PVC PIPE news

PVC Force Main Design Example

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The last time a force main design example was the subject of a *PVC Pipe News* article was the summer of 1989. [1] Since then, the cyclic capabilities of PVC have become better defined with additional study. [2-3] The *News* kept you informed of these developments with several articles that described the research and summarized the results. [4-6]

This article demonstrates the use of the latest cyclic design chart for PVC in a force main setting. Additionally, the concepts of Short Term Rating (STR) and Pressure Rating (PR) are revisited. The values used in the design example come from an actual project that was reviewed by one of our member companies.

PRESSURE RATING

This is the design step that most engineers are familiar with. The operating pressure is compared to the PR of the pipe. The PRs for various dimension ratios of PVC pipe are listed in Table 1. Mathematically, the Standard Dimension Ratio (SDR) is the same as the Dimension Ratio (DR). Both are defined in Equation 1.

TABLE 1
Pressure Ratings For PVC Pipe

SDR or DR	PR, psi (MPa)
51	80 (0.55)
41	100 (0.69)
32.5	125 (0.86)
26	160 (1.10)
25	165 (1.14)
21	200 (1.38)
18	235 (1.62)
14	305 (2.11)

EQUATION 1

$$SDR = DR = D_0 \div t_{min}$$

where:
D_0 = average outside diameter
t_{min} = minimum wall thickness

SHORT TERM RATING

An inherent property that PVC pipes have always offered is more pressure capacity as the duration of the application of that pressure is decreased. In fact, this is why the quick-burst and sustained-pressure test values used for quality control purposes far exceed a PVC pipe's Pressure Rating. An SDR41 product, with a 100 psi Pressure Rating, serves as an example. For the sustained-pressure test, an SDR41 must hold 210 psi in excess of 1,000 hours. For the quick-burst test, the pressure causing the pipe to burst must exceed 315 psi, where the time to burst is calibrated to be in the 60 to 70 second range.

While this property of PVC pipe has traditionally been incorporated for quality control and quality assurance purposes, it has only recently been recognized for design purposes. The latest edition of AWWA Manual M23, "PVC Pipe - Design and Installation," allows the designer to capitalize on this PVC pipe property. [7] For non-recurring pressure surges, such as those resulting from a power outage or fire fighting water flows, the designer is allowed to compare the potential pressures (including surge) against the STR rather than the PR.

STRs for various DRs are listed in Table 2. The STR is calculated using a safety factor of 2.0 against the pipe's quick-burst requirement.

TABLE 2
STR Values for PVC Pipe

SDR or DR	STR, psi (MPa)
51	128 (0.88)
41	160 (1.10)
32.5	203 (1.40)
26	256 (1.77)
25	264 (1.84)
21	320 (2.21)
18	376 (2.60)
14	488 (3.40)

CYCLIC CAPACITY

The new research on the cyclic capabilities of PVC pressure pipe [2-3] confirmed that predicting the fatigue capabilities of PVC is much like that of any other material. It is a function of two variables: the average stress and the stress amplitude. The design chart developed by the research is shown in Figure 1.

DESIGN STEPS

Having reintroduced all the concepts, let's review the design checks for our force main design example. There are three of them. First, normal operating pressures (including routine surges) are compared against the PR. The PR must meet or exceed the cyclic pressures routinely generated during the force main's operation. Second, non-cyclic peak pressures are compared against the STR. The STR must meet or exceed these occasional peak pressures generated by "infrequent" surge. Finally, the cyclic capability of the PVC, as represented by the value C, must meet or exceed the number of cycles expected, C', during the design life of the force main.

DESIGN REQUIREMENTS

The pipe under consideration is a 14-inch, SDR 41, CSA B137.3 pipe, with an IPS diameter regimen. As this is similar to the 14-inch IPS option in AWWA C905-97, the C905 standard will be referenced in this example. The design flow is 2.65 ft³/sec. It is estimated that the variable speed pump will have 24 starts and 24 stops each day. Once the steady-state-operating flow has been achieved, the operating pressure is 27 psi. During start-up or shutdown, the pressure fluctuations for the variable speed pump may be as large as 10 psi. The force main discharges into a manhole at atmospheric pressure at the upstream end.

From the AWWA C905 standard, the following dimensions may be looked-up or calculated:

D_0 = Average Outside Diameter
= 14.000 inches (Table 1 of C905)

t_{min} = Minimum Wall Thickness
= 0.341 inches (Table 1 of C905)

t_{min} tol = Tolerance on the Minimum Wall
= +0.048 inches (Table 1 of C905)

D_i = Inside Diameter
= $D_0 - 2t_{min} - t_{min}$ tol
= 14.000 - 2(0.341) - 0.048
= 13.270 inches

A_x = Cross Sectional Area
= $(\pi \div 4)(Di)^2$
= $(3.14 \div 4)(13.270)^2$
= 138 in^2
= 0.960 ft^2

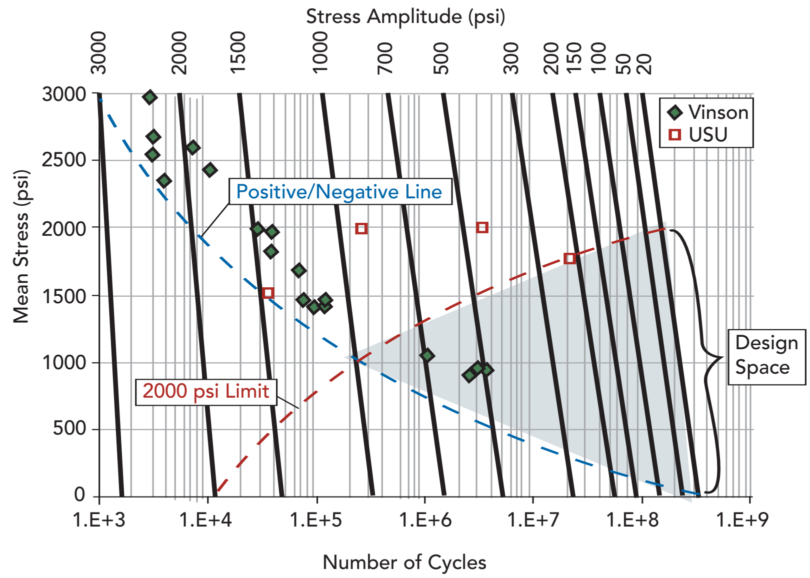

Figure 1.

Routine pressures the force main experiences are as follows:

P_{op} = Operating Pressure
= 27 psi (Known)

P_{amp} = Maximum Pressure Fluctuation
= 10 psi (Known)

P_{max} = Maximum Routine Pressure
= $P_{op} + P_{amp}$
= 27 + 10
= 37 psi

P_{min} = Minimum Routine Pressure
= $P_{op} - P_{amp}$
= 27 - 10
= 17 psi

Hoop stresses from routine pressures may now be calculated. See pages 53 to 58 of AWWA M23 [7] for details:

σ_{avg} = Average Hoop Stress
= $(P_{op} \div 2)$ (SDR -1)
= $(27 \div 2)(41 - 1)$
= 540 psi

σ_{amp} = Stress Amplitude
= $(P_{amp} \div 2)$ (SDR -1)
= $(10 \div 2)(41 - 1)$
= 200 psi

The fluid velocity while operating at the duty point is as follows:

Q = 2.65 ft³/sec (Known)

v = Fluid Velocity
= $Q \div A$
= 2.65 ft³/sec ÷ 0.960 ft²
= 2.78 ft/sec

The water hammer resulting from an instantaneous stoppage of flow serves as a conservative estimate of the worst-case, non-recurring surge. It will be assumed this occurs while the pump is operating at its normal duty point. With that information, the worst-case peak pressure may be determined as follows:

P_s' = Surge response to a 1 ft/sec instantaneous change in velocity
= 11.4 psi for SDR41(Table 5-6 AWWA M23 [7])

P_s = Worst-case surge
= $\Delta v_{max} P_s'$
= (2.78) (11.4)
= 31.7 psi

P_{peak} = Peak pressure from unusual event
= $P_{op} + P_s$
= 27.0 + 31.7
= 58.7 psi

Calculating the number of cycles endured by the force main over its design life is simple.

cycles/day = 24 starts + 24 stops
= 48 cycles/day (Known)

cycles/year = (cycles/days) (365 days/year)
= (48) (365)
= 17,520 cycles/year

Design Life = 100 years (Known)

C' = Anticipated number of cycles during force main's design life
= (cycles/year) (design life)
= (17,520) (100)
= 1.752×10^6

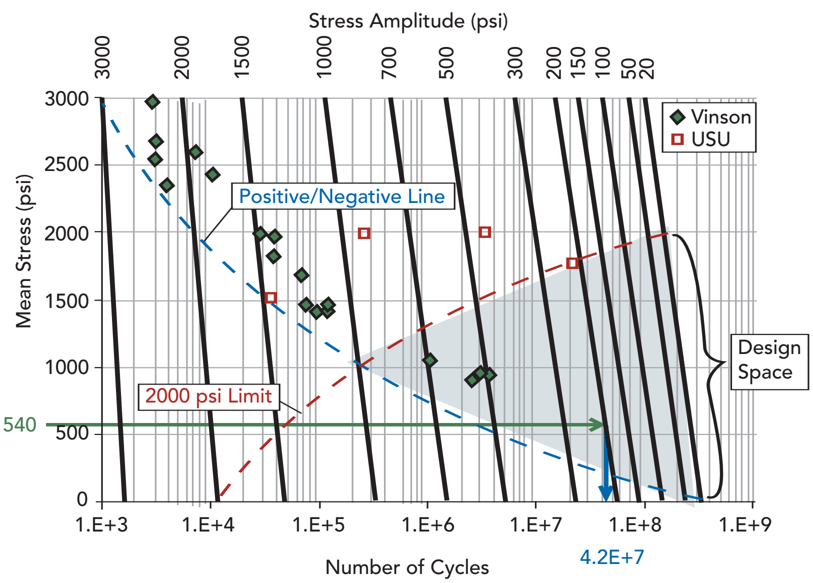

Figure 2.

DESIGN CHECKS

Is the operating pressure less than or equal to the PR of the SDR41 selected?

$P_{op} \leq PR?$
27 psi ≤ 100 psi (From Table 1)

Yes. The first design check is passed.

Is the peak pressure less than or equal to the STR of the SDR41 selected?

$P_{peak} \leq STR?$
58.7 psi ≤ 160 psi (From Table 2)

Yes. The second design check is passed.

Is the cyclic capacity greater than the anticipated number of cycles expected for the force main over its design life?

$C' \leq C?$
$1.752 \times 10^6 \leq 4.2 \times 10^7$ (From Figure 1)

Yes. The third and last design check is passed.

The design is satisfactory.

What cyclic life would the force main have under these operating conditions?

Cyclic Life = C ÷ Anticipated Number of Cycles per Year
Cyclic Life = 4.2×10^7 ÷17,520 cycles/year
Cyclic Life = 2,397 years

CYCLIC CHECK

The manner by which the 4.2×10^7 value for C was determined is further detailed for those not familiar with the cyclic design chart. Refer to Figure 2. First note that it is a semi-log chart. The x-axis has a logarithmic scale. One of the two independent variables, average stress, serves as the chart's y-axis. The second independent variable, stress amplitude, is represented by the diagonal black lines that overlay the chart. Each line represents a different stress amplitude. As one moves from left to right across the chart, the stress amplitudes represented by the black lines decrease. The x-axis is the dependent variable, and it denotes the cyclic life of the PVC pressure pipe.

In this example, the first independent variable, σ_{avg}, has a value of 540 psi. In Figure 2, that value is shown in green on the y-axis. A green line extends right from that value until it intersects the second independent variable, σ_{amp}. In the example, σ_{amp} has a value of 200 psi. At the intersection of the green line and the black line for the 200 psi stress amplitude, the tail of a blue line is shown. The blue line is extended downward until it hits the x-axis. The value for C in this example is 4.2×10^7, which is read from the x-axis of the chart at the point of intersection of the arrowhead of the blue line and the x-axis.

REFLECTED PRESSURE WAVES

In this example, no secondary or tertiary pressure waves are generated during a pump start-up or shut-down because the system is vented to the atmosphere. If the system were a closed system, and if surge pressures were able to be reflected, additional analysis using Miner's Rule would be needed to determine the system's cyclic life. Appendix A of Reference 3 discusses the theory as does Reference 6.

In this example, the cyclic life is recalculated with the following assumptions:

- The system is closed and the surge pressure wave is reflected throughout the system.
- The attenuation of the secondary and tertiary waves follows a dampened sinusoidal pattern as shown in Figure 3.

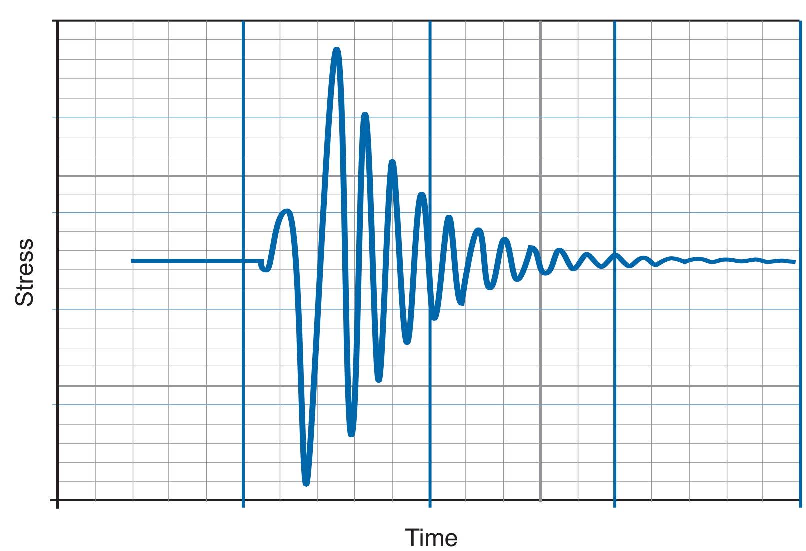

Figure 3. Typical surge pattern, where the pressures decay in a dampened sinusoidal pattern.

The first step is to represent the pressure pattern with the equivalent number of primary pressure waves. References 3 and 6 show that the secondary and tertiary waves have the fatigue equivalent of 0.55 primary waves. So, the number of cycles per year must be increased by 55% to account for the pressure pattern generated by reflected surge pressure waves.

Primary Cycles per Year = (1.55) (17,520)
Primary Cycles per Year = 27,156 cycles/year

Cyclic Life = C ÷ Anticipated Number of Primary Cycles per Year
Cyclic Life = 4.2 x 10^7 ÷ 27,156 cycles/year
Cyclic Life = 1,547 years

The design is again shown to be more than satisfactory from a cyclic fatigue point-of-view.

CLOSING

The real engineering work was done before our member was contacted to review this design. A pipe diameter and pump had already been selected. Presumably, the combination was the one most efficient for the flow desired and the alignment's topography. For that combination, operating pressures and pressure fluctuations were provided.

Admittedly, this is a straightforward design example. No iteration was required. The PR, STR, and cyclic capability provided were more than adequate. When realistic design values are used, the results shown here are typical. The PVC product that the utility routinely uses is normally very robust for the demands of the specific application.

References:

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9. *"CSA Standard B137.3, Rigid Polyvinyl Chloride (PVC) Pipe for Pressure Applications," Canadian Standards Association, Etobicoke, Ontario.*