APPROACHES TO FATIGUE DESIGN IN THERMOPLASTIC PIPE

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ABSTRACT

Cyclic loading of plastic pipe is a known risk factor that can lead to fatigue related failure. While the re-rating of plastic pipe based on cyclic loading is addressed by advisory documents on other continents, there is limited guidance for design engineers in North American practice. Domestic polyvinyl chloride (PVC) and polyethylene (PE) standards include surge allowances above rated working pressure based on limiting values of hoop stress, but only C900 and C905 for PVC pipe include a method for addressing fatigue in design and then only as an informational appendix, not as part of the adopted standard. In this paper, the author uses field measured transient data to develop three classes of cyclic loading that are typical of water and wastewater practice. Various standard design approaches are then applied to the selection of the appropriate pressure class of plastic pipe for each classified transient. Determination of the corresponding dimension ratios allow for the analysis of the transient data in terms of hoop stress. Given sufficient knowledge of the transient conditions in an existing or proposed piping system, the design engineer can not only design for a total number of lifetime cycles, but also reduce risk of fatigue failure by managing the magnitude of repeated stress cycling.

PROBLEM STATEMENT

Materials of construction are subject to fatigue failure resulting from repeated mechanical stress of sufficiently high frequency and magnitude to exceed the material’s performance limit. Fatigue resulting from internal cyclic loading (commonly the result of oscillating internal pressures) is a known risk to thermoplastic pipe and is the subject of ongoing research in the plastics industry. Despite awareness of the risk, there is little fatigue design guidance to be found in thermoplastic domestic pipe design standards. It will be shown in this paper that UK and Australian practice is somewhat ahead of the US in the area of fatigue design, with several industry guidance documents in print.

A recent comprehensive study of the long term performance of PVC pipe (AwwaRF, 2005) found that the current US practice of simple surge allowance without fatigue considerations is “overly simplistic”. It has also been suggested in a separate study (AwwaRF, 2007) that future PE pipe standards in the US need to provide guidance on pipe re-rating against fatigue failure from recurring surge pressures. Recent experimental studies by Marshall and Brogden (1999) in the UK and Moser et.al (2003) in the US have also shown that plastic pipe material is subject to fatigue and therefore merits fatigue analysis in design.

CURRENT DESIGN PRACTICES

The basic equation used in thermoplastic pressure pipe design is commonly identified as the ISO equation and the organization for which it was named (International Organization for Standardization) has adopted this basic hoop stress equation for pressure rating systems (Plastic Pipe Institute, 2008). The equation below is based on the ISO equation and expresses the basic pressure rating (PR) method for outside diameter dimension ratio controlled plastic pipe:

$$PR = \frac{2(HDS)}{\left[\frac{Do}{t} - 1\right]} \qquad \text{Equation (1.1)}$$

where:

where:	PR	=	Pressure rating (psi or, MPa)
	HDS	=	Hydrostatic Design Stress (psi or, MPa)
	Do	=	Outside diameter of pipe (in or, mm)
	t	=	Pipe wall thickness

The term $\frac{D_0}{t}$ represents the "dimension ratio" and is commonly abbreviated as *DR*. Manufacturers and standards committees have (over time) created a limited number of standard DR for a given pipe material that cover the desired range of service pressures. Because of the use of a standard HDS, all pipe sizes for a given DR will have the same PR.

The HDS represents the estimated maximum tensile stress in the wall of the pipe in the circumferential orientation due to internal hydrostatic pressure that can be continuously applied with a high degree of certainty that failure will not occur. In global practice today, there two major means of categorizing the HDS for a thermoplastic pipe material. Domestic practice is based on the ASTM D2837 method that develops a Hydrostatic Design Basis (HDB) rating for a given material that categorized long-term hydrostatic strength in the hoop direction. The HDS is developed from the HDB through the application of a strength reduction Design Factor (DF) of less than one (generally 0.5) which introduces the basic terms of conservatism. Other strength reduction factors may be applied to the pressure rating during the design process through the use of coefficients to reduce strength based on increased temperature or environmental factors.

The pipe rating system employed in Europe elsewhere is based on ISO 12162 standard and develops HDS by dividing a Minimum Required Strength (MRS) rating for a given material by a Design Coefficient (DC) greater than one. It is sufficient for the current study to understand that ISO and ASTM methods arrive at the basic HDS of a material differently and one must use caution in mixing the two methods. While the topic of this paper applies fatigue factors used in ISO design to ASTM materials, it should be understood that this is an academic exercise only. Pipe materials manufactured in various countries may have the same general material attribution (may be called "PE" or "PVC") but have very different material characteristics.

There is no standard approach to handling transient ("surge") pressures between plastic pipe standards and design manuals. While each of the standards listed in Table 1 address design of plastic pipe for transient pressures, coverage of the topic of mechanical fatigue is very limited.

Table 1. Common US Standards for Thermoplastic Pipe

Standard / Manual	Material	Size Range	Fatigue Design
AWWA C900-07	PVC	4" to 12"	Yes[1]
AWWA C905-10	PVC	14" to 48"	Yes[1]
AWWA C906-07	PE	4" to 63"	No
AWWA M23 (2002)	PVC	4" to 48"	Yes[2]
AWWA M55 (2006)	PE	4" to 63"	No

1) Appendix only, not part of the formal standard
2) Refers to Uni-Bell Handbook

The author has conducted a survey of overseas standards in an attempt to locate fatigue design approaches in use in other countries. It was found that the UK as well as the Australia/New Zealand markets had industry advisory documents for use in the allowance for plastic pipe fatigue in design.

WATER UK prepares Water Industry Specifications (WISs) for the specification and purchase of products used in water and wastewater practice. WISs generally cover products for which there is no suitable European or British standard. WATER UK also issues Information & Guidance Notes (IGNs) that are used to provide additional guidance to a WIS or provide interpretation and additional information to European or British standards. British practice is similar to US practice in that plastic pipe is manufactured to standard DRs and rated for a pressure based on the DR. Unlike domestic practice, UK pipe is designated by a nominal pressure classification (PN) rather than the DR. However, WIS and IGN documents are clear that the PN of a pipe is not an absolute strength rating and that application and installation factors must be applied in design. These standards and advisory documents provide the design with methods of calculating maximum allowable continuous operating pressure (PFA), maximum allowable operating pressure (PMA) and maximum allowable site test pressure (PEA). One document was found that applied directly surge and fatigue design for plastic pipes (Table 2).

Practice in Australia and New Zealand is similar to practice in the UK, with basic material strength PN ratings developed based on ISO methods. Australian practice is guided by pipeline codes (WSA) issued by Water Services Association of Australia (WSAA) as well as a set of standards the cover Australia and New Zealand (AS/NZS and others). Australian fatigue design guidance documents located by the author were issued by the Plastics Industry Pipe Association of Australia Limited (PIPA), an industry advisory organization. Table 2 summarizes overseas advisory documents used during the current study.

Table 2. UK and Australian Advisory Documents

Document / Country	Material	Title	Year
IGN 4-37-02 / UK	PVC / PE	*Design Against Surge and Fatigue Conditions in Thermoplastic Pipes*	1999
POP010A / AU	PE	*Polyethylene Pressure Pipes Design for Dynamic Stresses*	2010
POP101 / AU	PVC	*PVC Pressure Pipes Design for Dynamic Stresses*	2009

DESIGN FOR SURGE

From this point forward, discussion will be focused on AWWA C905 and C906 pipe. These standards cover large diameter PVC and PE pipe (respectively) used in water and wastewater transmission in the US. These standards will be used to develop current design practices for pipe design and will be the basis for subsequent design examples.

PVC pipe design guidance is found in AWWA Manual M23 which includes tables on selecting PR for C905 pipe used in transmission. PR for a given DR is limited to that pressure which equates to a hoop stress that is equivalent to HDS (2000 psi in the case of PVC). Design surge allowances in C905 design for transmission are kept relatively low, within approximately 25% of the PR for each DR of pipe.

Design for large diameter PE transmission pipe is guided by AWWA Manual M55 as well as AWWA C906. While PVC design approaches do not distinguish between types of surge, AWWA PE standards denote two major types: “recurring” and “occasional” surge. Recurring surge is defined as a transient pressure that will occur frequently on a pipeline and is inherent to the system. This type of surge will be generated as part of routine operation and may include pump starts and stops and normal valve operations. Occasional surges are defined as those transient events caused by emergency situations or events not anticipated by designers as occurring every day. These events might include full power pump trip, emergency valve operations, or a pipe rupture. Surge pressures of 1.5 times PR are allowed for recurring surge events, and pressures up to 2.0 times PR are allowed for occasional surge. It should be noted that this approach uses the full range of the pipe’s hoop stress, and can allow to designer to take the pipe up to the limiting value of HDB during occasional surge events.

DESIGN FOR FATIGUE

AWWA design standards address surge pressure, and provide allowances for transient conditions in the determination of overall strength design through the selection of PR. The long term performance of the pipeline under cyclic loading, however, is not addressed by the main body of design standards and manuals.

The fundamental approach to determining the fatigue characteristics of a material is the development of experimental data plotted as "S-N curves" (stress vs. number of cycles to failure). Work by Marshall et al (1998) presented S-N curves for the main plastic pipe materials in use in current UK practice. Marshall's study found that the main two factors controlling fatigue where the range of pressure transient (minimum to maximum pressures) and the total number of cycles. This research culminated in a set of de-rating factors for pipe strength developed by applying power law fits to average lines through experimental S-N data.

Similar research funded by Uni-Bell at about the same time (Jeffrey, 2004) analyzed the work of earlier researchers as well as engaging in laboratory study of cyclic loading and fatigue in PVC pipe. The number of cycles to failure in the pipe testing portion ranged from 36,300 to over 10,000,000. One of the main conclusions of the study was that stress amplitude (the range from minimum to maximum pressure) influences the fatigue of PVC more than mean stress, but mean stress does play a minor role as does the total number of cycles.

Fatigue Factor Methods

The advisory documents listed in Table 2 provide guidance on the application of fatigue factors to plastic pipe design. These documents follow the recommendation of Marshall et al (1998) that de-rating factors should be derived from S-N curves specifically developed for the design material. The approach is used as a check after the standard design method for PR is conducted. If fatigue is a concern, the designer calculates the pressure range based on analysis (or measurement of an operating system) and multiplies the range by the appropriate fatigue factor to determine and "equivalent pressure". The applicable fatigue factor is determined based on the projected number of lifetime pressure cycles (Figure 1). The equivalent pressure is then used to select an alternative PR which is checked against the standard design selection, and the lower DR chosen.

C900/C905 Appendices (Stress Curve / Design Space Method)

The experimental research and data analysis of Jeffrey et al produced the plot show in Figure 2, which appears in the AWWA C900/C905 Appendices. In this method, a DR is first selected using PR based on working pressure and surge, then checked for fatigue. The selected DR hoop stress range (amplitude) and mean hoop stress resulting from the design transient are used to enter the plot to check the total number of cycles. If the total number of cycles does not exceed design, or the resulting intersection is not within the design window, a lower DR must be selected. It should be noted that there is a factor of safety of 2 on the number of lifetime cycles using this method.

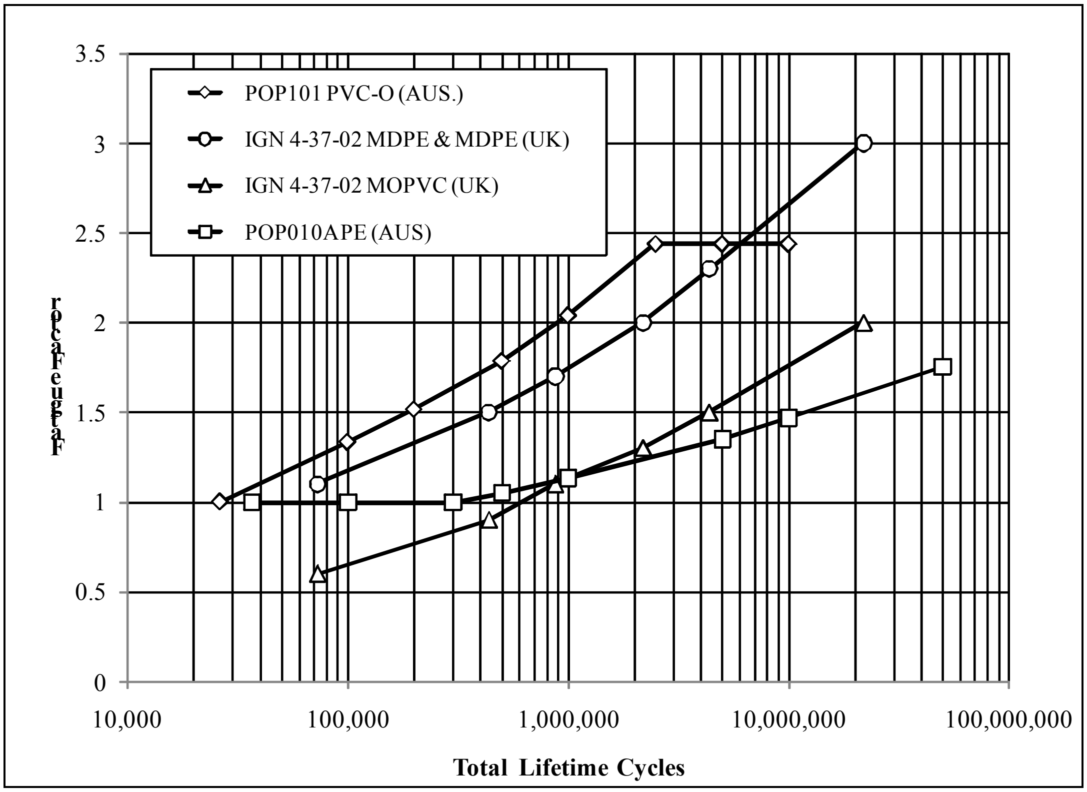

Figure 1. Fatigue Factors.

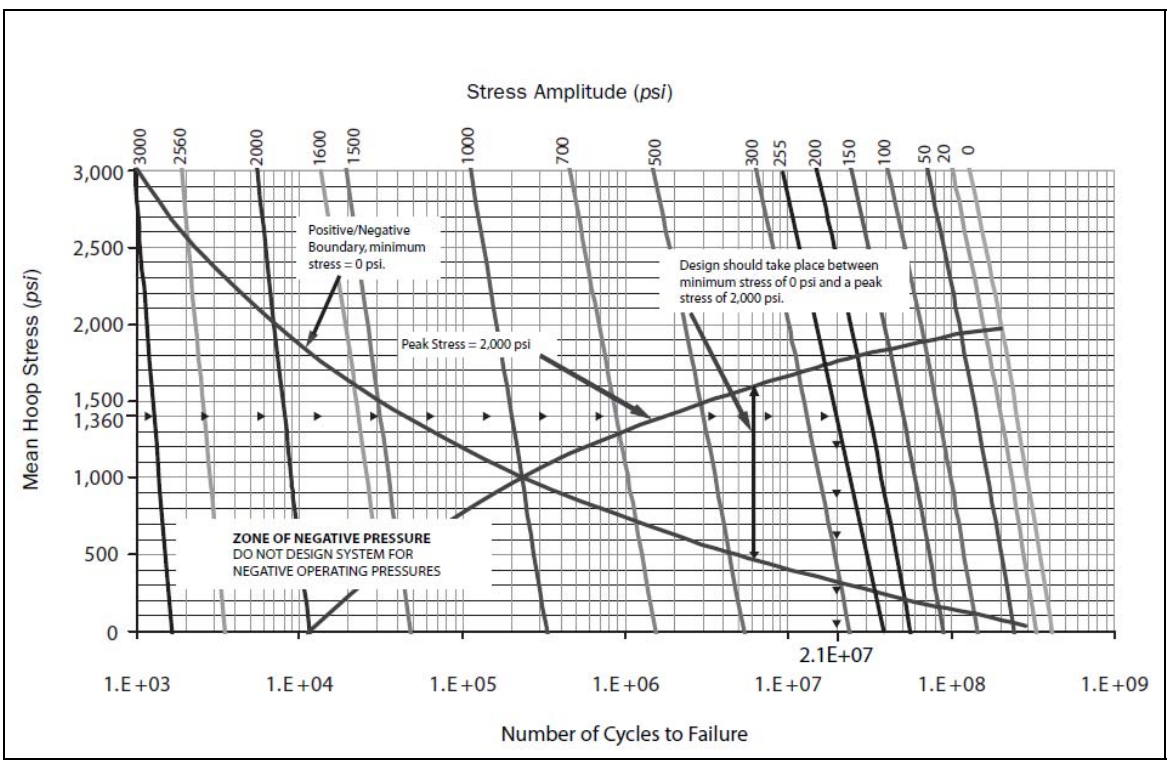

Figure 2. Uni-Bell / AWWA C900/C905 Fatigue Design.

CYCLIC LOADING CLASSIFICATION

In order to test the sensitivity of the fatigue design approaches described above, the author has created a set of three broad classes of hydraulic transients for use in design examples. In each case, measured field data were used to create an example of a typical transient for each class of cyclic loading. The data were manipulated to create a design setting where the working ("design") pressure would be approximately 85 psi so that the design process could be applied to a similar basic pressure class of pipe with different fatigue design criteria. While the plots shown are based on measured data, they could just as easily have been generated by hydraulic modeling during the planning and design phase of a pipeline project.

Class 1: Steady Pressure with Occasional Surge

The pressure trace shown in Figure 3 was recorded on the customer side of a water meter in a large municipal water distribution system. The plot shows that minor transients occurred during the recording period and that the system experienced a slow transition in the hydraulic grade line (HGL) over the six hour period. This pressure record is typical of extensive distribution systems where system pressure is mostly dictated by diurnal demand trends. In terms of surge and fatigue design, one would expect that Class 1 cyclic loading to have recurring and occasional surge pressures below the respective limits for PVC and PE pipe.

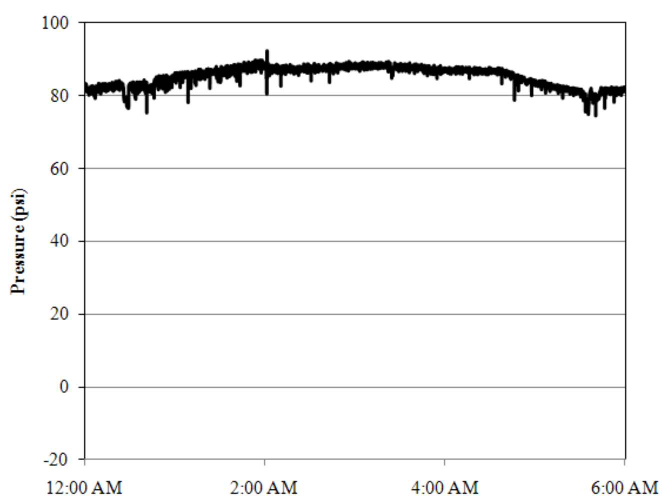

Figure 3. Loading Class 1.

Class 2: Steady Pressure with Recurring Surge

The pressure trace shown in Figure 4 was recorded on an operating raw water transmission pipeline. The pressure recorder in this case captures a major transient caused by pump shutdown and a smaller transient caused by a pump startup a few hours later. During the intervening period one pump remained operational. This pressure record is typical of water transmission applications where constant supply is required, with peak flow needed during high demand periods or during storage replenishment. In terms of surge and fatigue design, one would expect that Class 2 cyclic loading to have recurring and occasional surge pressures that may approach or exceed the respective limits for PVC and PE pipe.

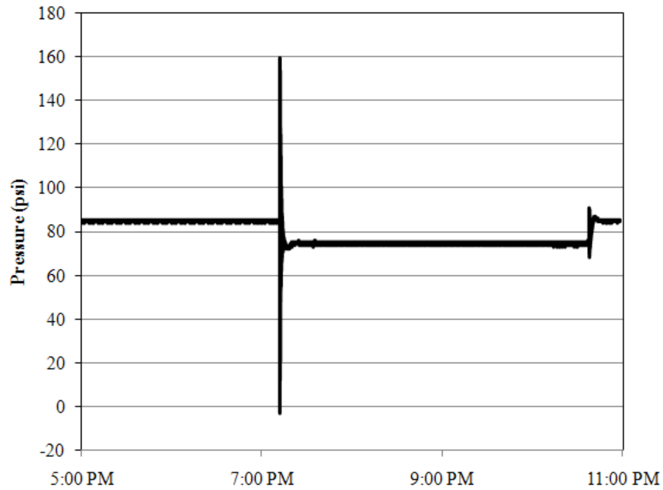

Figure 4. Loading Class 2

<u>Class 3</u>: Unsteady Pressure with Recurring Surge

The pressure trace shown in Figure 5 was recorded on an operating wastewater force main. The period of record covers a 1 hour period and captures a series of major transient events caused by the repeated pump starts and stops. This pressure record is typical of wastewater transmission applications where operation is dictated by sanitary flows as well as groundwater and surface water infiltration. In terms of surge and fatigue design, one would expect that Class 3 cyclic loading to have frequent pressure cycles that may run the entire range of the pipe's service rating. In this setting recurring and occasional surge pressures may approach or exceed the respective limits for PVC and PE pipe.

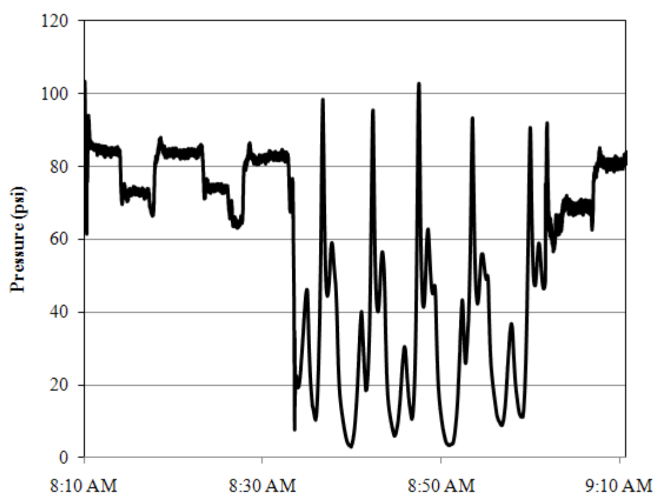

Figure 5. Loading Class 3.

APPLICATION OF LOADING CLASSES IN DESIGN

The cyclic loading cases above were used as design examples in order to apply the various fatigue design methods to a range of typical applications. Because the fatigue data were collected on pipe materials made outside of the US (with the exception of the C900 method) these examples would have no validity as designs, and are presented as illustrations only. The DR selections in Tables 5 and 6 indicate that Class 1 loading is not sufficient to justify de-rating based on fatigue. Class 2 and 3, however, clearly do require additional wall thickness to reduce hoop stresses in order to meet the required number of lifetime cycles.

Table 3. Pressure Design Variables

Cyclic Loading Class	Working Pressure (psi)	Max. Surge (psi)	Min. Surge (psi)	Pressure Range (psi)
1	85.0	92.2	81.6	10.6
2	85.0	160.0	0.0	160
3	85.0	100.9	5.7	95.2

Table 4. Fatigue Design Factors

Cyclic Loading Class	Total Cycles (50 yrs)	POP101 (PVC-O)	POPO10A (PE)	IGN 4-37-02 (MOPVC)	IGN 4-37-02 (PE)
1	1,460,000	2.08	1.16	1.19	1.83
2	146,000	1.37	1.00	0.66	1.18
3	3,942,000	2.44	1.28	1.46	2.24

Table 5. PVC Design DR (HDS 2000 psi)

Cyclic Loading Class	AWWA M23	C900/C905 Fatigue Design	POP101 (PVC-O)	IGN 4-37-02
1	41	41	41	41
2	32.5	21	18	21
3	41	18	18	26

Table 6. PE Design DR (HDS 800 psi)

Cyclical Loading Class	AWWA C906	POP010A	IGN 4-37-02
1	17	17	17
2	13.5	11	9
3	17	13.5	7.3

Figure 6 shows transient hoop stresses for various DR and illustrates the differences in mechanical stress graphically. The plotted hoop stresses are the result of the Class 2 transients occurring over a 35 second period following pump shutdown. The figure shows that selection of the lowest DR results in a net reduction of 400 psi (hoop stress) at peak pressure. Such stress reduction will certainly extend the useful life of thermoplastic pipeline at risk from cyclic loading.

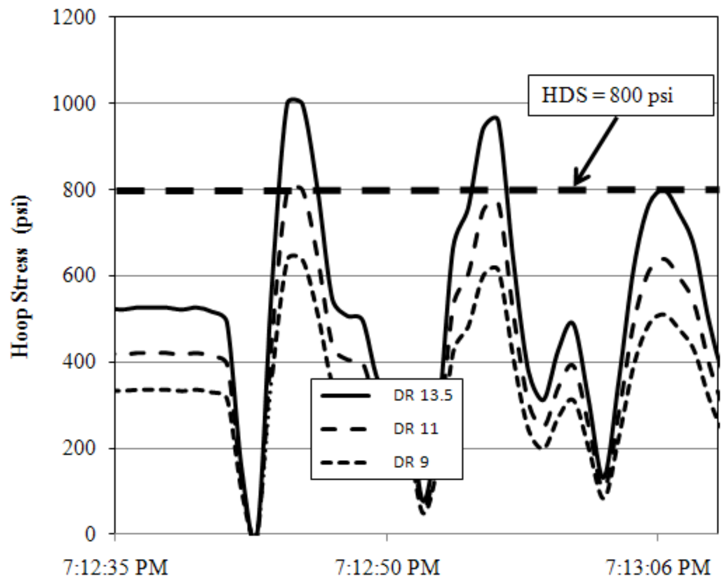

Figure 6. Loading Case 2 in Terms of Hoop Stress (PE; HDS = 800 psi).

CONCLUSIONS

Simple surge allowances in plastic pipe design are not sufficient to protect pipe from early failure due to fatigue. Therefore, fatigue analysis should be performed routinely in plastic pipe design. While considering general classes of service is useful in understanding the relative differences in application, every service setting is unique and transient analysis is required for safe design. Fatigue de-rating factors should be based on fatigue testing data from tests performed on the exact materials being applied in design.

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