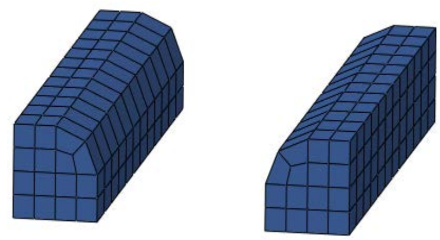


Figure 3-4, Lower bearings with Curved Edge

The full newton solution technique and direct equation solver were employed for the analysis. Supports (lower bearings) were restrained in every direction for boundary conditions. The pipe itself was restricted along the out of plane direction, and the upper bearing's degrees of freedom was restricted in all directions except y axis. It also subjected to downward displacement (displacement-control) in order to exert the load on the pipe.

3.1.4 Simulation's Verification

In order to verify the simulation's behavior, two tests were performed as specified in Chapter 2. Uniaxial cylinder tests were conducted in order to verify the material models credibility. Specimens have been simulated according ASTM C39 specifications.

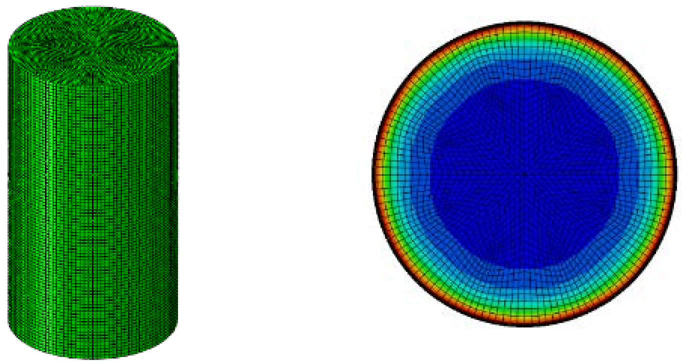
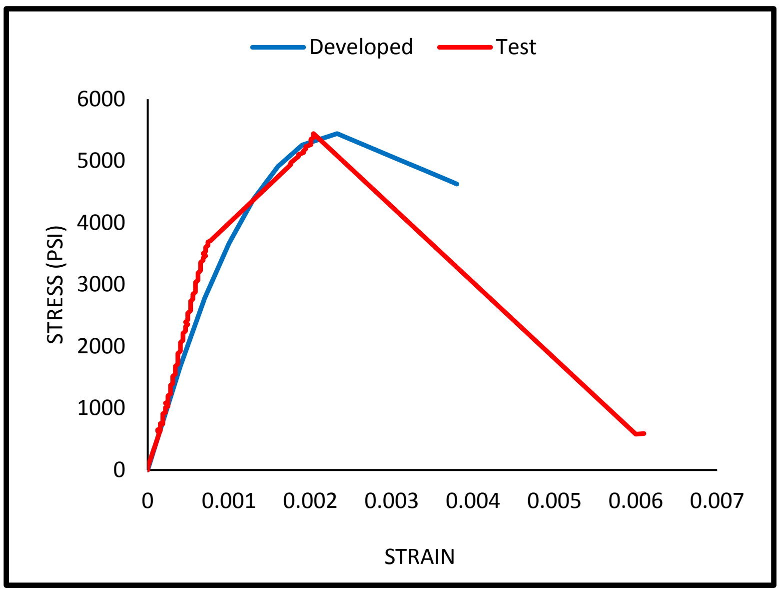
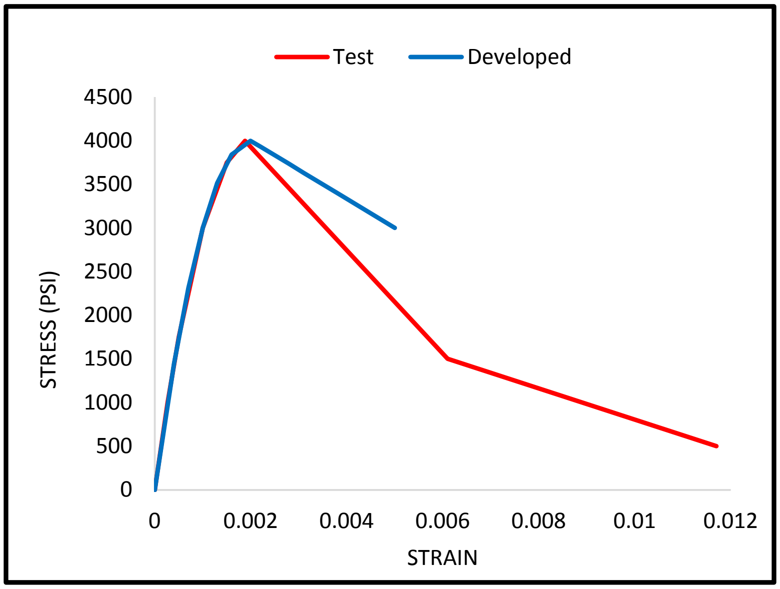


Figure 3-5, Uniaxial Compressive Cylinder Test

The cylinders were subjected to the downward uniaxial compressive force, Stress can be obtained by division of the force over the cross section area, while the Abaqus is able to extract stresses directly along any directions. Two tested specimen were simulated and the results were as follows:



Graph 3-8, Verified UC Tested Specimen #1with FEM



Graph 3-9, Verified UC Tested Specimen #2 with FEM

For RCP, simulations were compared with three TEB tests. For simulations as elaborated, the developed material was used for required compressive strength based on ASTM C76.

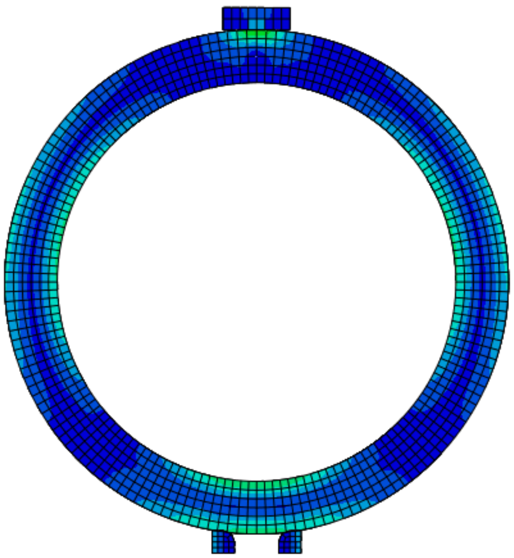


Figure 3-8, TEB Simulation, Max Principal Stress

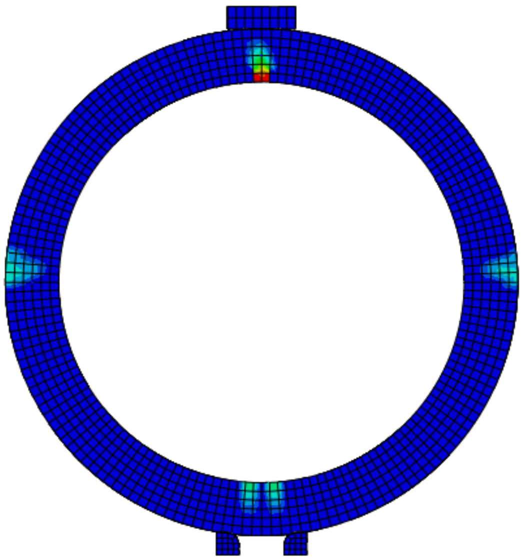
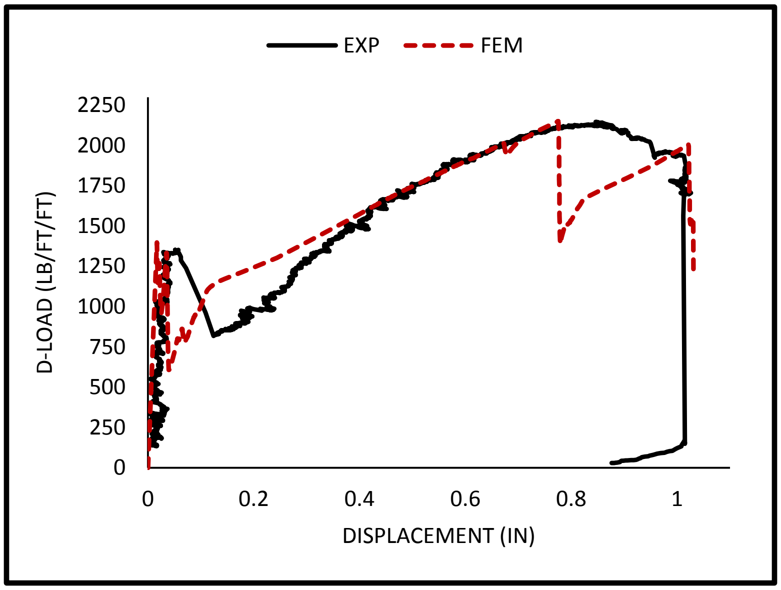
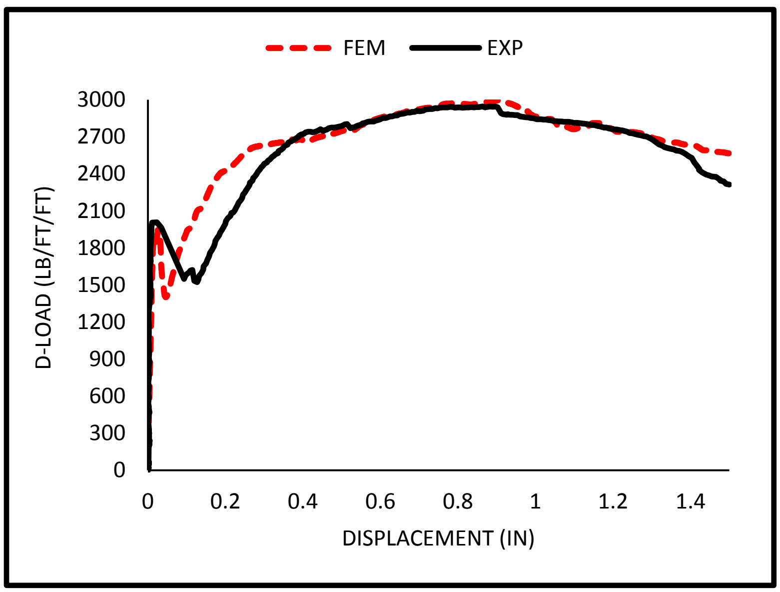


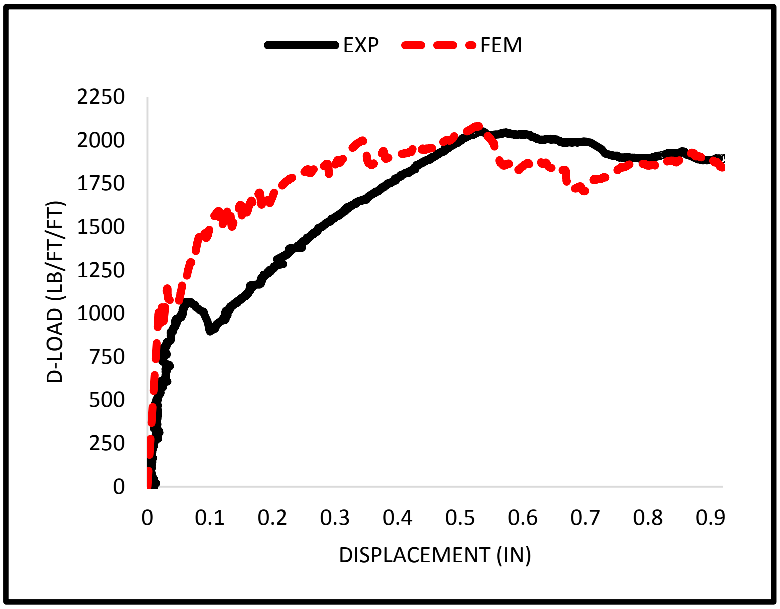
Figure 3-9, TEB Simulation, Plastic Strain



Graph 3-10 Verified TEB Tested Specimen #1 with FEM



Graph 3-11, Verified TEB Tested Specimen #2 with FEM



Graph 3-12, Verified TEB Tested Specimen #3 with FEM

In order to validate the experimental TEB tests, after analysis, vertical force was extracted from the Abaqus. The force was divided by the pipe diameter in order to convert it to D-load. Displacement was also extracted in order to develop the D-load- displacement graph.

As the graphs indicate, the FEM simulations work properly and it can simulate behavior of the RCP with high accuracy. Therefore, it was expected that FEM simulations would be able to predict any RCP under this test setup. For this study pipe classes III, IV and V with pipe diameters of 24, 36, 48, 60, 72 in. were studied. Each pipe was simulated for double cage and for three different single cages location. In the single cage, reinforcements were placed at 35%, 50% and 65% of wall thickness from the inner surface of pipe. According to ASTM C-76

Table 3 footnote E, as an alternative single cage reinforcement can be used with steel area of summation of both inner and outer reinforcement areas and increased by 25%. In this study, just single cage with summation of two cage areas were used. And for those which didn't satisfy the ASTM C76 benchmarks, the RCP was reanalyzed with 25% increase in the reinforcement area.

CHAPTER 4

4.1 Conclusions and Results

4.1.1 Summary

In this study, class III, IV, and V pipes with 24, 36, 48, 60, and 72 inch diameters for wall C were examined. Each pipe was analyzed four times, once with double cage reinforcement and three times with single cage using varying locations for the rebar placement. For the single cage, reinforcements were placed at 35, 50, and 65 percent of the wall thickness from the inner surface of the pipe. According to ASTM C-76 (Table 3, footnote E), a single cage reinforcement can be used for wall C; however, the reinforcement area is required to be at least equivalent to 125% of the total area of the inner and outer reinforcements. In this study, the single cage area is only equivalent to the total area of the inner and outer reinforcements. However, the small diameter RCP was reanalyzed using a total area of 125% of the total area of the inner and outer reinforcements in order to compare the capacities.

4.1.2 Discussion

Reinforced concrete pipe is a homogenous circular structure. During the TEB test, the RCP was subjected to bending moment along crown, invert, and spring line. Based on Paris's research on the pipe moment coefficients for uncracked circular RCP, the crown experiences twice the moment occurring at the spring line (graph 4-1, 4-2). All of the simulations conducted indicate that there is a direct correlation between the location of the circumferential reinforcements and the service and ultimate D-load. The closer the circumferential reinforcement is to the center of the pipe, the greater the capacity of the service D-load. While a greater ultimate D-load capacity can be achieved when the circumferential reinforcements are closer to the outside of the pipe. Therefore, the crown and the invert sections provide capacity for service D-load, and the spring line sections control the ultimate D-load. Due to this fact, ASTM-C76 assigns a higher reinforcement area for inner cages in order to control the 0.01 in. crack width (Figure 4-1).

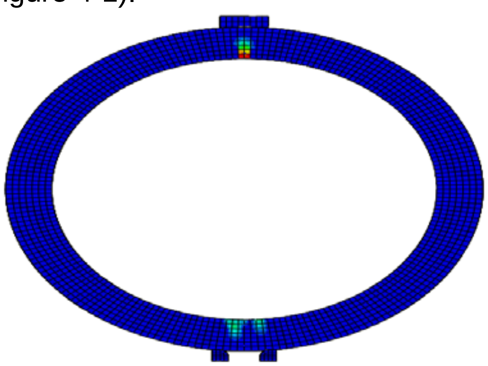


Figure 4-1, Plastic Strain at service D- load for RCP with 48in. Diameter

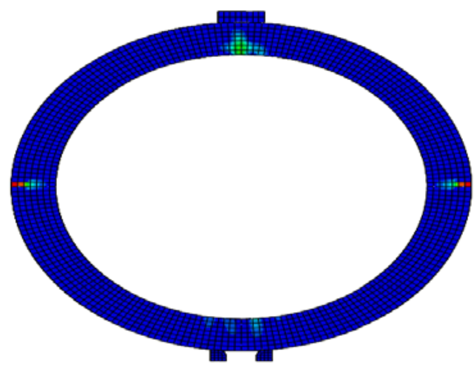
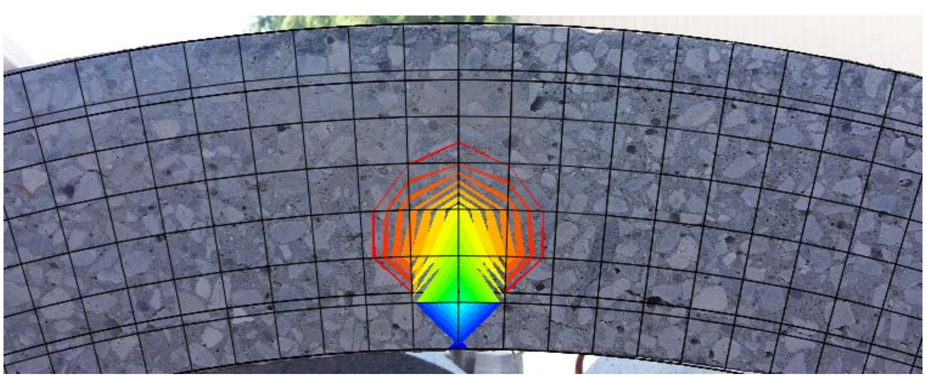
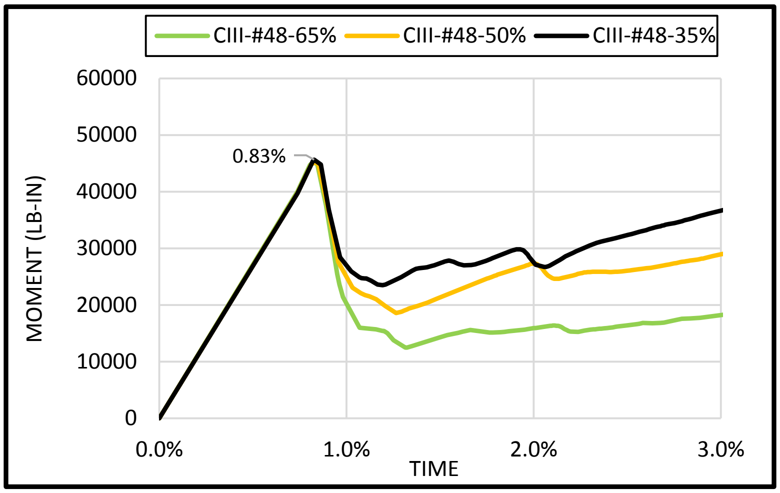


Figure4-2, Plastic Strain at Ultimate D-load for RCP with 48in. Diameter

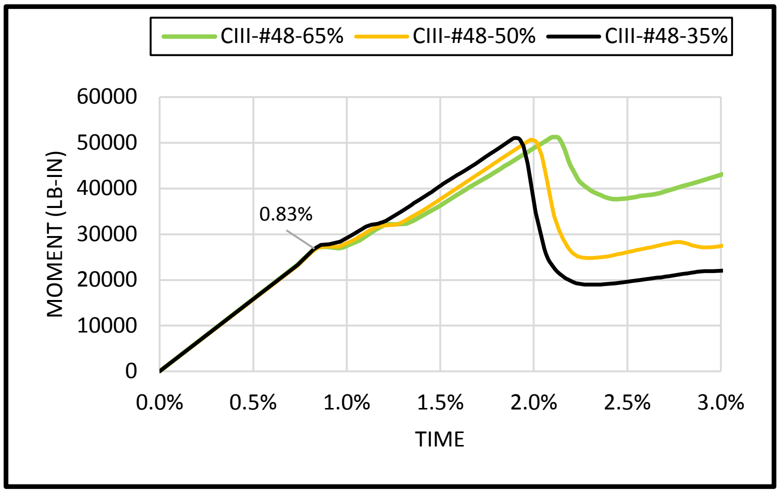


Picture 4-1, Indication of ISO-surface Plastic Strain for Service D-load on Pipe Diameter 48 in.

Due to the existence of two cross sections in the spring line versus the single cross section at the crown, the moment in the spring line is less than the moment at the crown. Another factor which could contribute to the uneven moment distribution at the crown and the spring line is due to the thrust in the crown being nil.



Graph 4-1, Moment in Crown



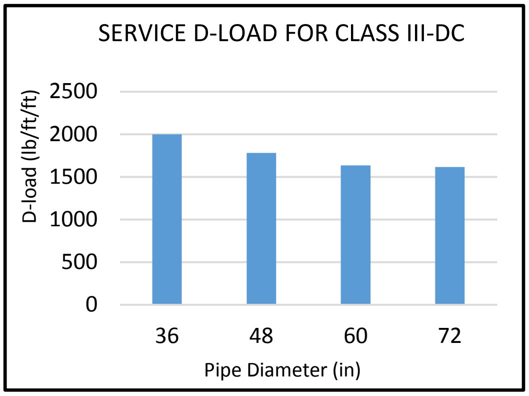
Graph 4-2, Moment at Spring Line

In the following sections, the results for each class will discussed.

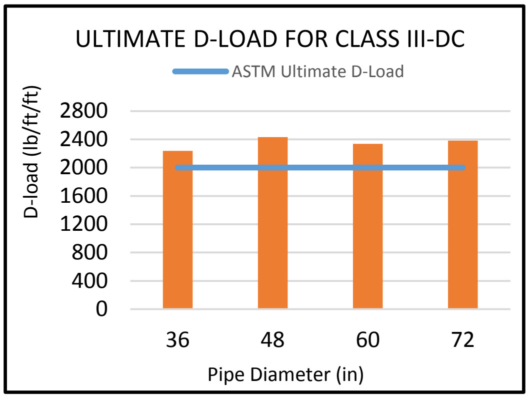
4.1.2.1 Class III

By implementing a single cage reinforcement, the RCP becomes more economical. According to Appendix B Table (B-1), implementation of a singular cage at 35% of the wall thickness from the inside surface reduces 31 percent of the steel weight for a 36 in. diameter pipe. The Graph (A-5) and Table (A-1) in Appendix A show the comparison between double cage, and single cage at 35%, 50%, and 65% of the wall thickness from the inner surface. For the single cage at 35%, the ultimate D-Loads increased by 19 percent while the service D-Load remained unaffected. The reinforcement cage at 50% decreased the service D-load by 13 percent, however the ultimate D-Load increased by 27 percent. By placing the cage at 65%, the service D-Load declines by 17 percent of the double cage service D-Load while the ultimate D-loads rose by 43 percent of the double cages. The same pattern was observed with varying percentages for the other pipe diameters, and may be viewed in Appendix A.

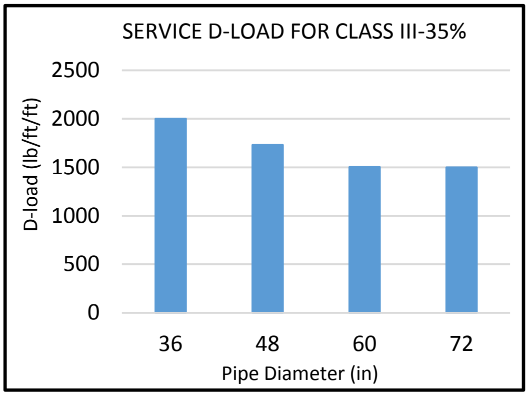
ASTM C-76 standard pipes are sorted by ascending diameters. By increasing the pipe diameter, the thickness over pipe diameter ratio decreases. The capacity of the singular cage is reduced since the aspect ratio is decreased. Graph (4-3 to 10) demonstrates that capacity is reduced when the diameter is increased. The ultimate D-load fluctuates due to the differing ratios between the inner and outer reinforcement areas for different pipe sizes with double cage reinforcement.



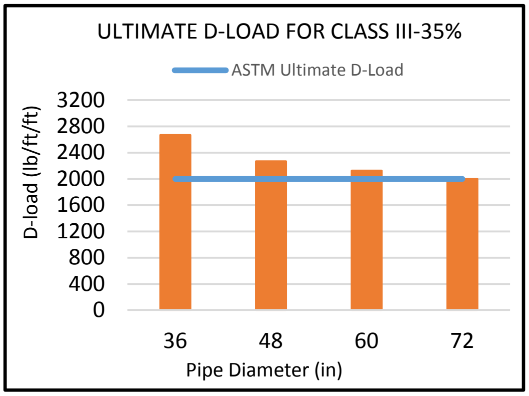
Graph 4-3, Service D-Load, Class III- DC



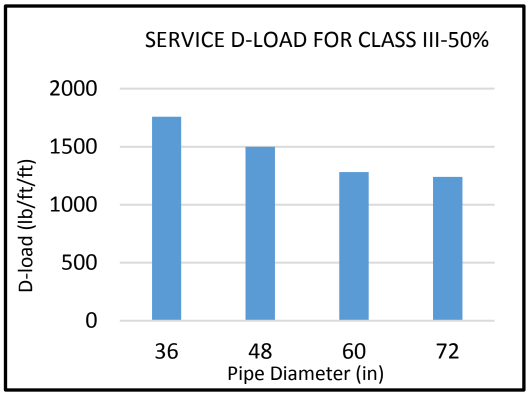
Graph 4-4, Ultimate D-Load, Class III- DC



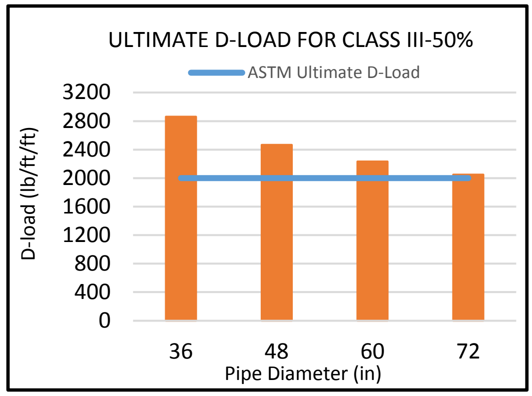
Graph 4-5, Service D-Load, Class III- 35%



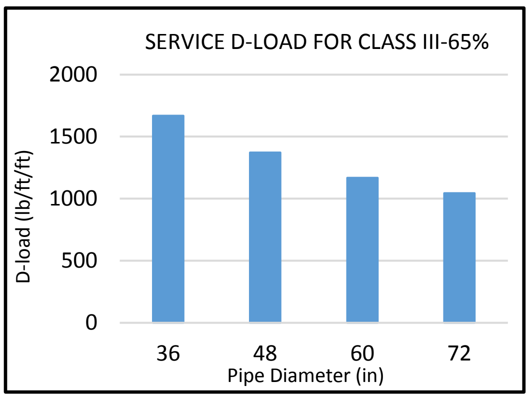
Graph 4-6, Ultimate D-Load, Class III- 35%



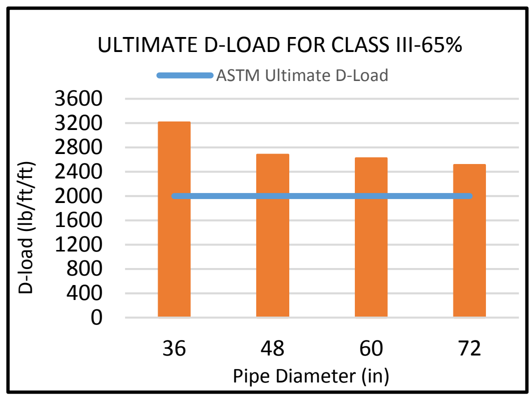
Graph 4-7, Service D-Load, Class III- 50%



Graph 4-8, Ultimate D-Load, Class III- 50%



Graph 4-9, Service D-Load, Class III- 65%

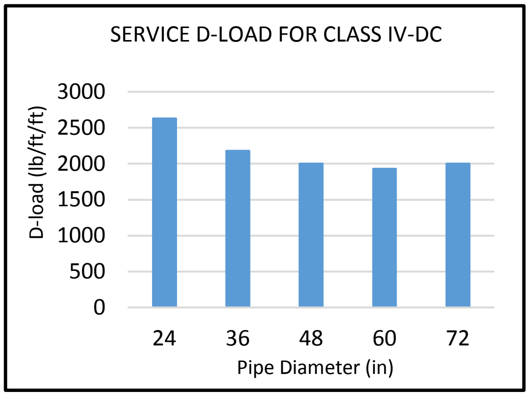


Graph 4-10, Ultimate D-Load, Class III- 65%

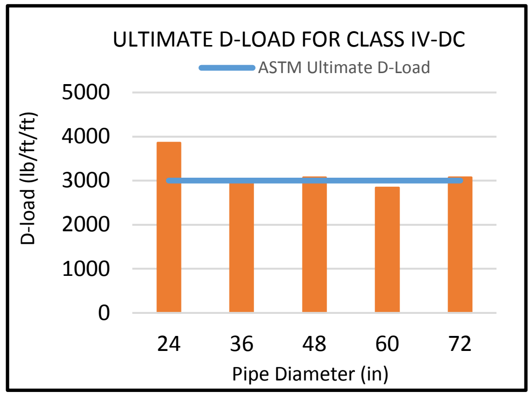
4.1.2.2 Class IV

According to Appendix B, Table (B-1), implementation of a singular cage at 35% of the wall thickness from the inside surface reduces 31.6% of the steel weight for a 24 in. diameter pipe. The Graph (A-33) and Table (A-5) in Appendix A show the comparison between double cage and single cage at 35%, 50%, and 65% of the wall thickness from the inner surface. For the single cage at 35%, the ultimate D-Loads decreased by 11 percent, while the service D-Load increased by 5 percent. The reinforcement cage at 50% decreased the service D-load by 7 percent; however, the ultimate D-Load increased by 8 percent. By placing the cage at 65%, the service D-Load declined to 8 percent of the double cage service D-Load, while the ultimate D-load rose by 19 percent of the double cages. For the other pipe diameters, the same pattern was observed with varying percentages, which can be viewed in the Appendix A. The pipe was reanalyzed with a 25 percent increase in the reinforcement area, and the results were compared to the previous 24 in. diameter pipe. For the 35% placement, the service and ultimate D-load increased by 3 percent and 4 percent, respectively. For the 50% placement, the service and ultimate D-load increased by 3 percent and 4 percent, respectively. For the 65% placement, the service and ultimate D-load increased by 1 percent and 17 percent, respectively.

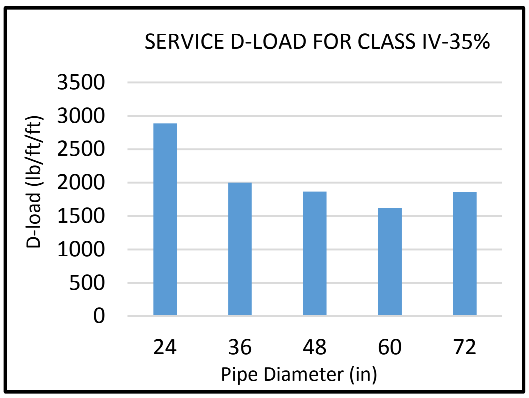
In this class, unlike class III, due to the differences in the concrete's compressive strength between pipes with a diameter of 72 in. and smaller diameters, an increase in the pipe with a diameter 72 in. is expected at both service and ultimate D-load.



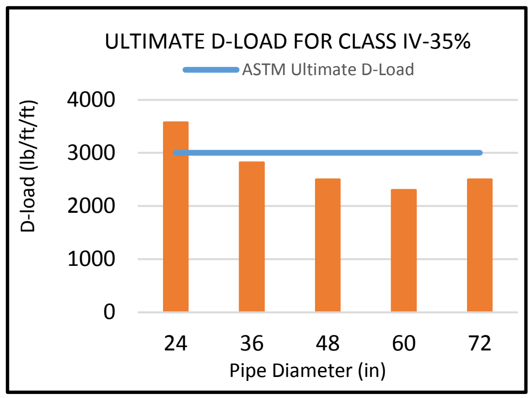
Graph 4-11, Service D-Load, Class IV- DC



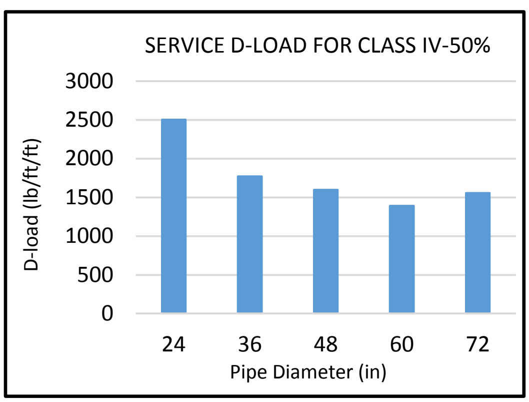
Graph 4-12, Ultimate D-Load, Class IV- DC



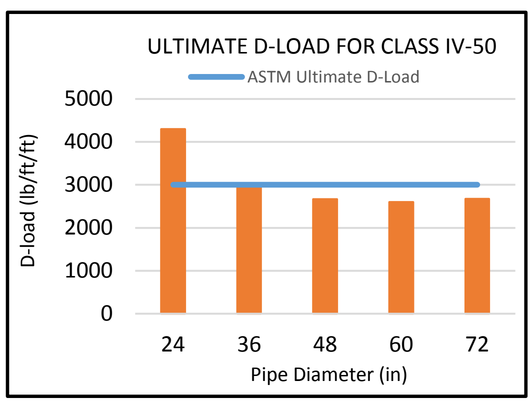
Graph 4-13, Service D-Load, Class IV- 35%



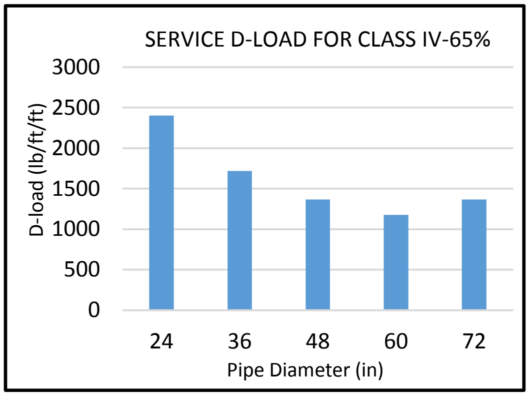
Graph 4-14, Service D-Load, Class IV- 35%



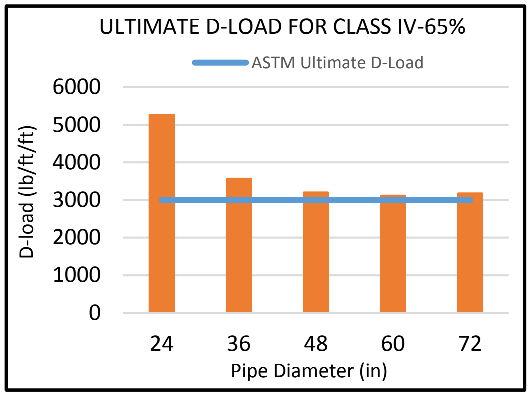
Graph 4-15, Service D-Load, Class IV- 50%



Graph 4-16, Service D-Load, Class IV- 50%



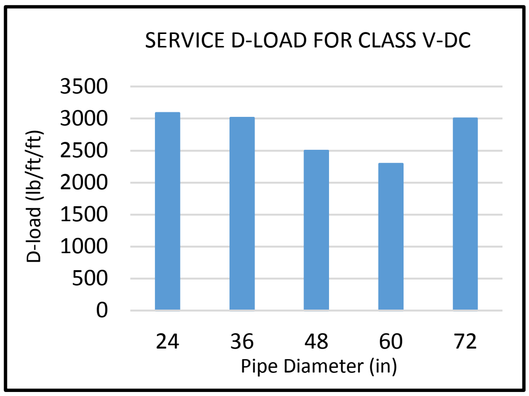
Graph 4-17, Service D-Load, Class IV- 65%



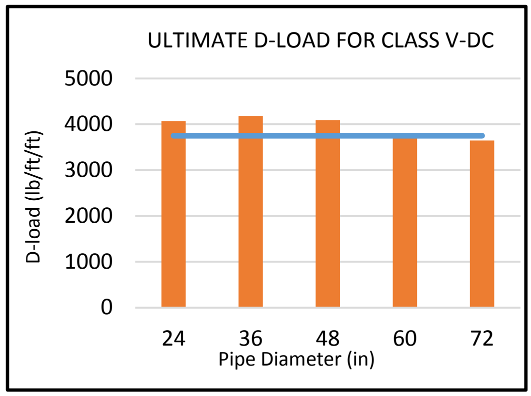
Graph 4-18, Service D-Load, Class IV- 65%

4.1.2.3 Class V

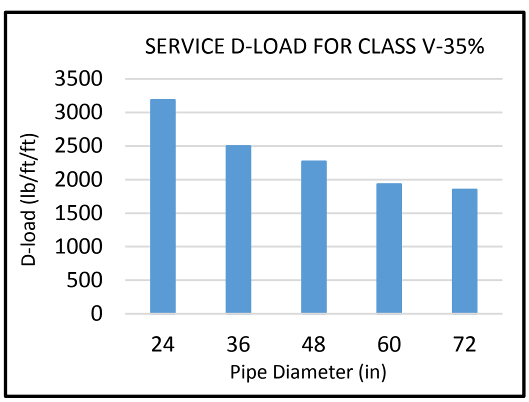
According to Appendix B Table (B-1), implementation of a singular cage at 35% of the wall thickness from the inside surface reduces 27.3% of the steel weight for a 24 in. diameter pipe. The Graph (A-73) and Table (A-12) in Appendix A shows the comparison between double cage, and single cage at 35%, 50%, and 65% of the wall thickness from the inner surface. For the single cage at 35%, the ultimate D-Loads decreased by 1 percent while the service D-Load increased by 3 percent. The reinforcement cage at 50% decreased the service D-load by 9 percent, however the ultimate D-Load increased by 15 percent. By placing the cage at 65%, the service D-Load declined to 11 percent of the double cage service D-Load while the ultimate D-loads rose by 34 percent of the double cages. For the other pipe diameters the same pattern was observed with varying percentages which can be viewed in the Appendix A. The pipe was reanalyzed with 25 percent increase in the reinforcement area and the results were compared to the previous 24 in. diameter pipe. For the 35% placement, the service and ultimate D-load increased by 4 percent and 3 percent, respectively. For the 50% placement, the service and ultimate D-load increased by 2 percent and 13 percent, respectively. For the 65% placement, the service and ultimate D-load increased by 0.5 percent and 13 percent, respectively.



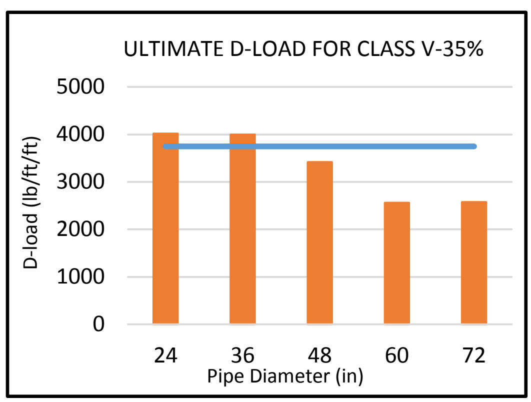
Graph 4-19, Service D-Load, Class V- DC



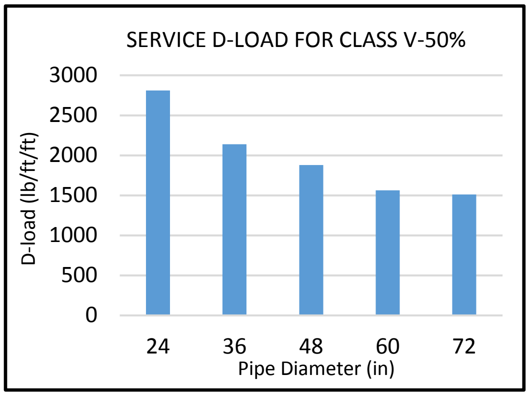
Graph 4-20, Ultimate D-Load, Class V- DC



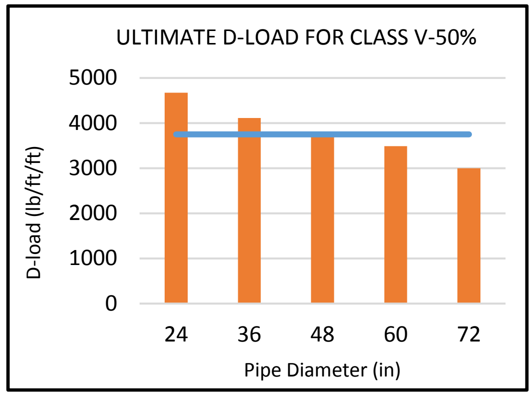
Graph 4-21, Service D-Load, Class V- 35%



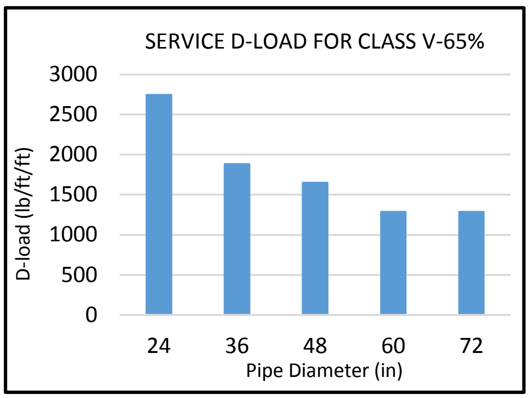
Graph 4-22, Service D-Load, Class V- 35%



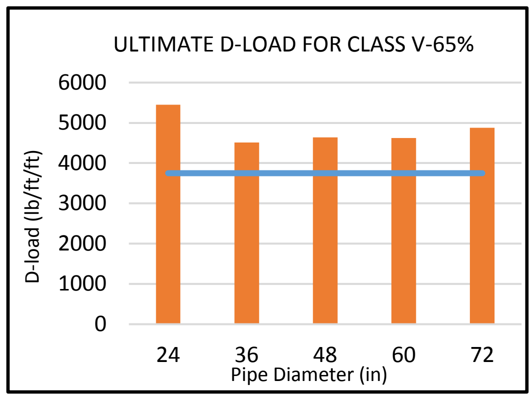
Graph 4-23, Service D-Load, Class V- 50%



Graph 4-24, Service D-Load, Class V- 50%



Graph 4-25, Service D-Load, Class V- 65%



Graph 4-26, Service D-Load, Class V- 65%

4.1.3 Conclusion

A three dimensional model of reinforced concrete pipe was created to simulate the real RCP behavior under the three edge bearing (TEB) test. Three full scale TEB tests were performed in order to verify FEM modeling. The uniaxial compressive tests were also performed in order to verify material properties. These experimental tests proved that the FEM analysis for any RCP under TEB test with proper material properties simulate perfectly.

All of the simulations indicate that there is direct correlation between the location of the circumferential reinforcements and the service and ultimate D-load. The closer the circumferential reinforcement is to the center of the pipe, the greater the capacity of the service D-load, while a greater ultimate D-load capacity can be achieved when the circumferential reinforcements are closer to the outside of the pipe.

The ASTM C-76 standard pipes are sorted by ascending diameters. By increasing the pipe diameter, the thickness over pipe diameter ratio decreases. The capacity of the singular cage is reduced since the thickness over internal diameter ratio is decreased. Therefore, according to Appendix A-1 implementation of the singular cage for pipe class III, which demands lower capacity, and class IV and V for 24 in. diameters is works properly. However, greater diameters for classes IV and V, demand an increase in the reinforcement area, in order to compensate for the aspect of ratio effect.

Table 4-1, RCP situation vs. ASTM C-76 minimum criteria

Pipe Dia.	Class	Reinf. Location
36	III	All
48	III	All
60	III	35%
72	III	35%
24	IV	35%
24	V	35%

4.1.4 Recommendation

The recommendations for future research studies are the following:

1- Analyze the implementation of singular cages for same pipes for Wall B and A. These pipes are more steel dependent and it is expected that observe substantial changes in pipe behavior observed.

2- Investigate a method for 0.01 in. crack width criteria for FEM analysis.

3- Employ FEM analysis for undefined ASTM C-76 pipe reinforcements. They would be designed with the direct design method.

4- The TEB test exerts point loads on the concrete pipes, which is too conservative due to the tension concentration. It is recommended that the pipes be placed in actual soil conditions and compared with the results of the analyzed pipes in this study.

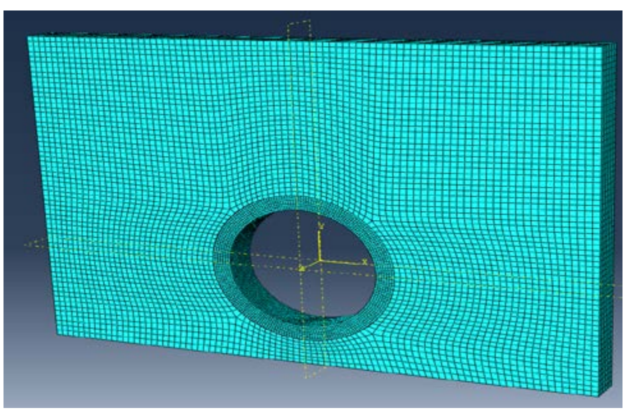
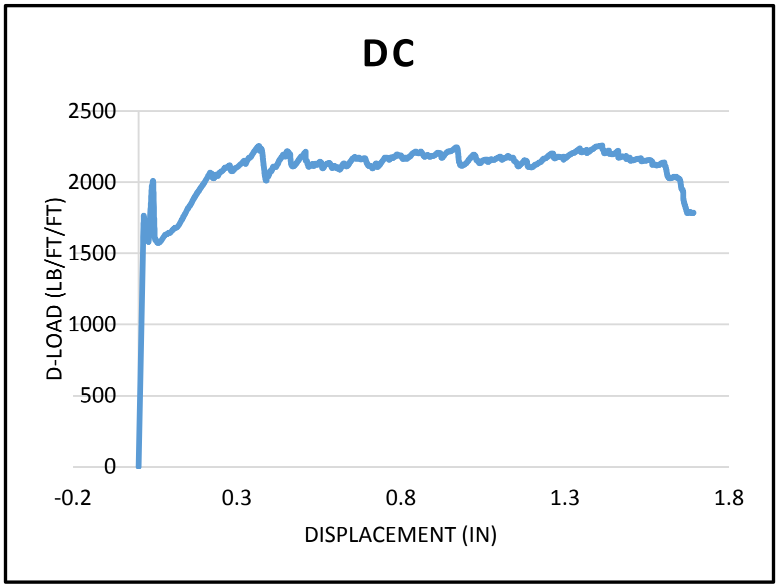


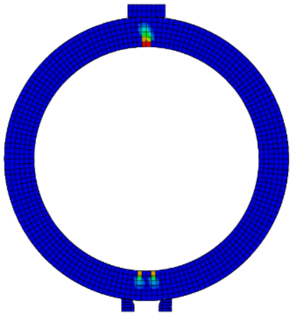
Figure 4-3, RCP in the soil (under distributed loading)

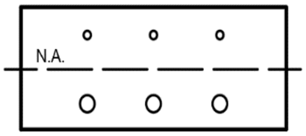
Appendix A

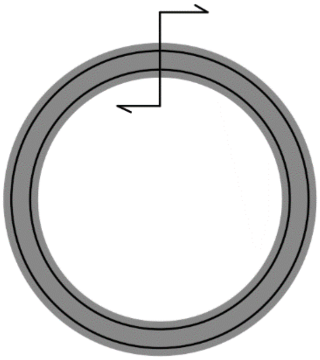
Class III - Wall C - Diameter 36 - Double Cage



Graph A-1, RCP Class III - Wall C - Diameter 36 - Double Cage



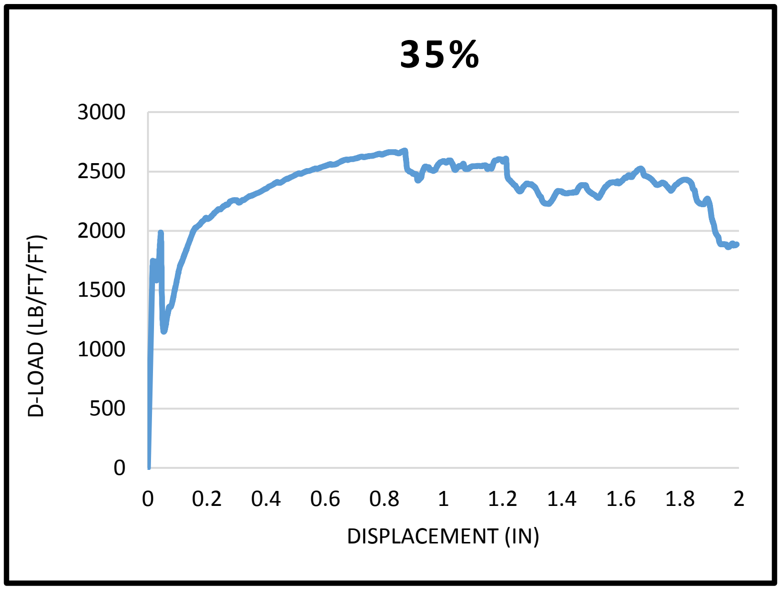




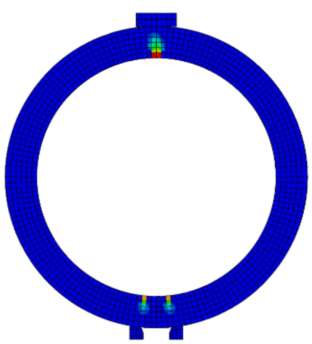
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.08	0.07	2000	2236

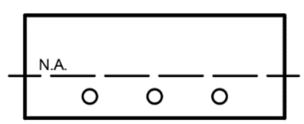
Contoured image shows plastic strain at service load.

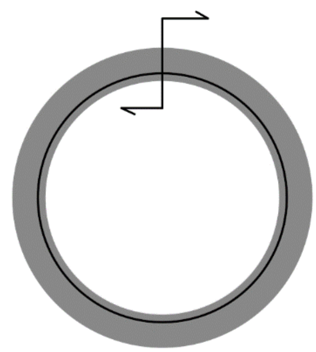
Class III - Wall C - Diameter 36 – 35%



Graph A-2, RCP Class III - Wall C - Diameter 36 – 35%



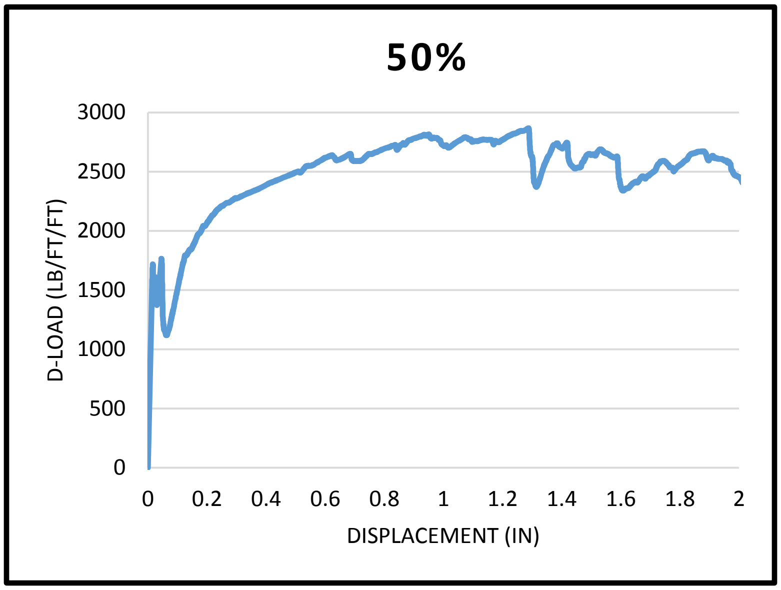




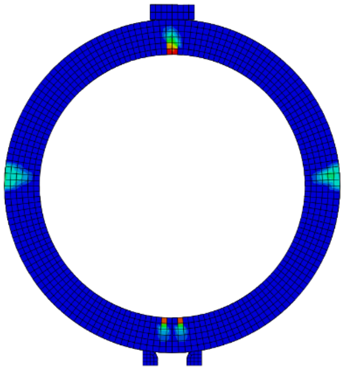
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.2	-	2000	2670

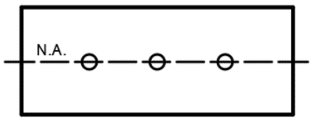
Contoured image shows plastic strain at service load.

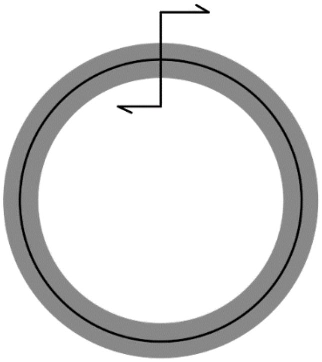
Class III - Wall C - Diameter 36 – 50%



Graph A-3, RCP Class III - Wall C - Diameter 36 – 50%



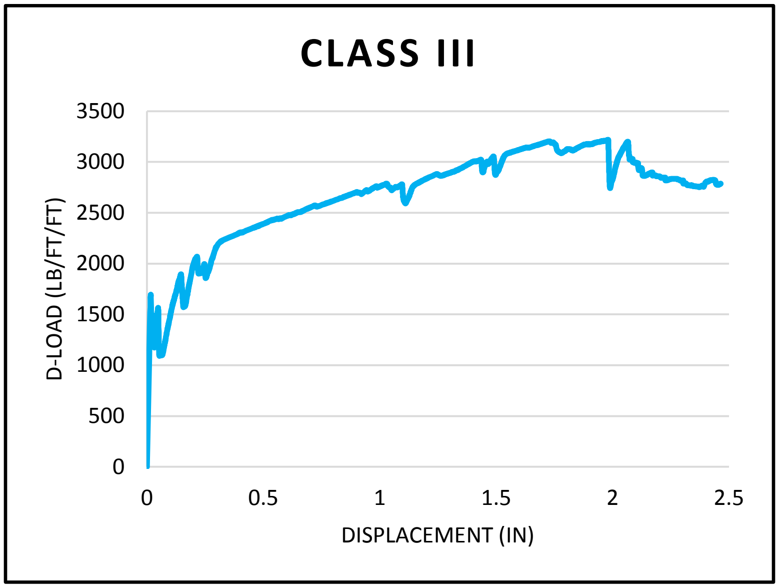




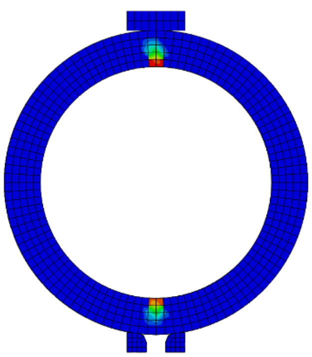
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.2	-	1759	2865

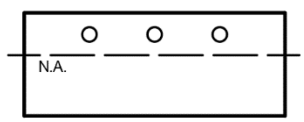
Contoured image shows plastic strain at service load.

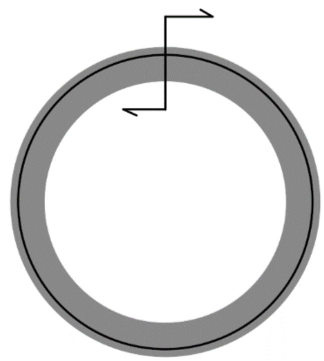
Class III - Wall C - Diameter 36 – 65%



Graph A-4, RCP Class III - Wall C - Diameter 36 – 65%

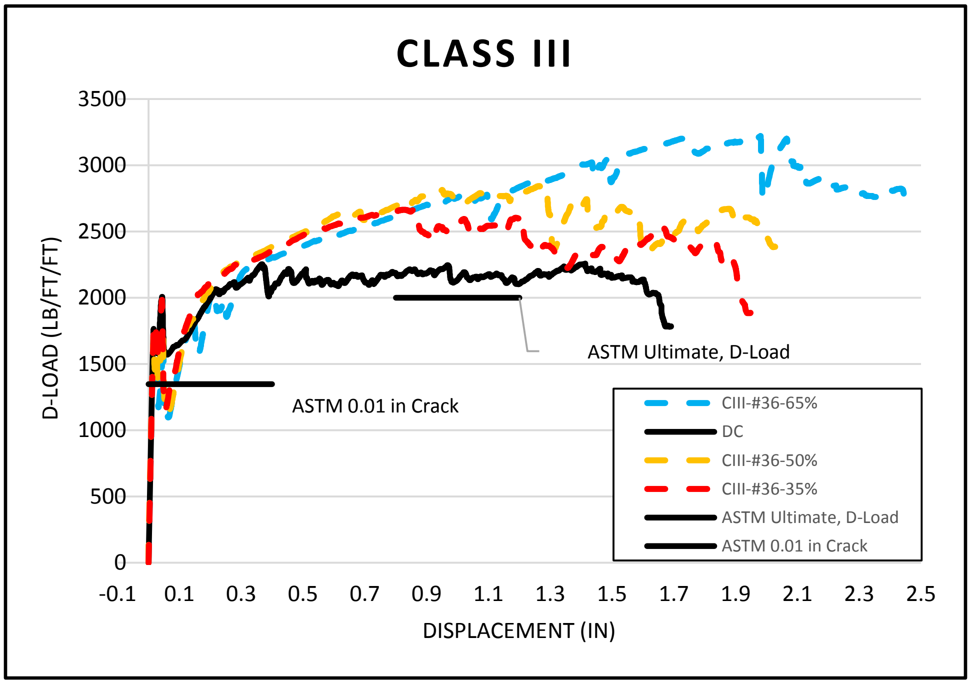






Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.2	-	1668	3208

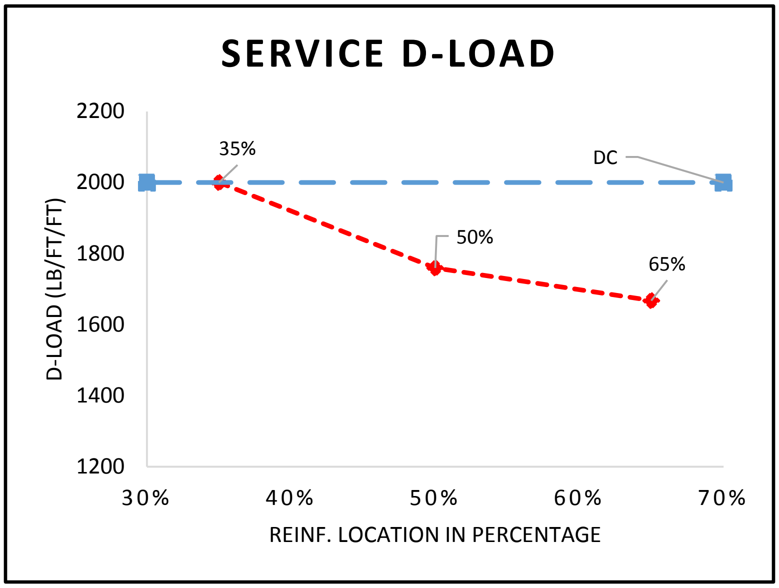
Contoured image shows plastic strain at service load.



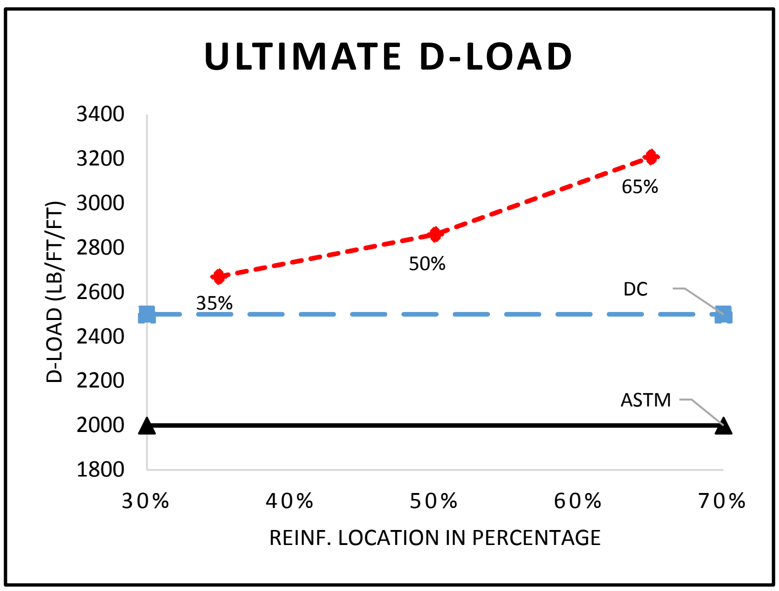
Graph A-5, Comprehensive Graph for Class III-36 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	36	4.75	0.08	0.07	2000	100	2236	100
35%	36	4.75	0.2	-	2000	100	2670	119
50%	36	4.75	0.2	-	1759	87	2860	127
65%	36	4.75	0.2	-	1668	83	3208	143

Table A-1, Comprehensive Table for Class III-36 in. Pipe diameter

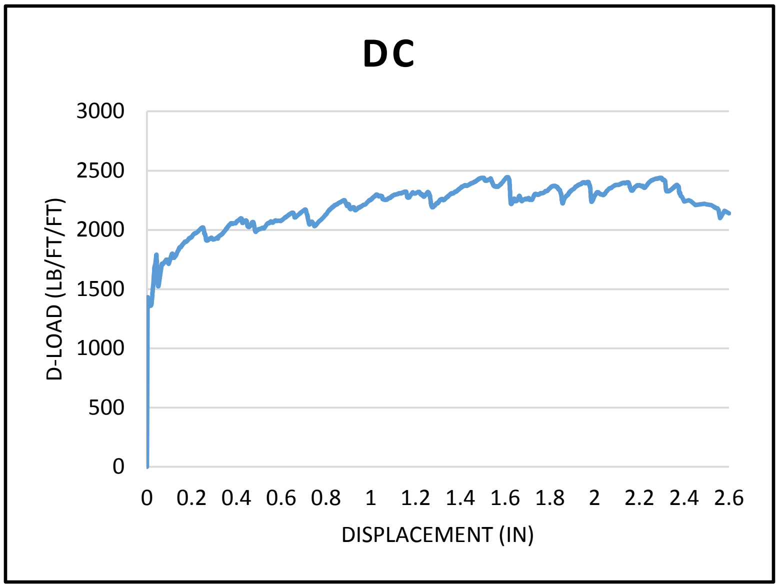


Graph A-6, Comprehensive Graph for Class III-36 in. Pipe diameter

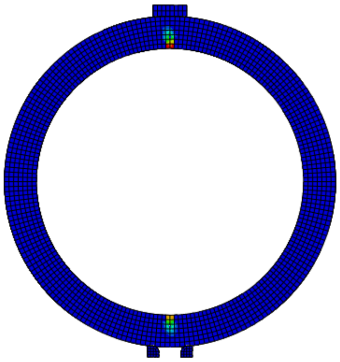


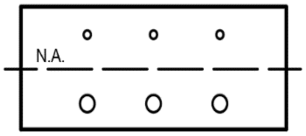
Graph A-7, Comprehensive Graph for Class III-36 in. Pipe diameter

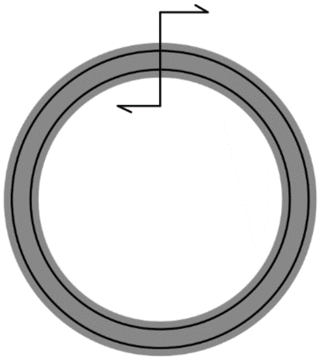
Class III - Wall C - Diameter 48 – DC



Graph A-8, RCP Class III - Wall C - Diameter 48 - Double Cage



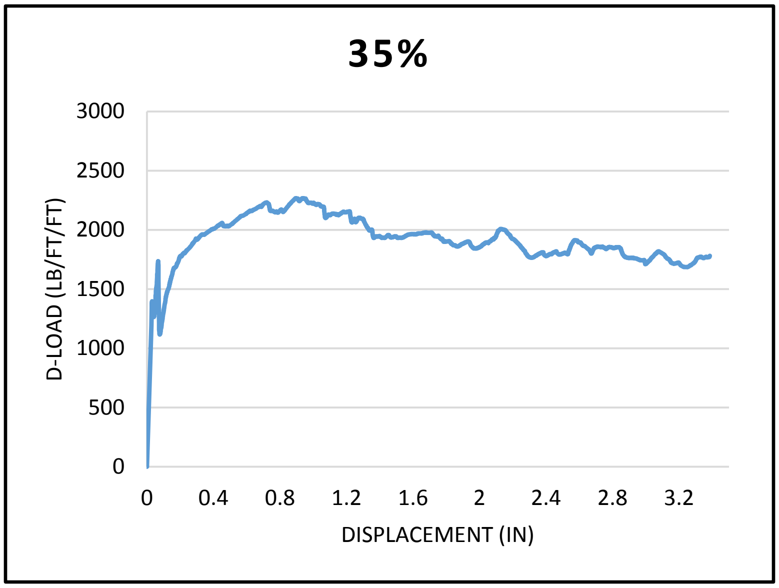




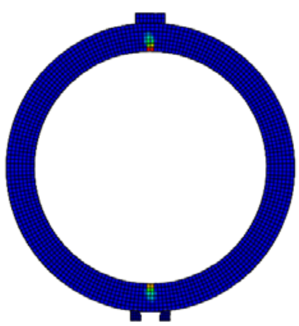
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.16	10	1781	2434

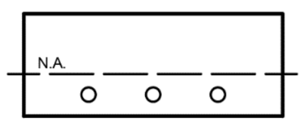
Contoured image shows plastic strain at service load.

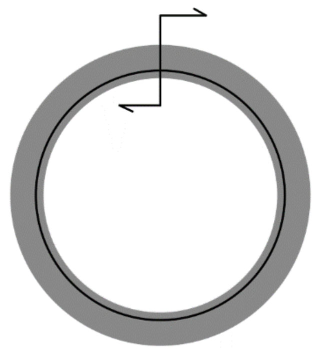
Class III - Wall C - Diameter 48 – 35%



Graph A-9, RCP Class III - Wall C - Diameter 48 – 35%



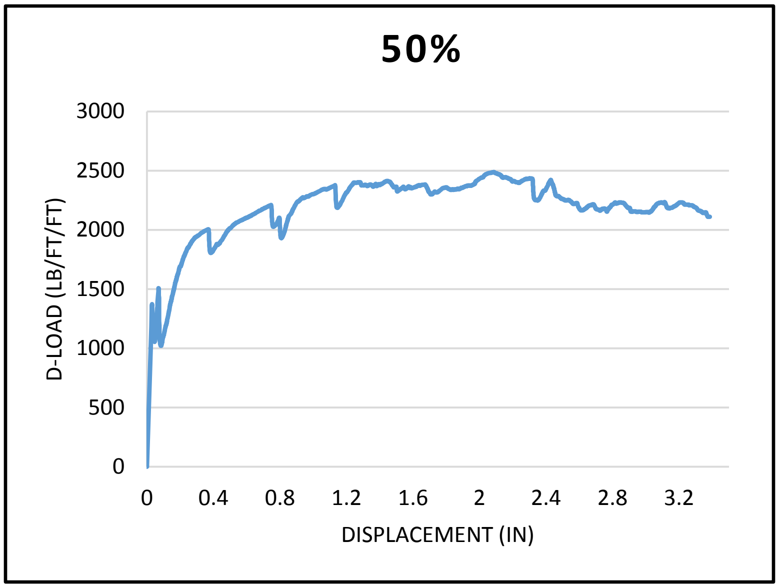




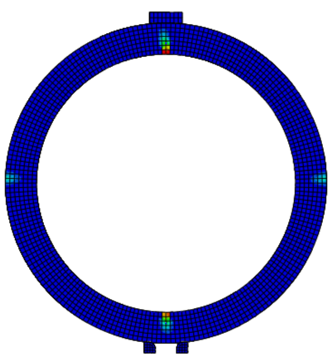
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.26	-	1730	2268

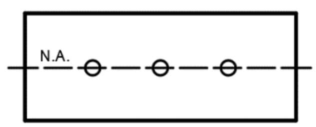
Contoured image shows plastic strain at service load.

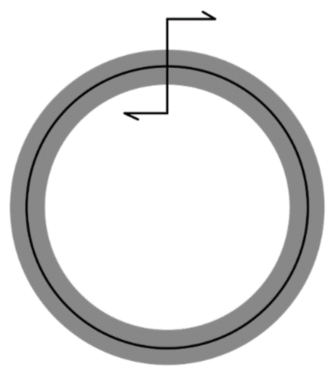
Class III - Wall C - Diameter 48 – 50%



Graph A-10, RCP Class III - Wall C - Diameter 48 – 50%



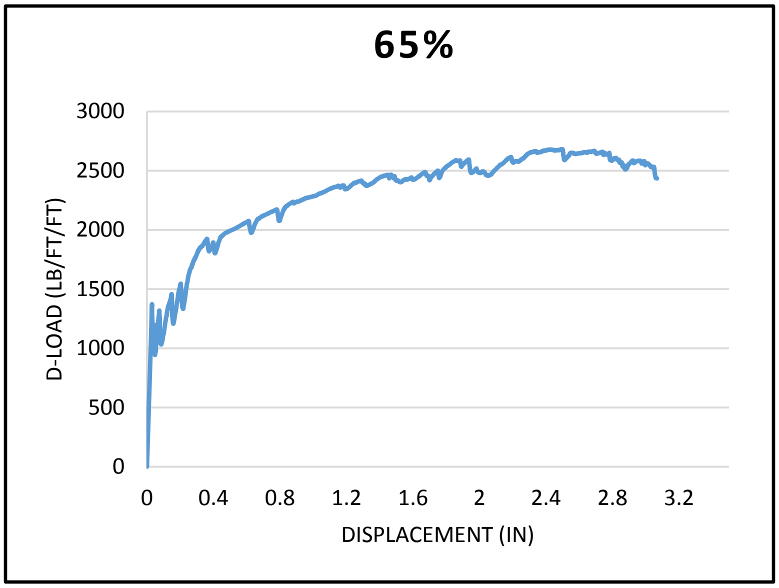




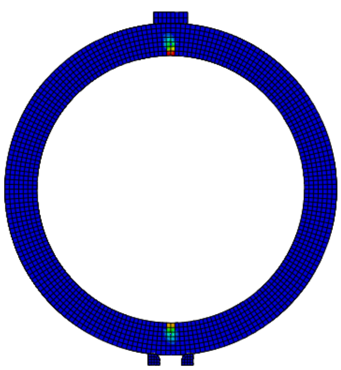
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.26	-	1500	2468

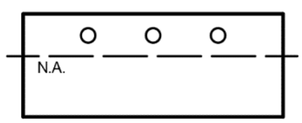
Contoured image shows plastic strain at service load.

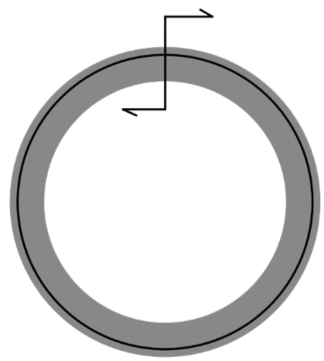
Class III - Wall C - Diameter 48 – 65%



Graph A-11, RCP Class III - Wall C - Diameter 48 – 65%

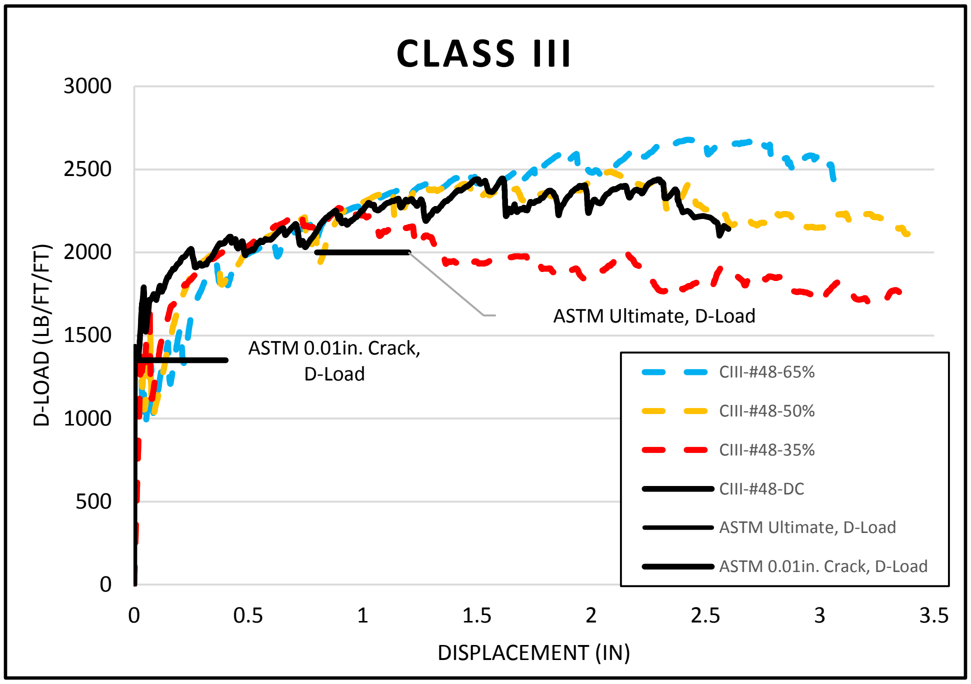






Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.26	-	1372	2680

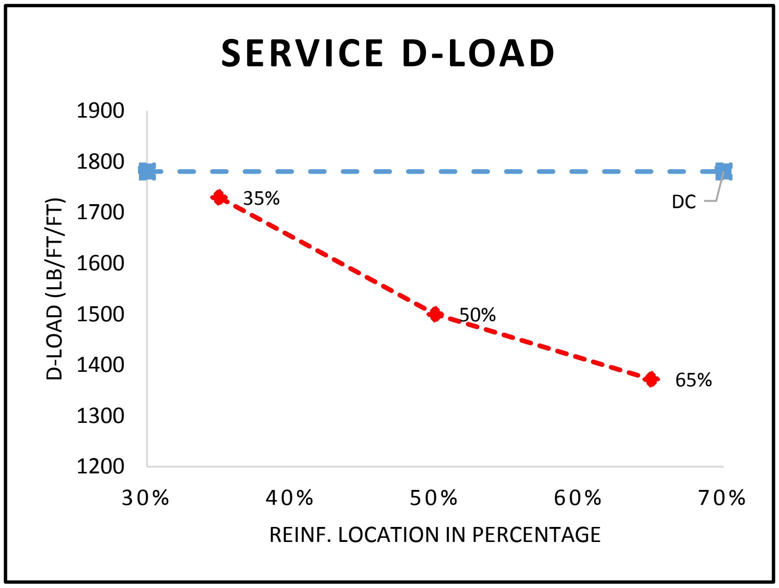
Contoured image shows plastic strain at service load.



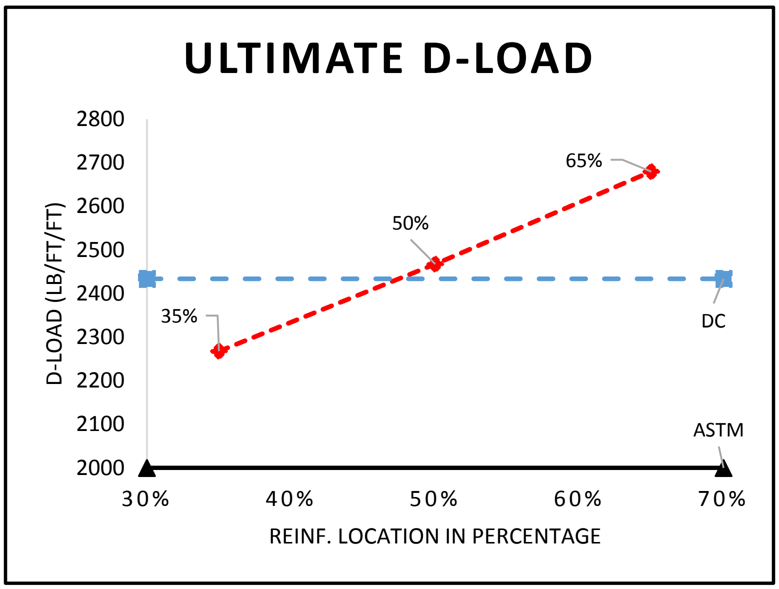
Graph A-12, Comprehensive Graph for Class III-48 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	48	5.75	0.16	0.10	1781	100	2434	100
35%	48	5.75	0.26	-	1730	97	2268	93
50%	48	5.75	0.26	-	1500	84	2468	101
65%	48	5.75	0.26	-	1372	77	2680	110

Table A-2, Comprehensive Table for Class III-48 in. Pipe diameter

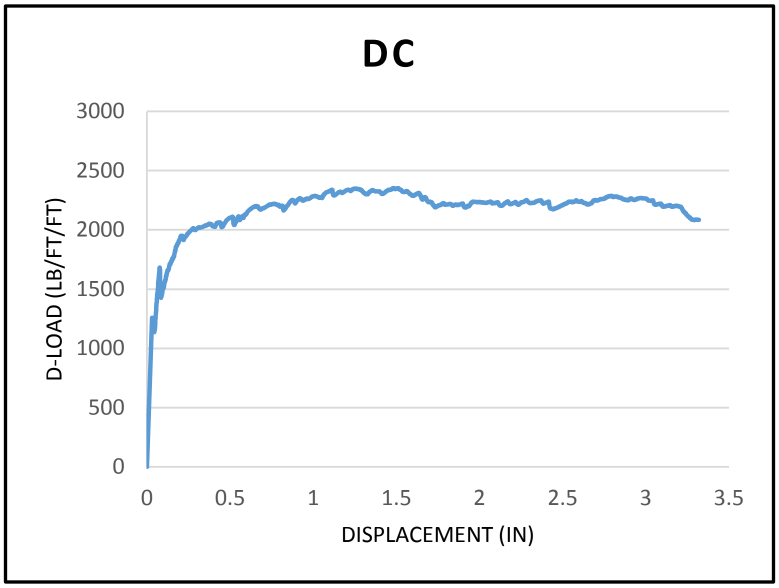


Graph A-13, Comprehensive Graph for Class III-48 in. Pipe diameter

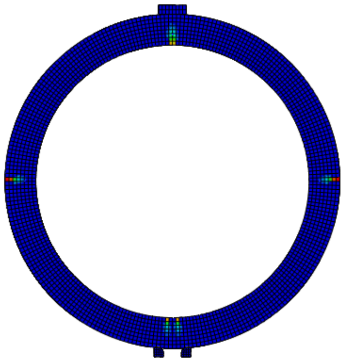


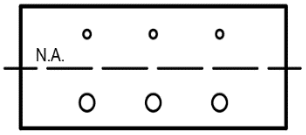
Graph A-14, Comprehensive Graph for Class III-48 in. Pipe diameter

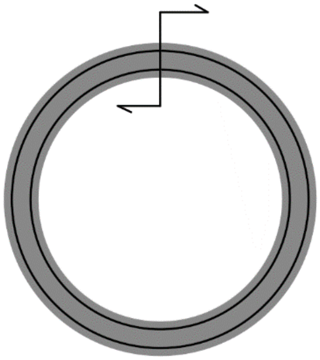
Class III - Wall C - Diameter 60 – DC



Graph A-15, RCP Class III - Wall C - Diameter 60 - Double Cage



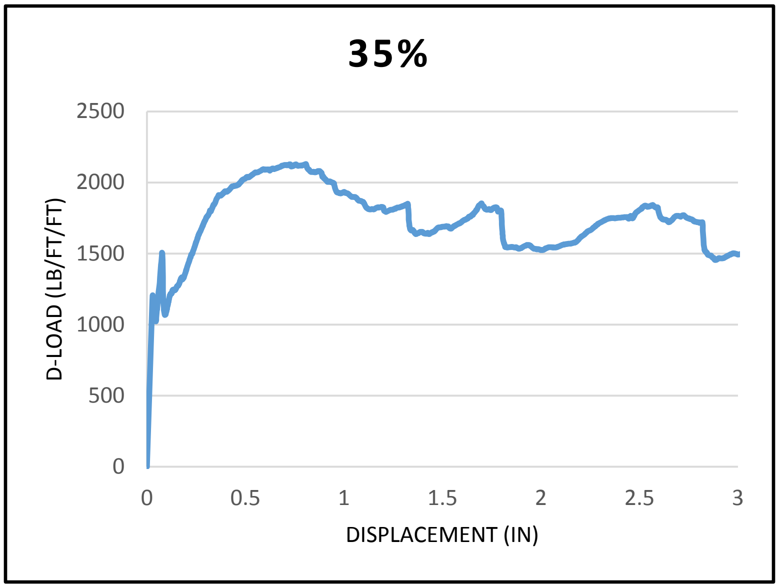




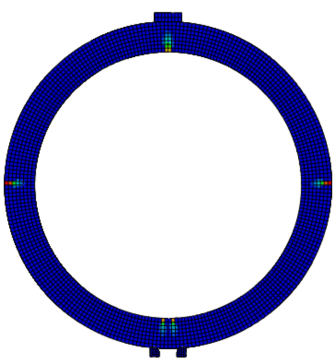
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	0.24	0.15	1342	2319

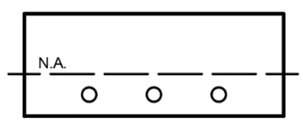
Contoured image shows plastic strain at service load.

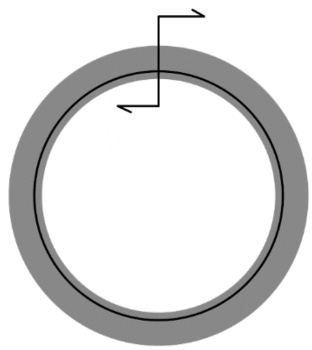
Class III - Wall C - Diameter 60 – 35%



Graph A-16, RCP Class III - Wall C - Diameter 60 – 35%



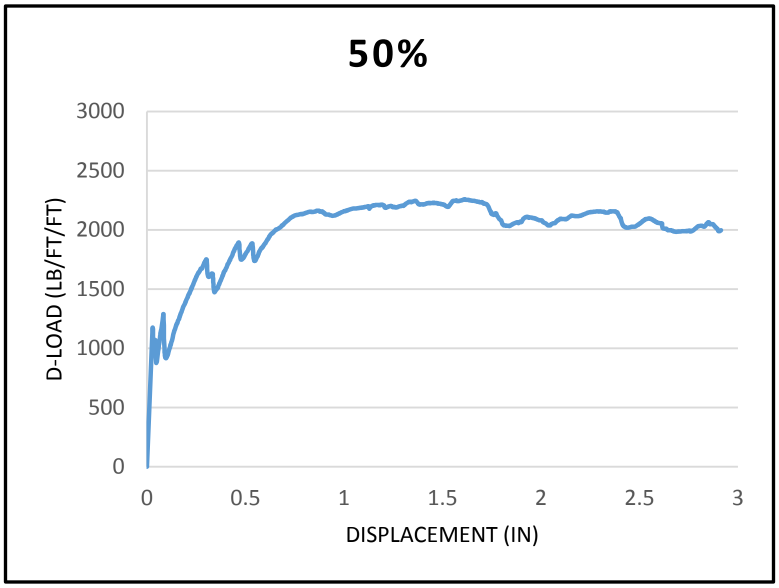




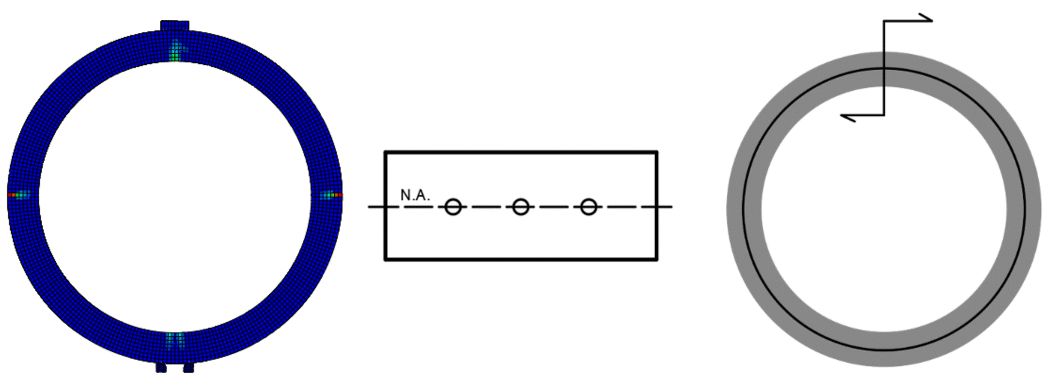
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	0.39	-	1503	2128

Contoured image shows plastic strain at service load.

Class III - Wall C - Diameter 60 – 50%



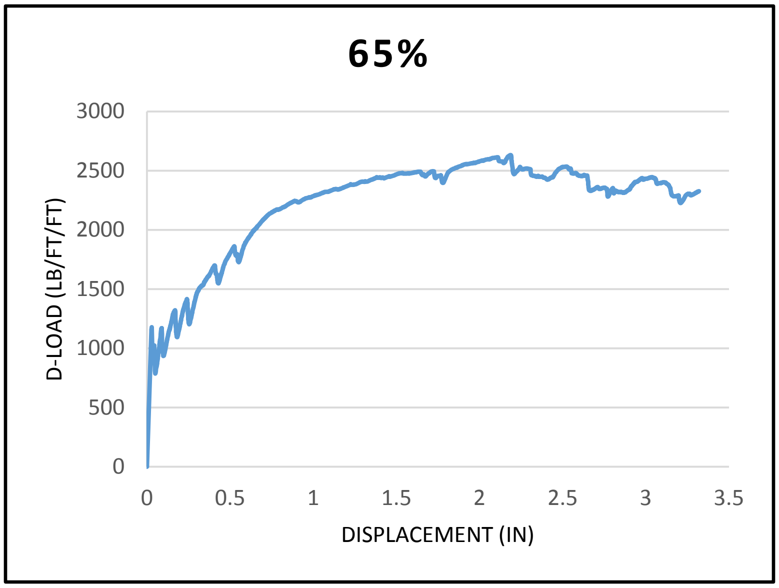
Graph A-17, RCP Class III - Wall C - Diameter 60 – 50%



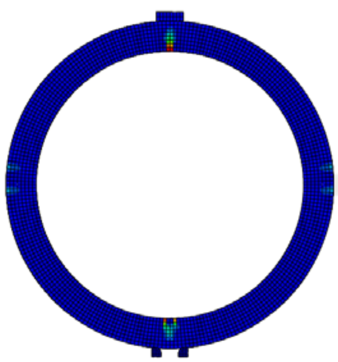
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	0.39	-	1281	2233

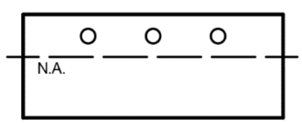
Contoured image shows plastic strain at service load.

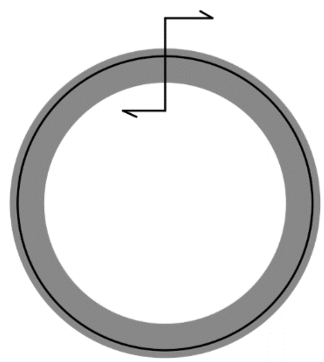
Class III - Wall C - Diameter 60 – 50%



Graph A-18, RCP Class III - Wall C - Diameter 60 – 65%

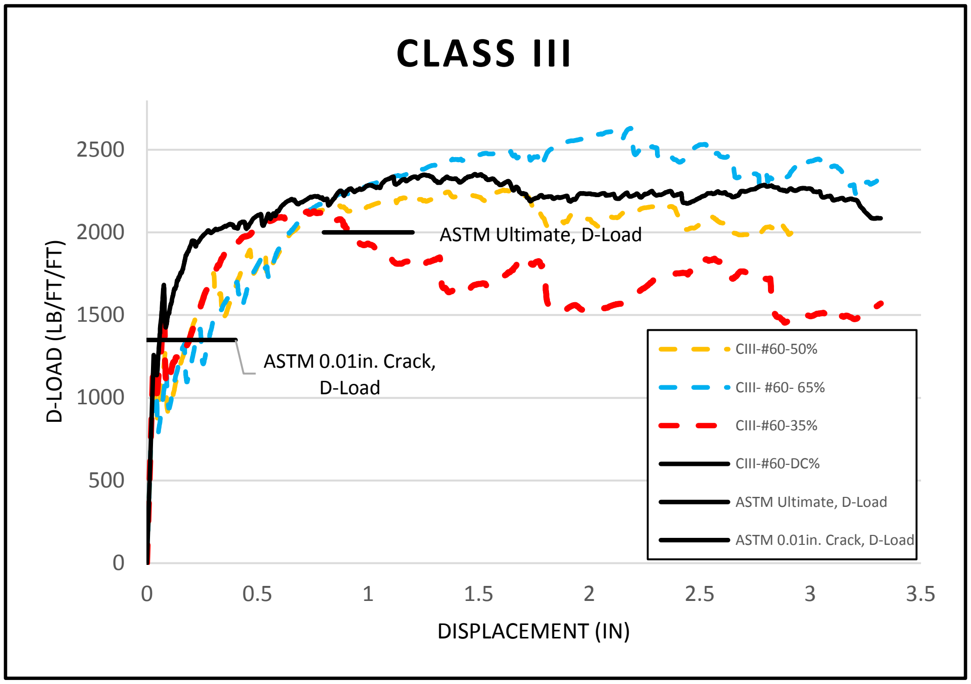






Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	0.39	-	1168	2622

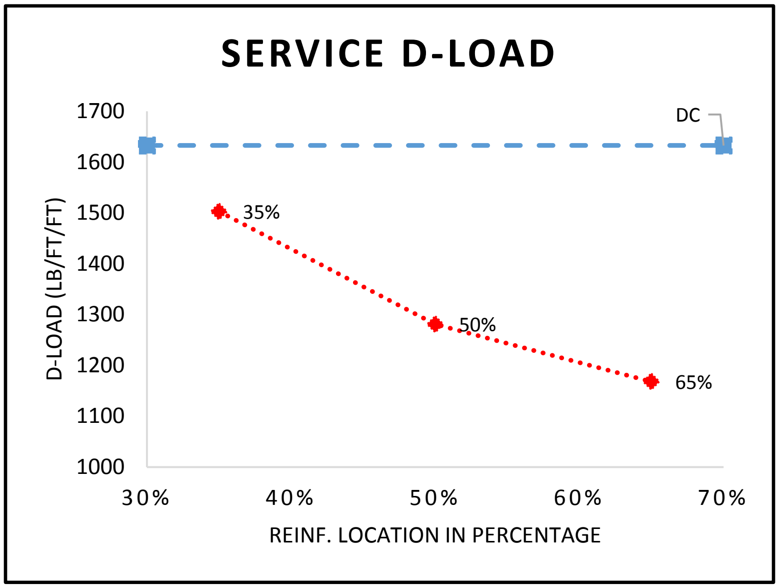
Contoured image shows plastic strain at service load.



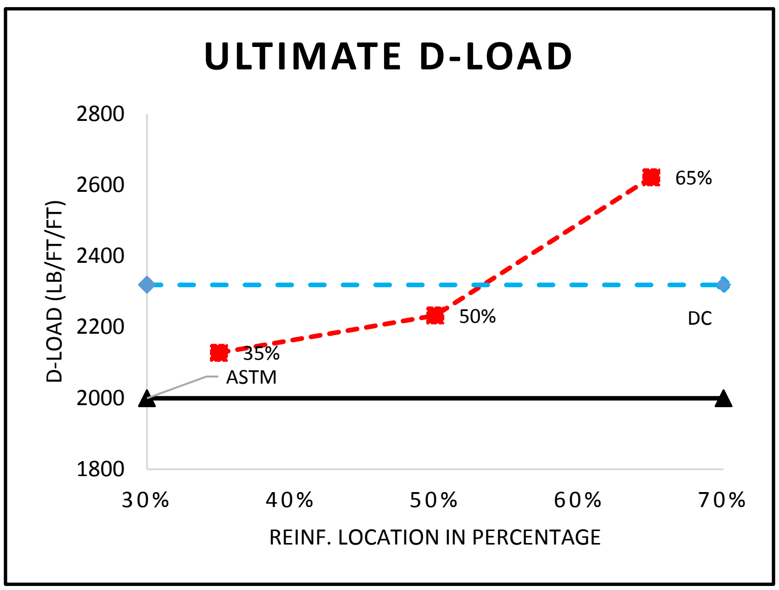
Graph A-19, Comprehensive Graph for Class III-60 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	60	6.75	0.24	0.15	1633	100	2319	100
35%	60	6.75	0.39	-	1503	92	2128	92
50%	60	6.75	0.39	-	1281	78	2233	96
65%	60	6.75	0.39	-	1168	72	2622	113

Table A-3, Comprehensive Table for Class III-60 in. Pipe diameter

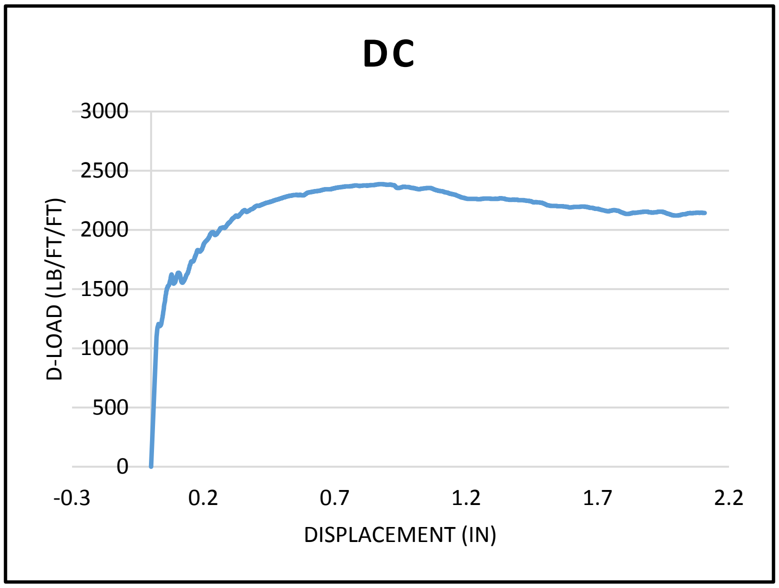


Graph A-20, Comprehensive Graph for Class III-60 in. Pipe diameter

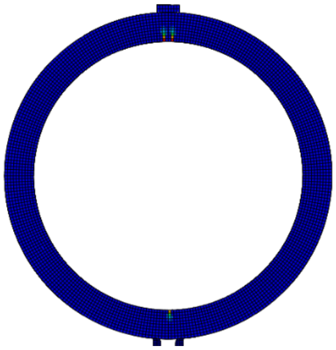


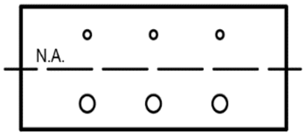
Graph A-21, Comprehensive Graph for Class III-60 in. Pipe diameter

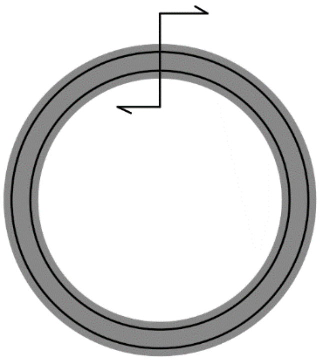
Class III - Wall C - Diameter 72 – DC



Graph A-22, RCP Class V - Wall C - Diameter 72 - Double Cage



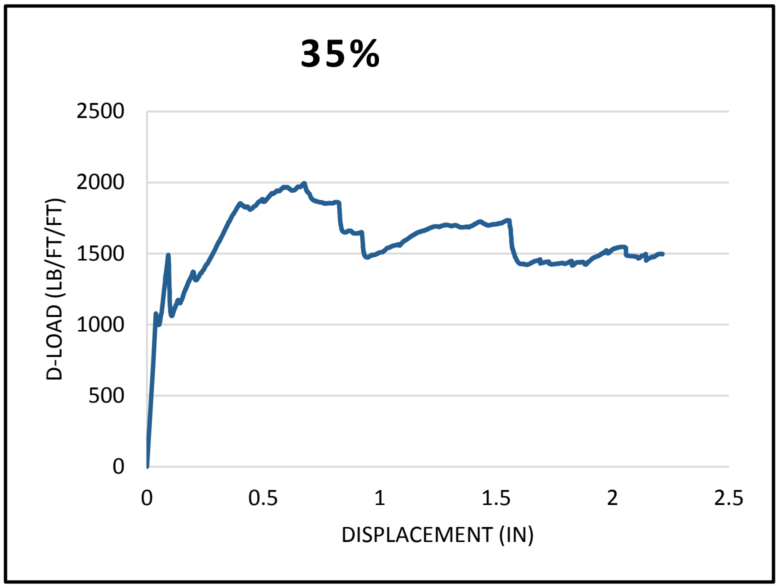




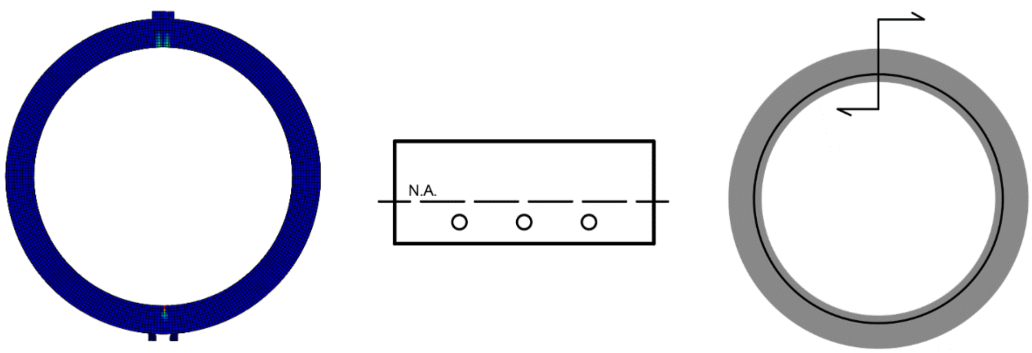
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	0.36	0.21	1614	2381

Contoured image shows plastic strain at service load.

Class III - Wall C - Diameter 72 – 35%



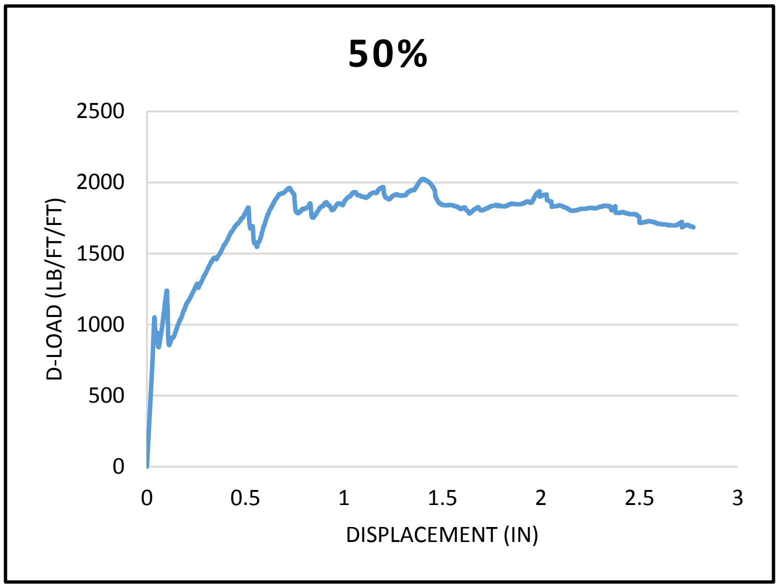
Graph A-23, RCP Class V - Wall C - Diameter 72- 35%



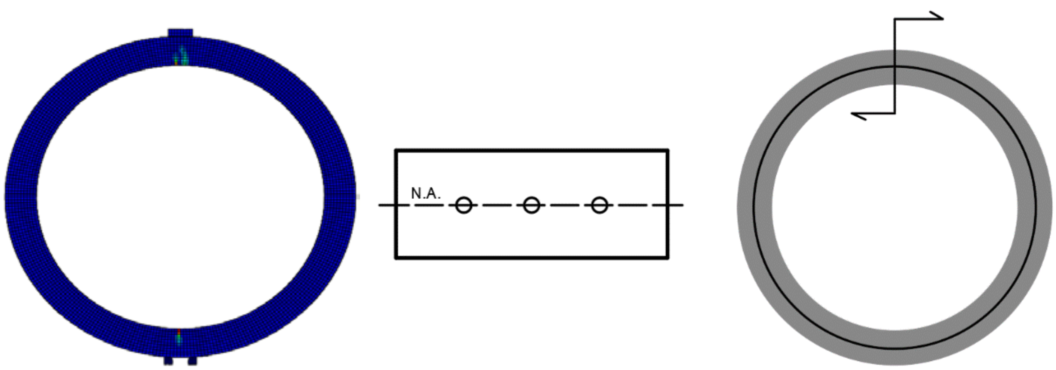
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	0.57	-	1500	2000

Contoured image shows plastic strain at service load.

Class III - Wall C - Diameter 72 – 50%



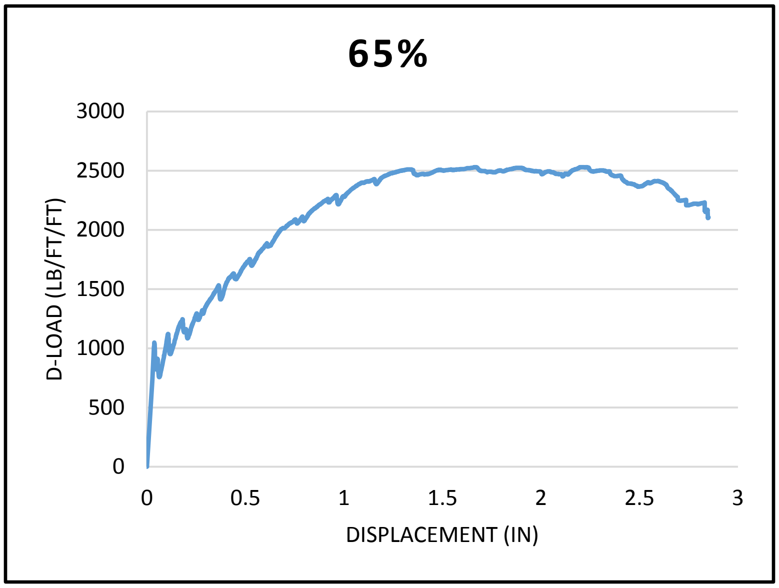
Graph A-24, RCP Class V - Wall C - Diameter 72- 50%



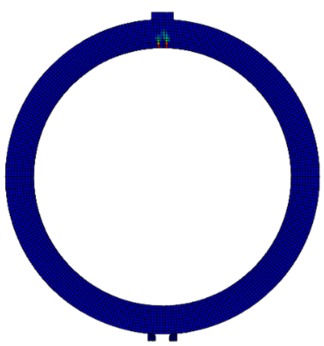
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	0.57	-	1239	2010

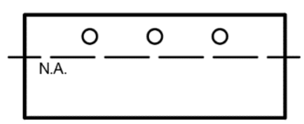
Contoured image shows plastic strain at service load.

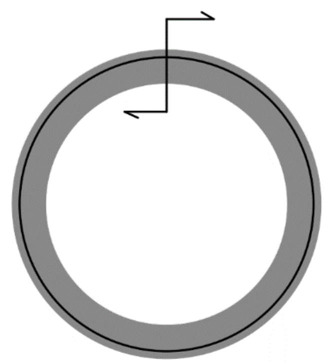
Class III - Wall C - Diameter 72 – 65%



Graph A-25, RCP Class V - Wall C - Diameter 72- 65%

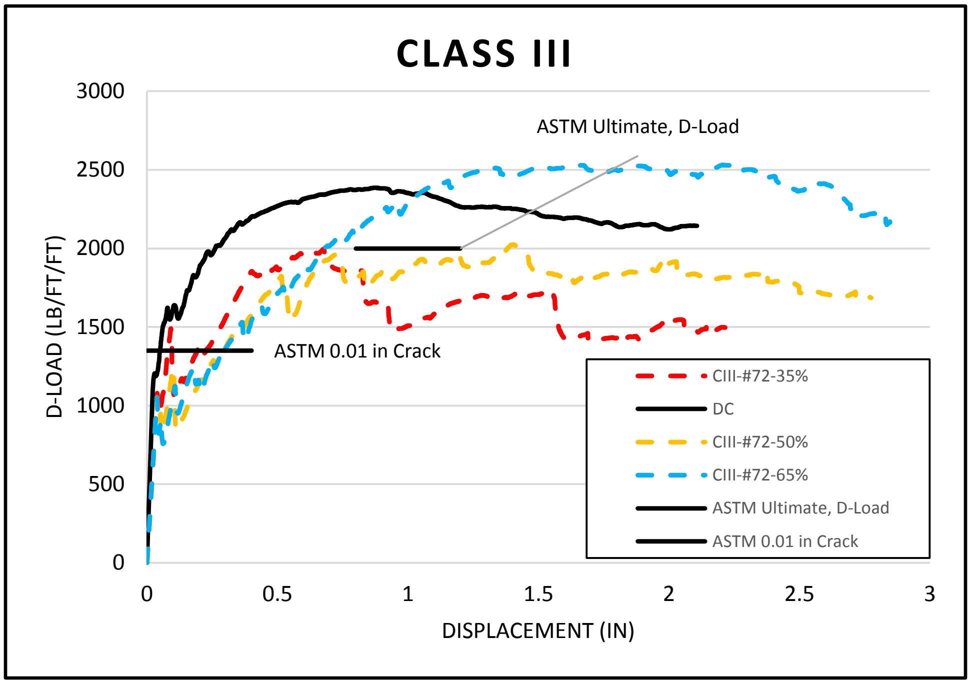






Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 1350)	D-Load for Ultimate (ASTM required = 2000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	0.57	-	1044	2510

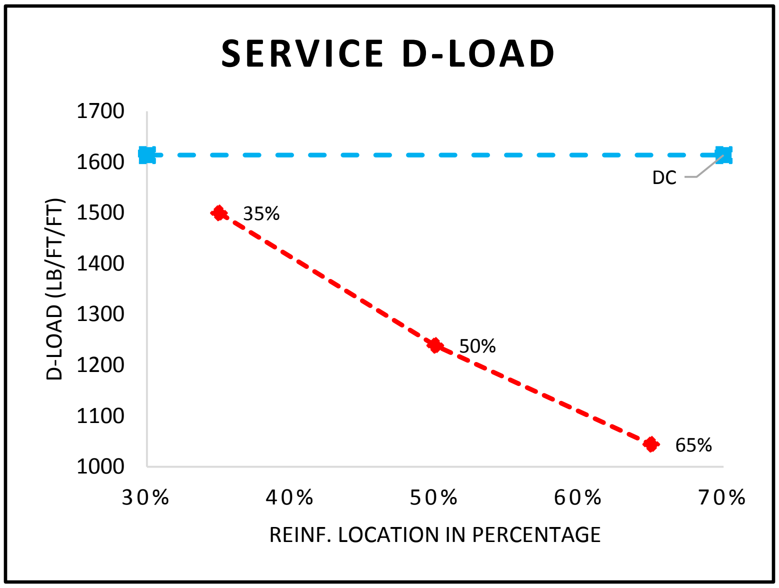
Contoured image shows plastic strain at service load.



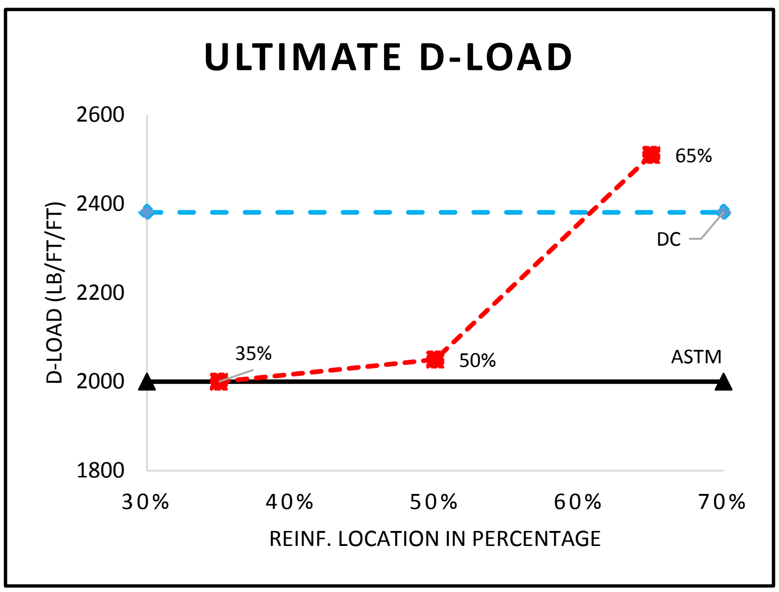
Graph A-26, Comprehensive Graph for Class III-72 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	72	7.75	0.36	0.21	1614	100	2381	100
35%	72	7.75	0.57	-	1500	93	2000	84
50%	72	7.75	0.57	-	1239	77	2050	86
65%	72	7.75	0.57	-	1044	65	2510	105

Table A-4, Comprehensive Table for Class III-72 in. Pipe diameter

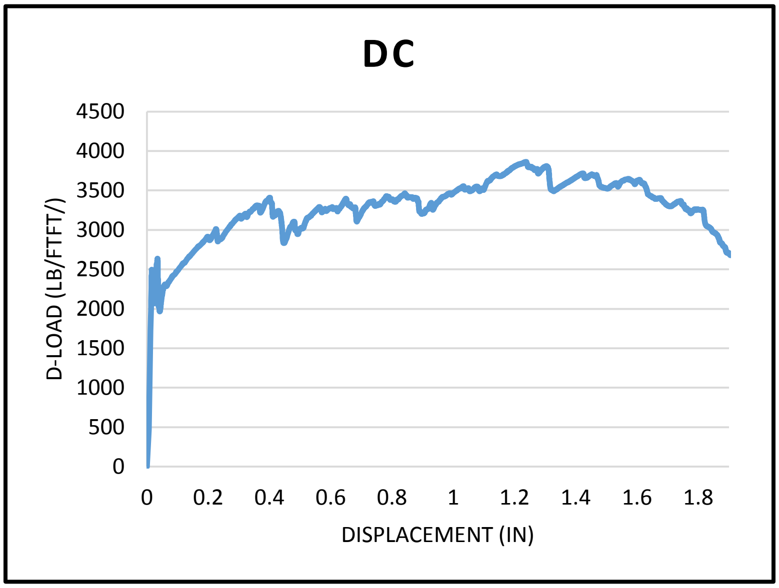


Graph A-27, Comprehensive Graph for Class III-72 in. Pipe diameter

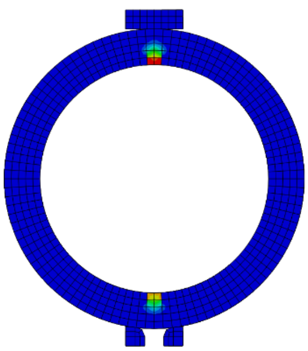


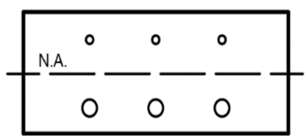
Graph A-28, Comprehensive Graph for Class III-72 in. Pipe diameter

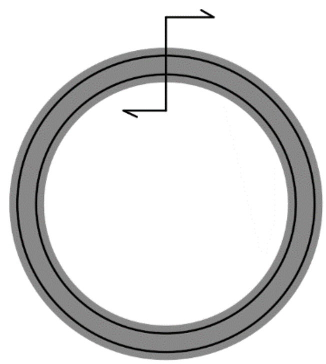
Class IV - Wall C - Diameter 24 – DC



Graph A-29, RCP Class IV - Wall C - Diameter 24 - Double Cage







Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.07	0.07	2629	3862

Contoured image shows plastic strain at service load.

Class IV - Wall C - Diameter 24 – 35%

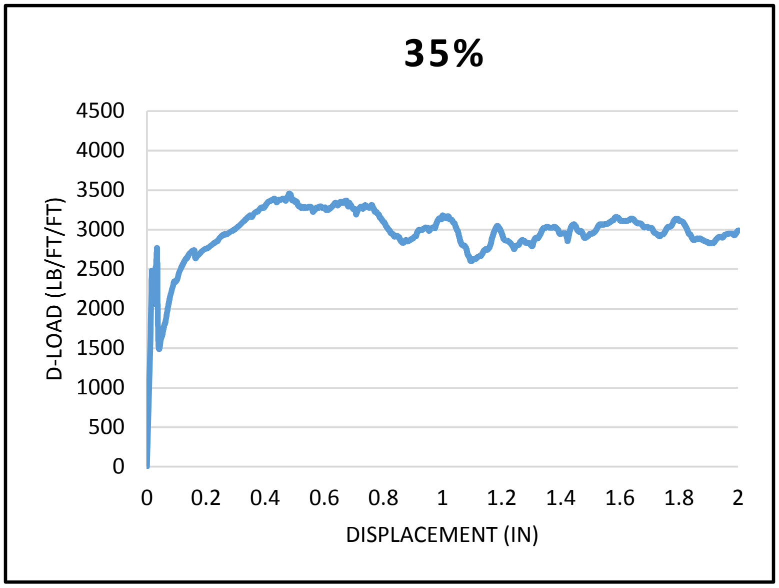
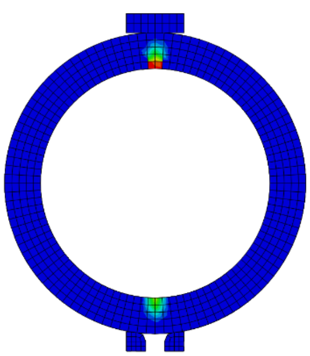
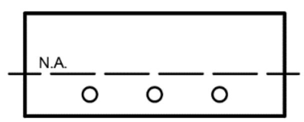
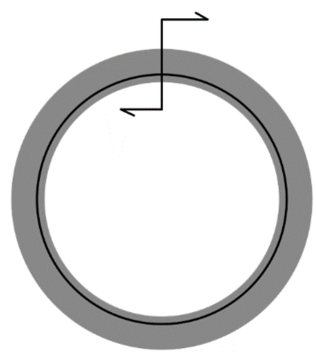


Figure A-30, RCP Class IV - Wall C - Diameter 24 – 35%



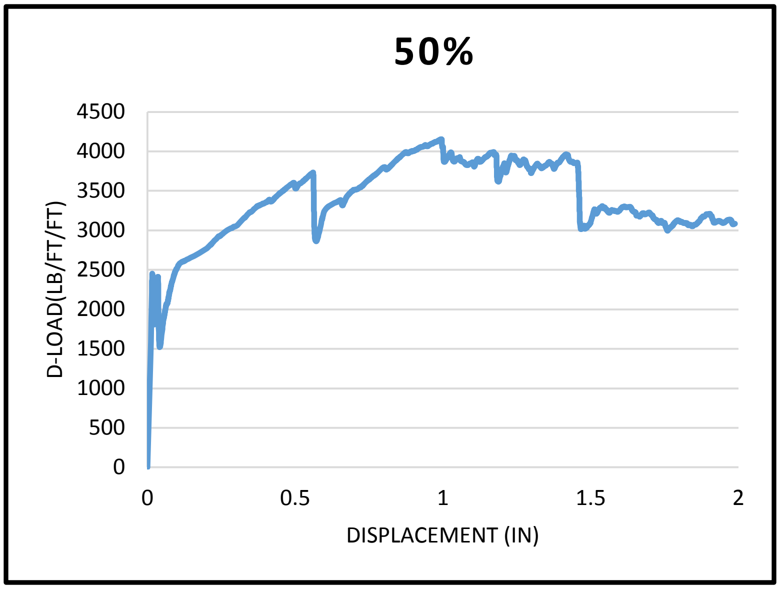




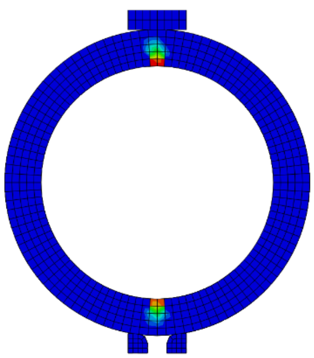
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.14	-	2760	3455

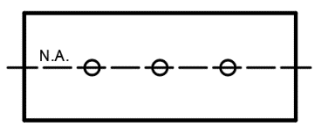
Contoured image shows plastic strain at service load.

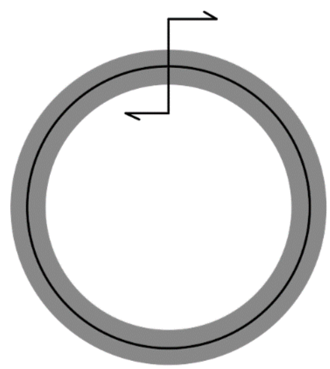
Class IV - Wall C - Diameter 24 – 50%



Graph A-31, Figure 4-5, RCP Class IV - Wall C - Diameter 24 – 50%



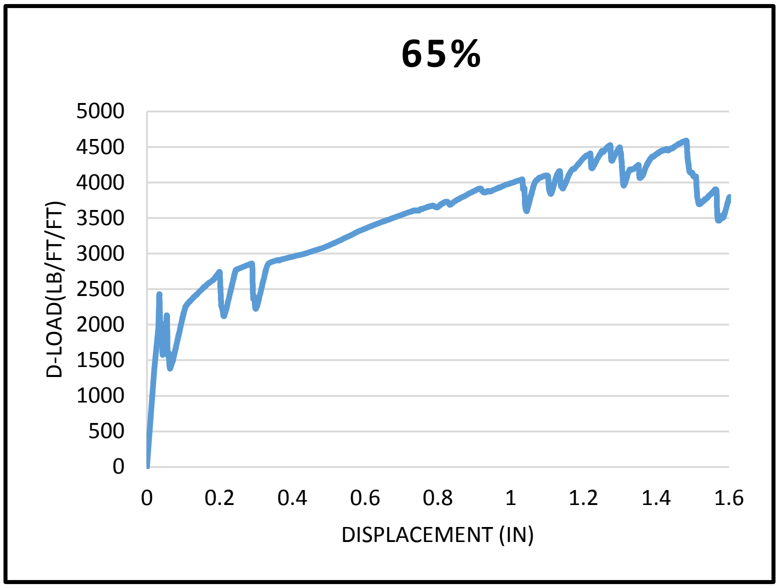




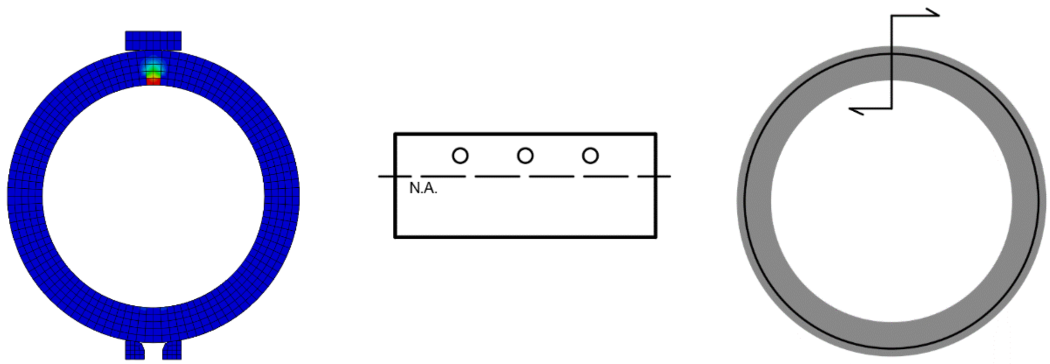
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.14	-	2441	4152

Contoured image shows plastic strain at service load.

Class IV - Wall C - Diameter 24 – 65%

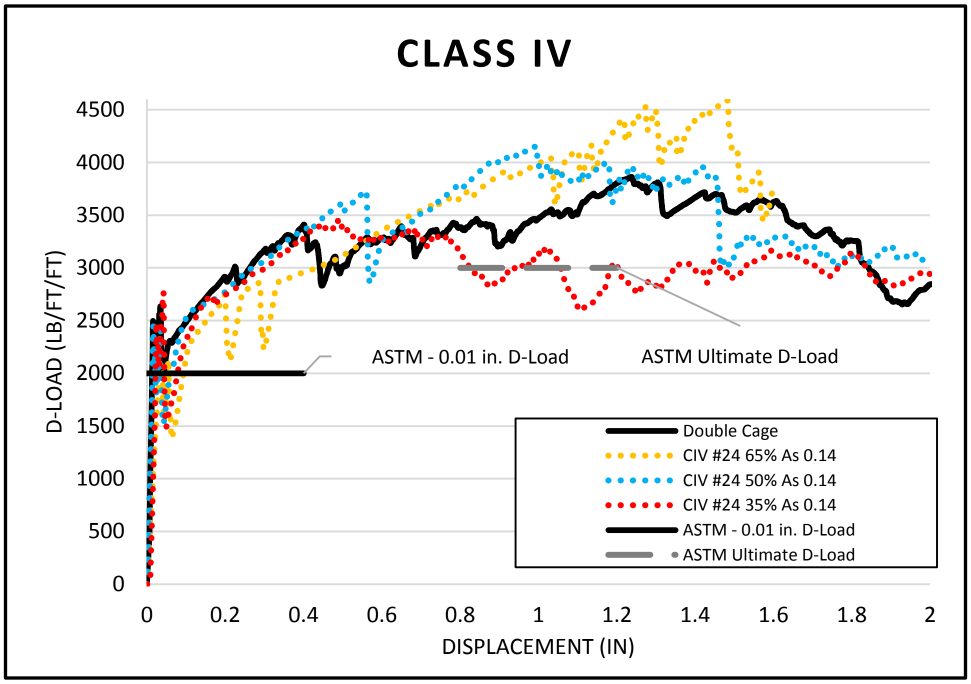


Graph A-32, Figure 4-5, RCP Class IV - Wall C - Diameter 24 – 65%



Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.14	-	2421	4586

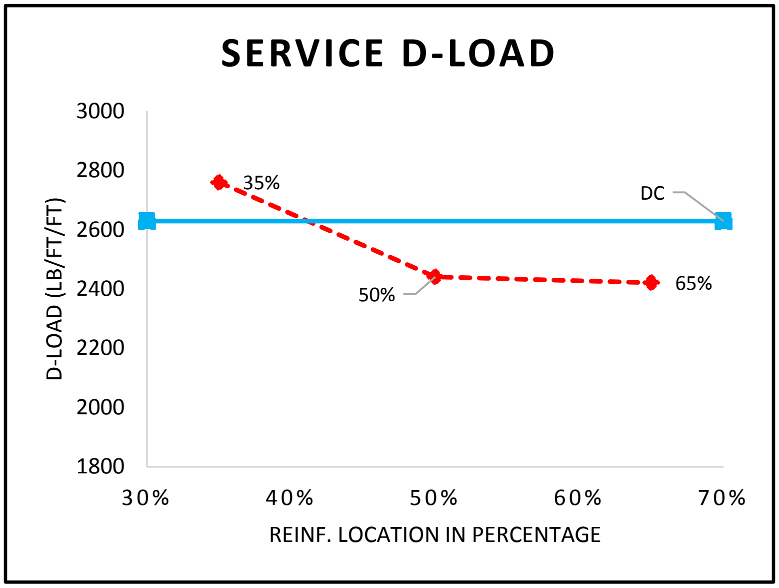
Contoured image shows plastic strain at service load.



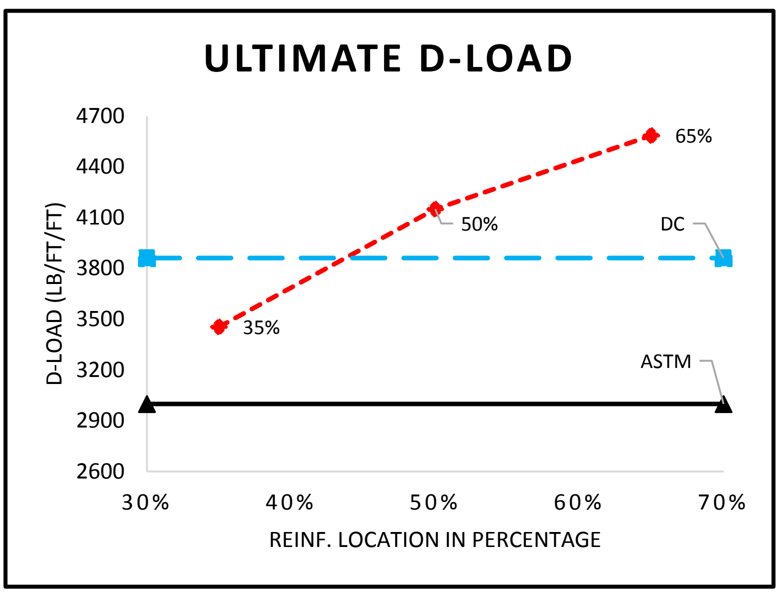
Graph A-33, Comprehensive Graph for Class IV-24 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	24	3.75	0.07	0.07	2629	100.0	3862	100.0
35%	24	3.75	0.14	-	2760	105	3455	89
50%	24	3.75	0.14	-	2441	93	4152	108
65%	24	3.75	0.14	-	2421	92	4586	119

Table A-5, Comprehensive Table for Class IV-24 in. Pipe diameter



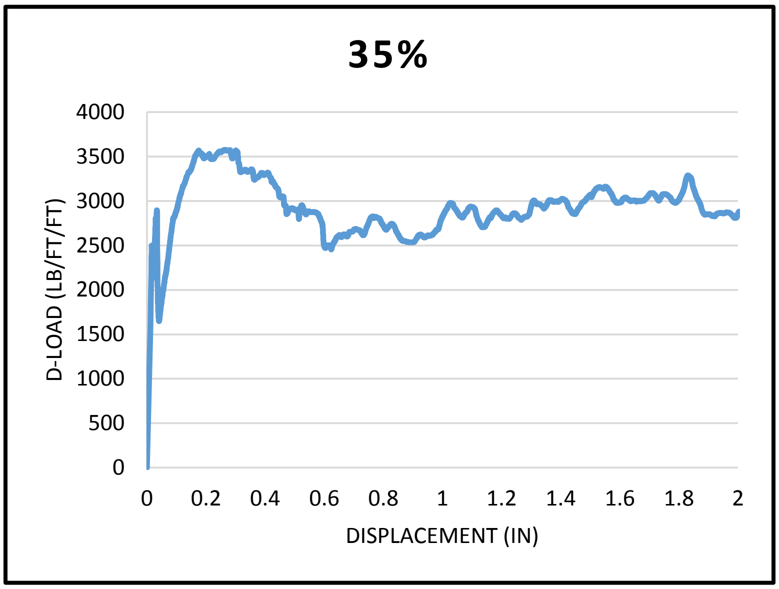
Graph A-34, Comprehensive Graph for Class IV-24 in. Pipe diameter



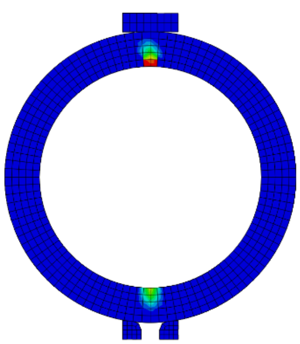
Graph A-35, Comprehensive Graph for Class IV-24 in. Pipe diameter

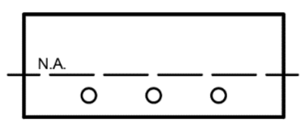
Class IV - Wall C - Diameter 24 – 35%

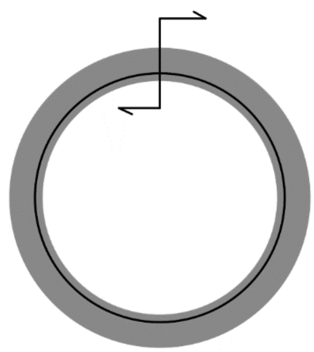
Reinforcement Area Increased by 25%



Graph A-36, RCP Class IV - Wall C - Diameter 24 – 35%
Reinforcement Area increased for 25%





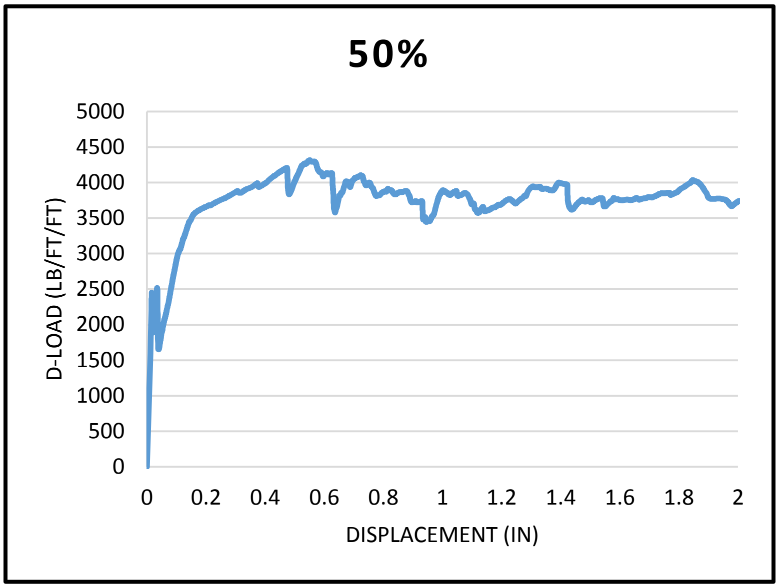


Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.2	-	2890	3574

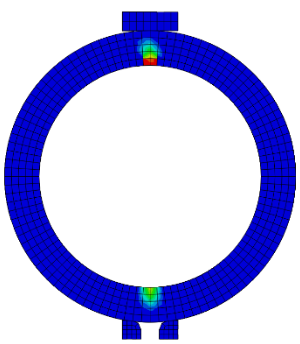
Contoured image shows plastic strain at service load.

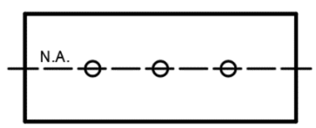
Class IV - Wall C - Diameter 24 – 50%

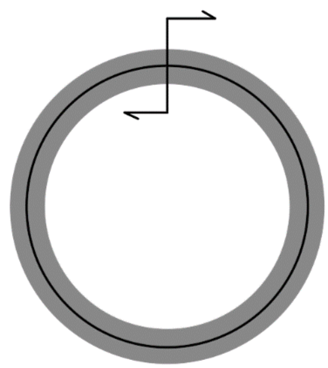
Reinforcement Area Increased by 25%



Graph A-37, RCP Class IV - Wall C - Diameter 24 – 50%
Reinforcement Area increased by 25%





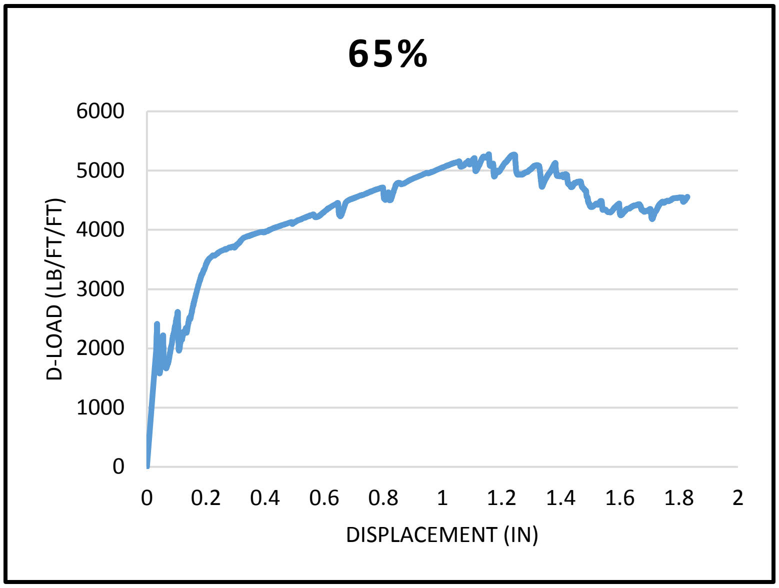


Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.2	- 114	2503	4297

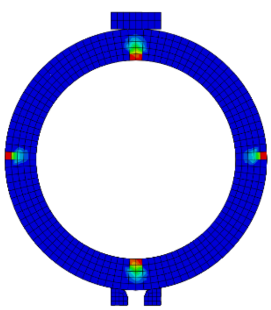
Contoured image shows plastic strain at service load.

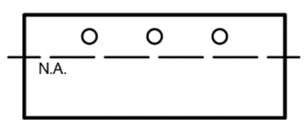
Class IV - Wall C - Diameter 24 – 65%

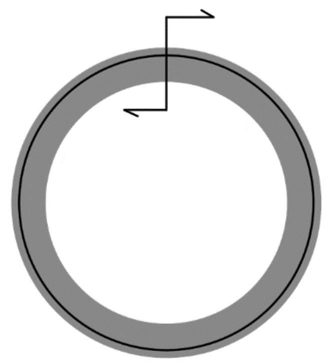
Reinforcement Area Increased by 25%



Graph A-38, RCP Class IV - Wall C - Diameter 24 – 65%
Reinforcement Area increased by 25%

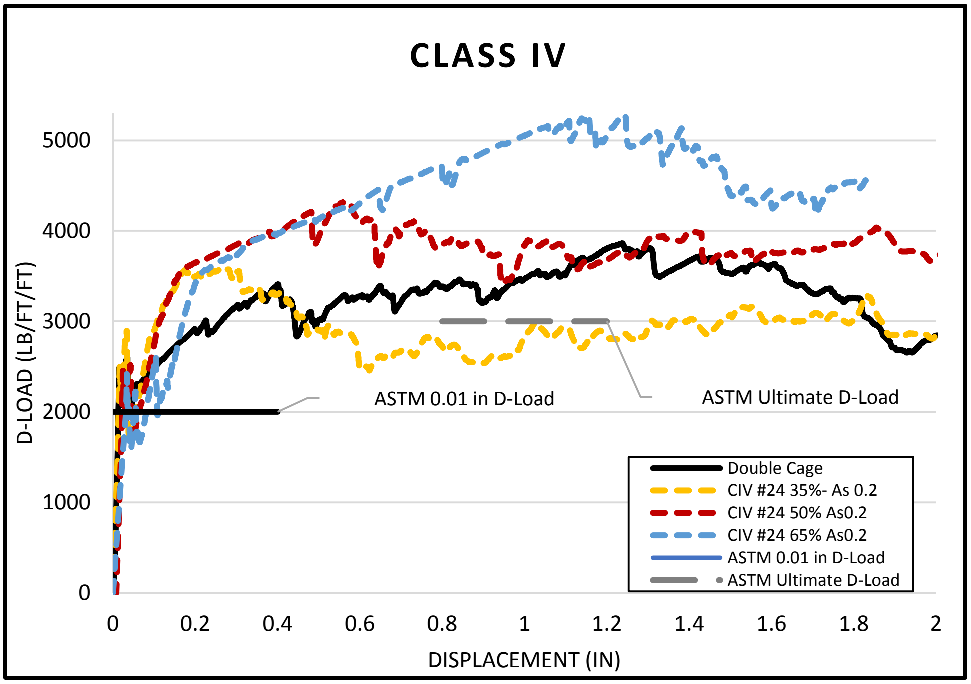






Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.2	-	2402	5257

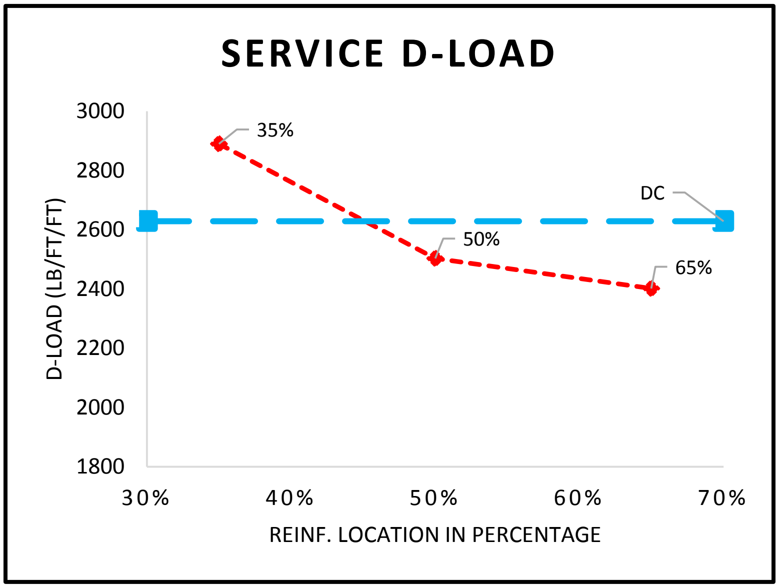
Contoured image shows plastic strain at service load.



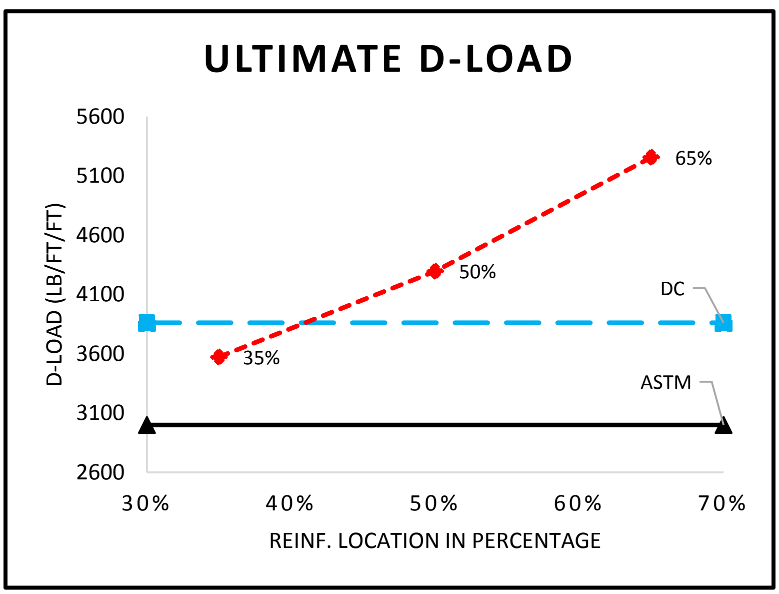
Graph A-39, Comprehensive Graph for Class IV-24 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load (Class-3000)		D-Load (Ultimate)	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	24	3.75	0.07	0.07	2629	100	3862	100
35%	24	3.75	0.2	-	2890	109	3574	93
50%	24	3.75	0.2	-	2503	95	4297	111
65%	24	3.75	0.2	-	2402	91	5257	136

Table A-6, Comprehensive Table for Class IV-24 in. Pipe diameter

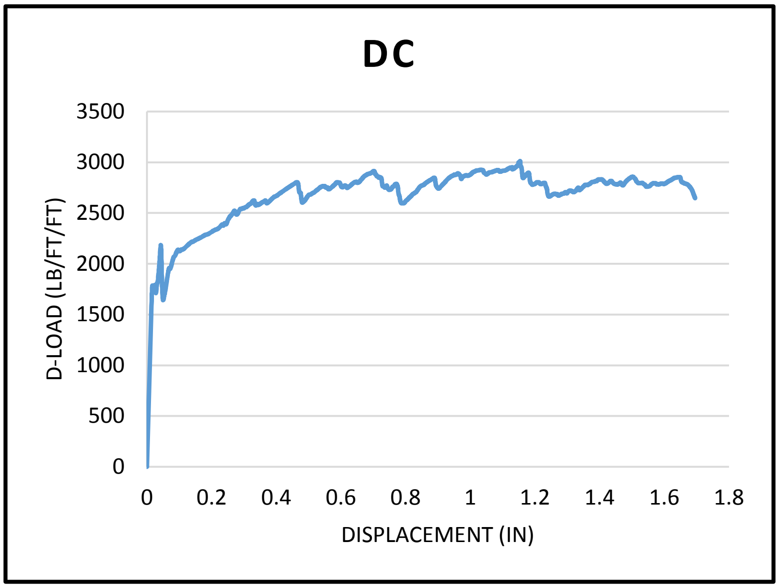


Graph A-40, Comprehensive Graph for Class IV-24 in. Pipe diameter

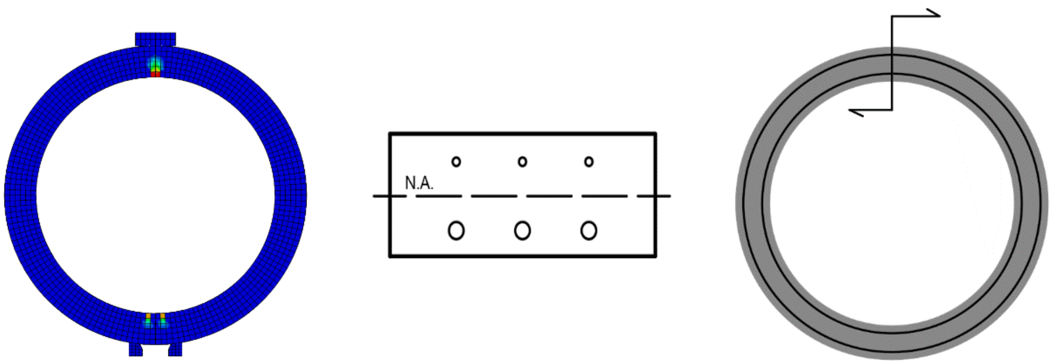


Graph A-41, Comprehensive Graph for Class IV-24 in. Pipe diameter

Class IV - Wall C - Diameter 36 – DC



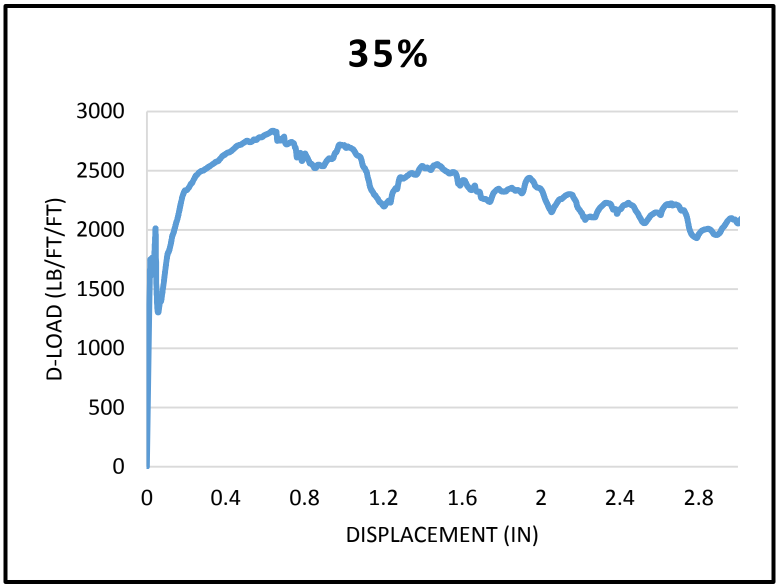
Graph A-42, RCP Class IV - Wall C - Diameter 36 – DC



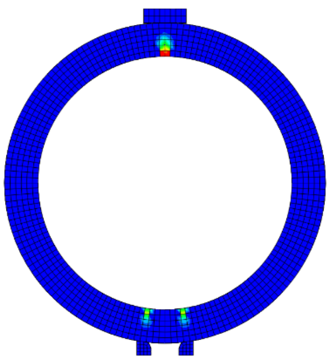
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.14	0.08	2179	3012

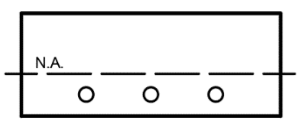
Contoured image shows plastic strain at service load.

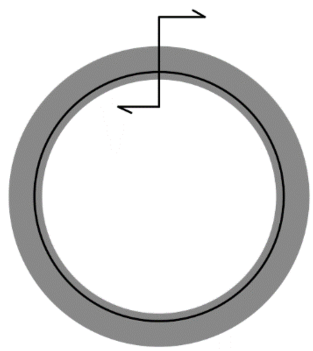
Class IV - Wall C - Diameter 36 – 35%



Graph A-43, RCP Class IV - Wall C - Diameter 36 – 35%



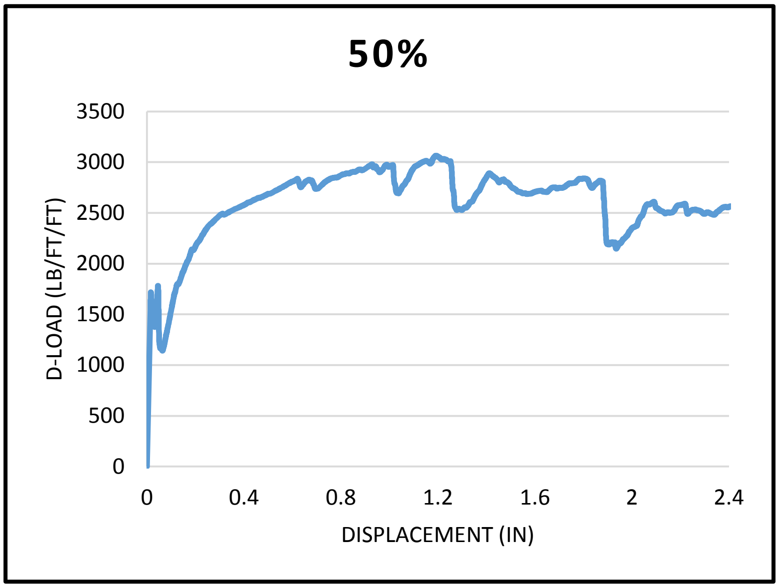




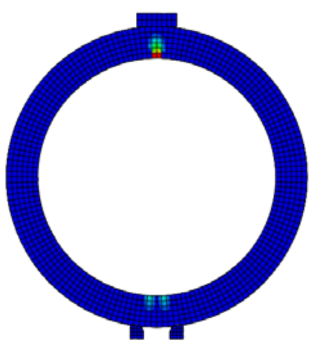
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.22	-	2000	2823

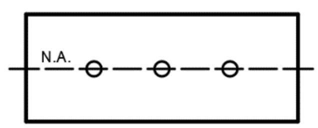
Contoured image shows plastic strain at service load.

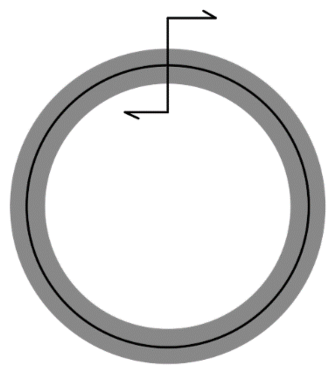
Class IV - Wall C - Diameter 36 – 50%



Graph A-44, RCP Class IV - Wall C - Diameter 36 –50%



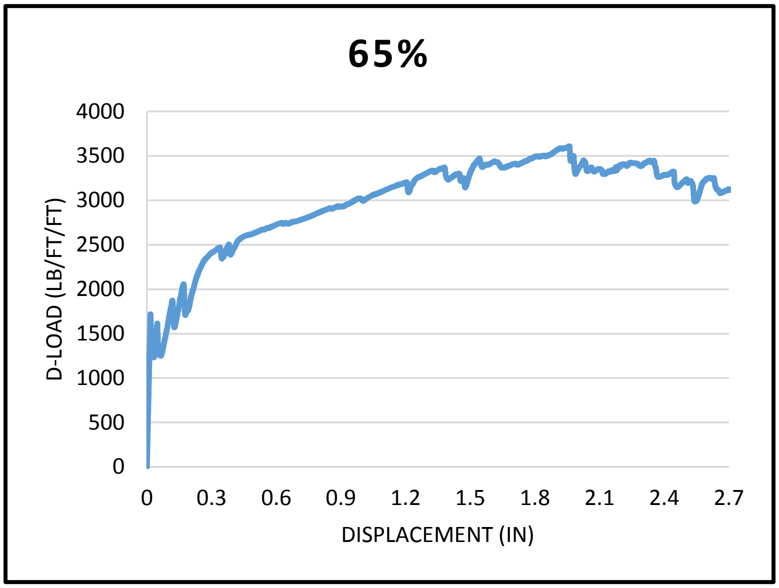




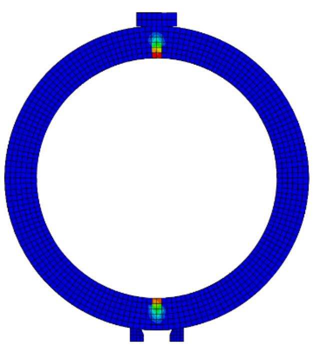
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.22	-	1771	3031

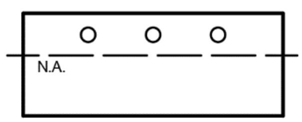
Contoured image shows plastic strain at service load.

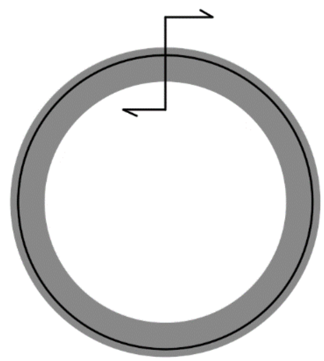
Class IV - Wall C - Diameter 36 – 65%



Graph A-44, RCP Class IV - Wall C - Diameter 36 –65%

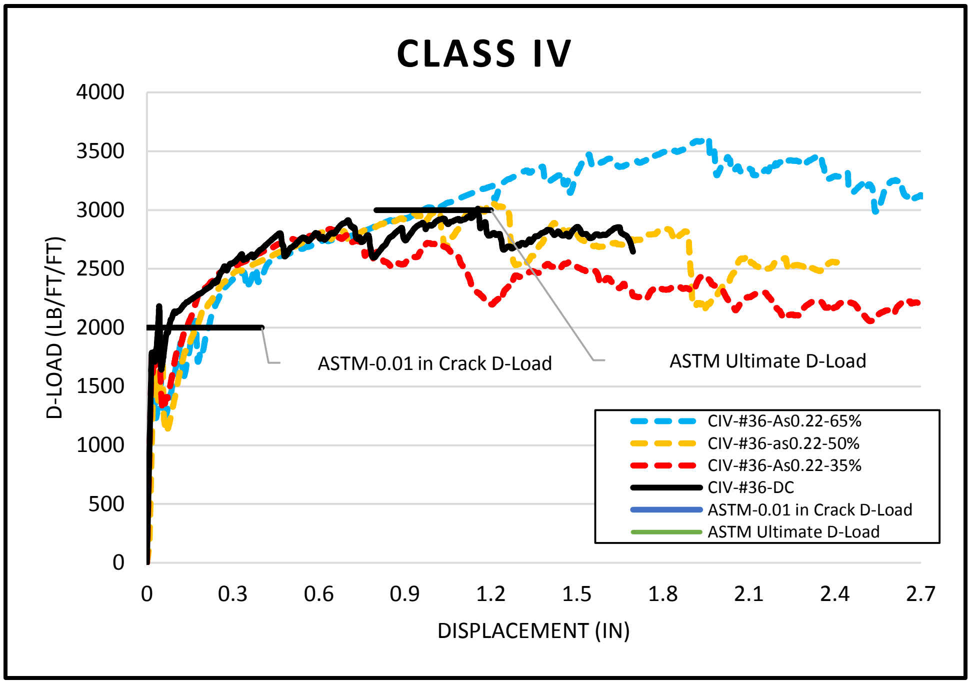






Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.22	-	1719	3568

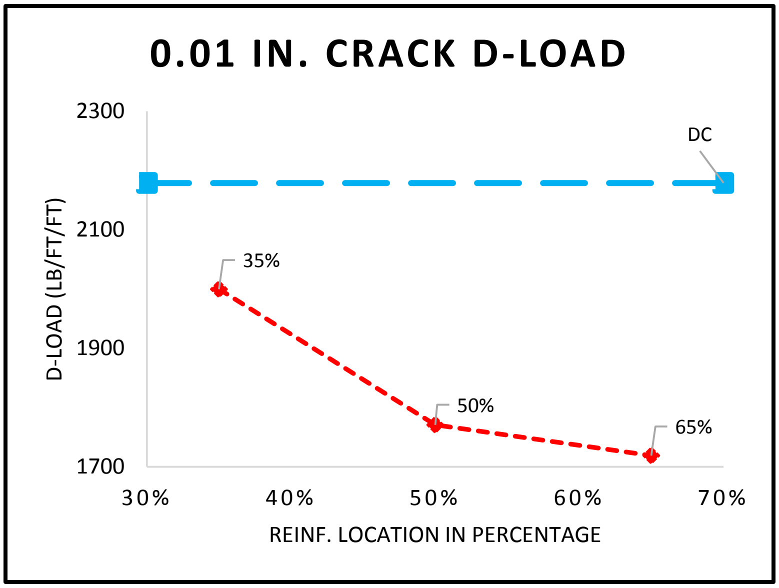
Contoured image shows plastic strain at service load.



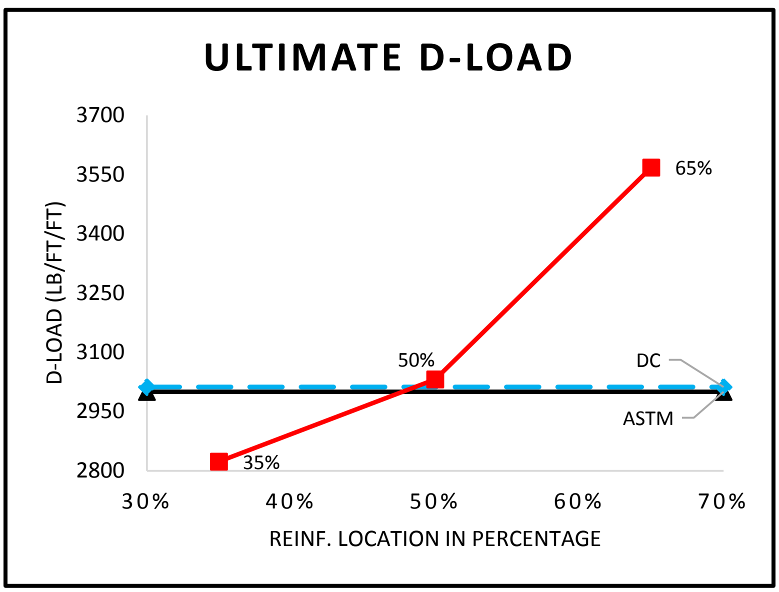
Graph A-45, Comprehensive Graph for Class IV-36 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load (Class-3000)		D-Load (Ultimate)	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	36	4.75	0.14	0.08	2179	100	3012	100
35%	36	4.75	0.22	-	2000	92	2823	94
50%	36	4.75	0.22	-	1771	81	3031	101
65%	36	4.75	0.22	-	1719	79	3568	118

Table A-7, Comprehensive Table for Class IV-36 in. Pipe diameter



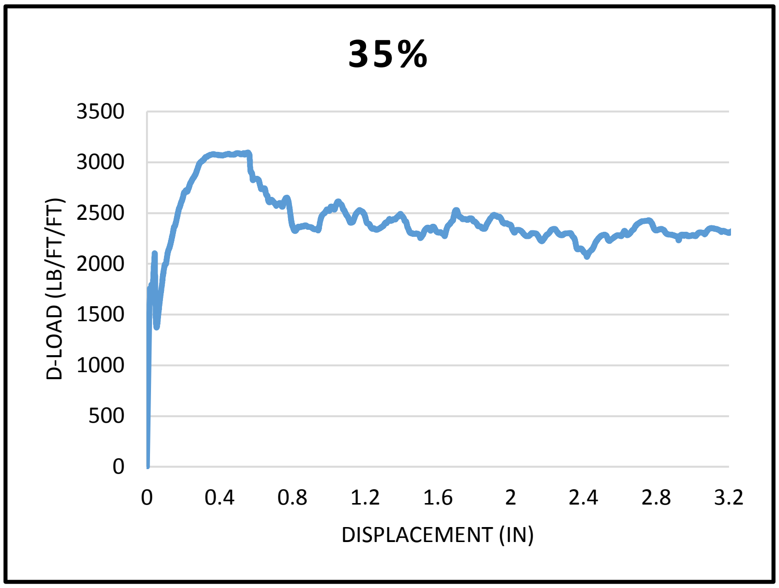
Graph A-46, Comprehensive Graph for Class IV-36 in. Pipe diameter



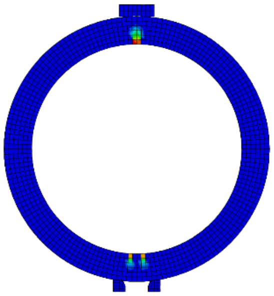
Graph A-47, Comprehensive Graph for Class IV-36 in. Pipe diameter

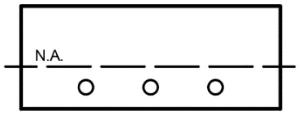
Class IV - Wall C - Diameter 36 – 35%

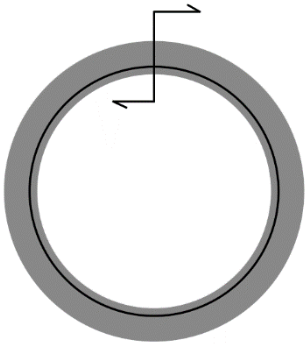
Reinforcement Area Increased by 25%



Graph A-48, RCP Class IV - Wall C - Diameter 36 –35%
Reinforcement Area Increased by 25%





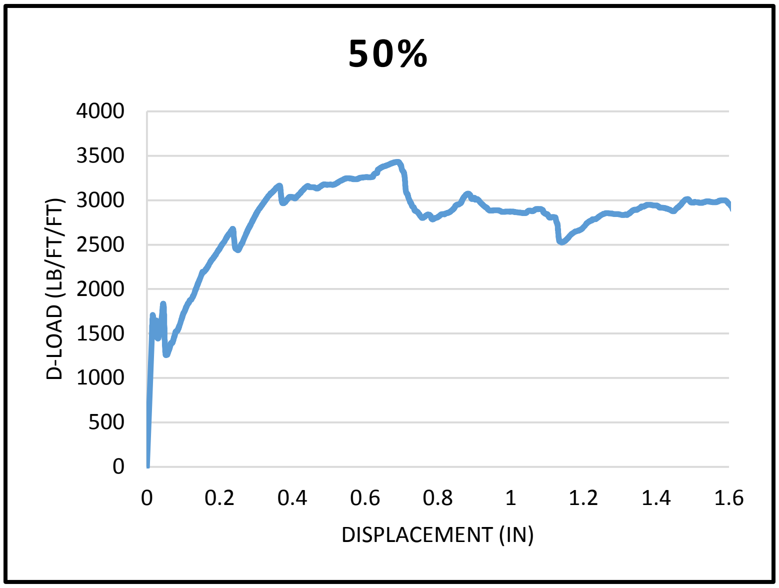


Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.3	-	2105	3091

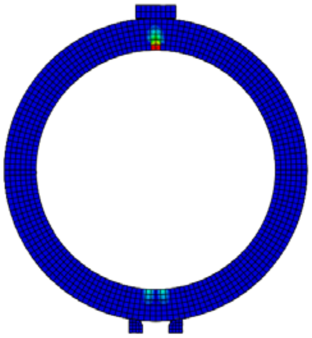
Contoured image shows plastic strain at service load.

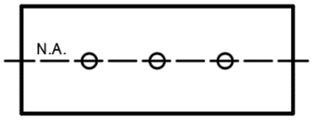
Class IV - Wall C - Diameter 36 – 50%

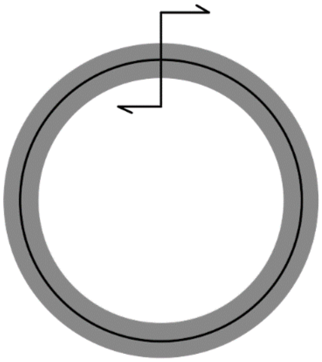
Reinforcement Area Increased by 25%



Graph A-49, RCP Class IV - Wall C - Diameter 36 –50% Reinforcement Area Increased by 25%





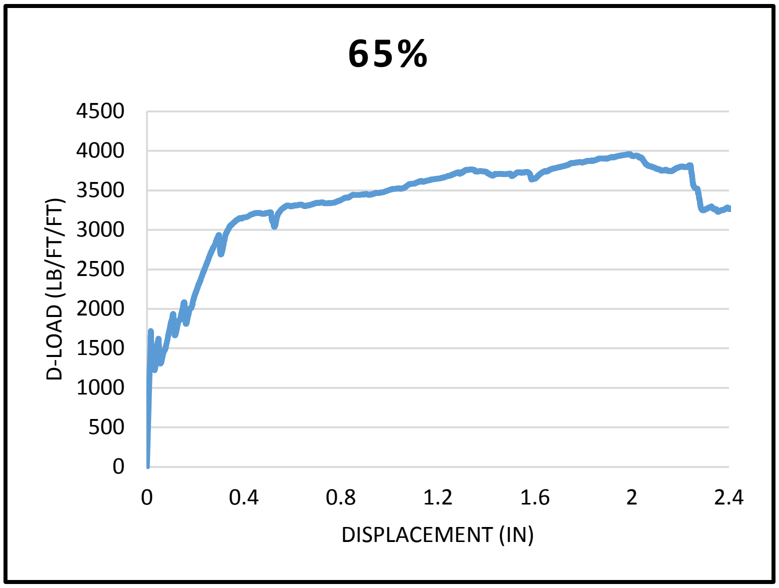


Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.3	-	1808	3416

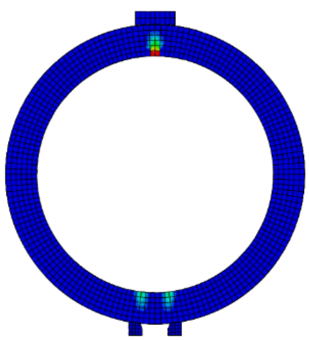
Contoured image shows plastic strain at service load.

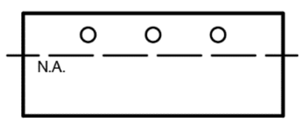
Class IV - Wall C - Diameter 36 – 65%

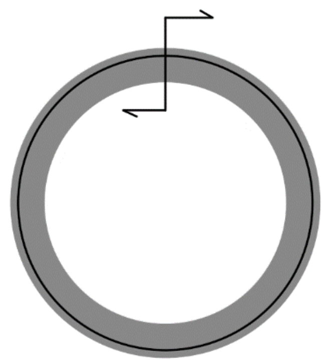
Reinforcement Area Increased by 25%



Graph A-50, RCP Class IV - Wall C - Diameter 36 –65%
Reinforcement Area Increased by 25%

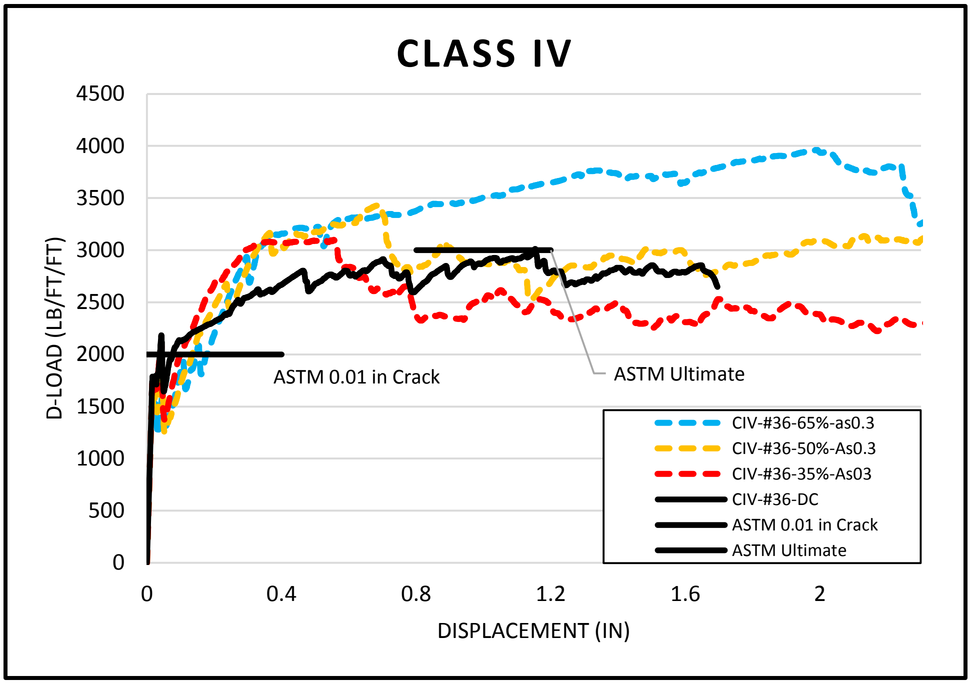






Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.3	-	1719	3939

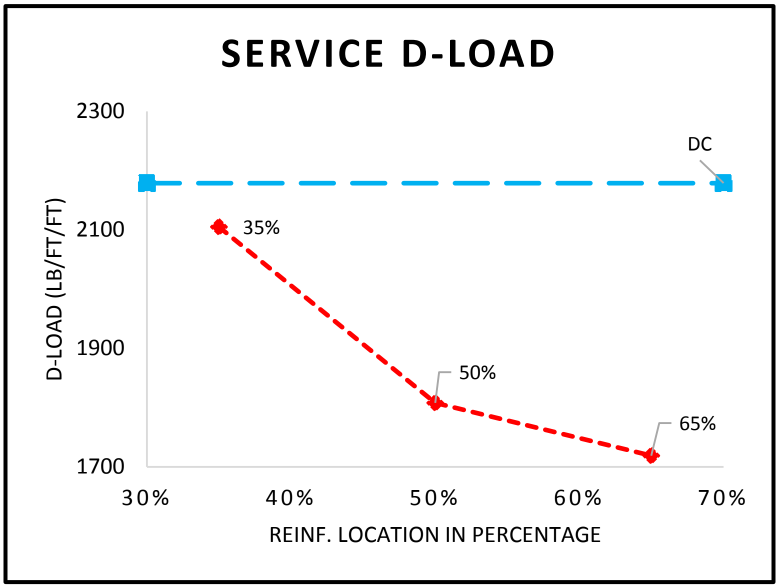
Contoured image shows plastic strain at service load.



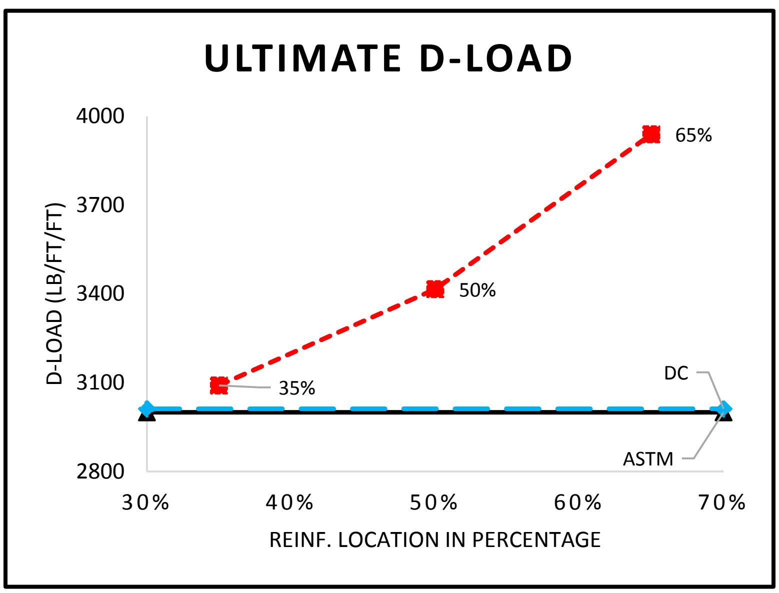
Graph A-51, Comprehensive Graph for Class IV-36 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load (Class-3000)		D-Load (Ultimate)	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	36	4.75	0.14	0.08	2179	100	3012	100
35%	36	4.75	0.3	-	2105	97	3091	103
50%	36	4.75	0.3	-	1808	83	3416	113
65%	36	4.75	0.3	-	1719	79	3939	131

Table A-8, Comprehensive Table for Class IV-36 in. Pipe diameter

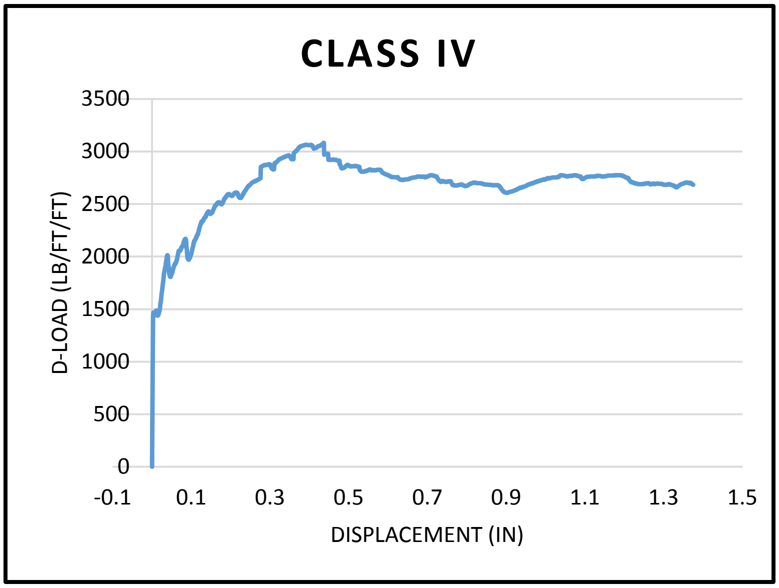


Graph A-52, Comprehensive Graph for Class IV-36 in. Pipe diameter

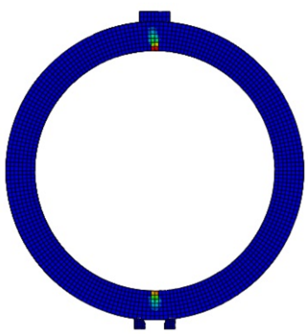


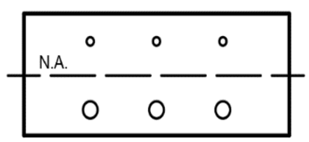
Graph A-53, Comprehensive Graph for Class IV-36 in. Pipe diameter

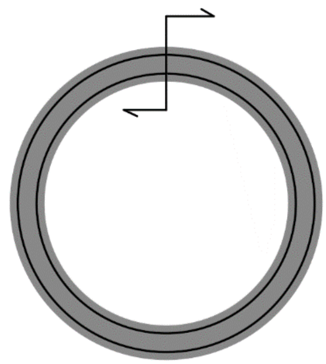
Class IV - Wall C - Diameter 48 – DC



Graph A-54, RCP Class IV - Wall C - Diameter 48 –DC



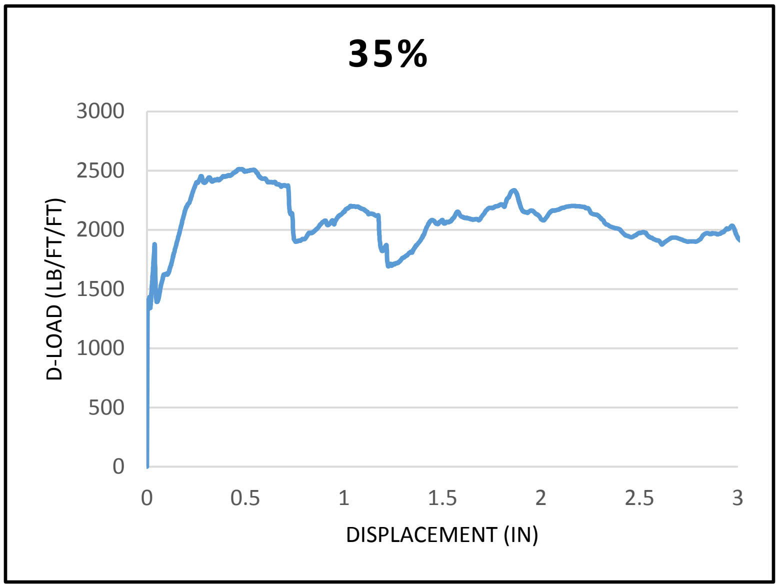




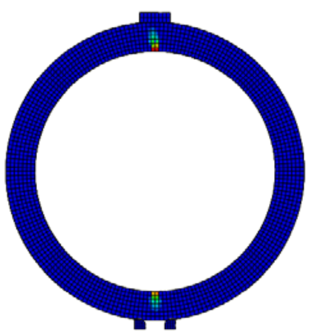
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.26	0.16	2000	3077

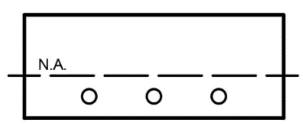
Contoured image shows plastic strain at service load.

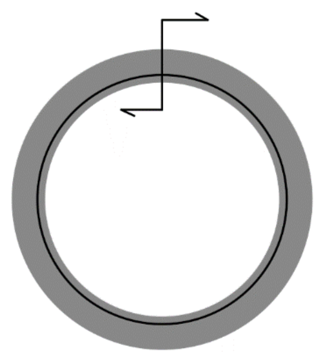
Class IV - Wall C - Diameter 48 – 35%



Graph A-55, RCP Class IV - Wall C - Diameter 48 –35%



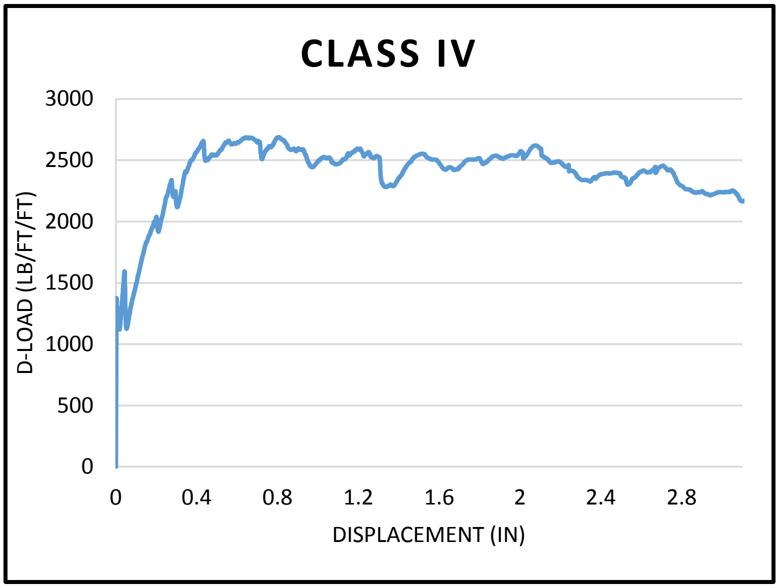




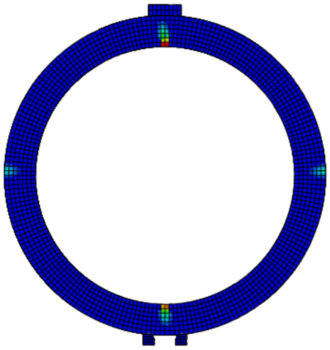
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.42	-	1867	2500

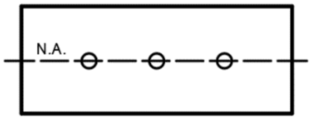
Contoured image shows plastic strain at service load.

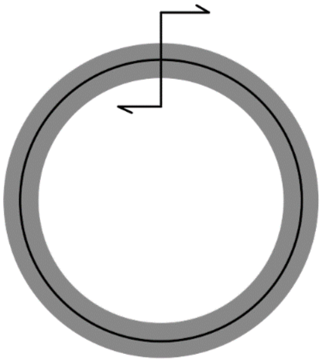
Class IV - Wall C - Diameter 48 – 50%



Graph A-56, RCP Class IV - Wall C - Diameter 48 –50%



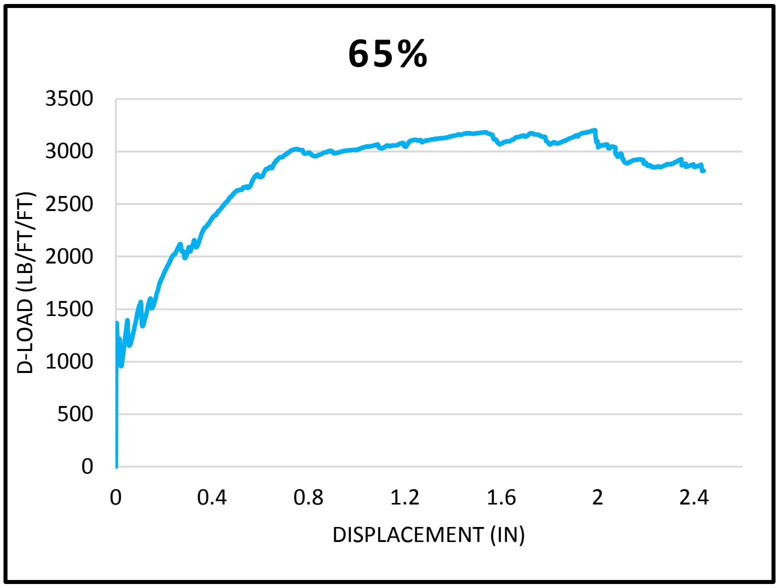




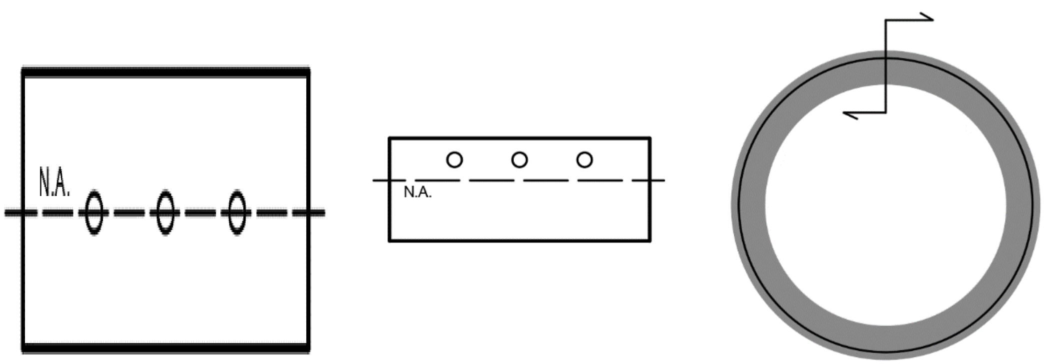
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.42	-	1600	2670

Contoured image shows plastic strain at service load.

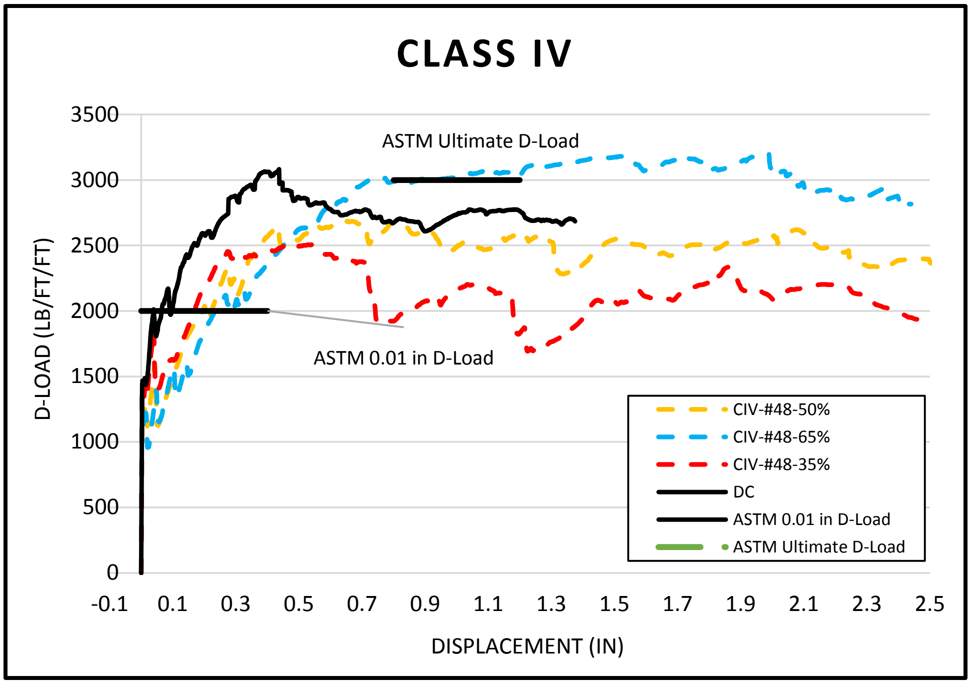
Class IV - Wall C - Diameter 48 – 65%



Graph A-57, RCP Class IV - Wall C - Diameter 48 –65%



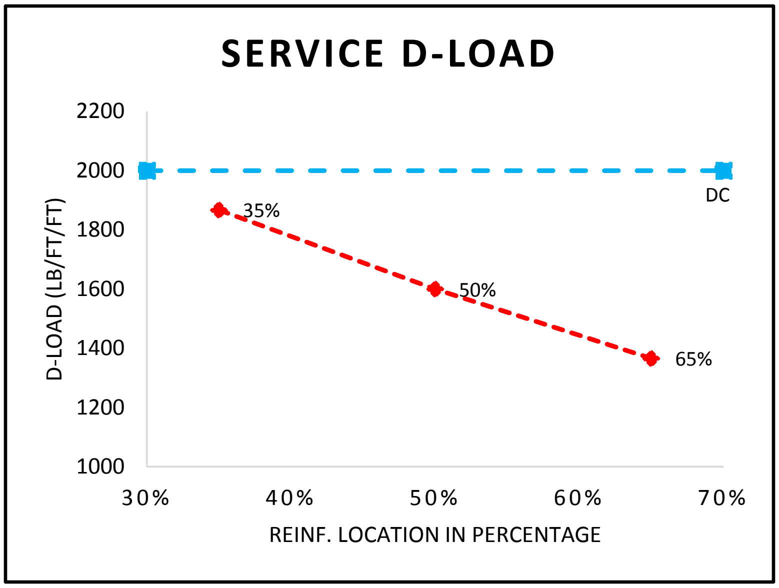
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.42	-	1366	3201



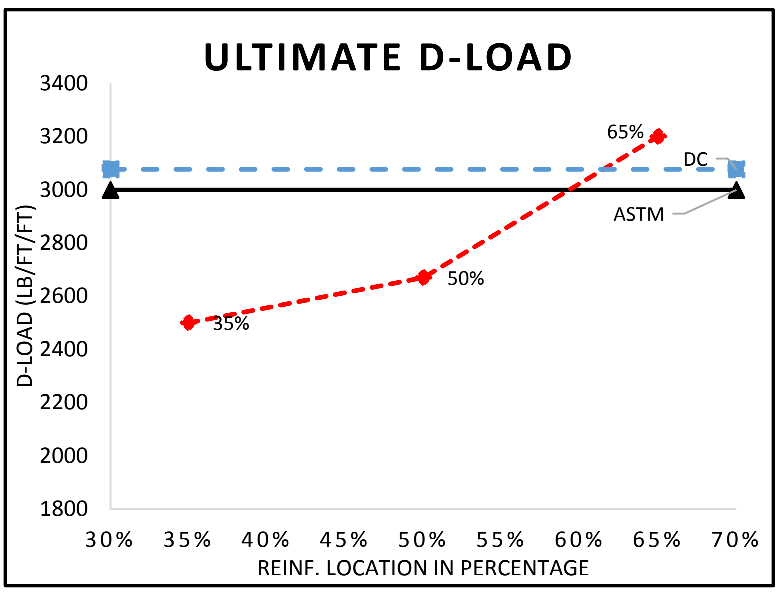
Graph A-58, Comprehensive Graph for Class IV-48 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	48	5.75	0.26	0.16	2000	100	3077	100
35%	48	5.75	0.42	-	1867	93	2500	81
50%	48	5.75	0.42	-	1600	80	2670	87
65%	48	5.75	0.42	-	1366	68	3201	104

Table A-9, Comprehensive Table for Class IV-48 in. Pipe diameter

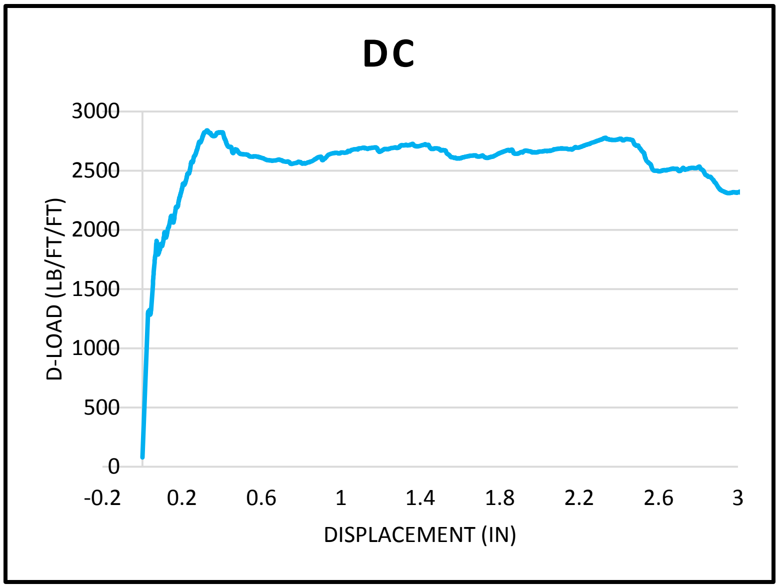


Graph A-59, Comprehensive Graph for Class IV-48 in. Pipe diameter

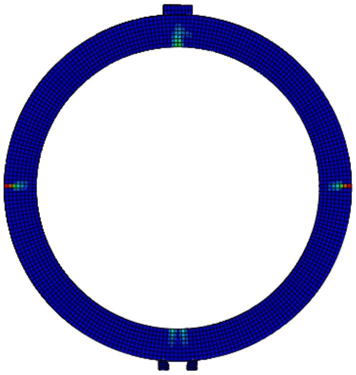


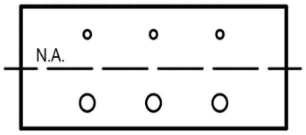
Graph A-60, Comprehensive Graph for Class IV-48 in. Pipe diameter

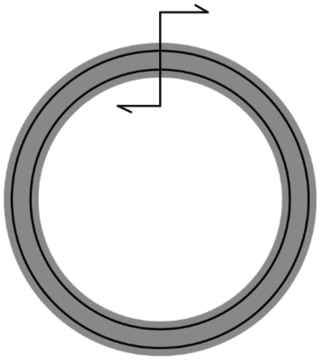
Class IV - Wall C - Diameter 60 – DC



Graph A-61, RCP Class IV - Wall C - Diameter 60 –DC



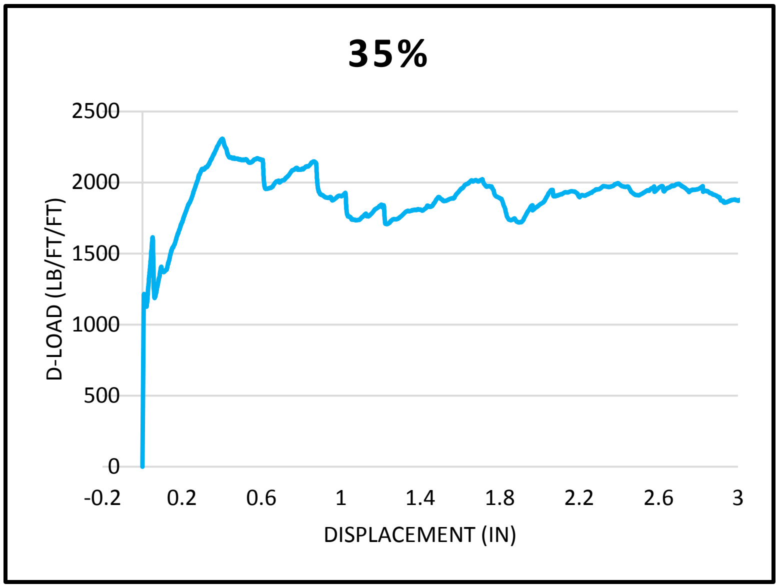




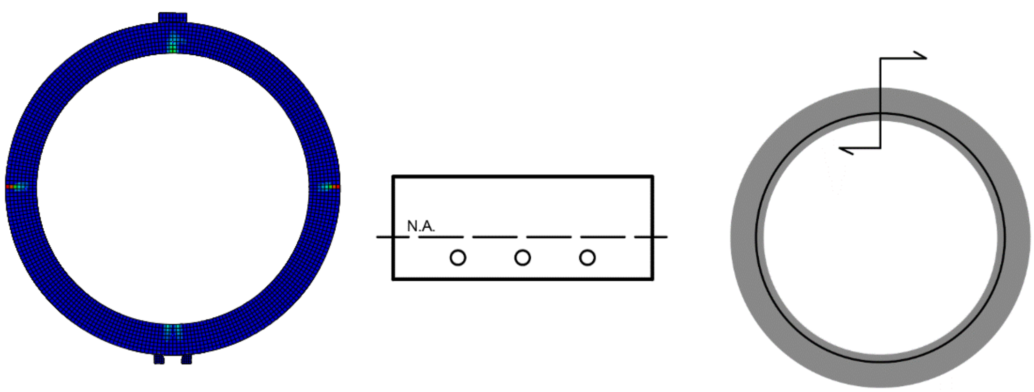
Concrete Strength, 4000 psi						
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	0.41	0.24	1931	2839

Contoured image shows plastic strain at service load.

Class IV - Wall C - Diameter 60 – 35%



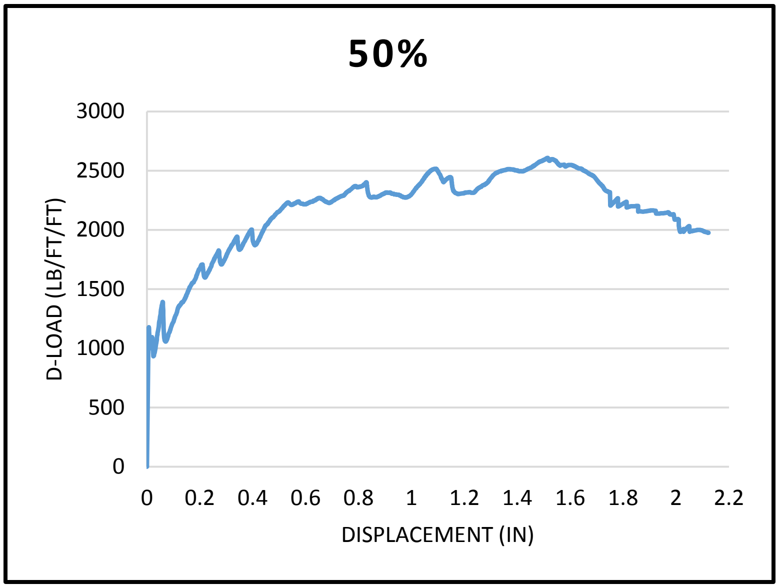
Graph A-62, RCP Class IV - Wall C - Diameter 60 –35%



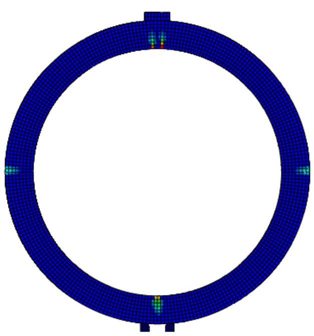
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	0.65	-	1615	2305

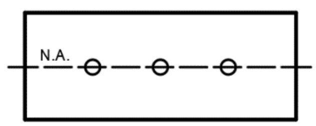
Contoured image shows plastic strain at service load.

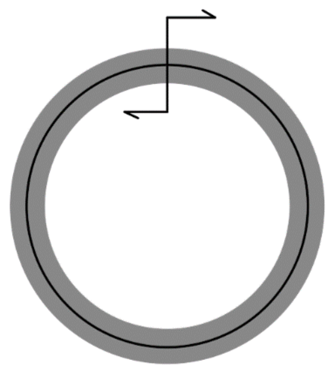
Class IV - Wall C - Diameter 60 – 50%



Graph A-63, RCP Class IV - Wall C - Diameter 60 –50%



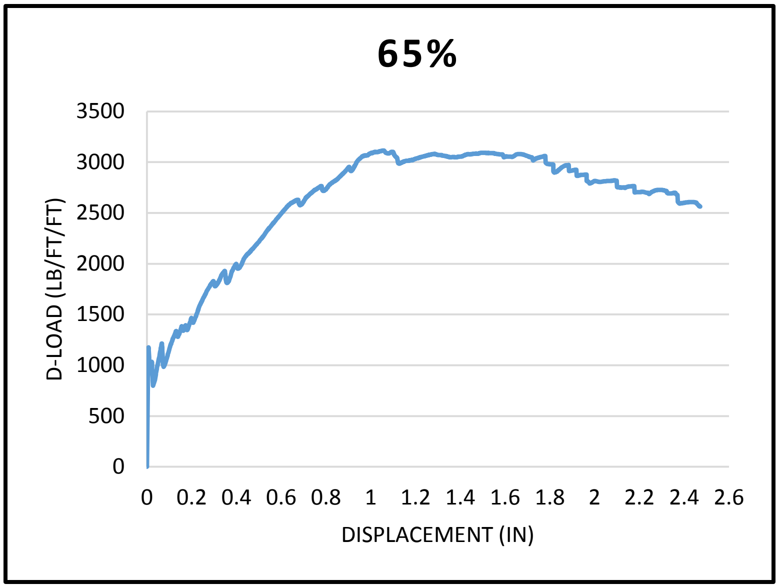




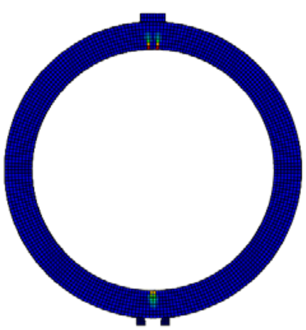
Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	0.65	-	1391	2596

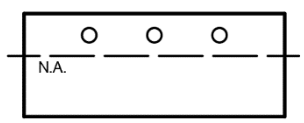
Contoured image shows plastic strain at service load.

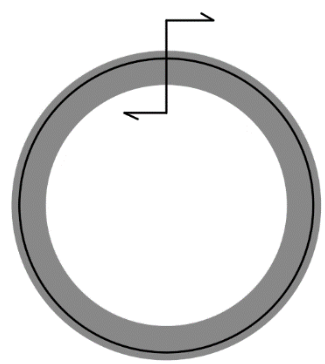
Class IV - Wall C - Diameter 60 – 65%



Graph A-64, RCP Class IV - Wall C - Diameter 60 –65%

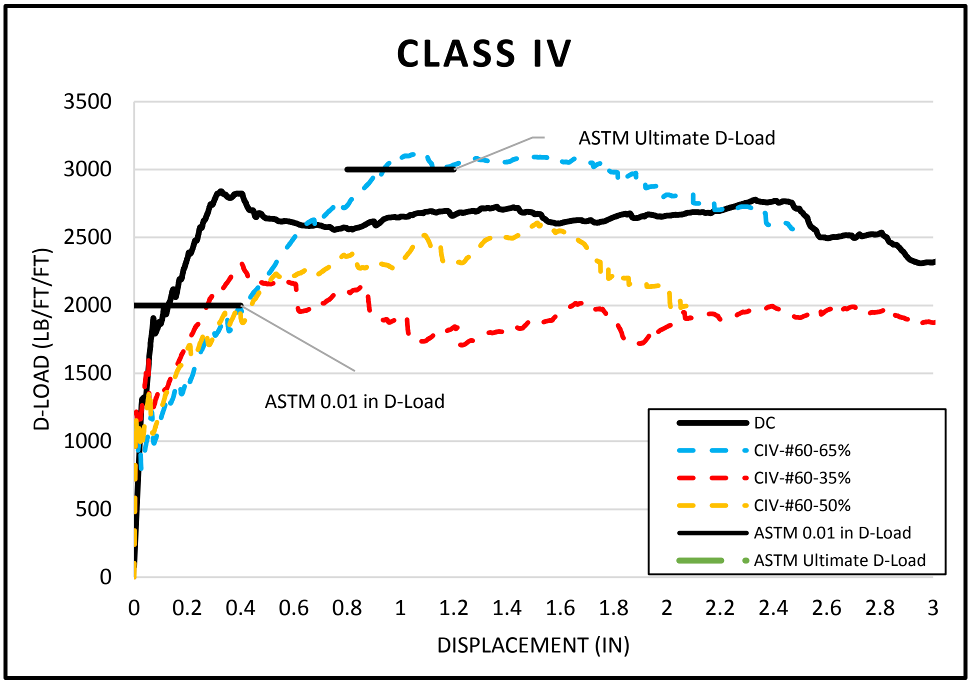






Concrete Strength, 4000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	0.65	-	1177	3114

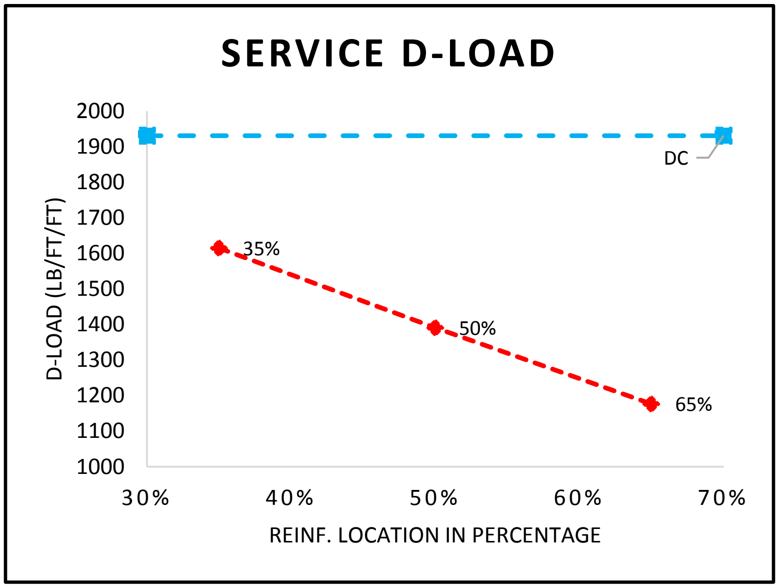
Contoured image shows plastic strain at service load.



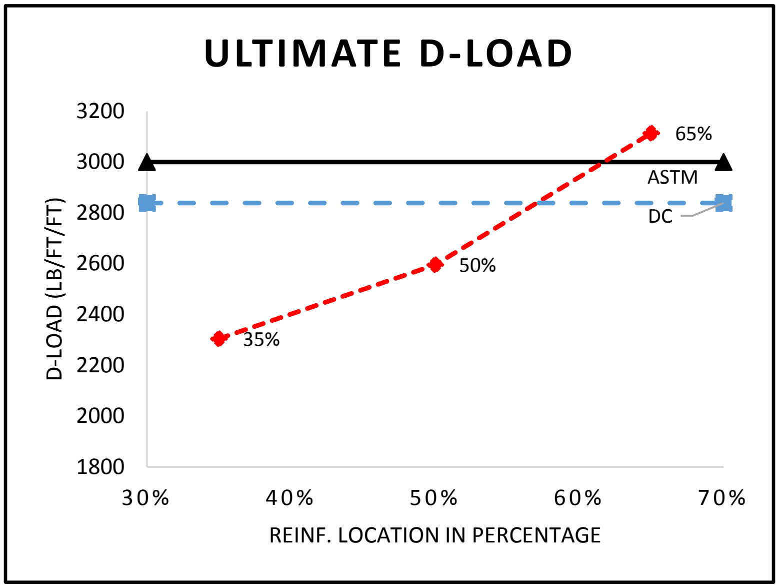
Graph A-65, Comprehensive Graph for Class IV-60 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	60	6.75	0.41	0.24	1931	100	2839	100
35%	60	6.75	0.65	-	1615	84	2305	81
50%	60	6.75	0.65	-	1391	72	2596	91
65%	60	6.75	0.65	-	1177	61	3114	110

Table A-10, Comprehensive Table for Class IV-60 in. Pipe diameter

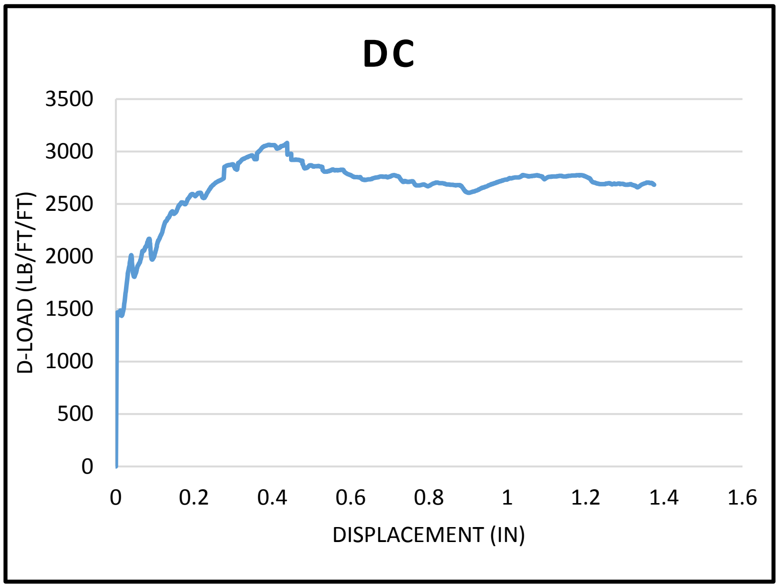


Graph A-66, Comprehensive Graph for Class IV-60 in. Pipe diameter

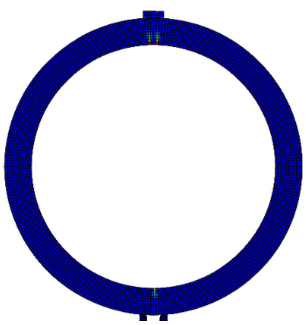


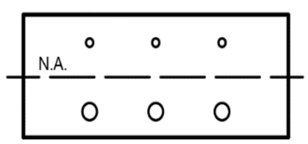
Graph A-67, Comprehensive Graph for Class IV-60 in. Pipe diameter

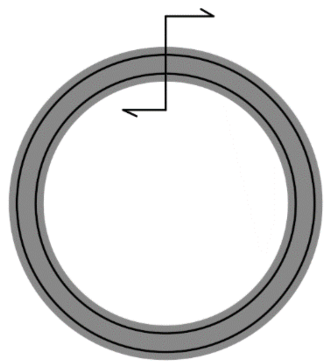
Class IV - Wall C - Diameter 72 – DC



Graph A-66, RCP Class IV - Wall C - Diameter 72 – DC



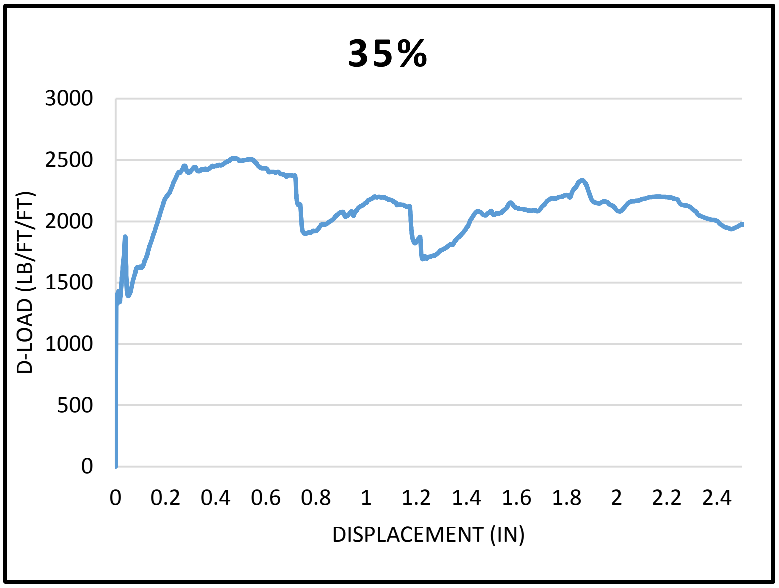




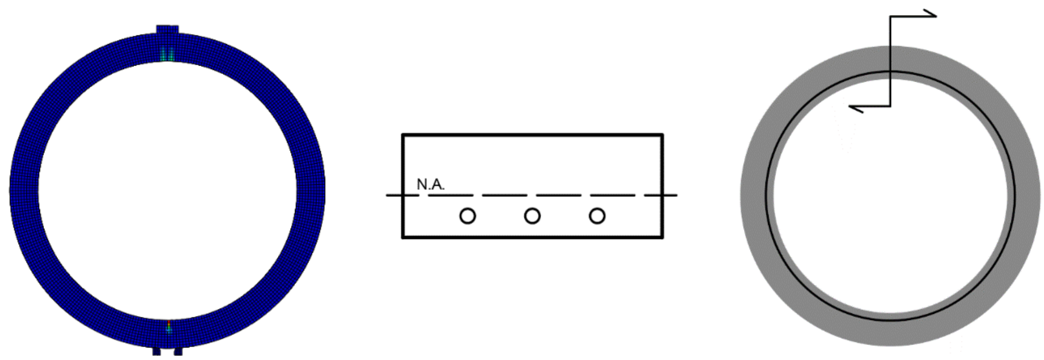
Concrete Strength, 5000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	0.6	0.36	2000	3074

Contoured image shows plastic strain at service load.

Class IV - Wall C - Diameter 72 – 35%



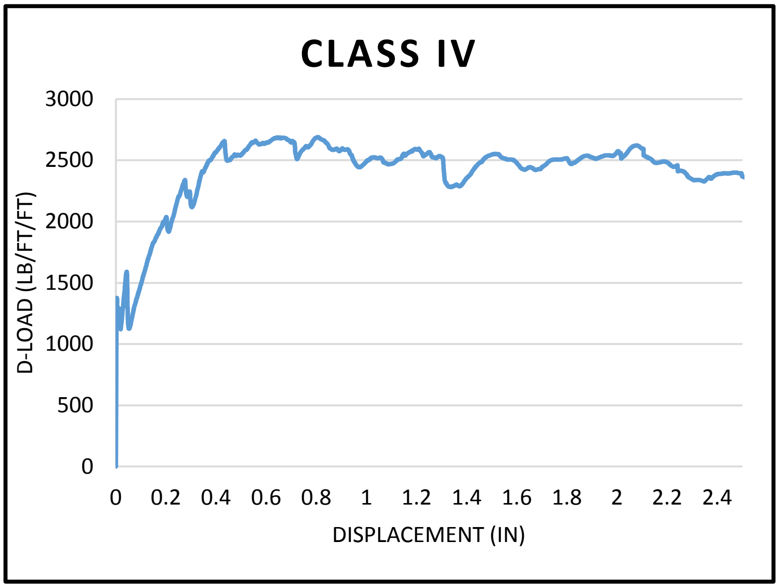
Graph A-67, RCP Class IV - Wall C - Diameter 72 – 35%



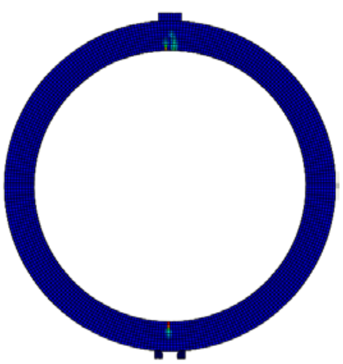
Concrete Strength, 5000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	0.96	-	1862	2500

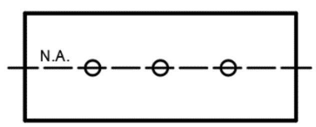
Contoured image shows plastic strain at service load.

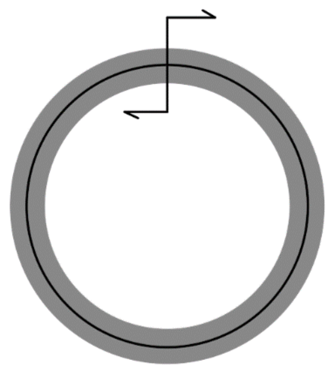
Class IV - Wall C - Diameter 72 – 50%



Graph A-68, RCP Class IV - Wall C - Diameter 72 – 50%



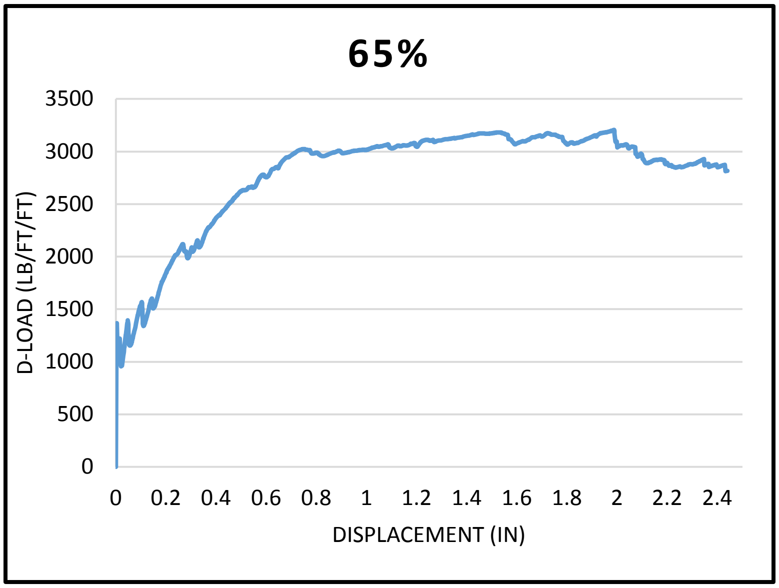




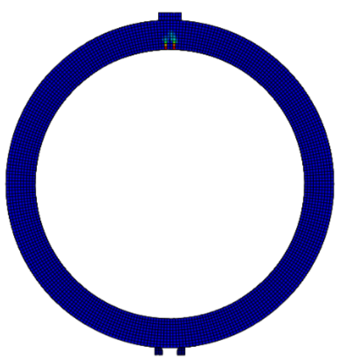
Concrete Strength, 5000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	0.96	-	1558	2673

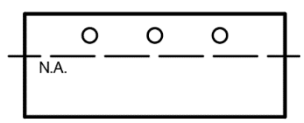
Contoured image shows plastic strain at service load.

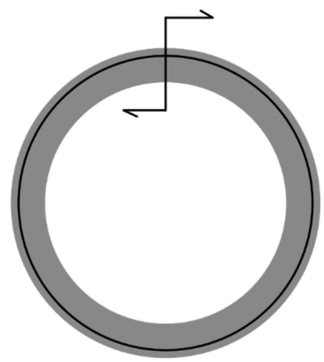
Class IV - Wall C - Diameter 72 – 65%



Graph A-69, RCP Class IV - Wall C - Diameter 72 –65%

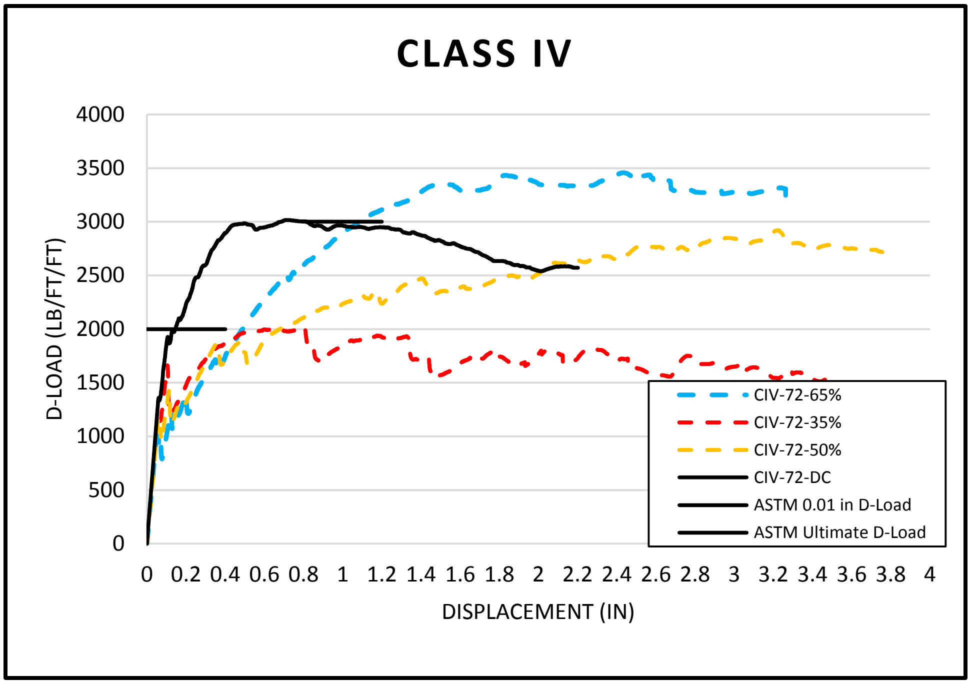






Concrete Strength, 5000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 2000)	D-Load for Ultimate (ASTM required = 3000)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	0.96	-	1366	3176

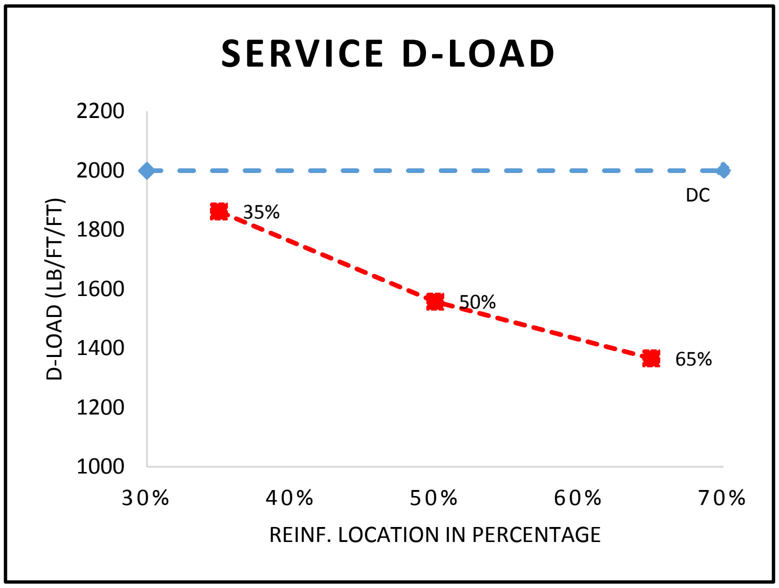
Contoured image shows plastic strain at service load.



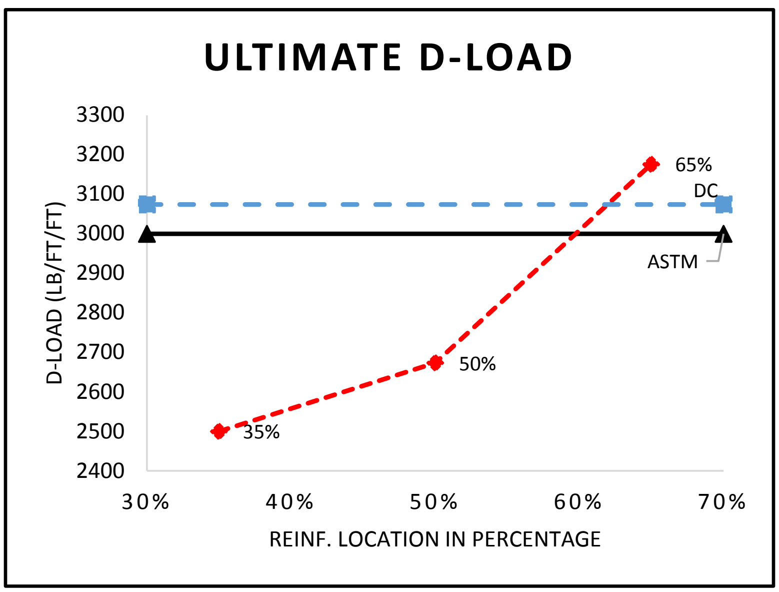
Graph A-70, Comprehensive Graph for Class IV-72 in. Pipe diameter

Concrete Strength, 5000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	72	7.75	0.6	0.36	2000	100	3074	100
35%	72	7.75	0.96	-	1862	93	2500	81
50%	72	7.75	0.96	-	1558	78	2673	87
65%	72	7.75	0.96	-	1366	68	3176	103

Table A-11, Comprehensive Table for Class IV-72 in. Pipe diameter

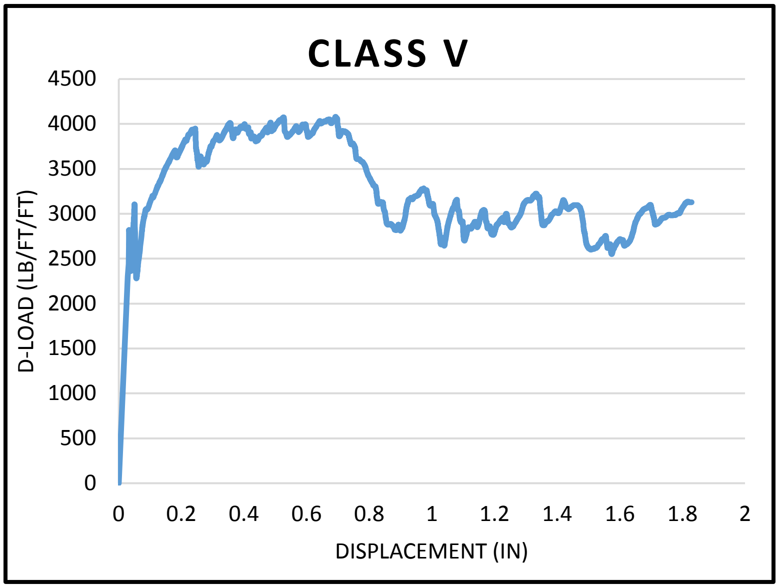


Graph 1 Graph A-71, Comprehensive Graph for Class IV-72 in. Pipe diameter

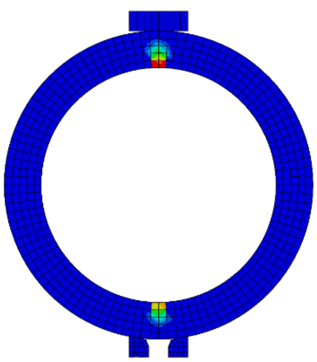


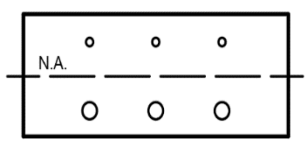
Graph A-72, Comprehensive Graph for Class IV-72 in. Pipe diameter

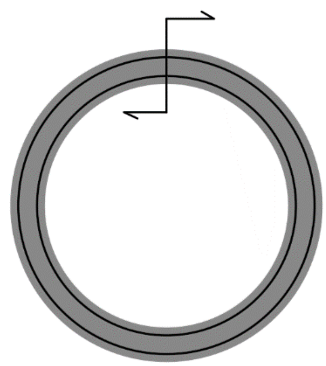
Class V - Wall C - Diameter 24 – DC



Graph A-73, RCP Class V - Wall C - Diameter 24 –DC



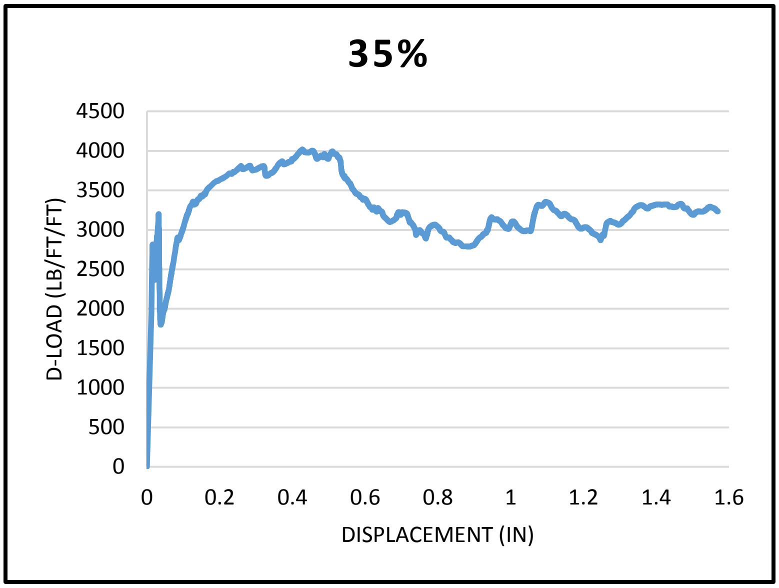




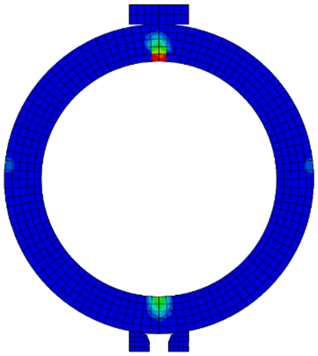
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.12	0.07	3088	4068

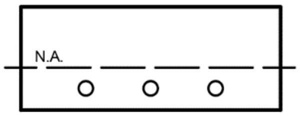
Contoured image shows plastic strain at service load.

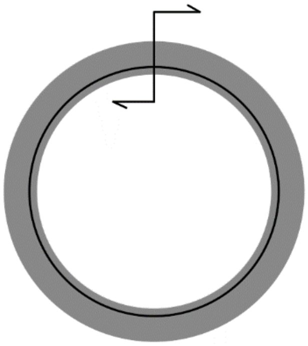
Class V - Wall C - Diameter 24 – 35%



Graph A-74, RCP Class V - Wall C - Diameter 24 –35%



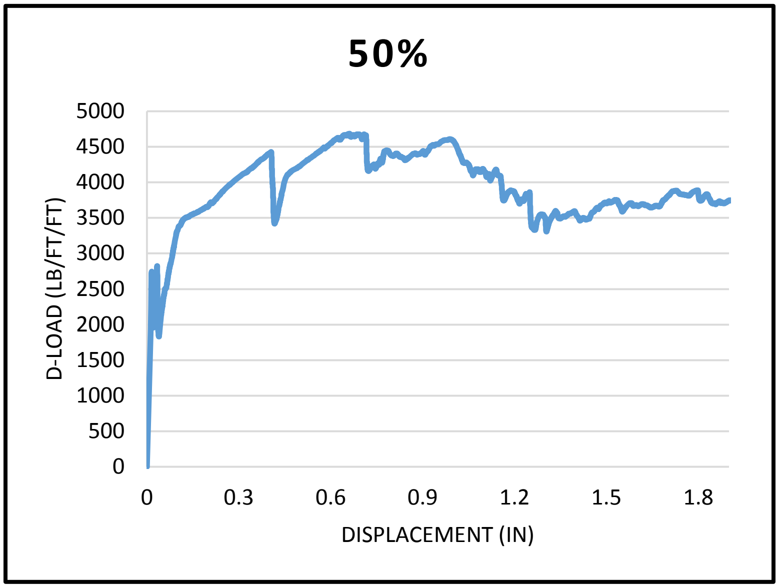




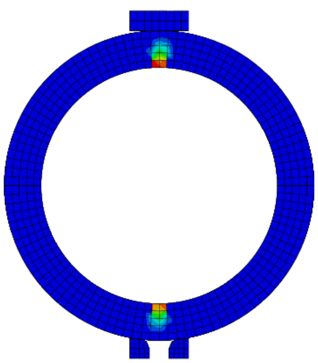
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.19	-	3188	4017

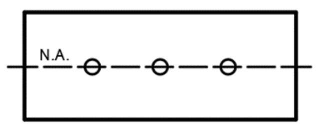
Contoured image shows plastic strain at service load.

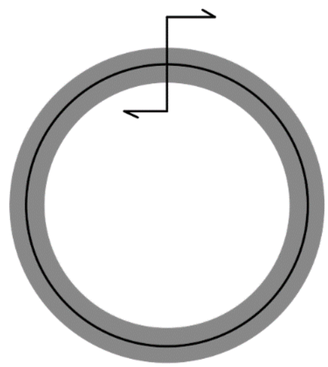
Class V - Wall C - Diameter 24 – 50%



Graph A-75, RCP Class V - Wall C - Diameter 24 –50%



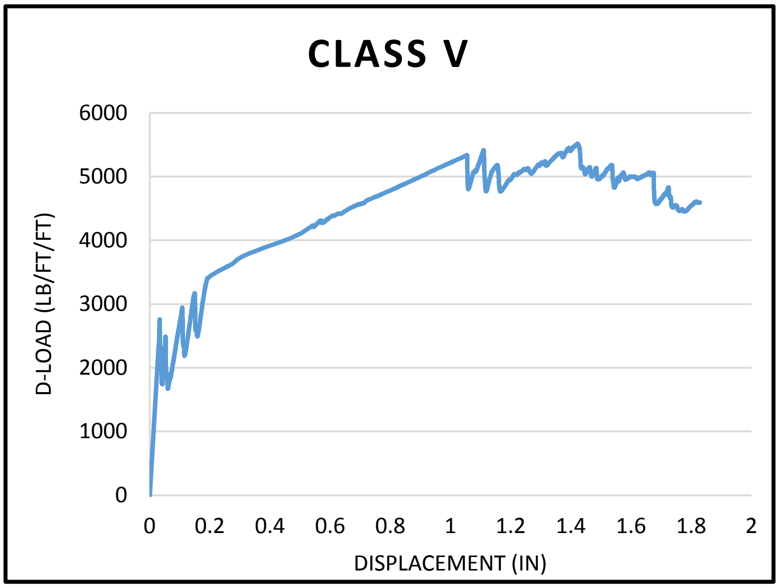




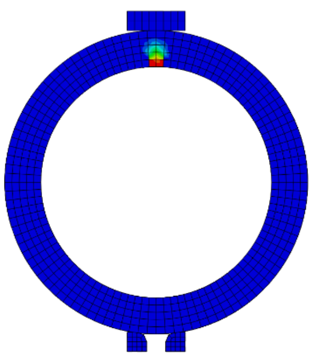
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.19	-	2810	4674

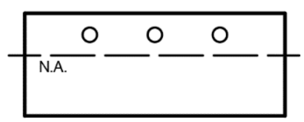
Contoured image shows plastic strain at service load.

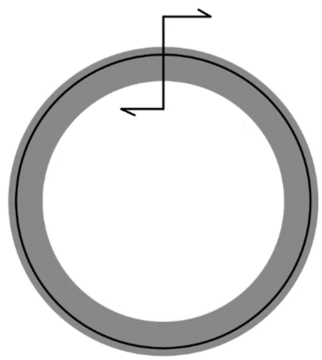
Class V - Wall C - Diameter 24 – 65%



Graph A-76, RCP Class V - Wall C - Diameter 24 –65%

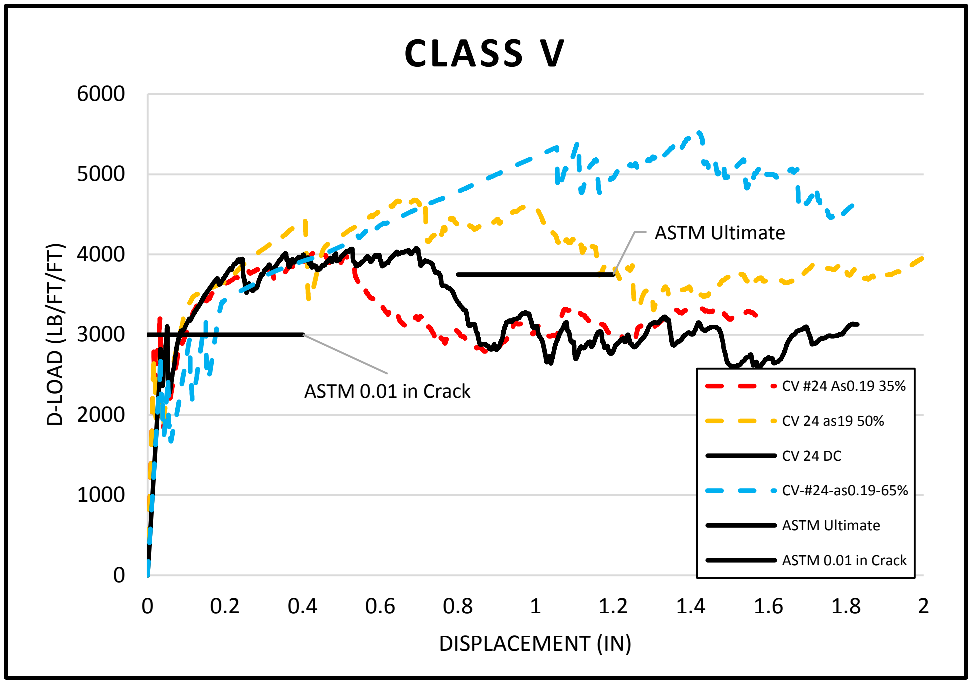






Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.19	-	2746	5454

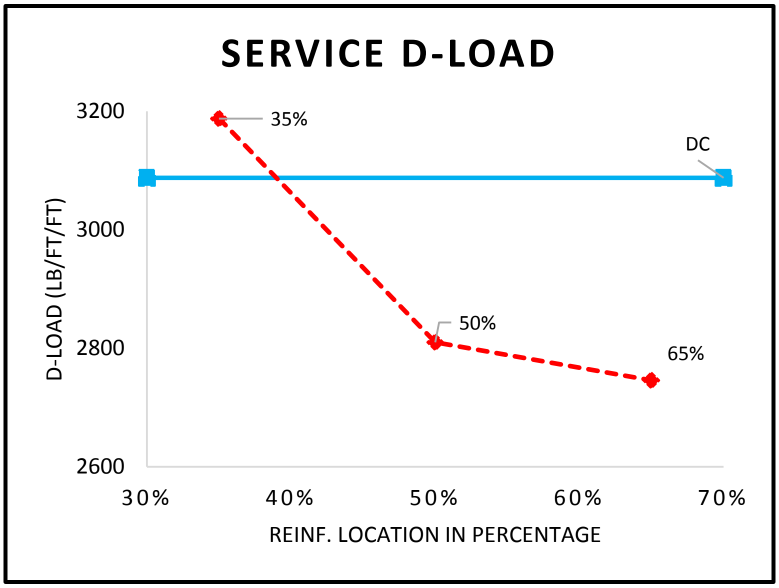
Contoured image shows plastic strain at service load.



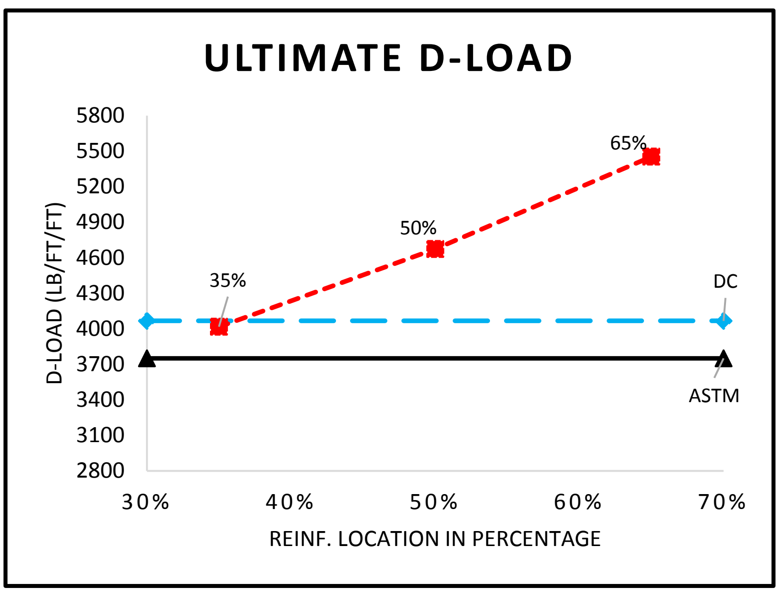
Graph A-77, Comprehensive Graph for Class V-24 in. Pipe diameter

Concrete Strength, 6000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	24	3.75	0.12	0.07	3088	100	4068	100
35%	24	3.75	0.19	-	3188	103	4017	99
50%	24	3.75	0.19	-	2810	91	4674	115
65%	24	3.75	0.19	-	2746	89	5454	134

Table A-12, Comprehensive Table for Class V-24 in. Pipe diameter



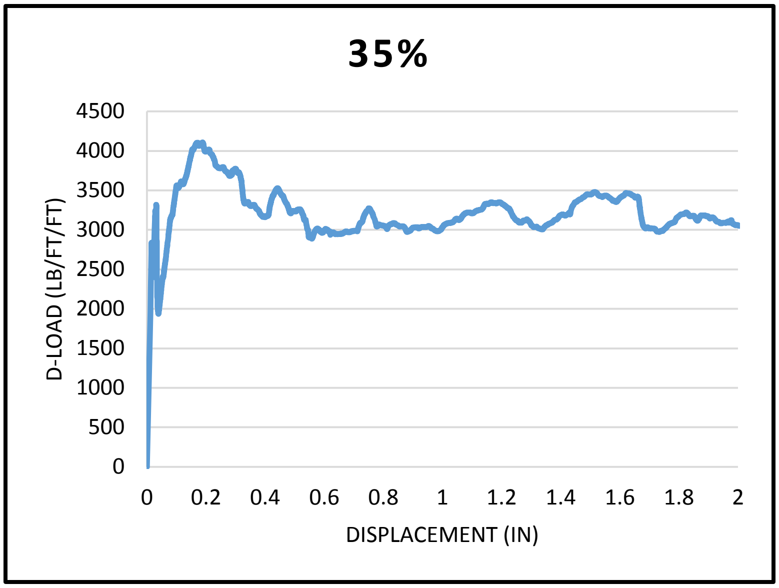
Graph A-78, Comprehensive Graph for Class V-24 in. Pipe diameter



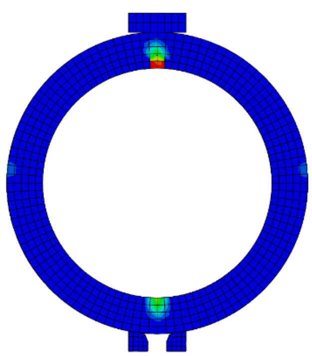
Graph A-79, Comprehensive Graph for Class V-24 in. Pipe diameter

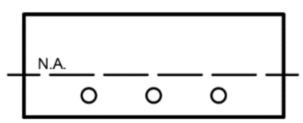
Class V - Wall C - Diameter 24 – 35%

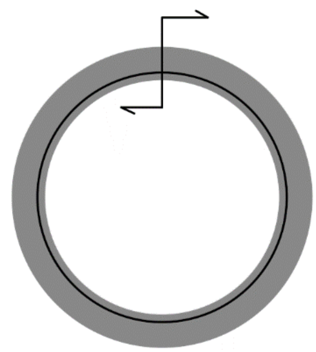
Reinforcement Area Increased by 25%



Graph A-80, RCP Class V - Wall C - Diameter 24 –35% Reinforcement Area Increased by 25%





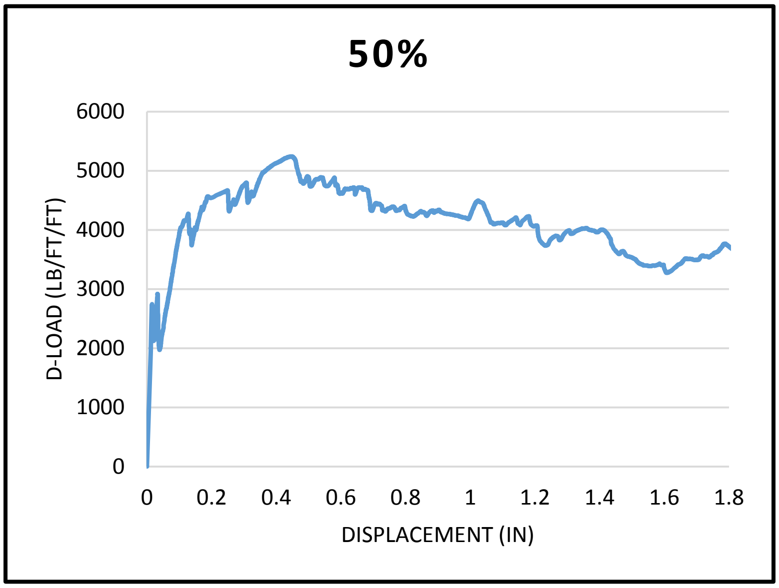


Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.25	-	3307	4106

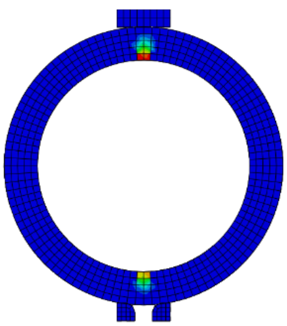
Contoured image shows plastic strain at service load.

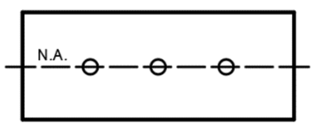
Class V - Wall C - Diameter 24 – 50%

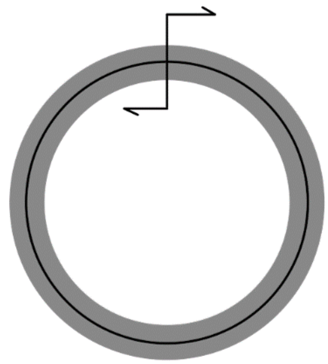
Reinforcement Area Increased by 25%



Graph A-81, RCP Class V - Wall C - Diameter 24 –50% Reinforcement Area Increased by 25%





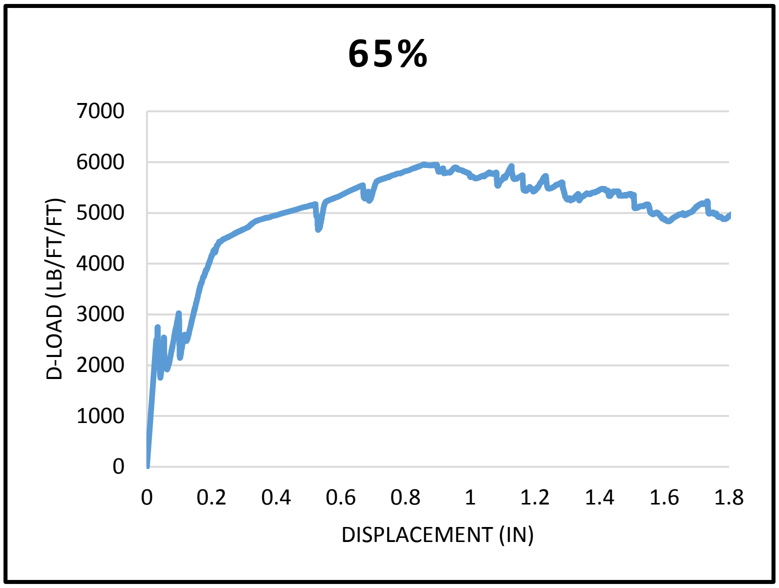


Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.25	-	2857	5200

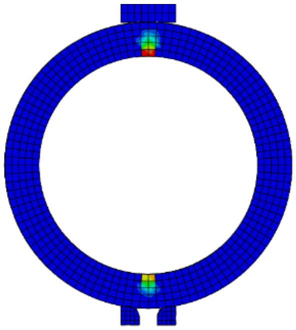
Contoured image shows plastic strain at service load.

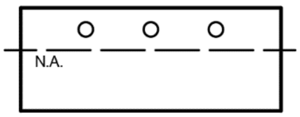
Class V - Wall C - Diameter 24 – 65%

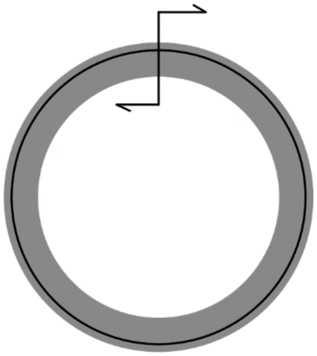
Reinforcement Area Increased by 25%



Graph A-82, RCP Class V - Wall C - Diameter 24 –65% Reinforcement Area Increased by 25%

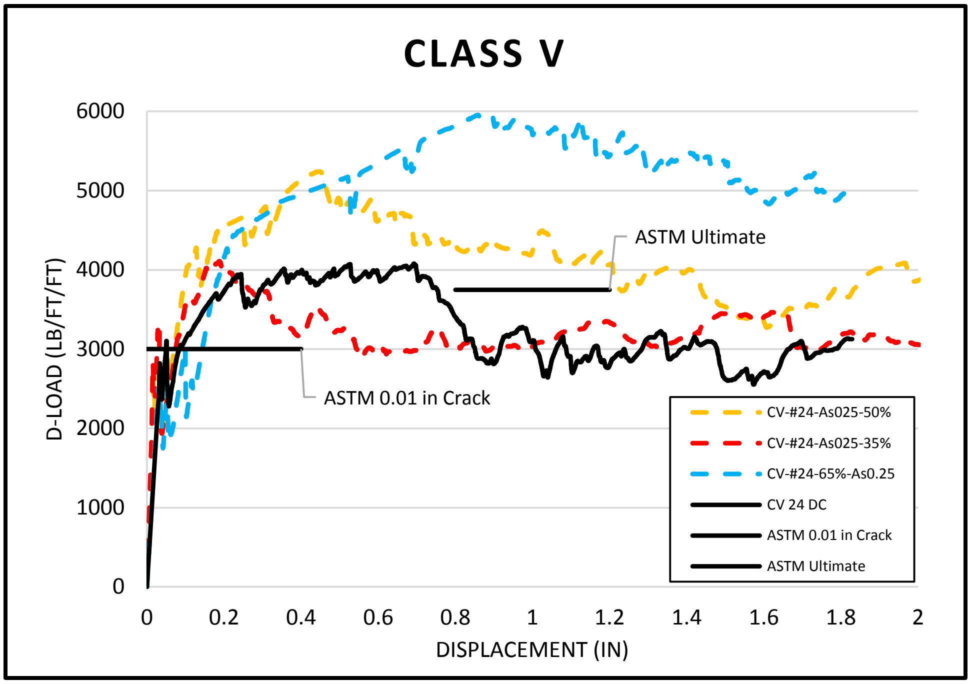






Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
24	3.75	0.25	-	2734	6000

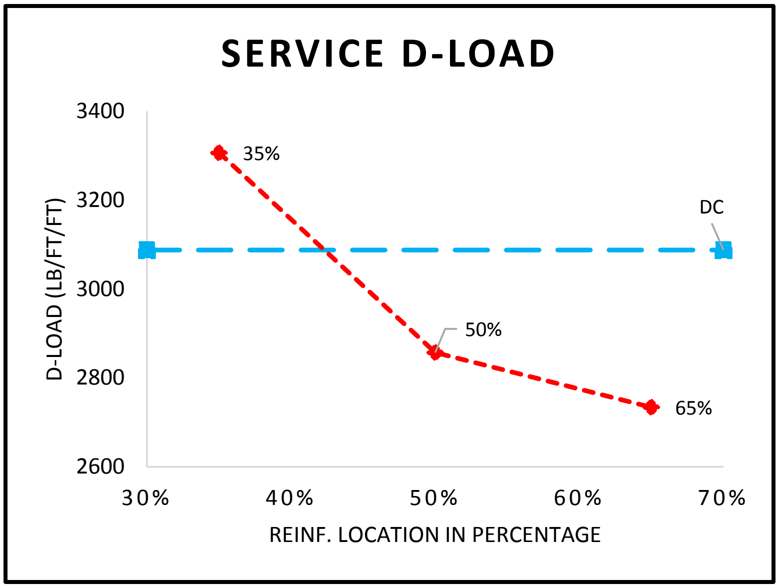
Contoured image shows plastic strain at service load.



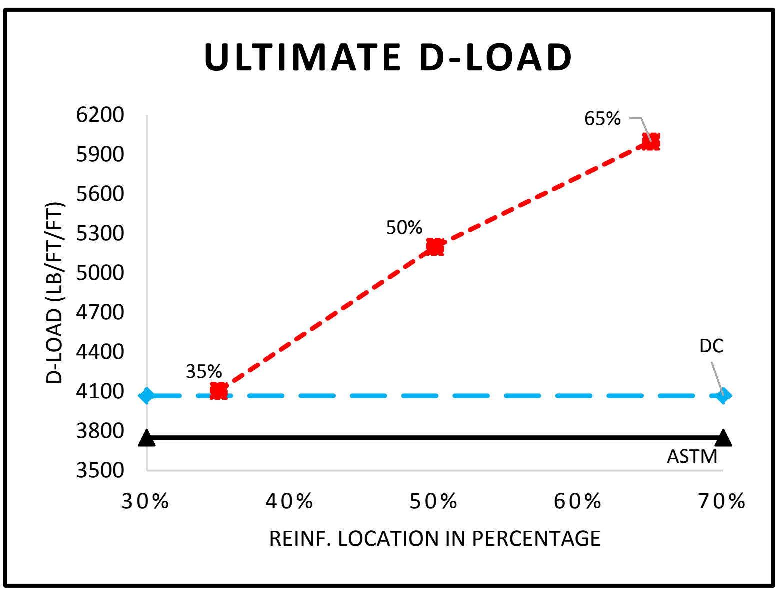
Graph A-83, Comprehensive Graph for Class V-24 in. Pipe diameter

Concrete Strength, 4000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	24	3.75	0.12	0.07	3088	100	4068	100
35%	24	3.75	0.25	-	3307	107	4106	101
50%	24	3.75	0.25	-	2857	93	5200	128
65%	24	3.75	0.25	-	2734	89	6000	147

Table A-13, Comprehensive Table for Class V-24 in. Pipe diameter

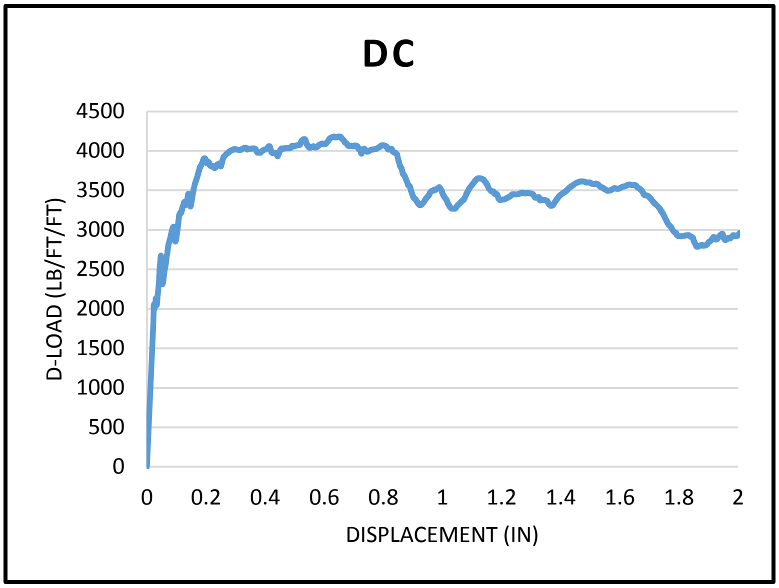


Graph A-84, Comprehensive Graph for Class V-24 in. Pipe diameter

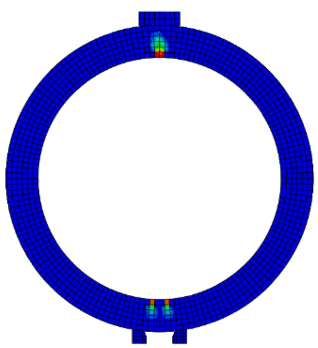


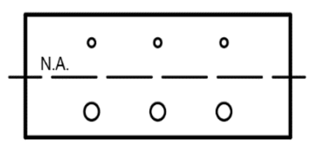
Graph A-85, Comprehensive Graph for Class V-24 in. Pipe diameter

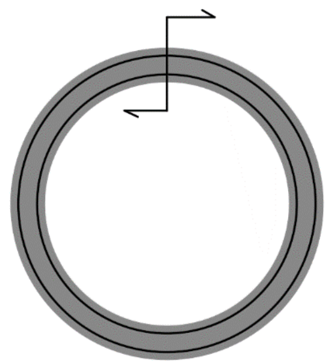
Class V - Wall C - Diameter 36 – DC



Graph A-86, RCP Class V - Wall C - Diameter 36 –DC



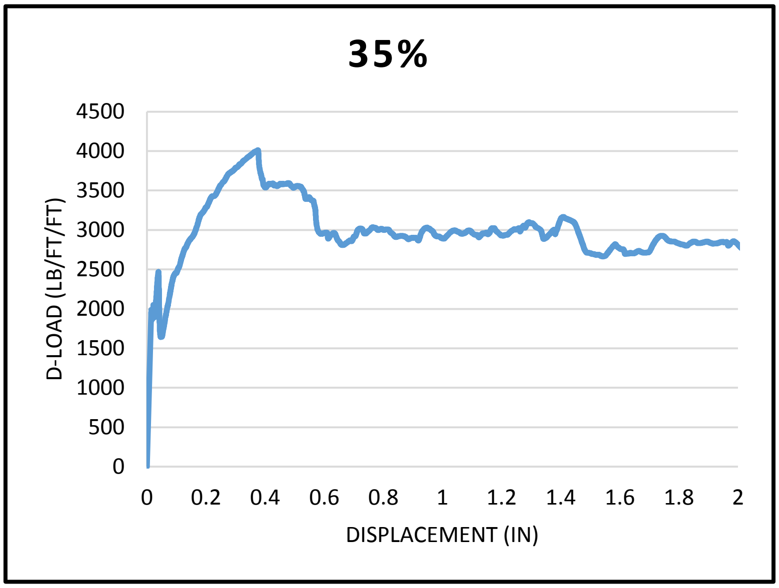




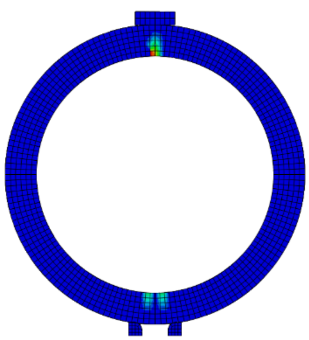
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.27	0.16	301[illegible]	4179

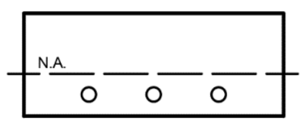
Class V - Wall C - Diameter 36 – 35%

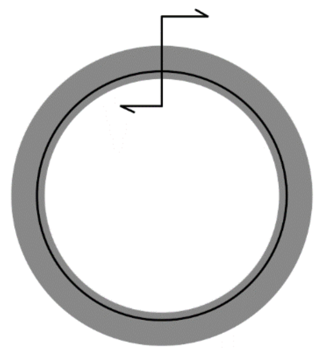
Contoured image shows plastic strain at service load.



Graph A-87, RCP Class V - Wall C - Diameter 36 –35%



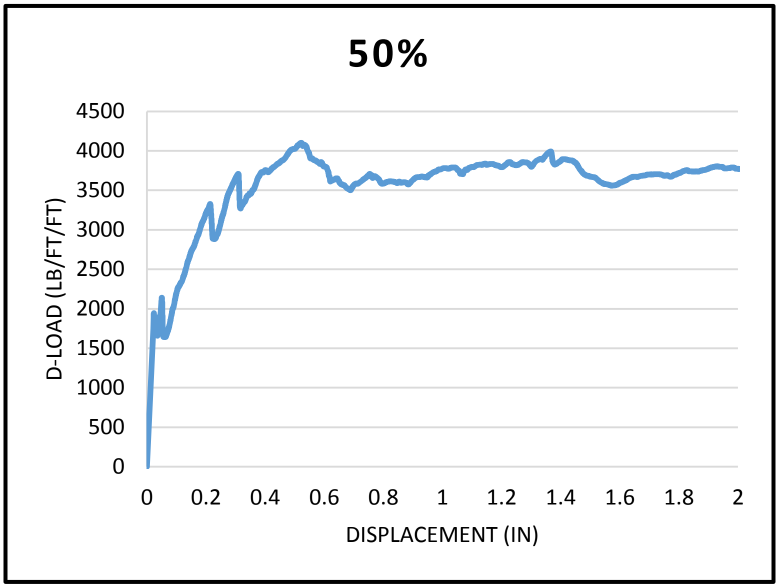




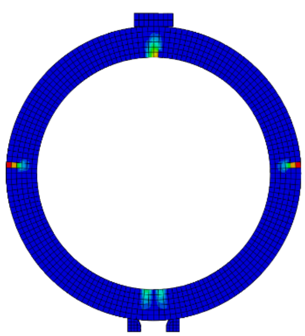
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.43	-	2500	4000

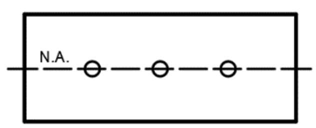
Contoured image shows plastic strain at service load.

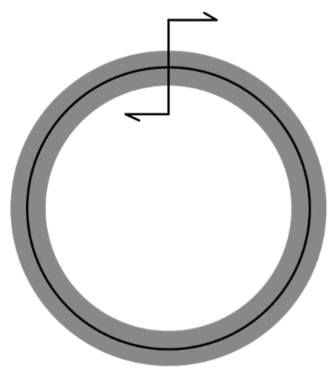
Class V - Wall C - Diameter 36 – 50%



Graph A-88, RCP Class V - Wall C - Diameter 36 –50%



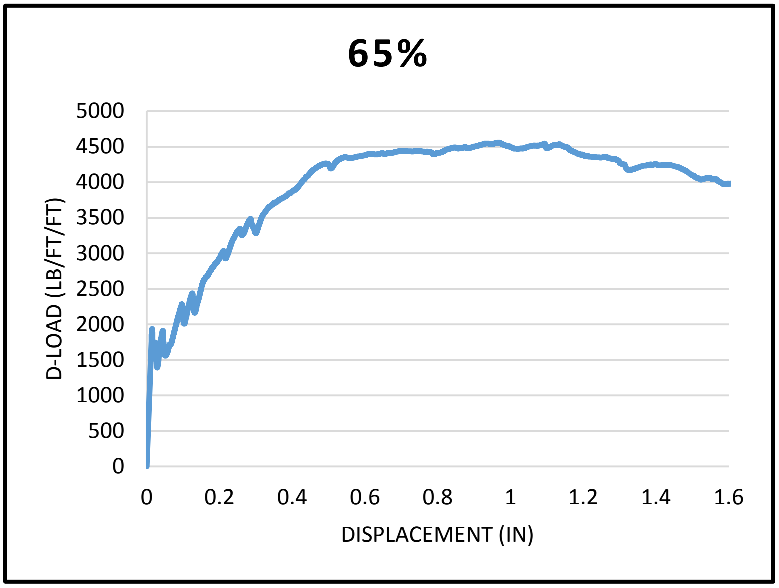




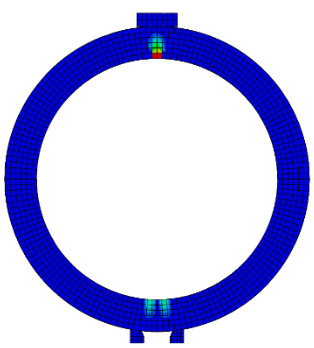
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.43	-	2139	4110

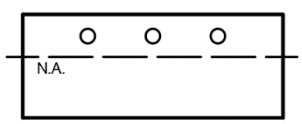
Contoured image shows plastic strain at service load.

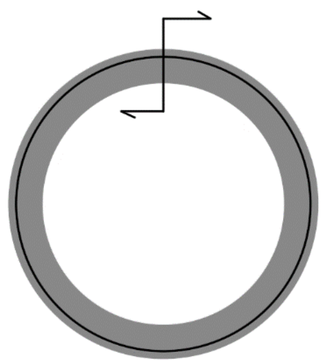
Class V - Wall C - Diameter 36 – 35%



Graph A-89, RCP Class V - Wall C - Diameter 36 –65%

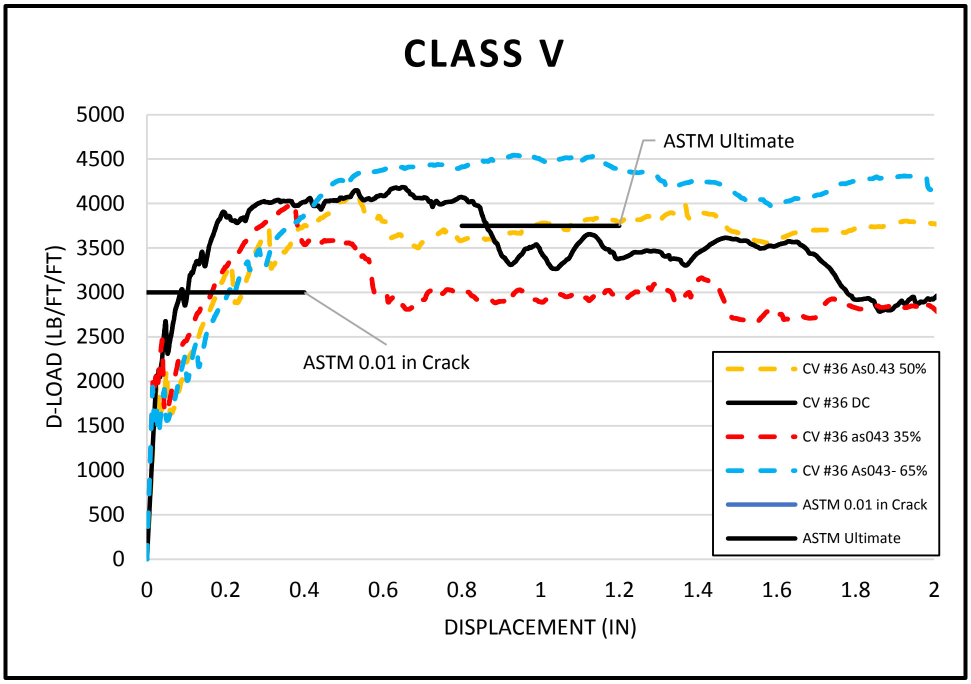






Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.43	-	1883	4510

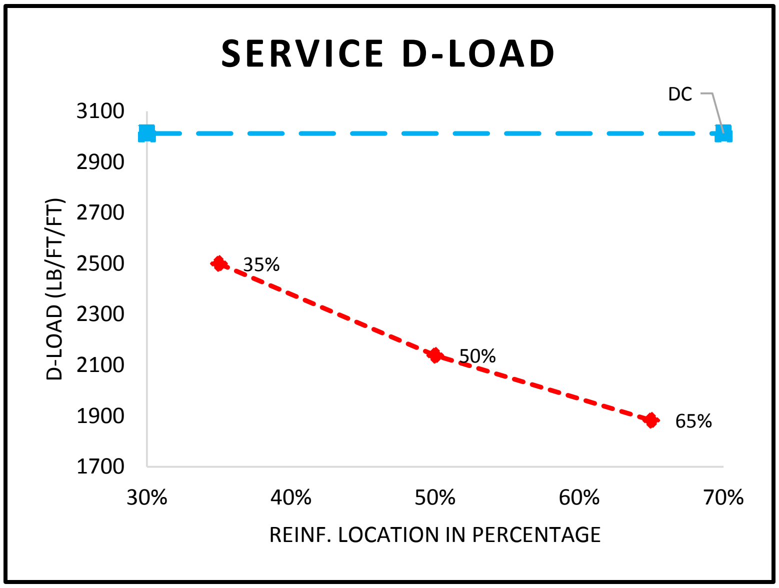
Contoured image shows plastic strain at service load.



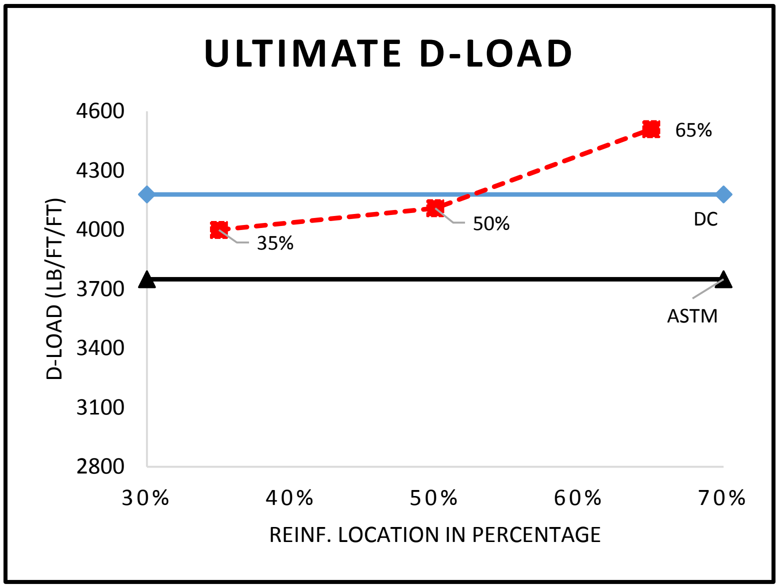
Graph A-90, Comprehensive Graph for Class V-36 in. Pipe diameter

Concrete Strength, 6000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	36	4.75	0.27	0.16	3013	100	4179	100
35%	36	4.75	0.573	-	2571	85	3768	90
50%	36	4.75	0.573	-	2194	73	4481	107
65%	36	4.75	0.573	-	2000	66	5480	131

Table A-14, Comprehensive Table for Class V-36 in. Pipe diameter



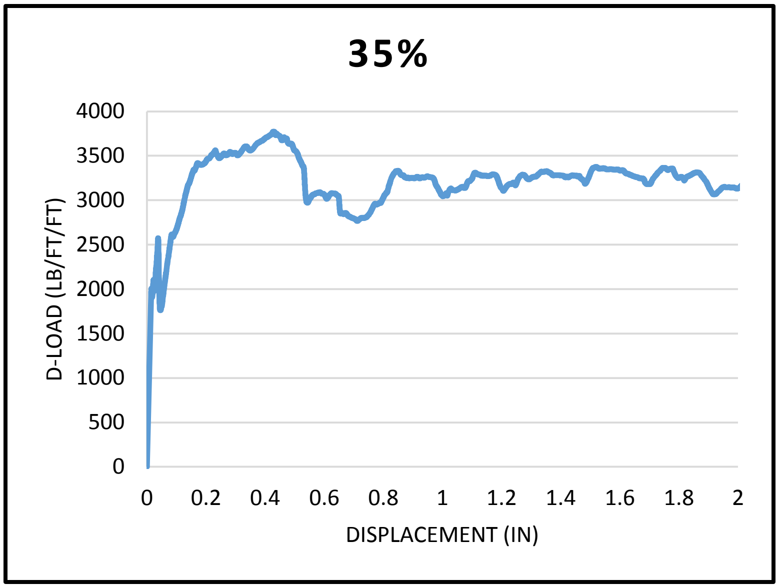
Graph A-91, Comprehensive Graph for Class V-36 in. Pipe diameter



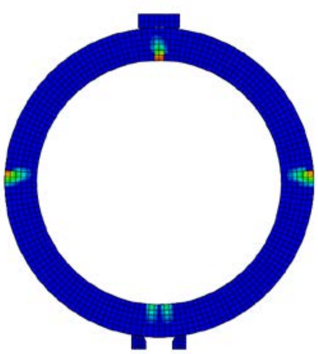
Graph A-92, Comprehensive Graph for Class V-36 in. Pipe diameter

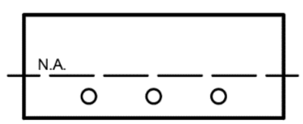
Class V - Wall C – Diameter 36 – 35%

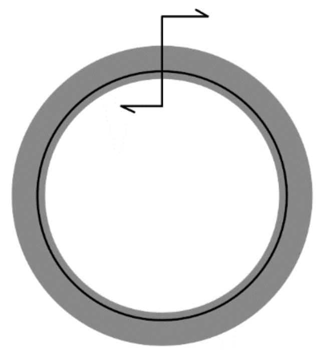
Reinforcement Area Increased by 25%



Graph A-93, RCP Class V - Wall C - Diameter 36 –35% Reinforcement Area Increased by 25%





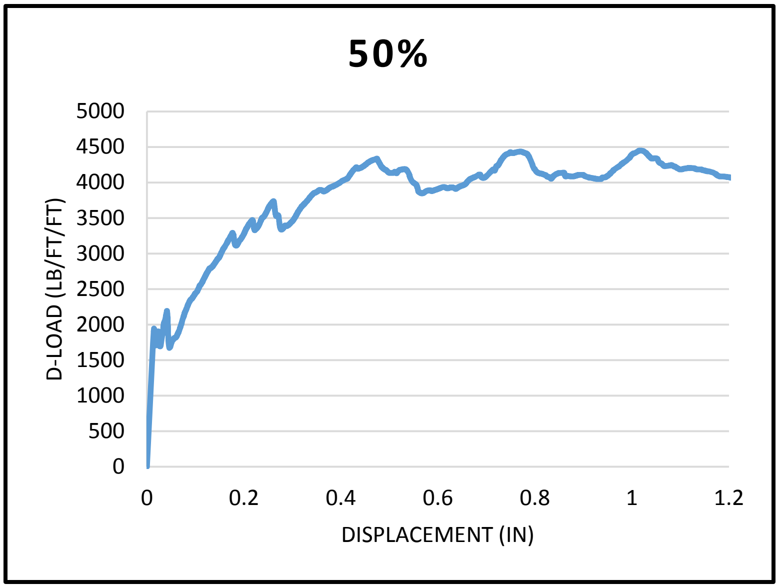


Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.573	-	2571	3768

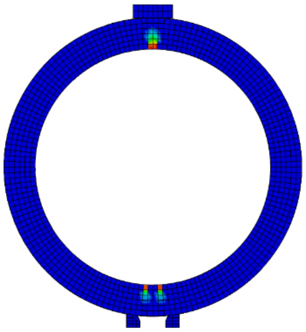
Contoured image shows plastic strain at service load.

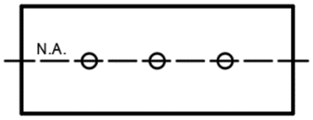
Class V - Wall C – Diameter 36 – 50%

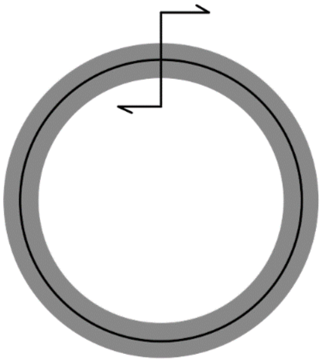
Reinforcement Area Increased by 25%



Graph A-94, RCP Class V - Wall C - Diameter 36 –50% Reinforcement Area Increased by 25%





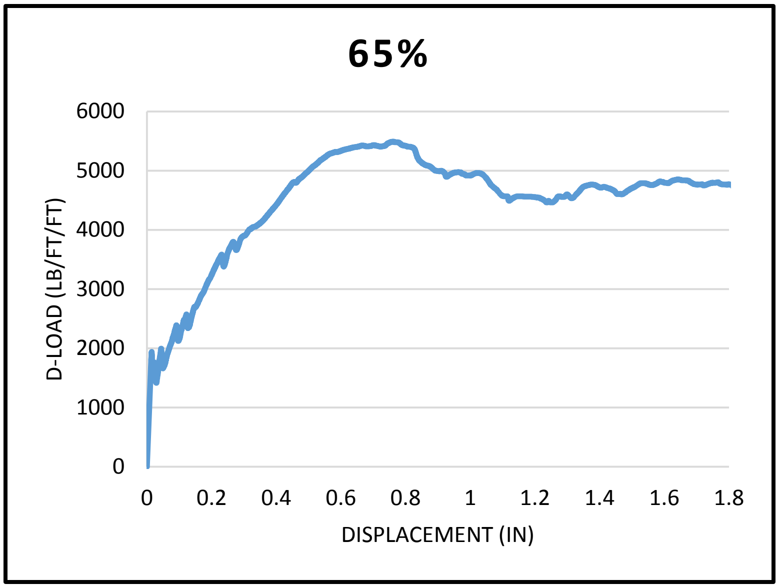


Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.573	-	2194	4481

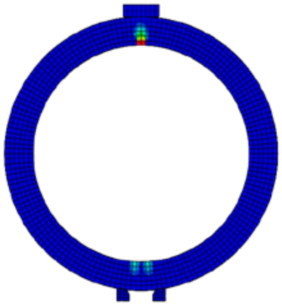
Contoured image shows plastic strain at service load.

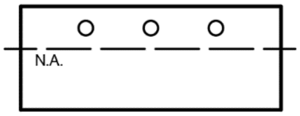
Class V - Wall C – Diameter 36 – 65%

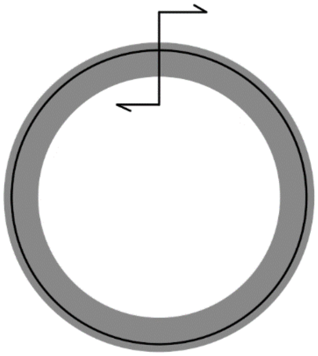
Reinforcement Area Increased by 25%



Graph A-95, RCP Class V - Wall C - Diameter 36 –50%
Reinforcement Area Increased by 25%

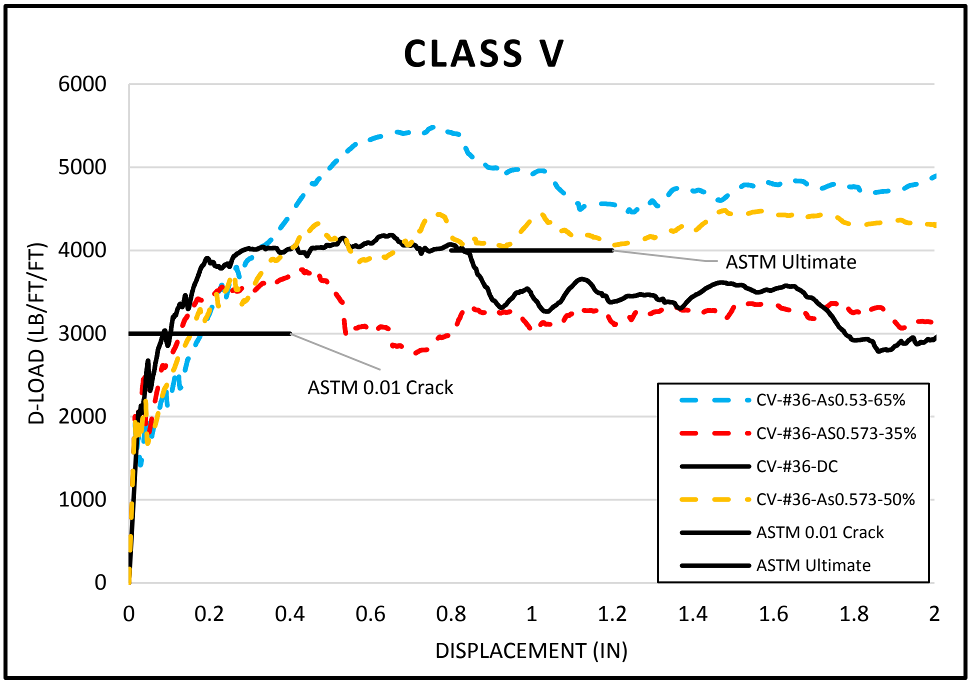






Concrete Strength, 6000 psi						
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
36	4.75	0.573	-	2000	5480

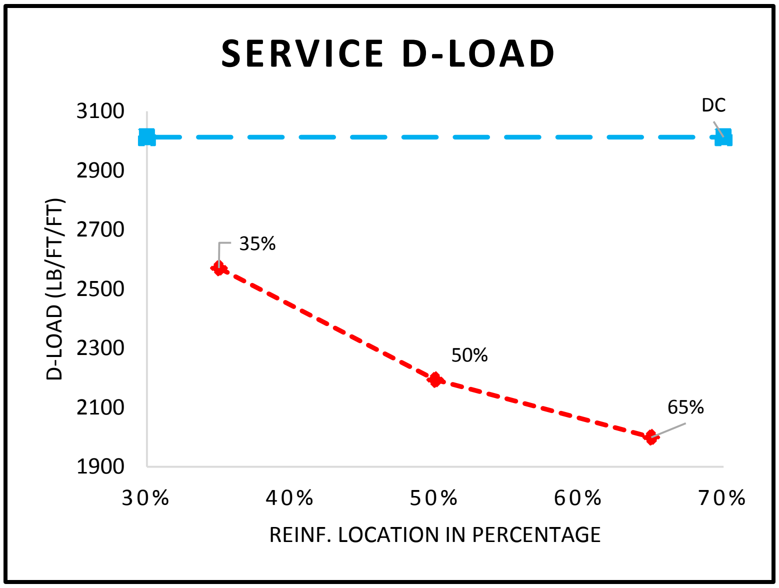
Contoured image shows plastic strain at service load.



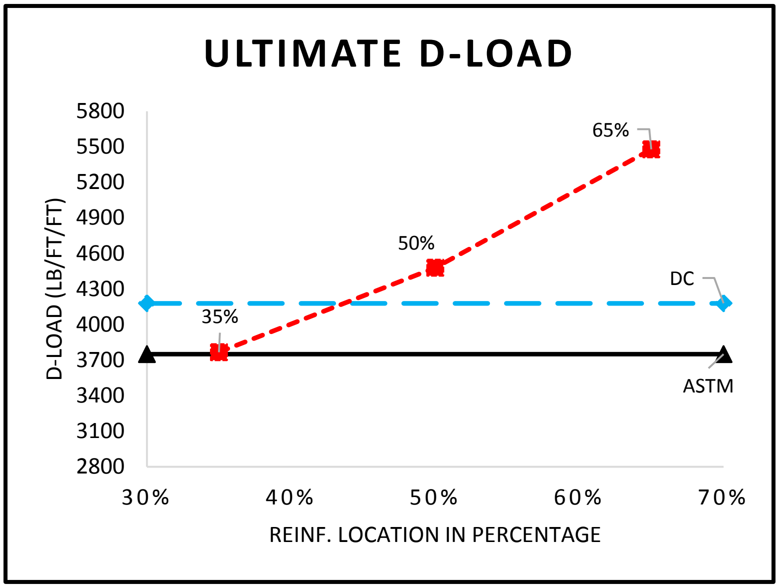
Graph A-96, Comprehensive Graph for Class V-36 in. Pipe diameter

Concrete Strength, 6000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	36	4.75	0.27	0.16	3013	100	4179	100
35%	36	4.75	0.573	-	2571	85	3768	90
50%	36	4.75	0.573	-	2194	73	4481	107
65%	36	4.75	0.573	-	2000	66	5480	131

Table A-15, Comprehensive Table for Class V-36 in. Pipe diameter

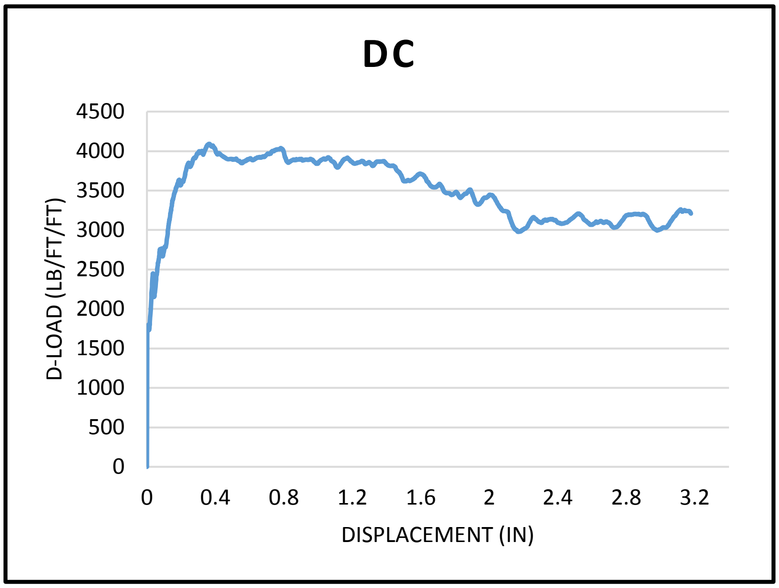


Graph A-97, Comprehensive Graph for Class V-36 in. Pipe diameter

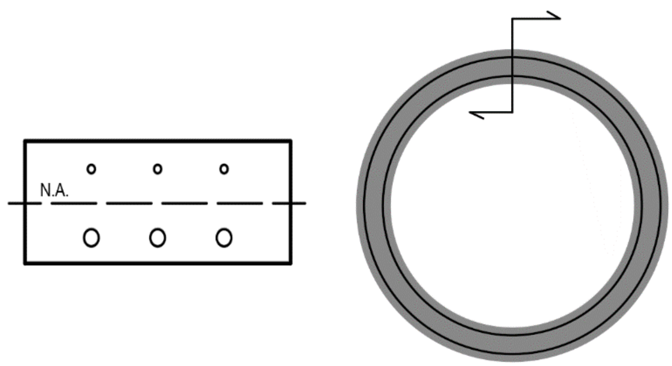


Graph A-98, Comprehensive Graph for Class V-36 in. Pipe diameter

Class V - Wall C - Diameter 48 – DC



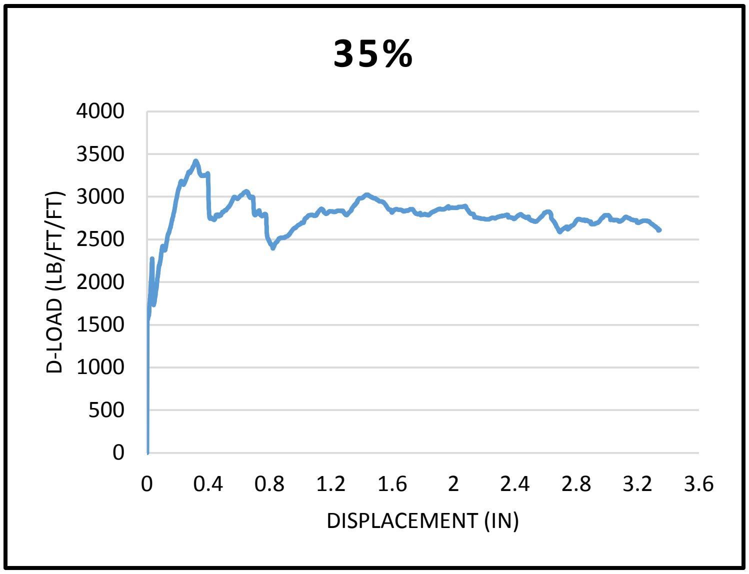
Graph A-99, RCP Class V - Wall C - Diameter 48 –DC



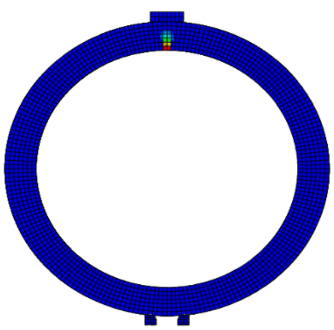
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	4.75	0.27	0.16	2500	4089

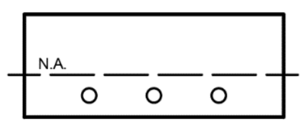
Contoured image shows plastic strain at service load.

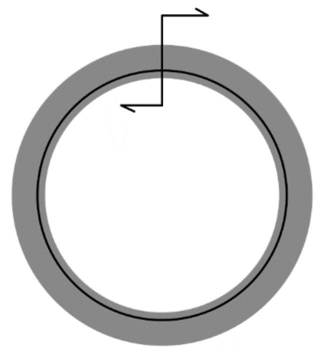
Class V - Wall C - Diameter 48 – 35%



Graph A-100, RCP Class V - Wall C - Diameter 48 –35%



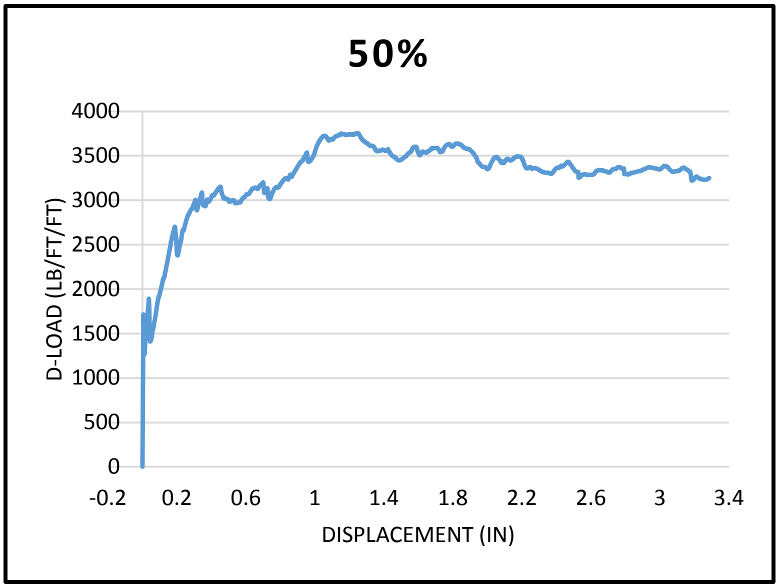




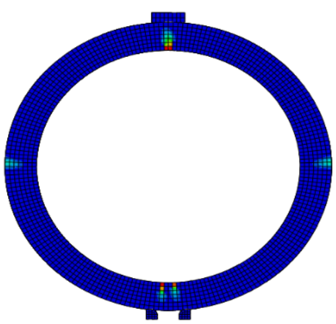
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.74	-	2272	3421

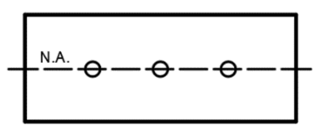
Contoured image shows plastic strain at service load.

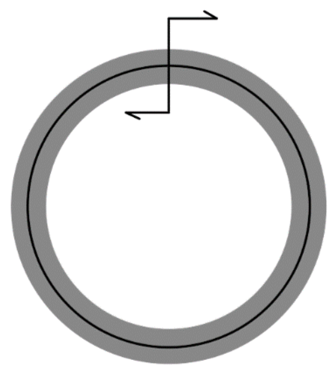
Class V - Wall C - Diameter 48 – 50%



Graph A-101, RCP Class V - Wall C - Diameter 48 –50%



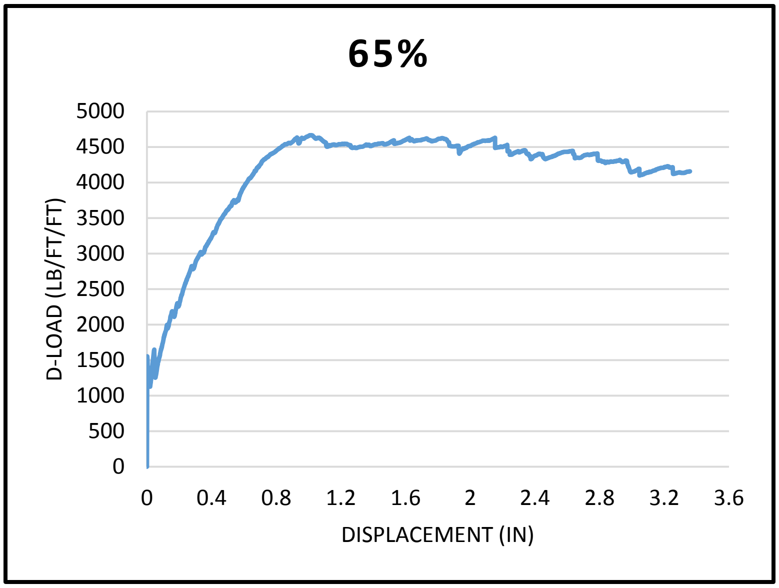




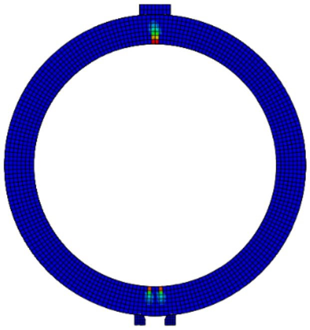
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 300)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.74		1880	3749

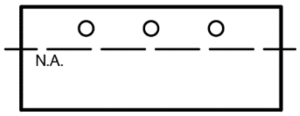
Contoured image shows plastic strain at service load.

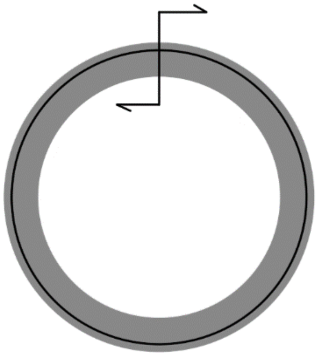
Class V - Wall C - Diameter 48 – 65%



Graph A-102, RCP Class V - Wall C - Diameter 48 –65%

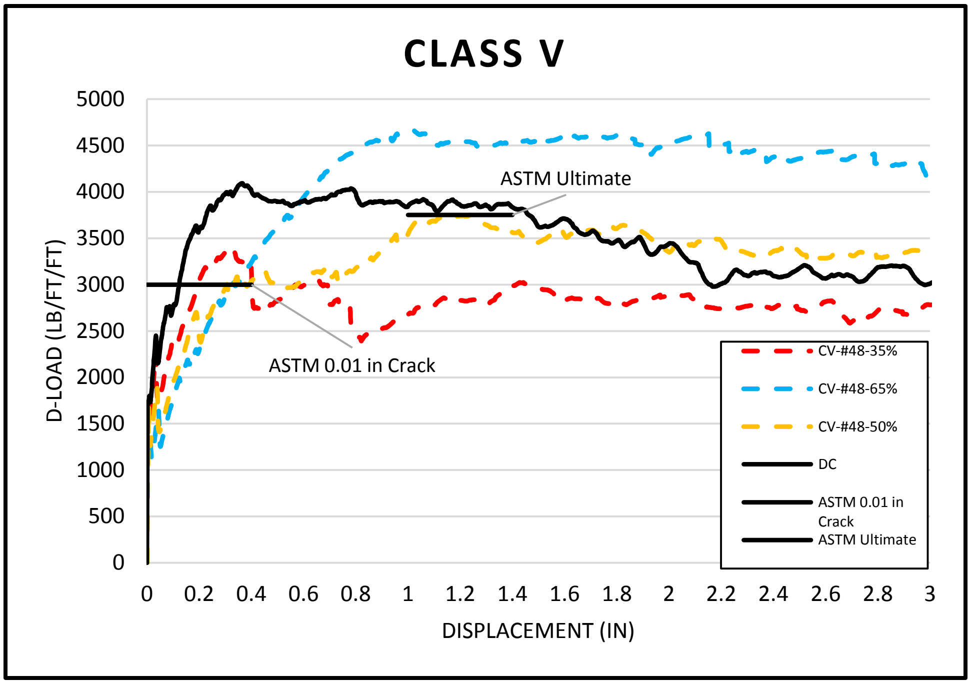






Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
48	5.75	0.74	-	1650	4642

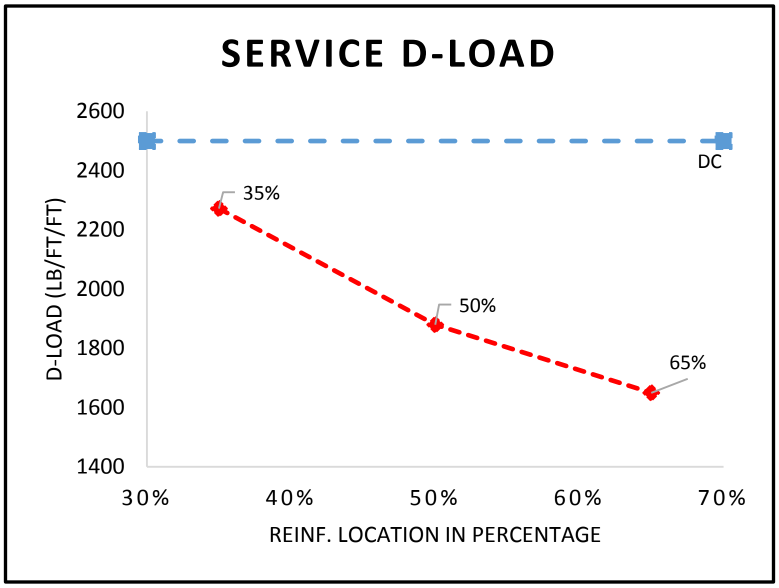
Contoured image shows plastic strain at service load.



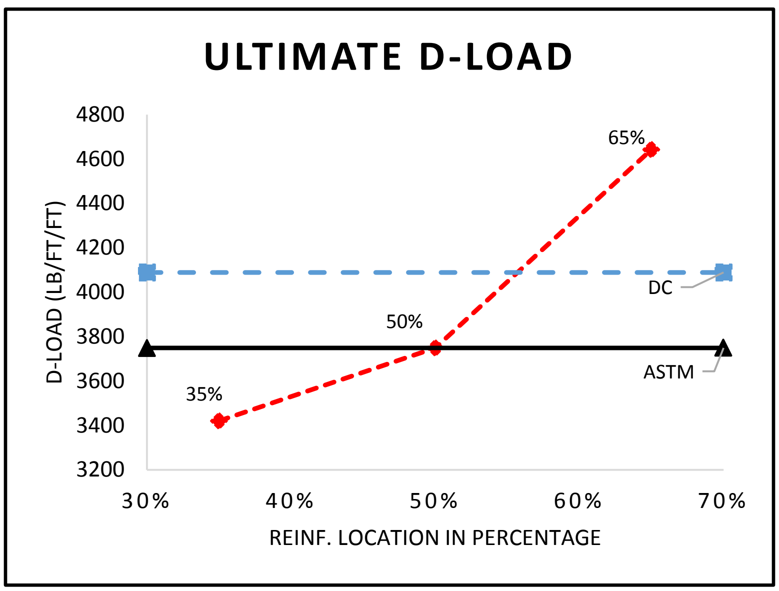
Graph A-103, Comprehensive Graph for Class V-48 in. Pipe diameter

Concrete Strength, 6000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	48	5.75	0.47	0.27	2500	100	4089	100
35%	48	5.75	0.74	-	2272	91	3421	84
50%	48	5.75	0.74	-	1880	75	3749	92
65%	48	5.75	0.74	-	1650	66	4642	114

Table A-16, Comprehensive Table for Class V-48 in. Pipe diameter

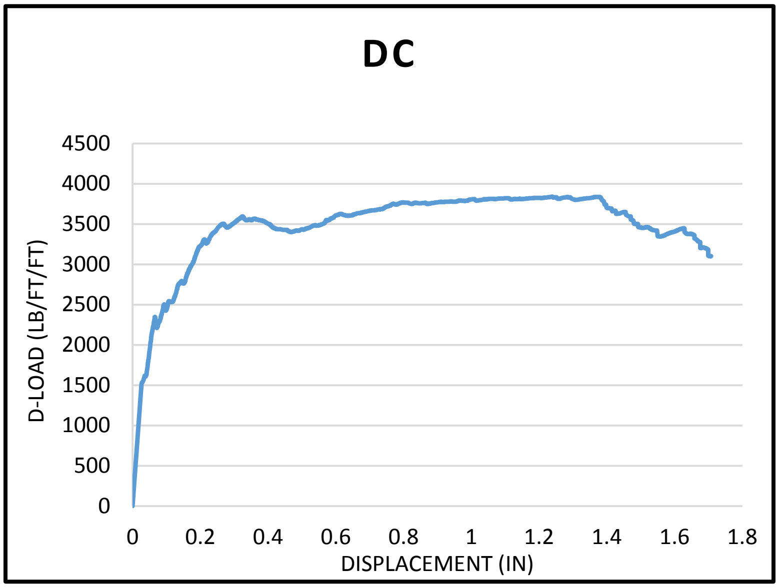


Graph A-104, Comprehensive Graph for Class V-48 in. Pipe diameter

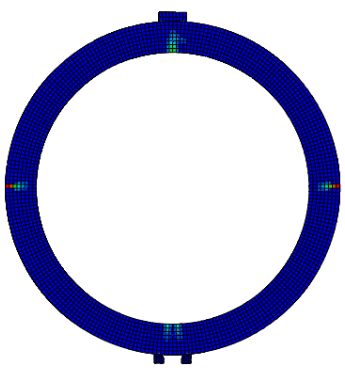


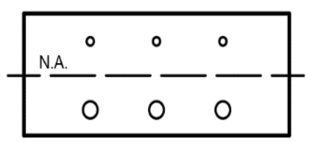
Graph A-105, Comprehensive Graph for Class V-48 in. Pipe diameter

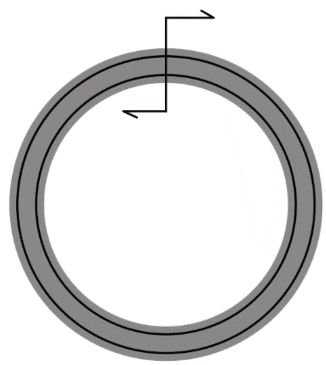
Class V - Wall C - Diameter 60 - DC



Graph A-106, RCP Class V - Wall C - Diameter 60 – DC



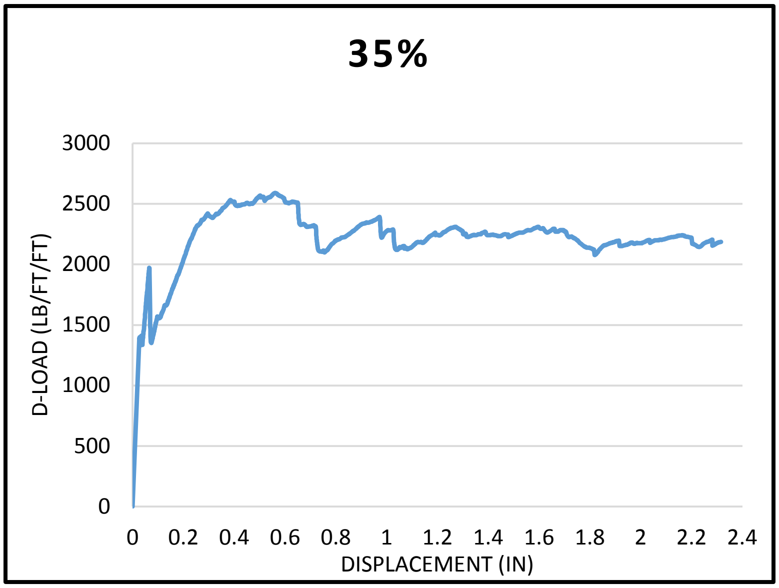




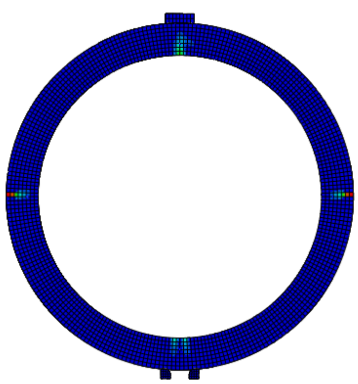
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	0.7	0.42	2293	3800

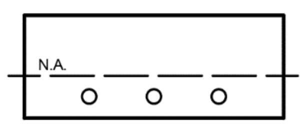
Contoured image shows plastic strain at service load.

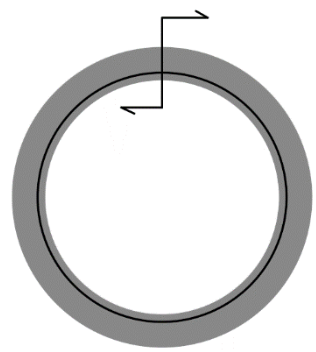
Class V - Wall C - Diameter 60 – 35%



Graph A-107, RCP Class V - Wall C - Diameter 60 – 35%



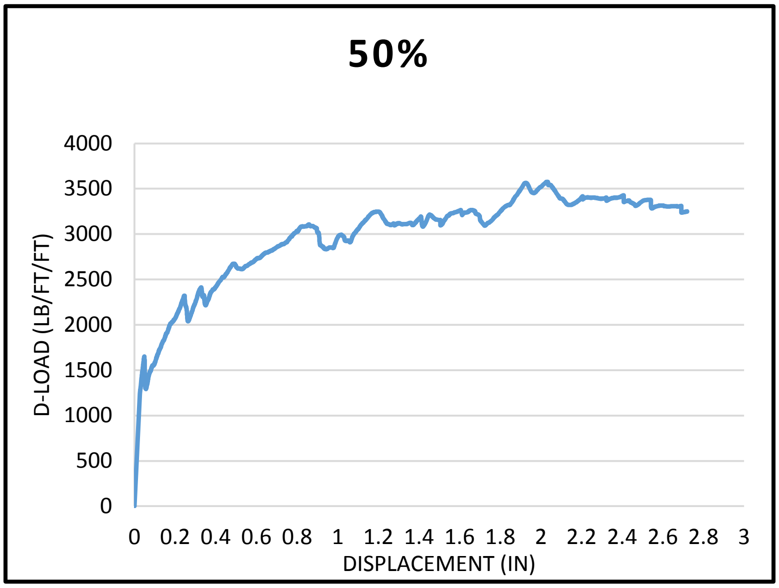




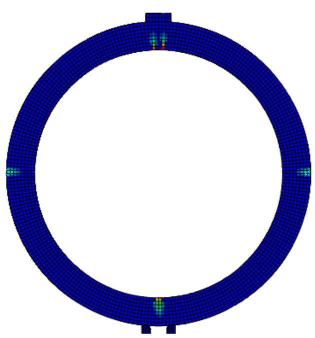
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	1.12	-	1930	2562

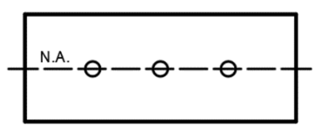
Contoured image shows plastic strain at service load.

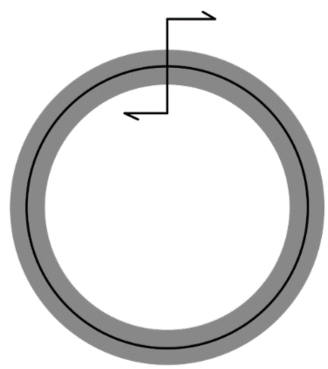
Class V - Wall C - Diameter 60 – 50%



Graph A-108, RCP Class V - Wall C - Diameter 60 – 50%



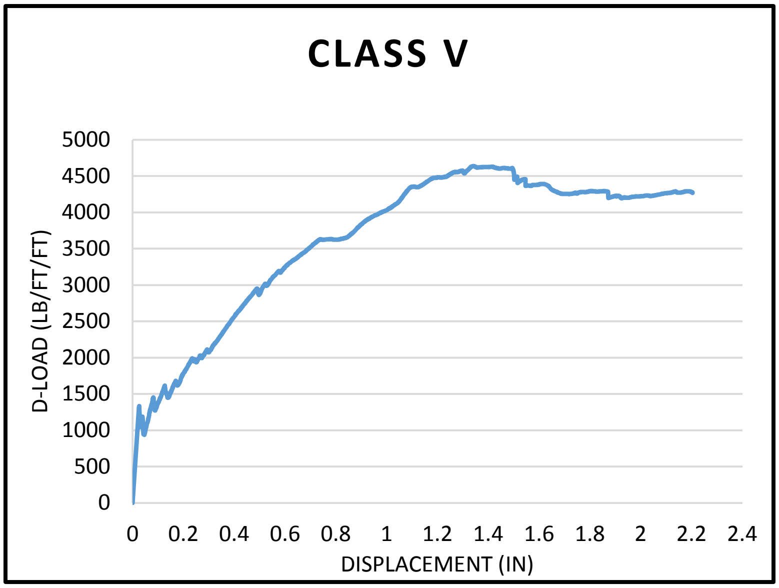




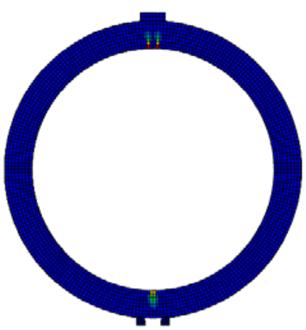
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	1.12	-	1563	3492

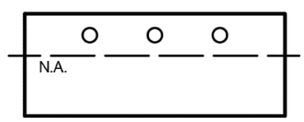
Contoured image shows plastic strain at service load.

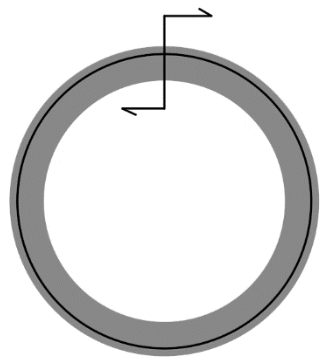
Class V - Wall C - Diameter 60 – 65%



Graph A-109, RCP Class V - Wall C - Diameter 60 –65%

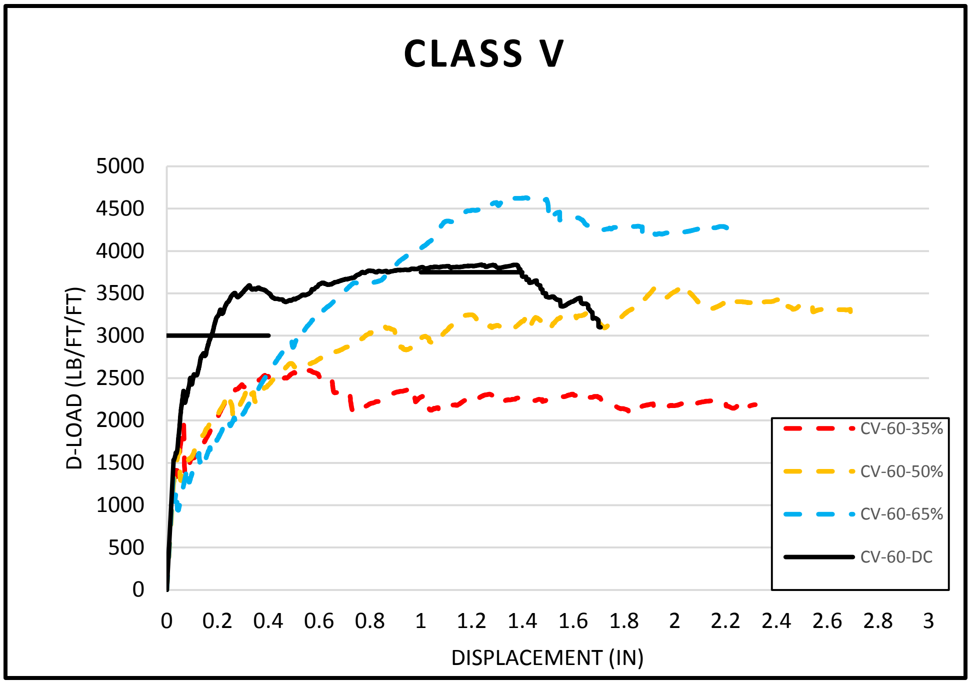






Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
60	6.75	1.12	-	1284	4625

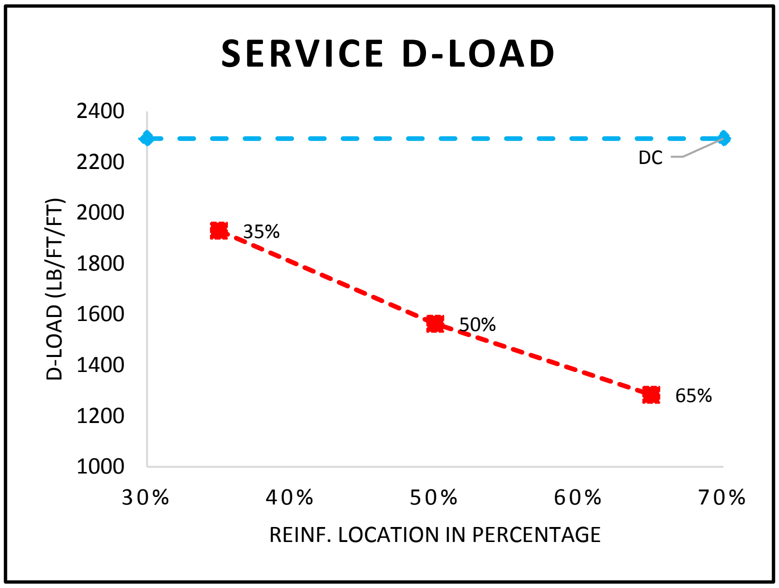
Contoured image shows plastic strain at service load.



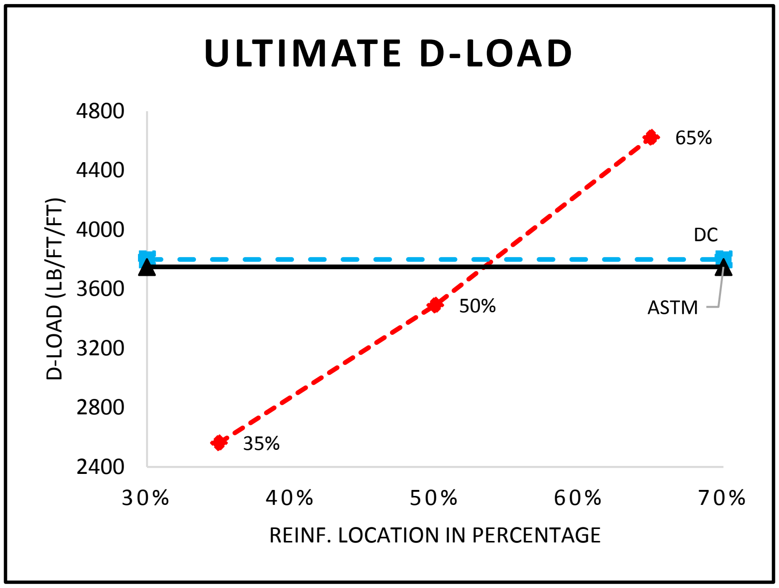
Graph A-110, Comprehensive Graph for Class V-60 in. Pipe diameter

Concrete Strength, 6000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	60	6.75	0.7	0.42	2293	100	3800	100
35%	60	6.75	1.12	-	1930	84	2562	67
50%	60	6.75	1.12	-	1563	68	3492	92
65%	60	6.75	1.12	-	1284	56	4625	122

Table A-17, Comprehensive Graph for Class V-60 in. Pipe diameter

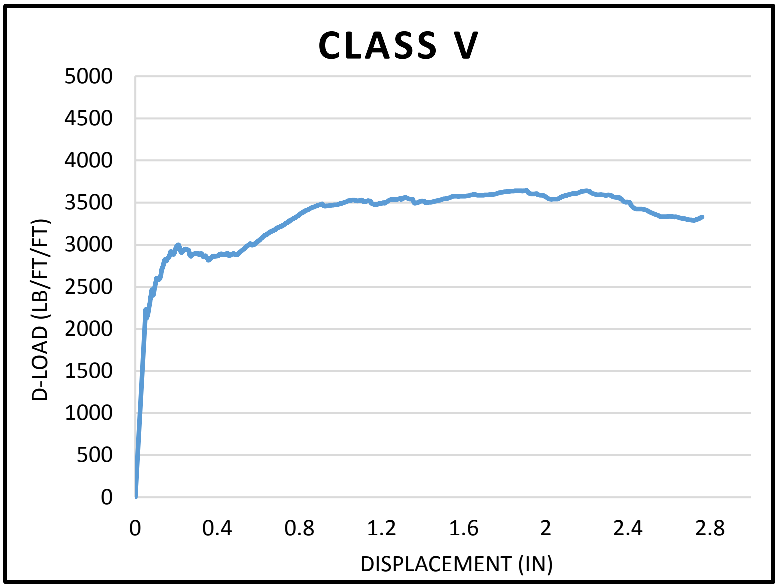


Graph A-111, Comprehensive Graph for Class V-60 in. Pipe diameter

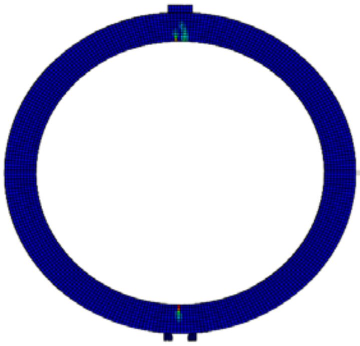


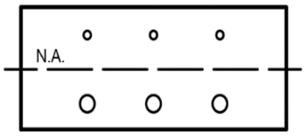
Graph A-112, Comprehensive Graph for Class V-60 in. Pipe diameter

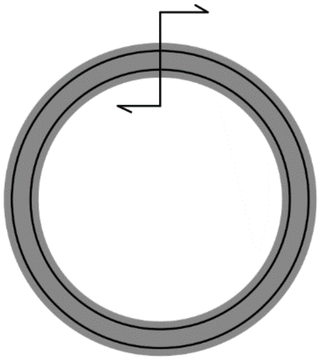
Class V - Wall C - Diameter 72 – DC



Graph A-113, RCP Class V - Wall C – Diameter 72- DC



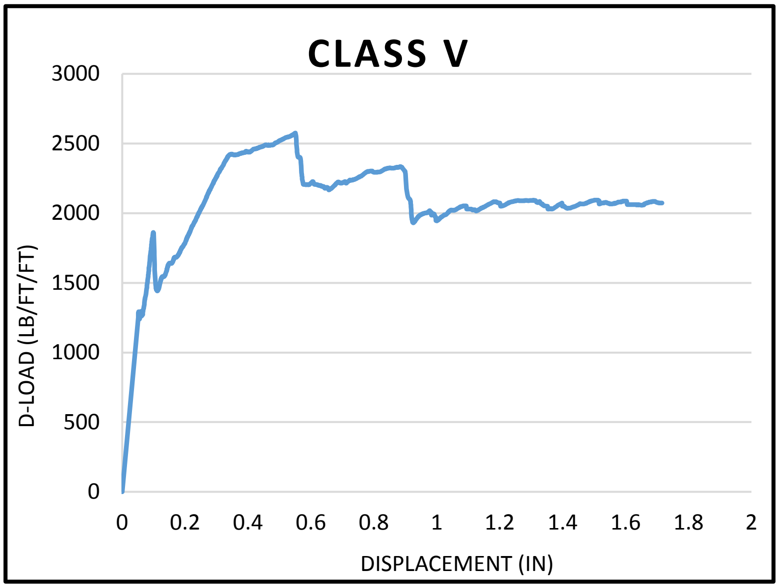




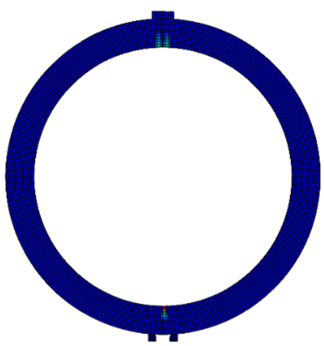
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	0.99	0.59	3000	3644

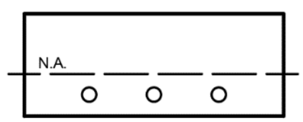
Contoured image shows plastic strain at service load.

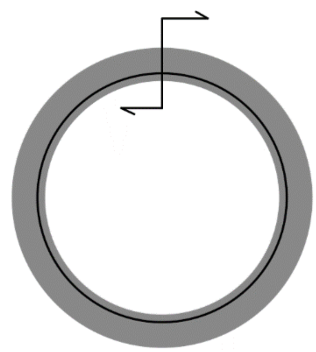
Class V - Wall C - Diameter 72 – 35%



Graph A-114, RCP Class V - Wall C – Diameter 72- 35%



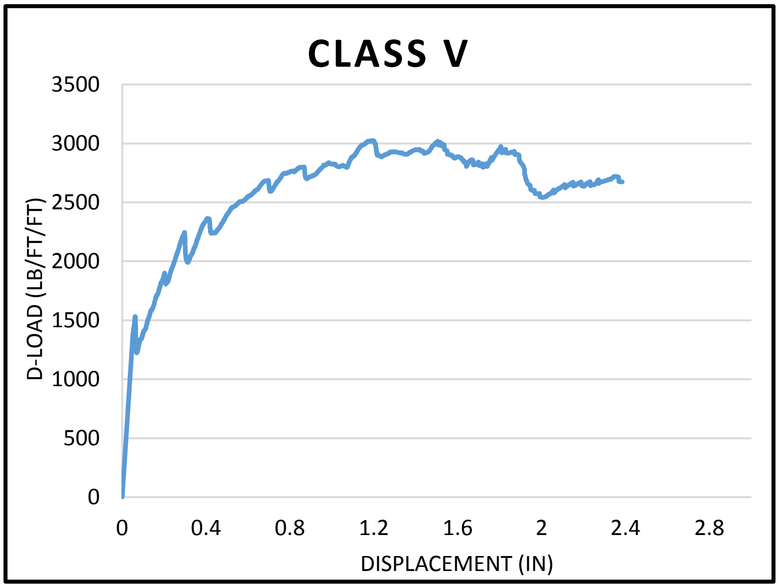




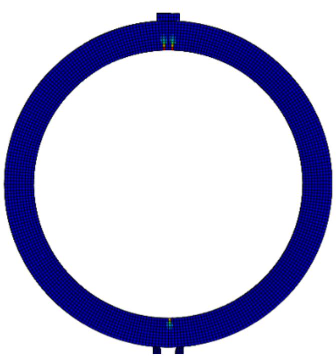
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in²/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	1.58	-	1852	2573

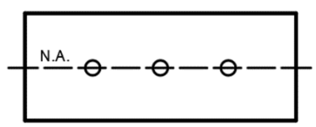
Contoured image shows plastic strain at service load.

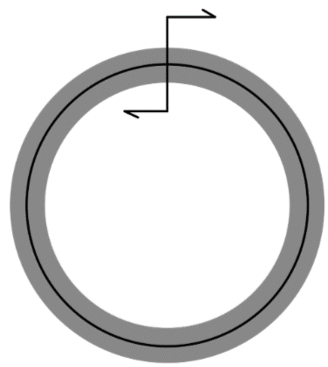
Class V - Wall C - Diameter 72 – 50%



Graph A-115, RCP Class V - Wall C – Diameter 72- 50%



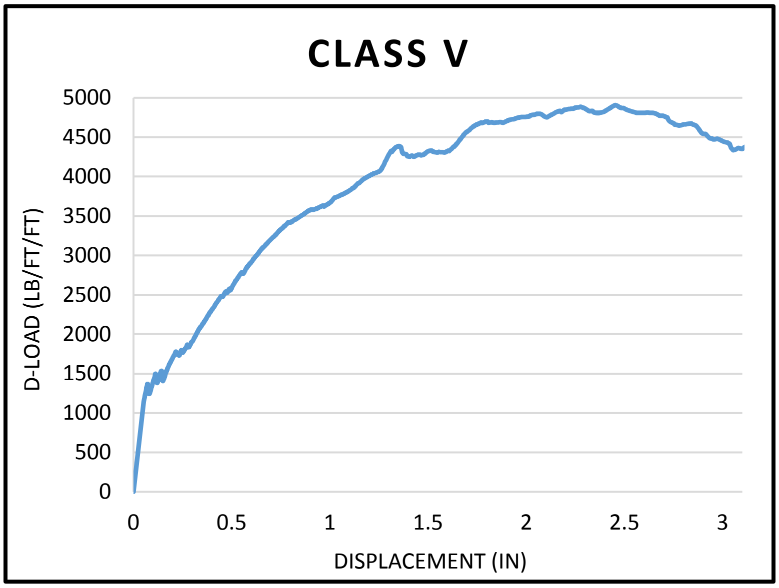




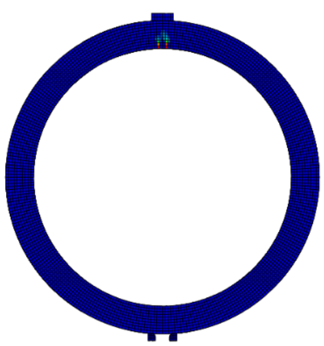
Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	1.58	-	1512	3000

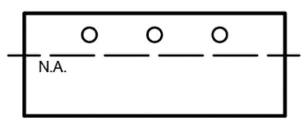
Contoured image shows plastic strain at service load.

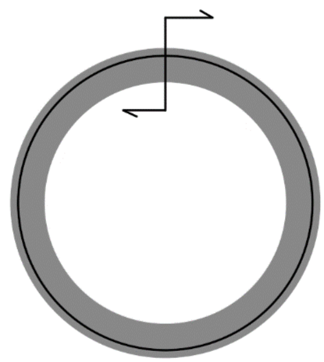
Class V - Wall C - Diameter 72 – 65%



Graph A-116, RCP Class V - Wall C – Diameter 72-65%

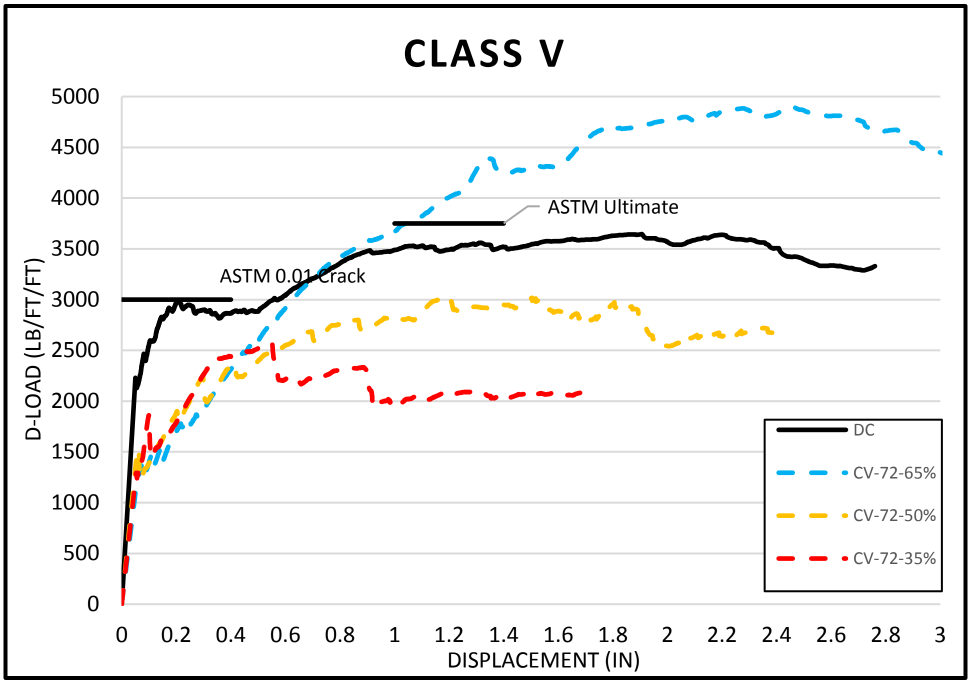






Concrete Strength, 6000 psi					
Inside Diameter (in)	Wall Thickness (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack (ASTM required = 3000)	D-Load for Ultimate (ASTM required = 3750)
		Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	(lb/ft/ft)
72	7.75	1.58	-	1285	4880

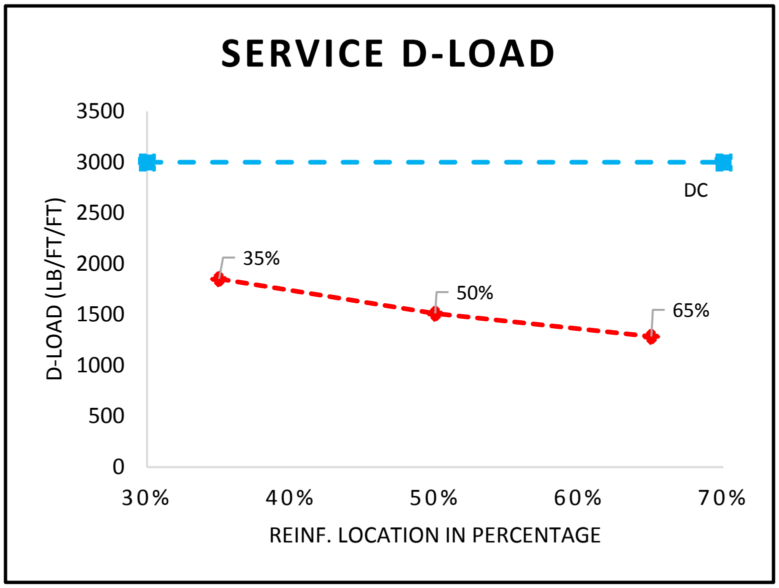
Contoured image shows plastic strain at service load.



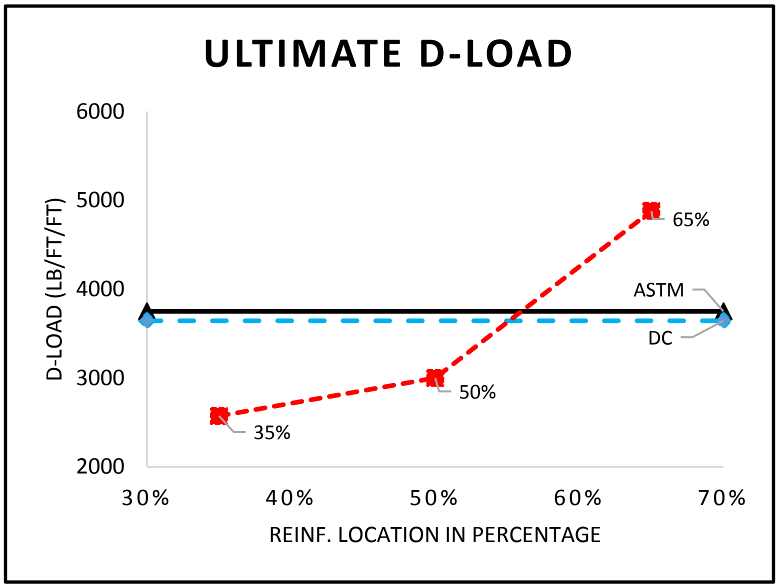
Graph A-117, Comprehensive Graph for Class V-72 in. Pipe diameter

Concrete Strength, 6000 psi								
Pipe Name	Inside Di. (in)	Wall Thick. (in.)	Circular Reinforcement (in^2/ft)		D-Load for 0.01 in crack		D-Load for Ultimate	
			Inner Cage (in^2)	Outer Cage (in^2)	(lb/ft/ft)	Ratio %	(lb/ft/ft)	Ratio %
DC	72	7.75	0.99	0.59	3000	100	3644	100
35%	72	7.75	1.58	-	1852	62	2573	71
50%	72	7.75	1.58	-	1512	50	3000	82
65%	72	7.75	1.58	-	1285	43	4880	134

Table A-18, Comprehensive Graph for Class V-72 in. Pipe diameter

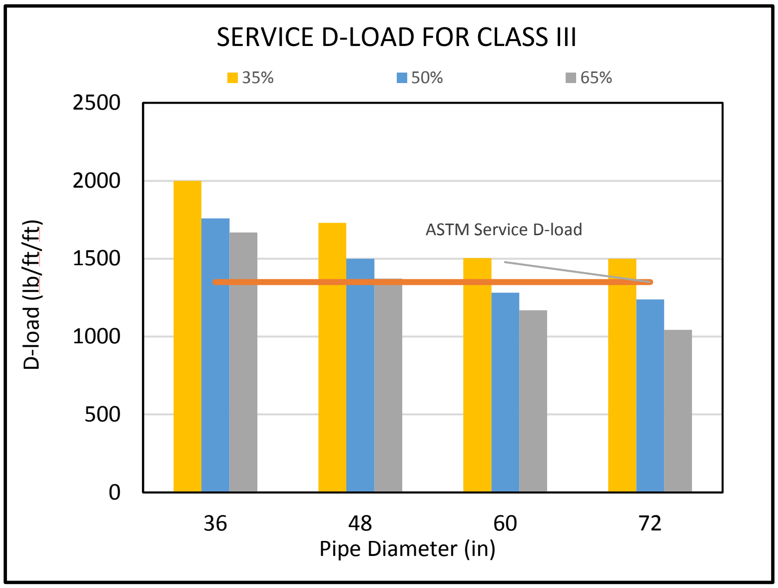


Graph A-118, Comprehensive Graph for Class V-72 in. Pipe diameter

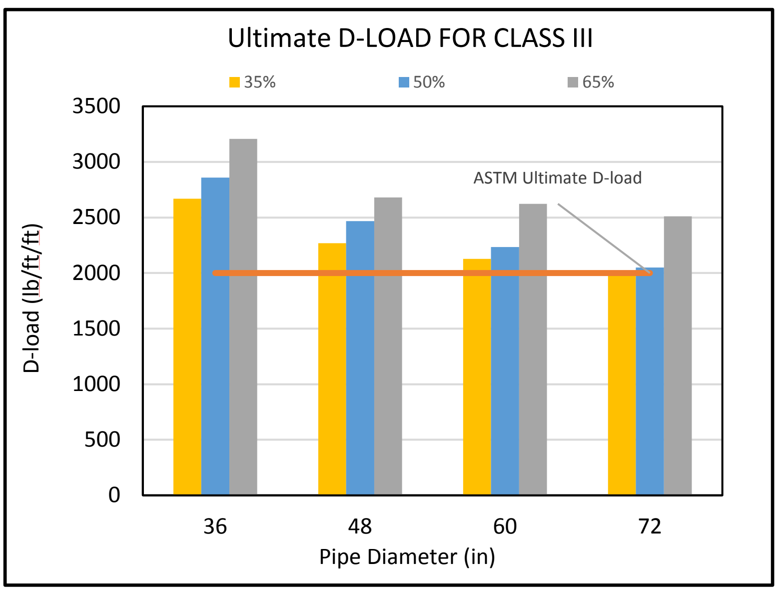


Graph A-119, Comprehensive Graph for Class V-72 in. Pipe diameter

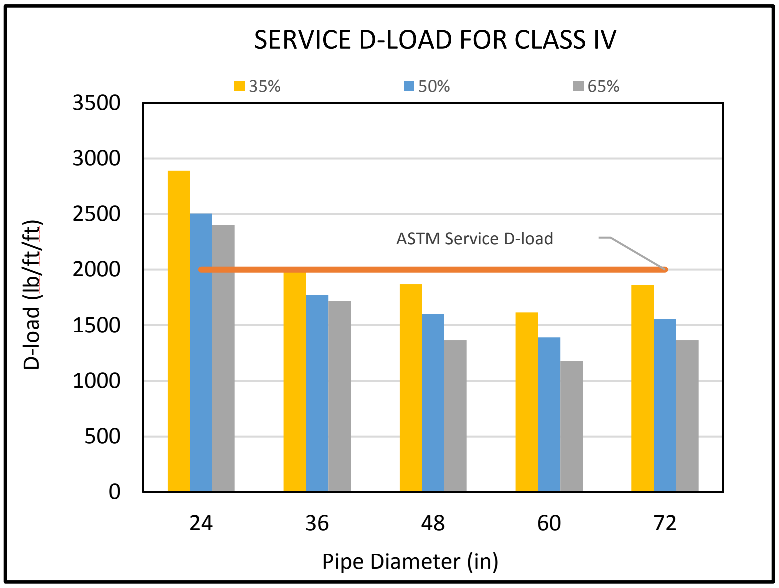
Appendix A-1



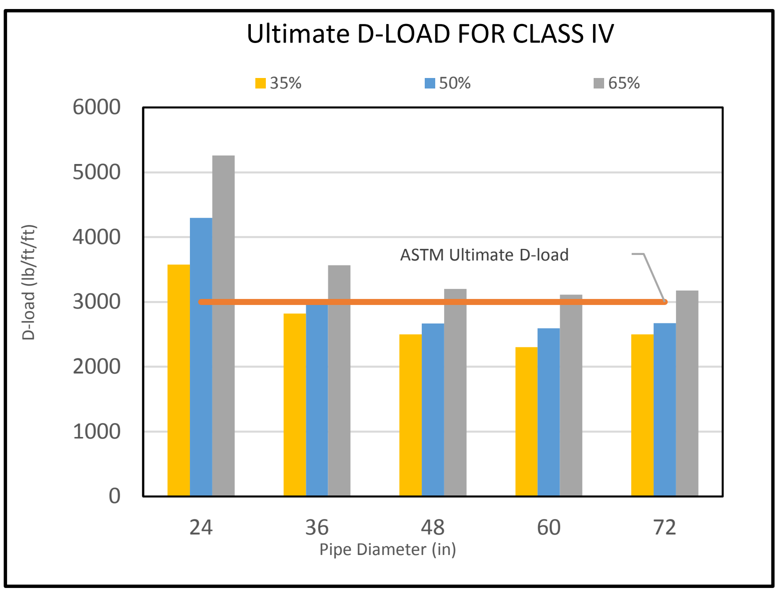
Graph A-1-1, Comprehensive Graph for Class III



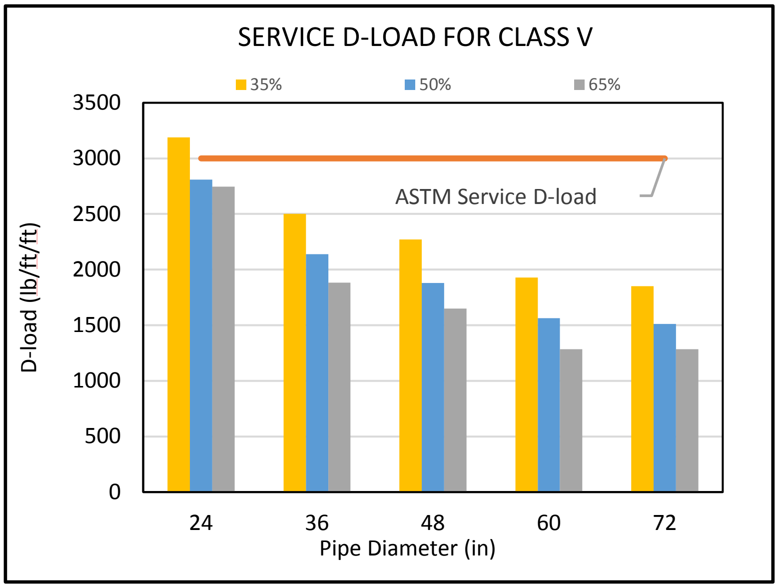
Graph A-1-2, Comprehensive Graph for Class III



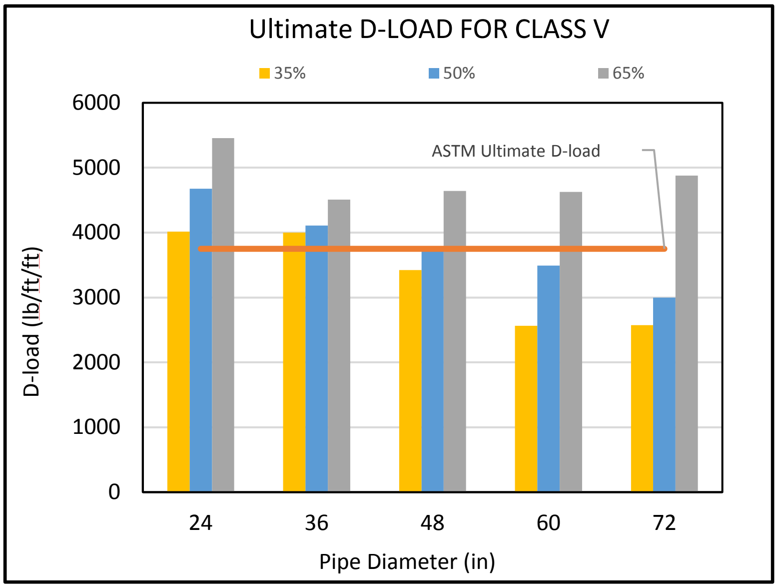
Graph A-1-3, Comprehensive Graph for Class IV



Graph A-1-4, Comprehensive Graph for Class IV



Graph A-1-5, Comprehensive Graph for Class V



Graph A-1-6, Comprehensive Graph for Class V

Appendix B

Double Cage					Single Cage at 35%		
Pipe Dia	Class	Wall	No. of Long.	weight per feet	Number of Long.	weight per feet	Weight percentage (%)
36	3	C	28	12.1	13	8.3	30.9
48	3	C	37	21.0	18	16.3	22.4
60	3	C	46	33.7	22	27.7	17.9
72	3	C	55	52.8	27	45.7	13.4
24	4	C	19	8.0	9	5.5	31.6
36	4	C	28	14.5	13	10.8	25.5
48	4	C	37	28.6	18	23.7	16.9
60	4	C	46	48.8	22	42.7	12.6
72	4	C	55	80.0	27	72.6	9.3
24	5	C	19	9.1	9	6.6	27.3
36	5	C	28	22.0	13	18.1	17.5
48	5	C	37	43.5	18	38.6	11.5
60	5	C	46	76.3	22	69.8	8.6
72	5	C	55	123.2	27	115.3	6.4

Table B-1, Weight Ratio of Singular cage at 35% of Wall Thickness

Double Cage					Single Cage at 50%		
Pipe Dia	Class	Wall	No. of Long.	weight per feet	Number of Long.	weight per feet	Weight percentage (%)
36	3	C	28	12.1	14	8.8	27.4
48	3	C	37	21.0	18	16.7	20.5
60	3	C	46	33.7	23	28.6	15.1
72	3	C	55	52.8	27	46.9	11.2
24	4	C	19	8.0	9	5.6	29.8
36	4	C	28	14.5	14	11.3	22.0
48	4	C	37	28.6	18	24.4	14.7
60	4	C	46	48.8	23	44.1	9.7
72	4	C	55	80.0	27	74.6	6.8
24	5	C	19	9.1	9	6.8	25.2
36	5	C	28	22.0	14	18.9	13.9
48	5	C	37	43.5	18	39.7	8.9
60	5	C	46	76.3	23	72.0	5.6
72	5	C	55	123.2	27	118.6	3.7

Table B-2, Weight Ratio of Singular cage at 50% of Wall Thickness

Double Cage					Single Cage at 65%		
Pipe Dia	Class	Wall	No. of Long.	weight per feet	Number of Long.	weight per feet	Weight percentage (%)
36	3	C	28	12.1	14	9.0	25.8
48	3	C	37	21.0	19	17.4	17.5
60	3	C	46	33.7	23	29.3	13.0
72	3	C	55	52.8	28	48.3	8.5
24	4	C	19	8.0	10	6.0	25.1
36	4	C	28	14.5	14	11.6	20.1
48	4	C	37	28.6	19	25.3	11.6
60	4	C	46	48.8	23	45.3	7.3
72	4	C	55	80.0	28	76.8	4.0
24	5	C	19	9.1	10	7.3	20.5
36	5	C	28	22.0	14	19.5	11.5
48	5	C	37	43.5	19	41.1	5.7
60	5	C	46	76.3	23	74.0	3.0
72	5	C	55	123.2	28	122.1	0.9

Table B-3, Weight Ratio of Singular cage at 65% of Wall Thickness

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