Stress Crack Resistance of Structural Members in Corrugated High Density Polyethylene Pipe

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Abstract

The long-term performance of dual wall corrugated high density polyethylene (HDPE) pipe is directly impacted by the integrity of the critical structural members to resist stress cracking under applied field loads, predominately earth induced pressures. Much of the work to-date in this regard has centered on addressing the circumferential cracking observed at the interface between the corrugation wall and inner wall. This area, however, has no structural implications for the pipe's long-term performance, and therefore, does not reflect a critical structural member. The primary load bearing component of a dual wall corrugated HDPE pipe is the annular corrugated wall. It is this area that necessitates engineering evaluation with regards to the maximum permissible strains and the associated stress-crack resistance of this thermoplastic material. This paper presents the basis for evaluating the stresses in these critical structural members and proposes the use of an established American Standard and Testing Material (ASTM) method in conjunction with the Rate Process Method (RPM) for determining the long-term stress capacity or service life for these members.

Introduction

The growing use of dual wall corrugated HDPE pipe on interstate highways, state highway systems and municipal arterials necessitates the need to design these pipelines to engineering criteria that maintain the highest performance integrity for these vital infrastructure facilities. The design criteria contained in Section 12 of the American Association of State Highway Transportation Official's (AASHTO) Load Resistance Factor Design (LRFD) Bridge Design Specifications (1) provides the basis for determining the maximum thrusts, strains and stresses within each corrugated HDPE structural component. Since the durability of the material directly impacts structural performance, the stress-crack resistance of critical structural members must be accurately assessed to determine the long-term implications on the pipe and installation's integrity. Service life, therefore, directly impacts structural integrity and provides the basis for requiring materials to meet or exceed the specified performance life of the facility, which in many cases approaches 100 years.

The basis of determining service life on the performance of key structural components is well founded within engineering design, and specifically, pipelines. If one of these components experiences deterioration due to long-term tensile strains (stress cracking), corrosion or repetitive loading (fatigue) condition, it must be assessed as a service life limit. Corrugated steel pipe, for example, loses wall thrust capacity (cross-sectional area) as the metal deteriorates due to corrosion or abrasion.

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Failure modes or strength limit state designs are provided for each the various types of pipe in Section 12 of the AASHTO LRFD Bridge Design Specifications. For reinforced concrete pipe, these strength limit states are flexure, thrust, shear (diagonal tension) and radial tension. Corrugated metal pipe experience failures by either buckling or thrust. Thermoplastic pipe have strength limit state designs for thrust, buckling and combined strain. These failure modes for each pipe material manifest themselves on the longitudinal axis of the pipe. The overriding failure mode for HDPE pipe is typically either thrust or combined strain. Buckling seldom governs design, as unstable or very thin cross-sections, such as the inner liner, are eliminated when assessing the profile's effective area for thrust capacity. Circumferential problems, such as beam breaks or cracking, are localized issues that do not affect either the load bearing capacity of the pipe or long-term service life of the installation. As such, they can be repaired in place with no consequences to the service life of the facility.

The service life of dual wall corrugated HDPE pipe has historically been assessed based on stress cracking at the inner liner and corrugation wall interface. Although this circumferential cracking is easy to observe and assess, it does not represent a critical structural component of the pipe. The fact that one could remove the entire inner liner of a dual wall corrugated HDPE pipe and not influence its structural performance is evidence of the fallacy of basing a service life on such a non-critical component. The highest tensile stress locations of buried corrugated HDPE pipe occur in the outer most fiber of the corrugation, where the bending strains are the greatest. Compression related strains do not result in any long-term stress cracking, so one must concentrate on tensile strains. These tensile bending strains are associated with deflection, which is a key AASHTO design parameter. It makes sense, therefore, to concentrate our efforts on determining the stress-crack resistance of these corrugation members rather than on a non-structural component of the pipe, such as the liner.

In order to produce the type of effects long-term strain can induce in a corrugation HDPE profile, several HDPE testing protocols were reviewed with the intent to provide a widely accepted test method, which either models these conditions directly or could be slightly modified to emulate these long-term effects. The test protocol that was found to be best aligned with these goals was the Rate Process Method (RPM).

The Rate Process Method (RPM) can be used to project performance of corrugated HDPE pipes at their in-ground service temperatures by simulating external loads, such as rock impingement and deflection that result in slow crack growth (SCG) failures at the outer most fiber of a corrugated pipe crown. The Rate Process Method involves subjecting corrugated HDPE pipe samples to laboratory elevated temperature sustained pressure testing that result in slit failures. Introduction of loading devices such as indentation or parallel plates can simulate field loading conditions and localize the failure at the crown of the pipe. These slit or SCG failures at the crown are indicative of the long-term failure mode for these critical components in a corrugated HDPE pipe and are indicative of its structural integrity. The three-coefficient RPM equation can then be used to project performance (lifetime) of corrugated HDPE pipe at its actual service conditions.

The Rate Process Method (RPM)

The concept and mathematical basis for using the Rate Process Method for polyethylene (PE) pipe and fitting service projections was originally presented by Bragaw (2) (3). The Plastics Pipe Institute (PPI) Hydrostatic Stress Board (HSB) conducted an extensive evaluation of this and other methods for forecasting the effective long-term performance of PE piping materials. Basically, all these methods require elevated temperature sustained pressure testing of pipe where the type of failure is of the slit or brittle-like mode.

As a result of these studies, HSB determined that the three-coefficient Rate Process Method (RPM) equation provided the best correlation between calculated long-term performance projections and known field performance of several PE piping materials. It also had the best probability for extrapolation of data based on the statistical "lack of fit" test. Further validation of the Rate Process Method was made by comparing RPM projections for PE pipe and fittings obtained at elevated temperatures with actual room temperature laboratory failures for the same pipe and fittings (4).

Rate Process Method testing of pipe or fitting assemblies is conducted in accordance with ASTM D 1598, "Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure" (5). Fittings are joined to pipe using standard joining procedures. Conducting an RPM experiment requires a minimum of 18 to 20 specimens at various temperature/pressure conditions. As with any test protocol, increasing the number of specimens provides a higher confidence level in the failure mode validation and limits.

Using slit failure mode data points, one calculates the A, B and C coefficients for the following three-coefficient Rate Process Method extrapolation equation:

$$\text{Log } t = A + \frac{B}{T} + \frac{C \text{ Log } S}{T}$$

Where:

t = slit mode failure time (hours)
T = absolute temperature (K)
S = stress (psi)

Once the A, B and C coefficients are determined, the RPM equation can be used for various performance projections (average failure time) at typical use temperature (average annual ground temperature) and stress conditions.

The RPM provides the means for not only validating the long-term performance capacity for corrugated HPDE pipe, but it provides a basis for assessing the manufacturer's quality assurance or quality control program. After establishing the RPM coefficients, an appropriate single-point elevated temperature stress rupture test may be established for quality purposes (6).

Mathematically, these RPM projections are sound. They are, however, not absolute and are subject to various experimental errors, unknown deviations and judgment factors. The calculations from the RPM equation are used in conjunction with other known mechanical, performance, and design factors specifically relating to corrugated HDPE pipe to validate the service life projections for these applications.

RPM Projections for HDPE Pipe

Most of the history for projecting service life by the RPM relates to work associated with solid wall HDPE gas pressure pipe. A correlation has been determined between RPM projected performance for solid wall gas pressure pipe and the corresponding field performance for that pipe (7). This study discusses the results for an exhumed control pipe, which was only subjected to internal pressure during RPM testing, and results for various external loads, such as rock impingement, deflection and bending. It is the deflection and point load impingement analysis that presents the most appropriate correlation between the AASHTO corrugated HDPE pipe strength limit state designs and the RPM with respect to service life as determined by the structural member's stress-crack resistance.

By design, thermoplastic pipe is expected to deflect, with most specifications, including those for solid wall HDPE pressure pipe and corrugated HDPE pipe, limiting diametric deformation to 5%. Developing a model to simulate field deflection from earth loading was extremely complicated due to the impact of the restraining forces associated with soil pressures. It was found, however, that the maximum bending stresses at the outer fibers of the pipe wall would develop if the pipe was simply deformed between two rigid members. Although very conservative, this "deflection jig," which is essentially a set of parallel plates as shown in Figure 1, produced high stress conditions in the area of the pipe typically associated with this type of loading. The jig permits the analysis of varying levels of deflection, where deflection is defined as the change in OD (ΔY) divided by the OD.

For this RPM gas pressure pipe experiment, all deflection levels (5%) and failure modes were the same. The typical deflection failure mode was an axial slit (longitudinal crack) on the larger radius surface of the oval shaped pipe, which is the top of the pipe next to the deflection jig. At the use condition of 70°F and 60 psig, this pipe has an average failure time of 18 years with a lower confidence level of 9 years. In the field, deflection failures for solid wall gas pressure pipe occur at the top or crown of the pipe where the radius to the centroid of the pipe wall was the largest and the stresses the greatest. In the RPM test protocol using the deflection jig (parallel plates), the failure mode also occurs in the crown of the pipe, which is where the load or internal bending stresses from the parallel plates is the highest.

Figure 2 represents a finite element model of the parallel plate test loading condition for corrugated HDPE pipe. The highest stresses, as with the gas pressure pipe, occur longitudinally on the inside surface of the crown and invert, and the external outer most fibers at the springline as a result of bending. It is this latter area, which is of most interest in assessing the stress-crack resistance of the performance of the key structural members in corrugated HDPE pipe.

Rock impingement failures experienced by the gas utility are the result of a high stress riser under pressure. Such loading is very typical of a pipe being placed on a non-uniform bedding, either a hard bedding with rock impingements or a soft bedding that creates similar rock impingements due to pipe settlement. An indentation jig (Figure 3) was developed to model this loading condition as part of this solid wall HDPE gas pressure pipe study (7). The jig consists of a collar with a bolted thread to impart an indentation of ¼-inch. The bolted collar remains on the pipe the entire time it is subjected to stress rupture testing to simulate the indentation from rock impingement in the field.

Testing was conducted at 80°C and 60°C with the internal pressure selected to assure failure at the indentation. At the lower pressures, all cracks developed on the inside surface of the pipe initiating at the indentation and propagated to outside surface, at which time, the pipe failed. When the indentation jig was removed, there was residual indentation, which looked identical to the failure mode observed by the gas utility in the field failures. At the gas utility use conditions of 70°F and 60 psig the RPM projected performance for the indented pipe was an average failure time of 12 years with a lower confidence level of 8 years. The gas utility first started to experience rock impingement failures in this pipe after five years of in-ground service. The number of rock impingement failures increased every year and peaked after 12 years of installation. This field experience exactly correlates with the RPM projected performance of indented pipe at their use conditions. The reason for this good correlation between laboratory projection and field experience was the ability to duplicate the SCG failure mode for the field failure in the RPM laboratory test protocol.

Corrugated HDPE pipe do not experience the same level of severe reactions or failure due to impingement point stresses. Although these point loads also exist with gravity flow pipe, they do not induce the failures associated with gas pressure pipe due to the lack of internal pressure. The proposed testing protocols for corrugated HDPE pipe, however, will incorporate these stress risers in the determination of the stress-crack resistance for the wall.

Figure 4 is a composite plot for the exhumed pipe summarizing RPM projected slit slopes at the gas utility average temperature of 70°F for control pipe (internal pressure only) and secondary field induced loads manifesting themselves as deflection and rock impingement. This composite plot demonstrates the change in slopes for the deflection and impingement failure modes.

Evaluation of Stresses in HDPE Corrugate Pipe Profiles

Corrugated HDPE pipe is a profile wall pipe with three distinct cross-sectional components (Figure 5): the corrugation, valley and liner. The corrugation consists of a crest, web, period, and depth or height, but for discussions in this paper, they will be discussed as a monolithic unit. The wall thicknesses and geometric configurations of each of these primary components vary significantly from one another. Based on the geometric intersections of these three components and the large differential in cross-sectional area, an inherit stress riser, Point A, is created at the intersection of inner wall and exterior corrugation (Figure 5). Due to these factors, under high stress conditions, circumferential cracking may occur at this location. It is this cracking that has prompted much of the concerns pertaining to the service life of corrugated HDPE pipe.

If one examines the impact of circumferential cracking at the liner-corrugation interface, it is clearly not a principal design concern as it does not result in any structural distress in the pipe. This cracking does not even increase the possibility of infiltration or exfiltration in the pipeline as the circumferential cracking at this interface only opens a path to the inside of the corrugation. Since the cracking also does not result in any significant offsets that may affect hydraulic performance, these cracks are merely cosmetic and may be repaired in place with no long-term implications to the pipe's performance.

The principal structural components must, therefore, be identified and the stress cracking assessed and service life determined in these members. With the elimination of the inner liner, the two remaining members are the corrugation and valley. The valley is by far the thicker of the two members as it is the welded combination of the inner wall and corrugation extrusions. This member also experiences a lower level of strain than predicted by the AASHTO design criteria (8), and due to external load distribution and profile geometry in a typical corrugated HDPE pipe, this member experiences predominately compression not bending strains.

In comparison, the corrugation is a much more complex member, subject to relatively high bending strains depending on the height of the corrugation. In any event, this member would have the thinner of the two walls with respect to the valley and its extreme fiber would be the furthest from the centroid of the wall. Both of these factors indicate this member would be the most likely to have the highest bending strains, and therefore, the greatest possibility to have stress crack issues that could affect the structural durability of a corrugated HDPE pipe.

Use of RPM for Corrugated HDPE Pipe

The combination of the research efforts on the RPM projected performance on soil wall PE pressure pipe with the design methodology presented in the AASHTO LRFD Bridge Design Specifications provide a means to determine the slow crack growth impacts on the structural members of corrugated HDPE pipe. A recent research study (9) showed that the RPM methodology is in fact applicable to corrugated HDPE pipe. Internal pressure testing at elevated temperatures of pipe ring samples resulted in SCG or slit failures in the corrugated HDPE pipe liner that fit the RPM model very well (Figure 6). RPM mathematical modeling of data from these corrugated HDPE pipe ring samples then allows us to project failure times for that same failure mode at the end use conditions for corrugated pipe. Although this pipe ring test method was useful to project the SCG failure in the liner of corrugated HDPE pipe, it does not give us any information on the structural integrity or the projected useful life of corrugated HDPE pipe.

In this paper, it has been emphasized several times that to project performance of a particular failure mode at end use conditions, the test method must be able to duplicate that same failure mode in the laboratory. Similar RPM mathematical modeling techniques can now be used to determine the SCG integrity of structural members of corrugated HDPE pipe, specifically the corrugation, at its end use conditions. By conducting such an RPM experiment we can then determine the projected life of corrugated HDPE pipe.

Since the AASHTO LRFD analysis (8) has shown that buried corrugated HDPE pipe have high bending strains on the corrugation crests at the springline of the pipe, a laboratory test method needs to be developed that results in the same SCG failure mode at the crown or crest of the corrugation. These bending strains are a result of pipe deflection so it is imperative to develop a test method that includes deflection. The AASTHO LRFD design criteria combine flexural or bending strain to hoop compression strains to determine the total or combined strain. It is these values with an appropriate safety factor that will be used to assess the SGC resistance of this member.

In selecting a bending strain for the laboratory test, the Florida Department of Transportation protocol for 100-year service life for corrugated HDPE pipe (10) was deemed to be the most comprehensive study in this regard and the recommendations herein utilized for bending strains found to be an objective determination for this value. The findings in this study indicate the tension strains are relatively low at AASHTO defined deflection limits. Even when these deflections are exceeded, the tension strains actually decrease because the hoop compression strains increase faster than the bending strains. The most conservative value for tensile strain is determined by neglecting the beneficial effect of compressive thrust, thereby yielding a bending strain at 5% deflection of approximately 1.7% (10) at a 350 psi stress. With a safety factor of 1.5, the resulting strength limits of approximately 500 psi long-term stress and 2.5% strain are obtained.

In developing a laboratory test method to determine corrugated HDPE pipe service life or structural integrity, the external jig must localize the failure mode at the crown area, which would be the same area of high stress as defined in the AASHTO analysis and would be the field failure mode location if subjected to severe external loading. The test methods will utilize a combined indentation and a deflection jig to model a worst case scenario: a deflected pipe with a rock impingement. The proposed test method utilizes a three-foot section of corrugated HDPE pipe that has been capped on both ends. The inner liner of the pipe is perforated to insure the internal applied pressure is applied to the corrugation and the liner does not affect any of the test results. The sealed specimen is pressurized and tested at elevated temperatures to result in SCG failures, similar to the pipe ring specimen (9). The main difference being failure is now occurring at the crown.

Each specimen in the RPM experiment will have a combination indentation-deflection jig around the pipe, Figure 7. The indention jig will be similar to Figure 3, and the deflection jig (parallel plates) similar to Figure 1. The deflection jig will represent the external earth load that would occur in buried corrugated HDPE pipe when deflected 5%. The indentation jig will represent a point load that could occur in buried corrugated HDPE pipe. This ¼-inch impingement would be identical to that used for the solid wall PE gas pressure pipe and applied at the springline of corrugation after the pipe is deflected 5%. The failure mode in both cases will be an SCG failure at the high stress area, the top of the crown, where the bending strains are the greatest and a stress riser is present.

By conducting these experiments at multiple temperatures and multiple internal pressures, at a constant indent and constant deflection, the RPM mathematical modeling can be utilized to project the service life of corrugated HDPE pipe at its end use temperature and in the presence of external loads that result in a failure at the crown. Since HDPE is a viscoelastic material and will experience some degree of stress relaxation especially at elevated temperatures, the test protocol will be adjusted to maintain a constant stress on the crown. Ultimately, this test protocol will be a true measure of the structural integrity of the corrugated HDPE pipe.

Summary

The Rate Process Method is a very powerful tool that can be used to determine the projected life solid wall or corrugated polyethylene pipe in various service applications. RPM can project not only the life of control pipe based on internal pressure, but also the life of the pipe subjected to secondary loads such as rock impingement, bending and deflection. In addition, based on scatter of the data, RPM can project the mean or average failure time at use conditions and the lower confidence level at use conditions.

By use of FEA and testing, the high stress areas in the structural components of a buried corrugated HDPE pipe have been determined. By applying the principles of RPM testing that have been demonstrated for solid wall PE pipe (7) and corrugated HDPE pipe (9), a new test protocol that results in a failure mode at the same high stress area defined by these methods can be utilized to determine the structural integrity and service life of corrugated HDPE pipe at end use conditions. This new protocol would concentrate on the principal structural member, the corrugation, which has the highest tensile strain from deflection and greatest potential for point stresses from rock impingement.

This protocol is currently under laboratory testing with final results expected to be available by the second quarter of 2007. The results of this research program will be presented in a subsequent TRB paper.

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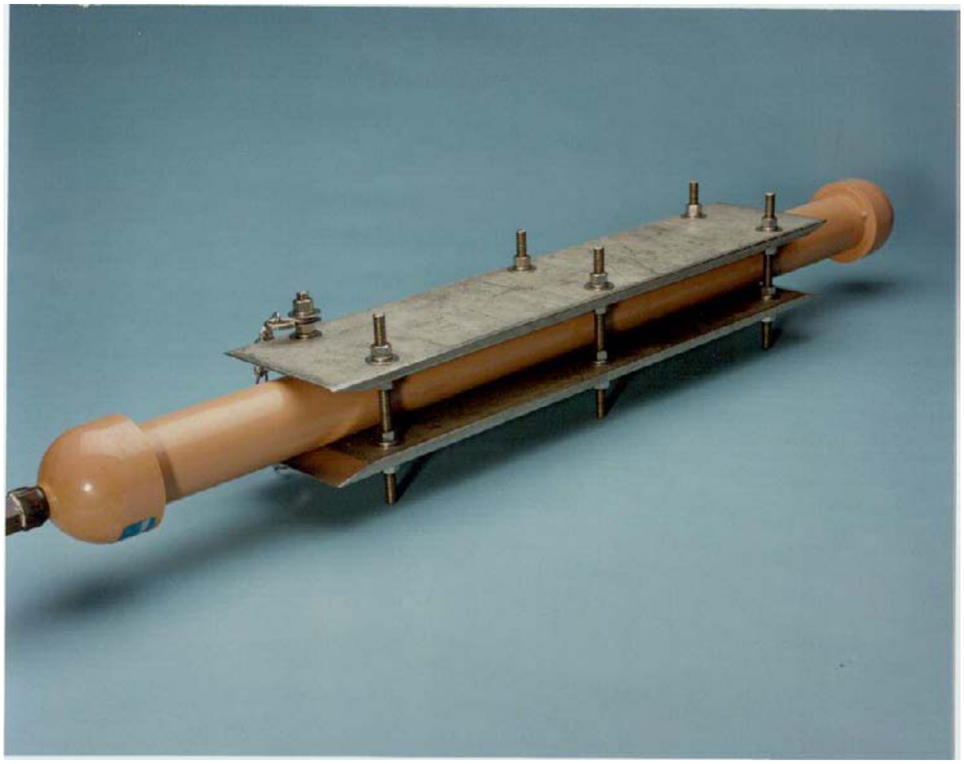

Figure 1 – Deflection Jig

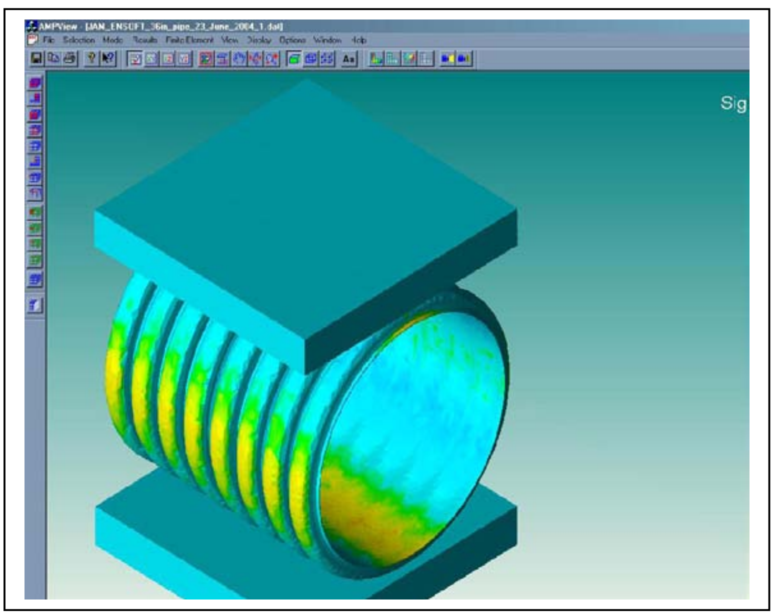

Figure 2 – High Stress Locations Associated with Parallel Plate Loading

Figure 3 – Rock Impingement Jig

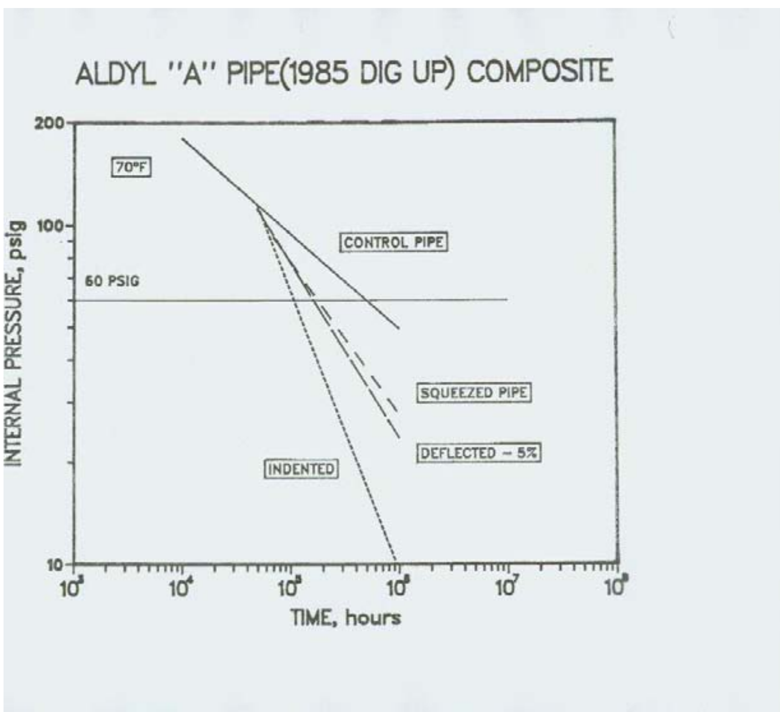

Figure 4 – Composite Showing Control Pipe and Secondary Loading Effects

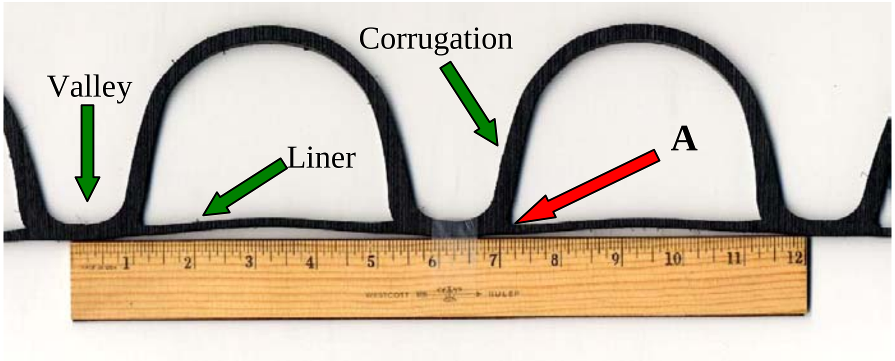

Figure 5 – Corrugation HDPE Pipe Profile

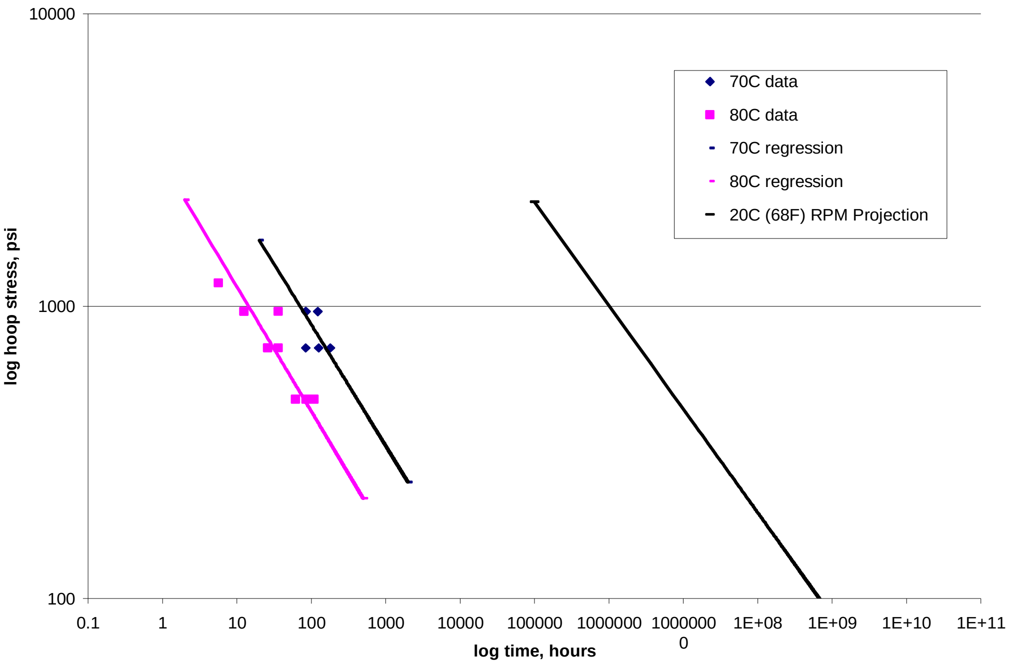

Figure 6: RPM Analysis of Control Corrugated HDPE Pipe

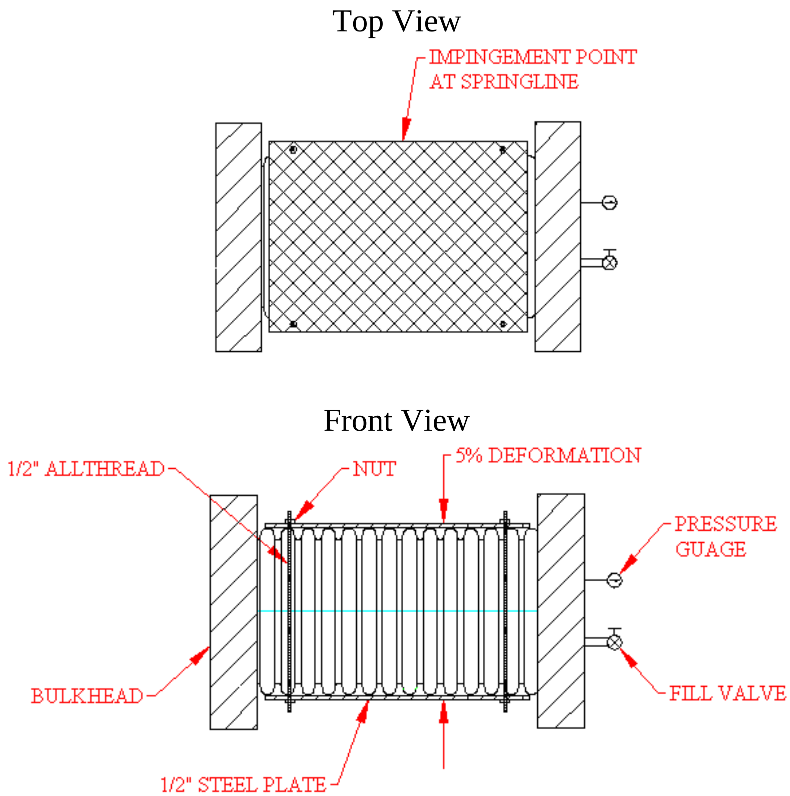

Figure 7: Deflection – Impingement Jig