A Subsurface Interference Design Study on a Steam Distribution System

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ABSTRACT

In any Utility or Energy Company the distribution of fluid or gas is transmitted along a system of pipes. The configurations of these pipes are dependent on their system loads, geometric constraints and their thermal growth. The purpose of this project is to investigate the nature and behavior of such a system when it is modified to accommodate new facilities or infrastructures. It is desirable to examine several possible engineering solutions while at the same time maintaining a cost effective design.

Two configurations were developed to eliminate a direct interference between a steam main and a water main. Both configurations included the use of a thermal loop but varied in terms of lengths and bend angles. A thermal stress calculation was done on the new configurations in order to predict any possible stress failures and to abide to the ASME B31.1 Power Piping code standards. Results obtained through the use of a stress pipe program revealed a 6'x6' thermal loop with 90˚ bends was the smallest practical loop to use in order to avoid the water main interfering with the steam main.

Keywords: Steam distribution system, thermal stress analysis, ASME B31.1 power piping, water hammer

1. INTRODUCTION

Steam is a gaseous phase of water. When water is heated beyond its boiling point, it evaporates to a vapor state known as steam. Steam can be used to transport controllable amounts of energy in an efficient and economic manner. This makes it ideal for many industries to use steam as a source of power or to heat their facilities. There are many benefits for using steam in terms of processing, controlling, converting, managing, and distributing.

In order for a steam user to receive steam it must have a way of receiving it from a steam generator plant. This method is achieved by having a steam distribution system. Steam is typically created in a boiler chamber where water is heated beyond its boiling point. The steam produced is then directed to a turbine and then condensed in a condenser. Condensation is the result of steam reverting to its liquid state. In a steam distribution system, such as the one in NYC, transmission and distribution pipes run from the steam generating plant to the steam user.

The steam distribution system in NYC dates back before the wide use of electricity. It is a very efficient way to distribute energy throughout the city. The steam pipes in NYC are a public utility, and steam is produced in several huge city-owned buildings in Manhattan. Today, most of the steam produced is not used directly but drives steam generators that provide electricity to the NYC area.

Although the usefulness of such a system is apparent, maintaining and adding to the current steam system can be troublesome in regard to maintaining enough clearance between the utilities that are competing for underground space. This is evident as shown in figure 1 below.

Fig. 1: Actual subsurface interference picture in NYC

2. PROBLEM STATEMENT

An underground steam piping system is currently in direct interference with a NYC water main project that will run perpendicular to it. The proposed water main is 36" in nominal diameter running north to south along McGraw Avenue. The steam system being impacted has a nominal diameter of 20" which runs west to east along John Street and has a concrete housing encasing the steam pipe. Figure 2 is a detail drawing of the problem described above.

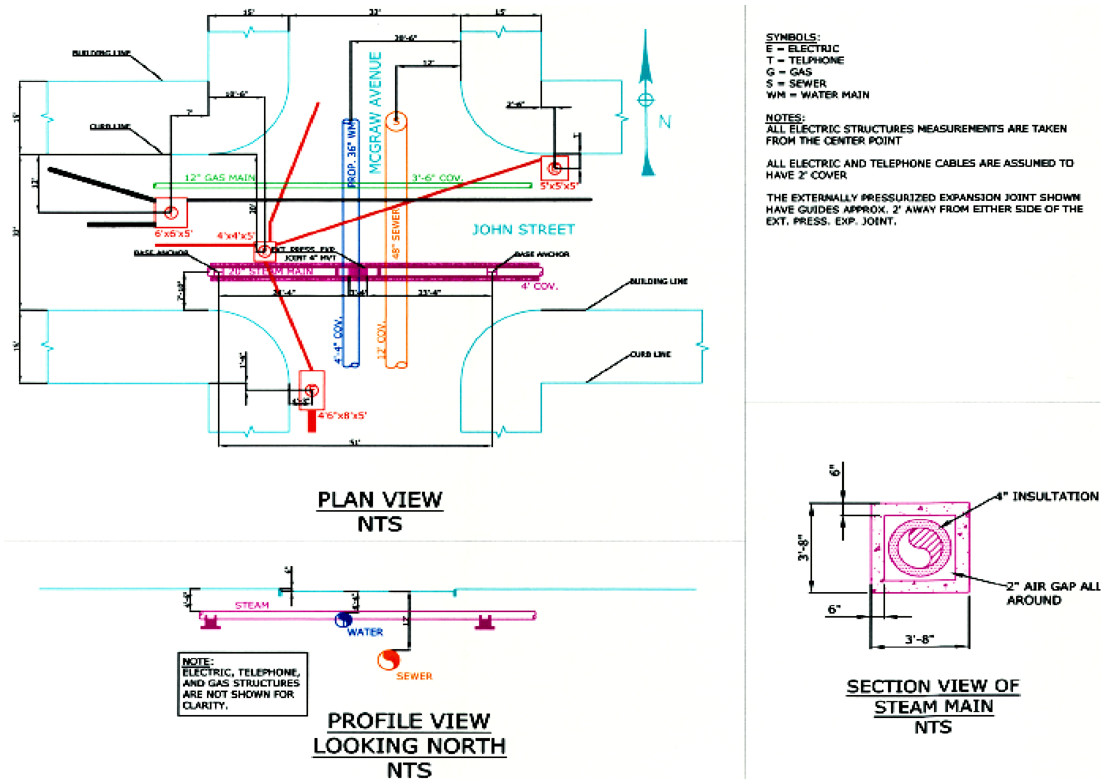


Fig. 2: Technical drawing showing the steam main in direct interference with the water main

A new design must be implemented on the steam system in order to accommodate the proposed water main being installed. In order to maintain a safe and acceptable design, some geometric constraints must be enforced. The geometric constraints for the new steam system includes having a minimum distance of 12" from the top of the concrete steam housing to the surface of the road way and maintaining a minimum distance of 6" from either side of the concrete steam housing to the new 36" diameter water main. It is worthy to note that the Department of Design and Construction (DDC) has minimum distance requirements between its infrastructures and other utilities but for the purpose of this project we use the minimum distance specified previously.

There are various designs that can be implemented to achieve a safe design. Some possibilities include the use of an eccentric reducer to achieve greater spatial surrounding, offsetting around the water main by creating a thermal loop, or using both. A solution that achieves a safe configuration free of interference of the water main and the steam main must also be free of excess thermal stresses specified in the ASME B31.1 power piping code.

The ASME B31.1 code prescribes minimum requirements for the design, materials used, fabrication, testing, and inspection of power and auxiliary service piping systems for electric generation stations, industrial plants, central and district heating plants. The code covers boiler external piping for power boilers and high temperature, high pressure water boilers in which steam or vapor is generated at a pressure of more than 15 psig, and high temperature water is generated at pressures exceeding 160 psig and/or temperature exceeding 250 °F.

The following are the design parameters of the steam distribution system for this project.

- Material: A53 B – Carbon Steel
- Nominal Pipe size: 20"
- Insulation: Fiber Glass
- Pressure: 200 psi

- Temperature: 413˚F
- 4" Movement Externally Pressurized Expansion Joint (if applicable)

Once a preliminary design has been achieved it will be analyzed though a thermal stress analysis program (CAEPIPE) in order to check that the new design configuration does not exceed the stress values recommended and specified in the B31.1 code. A 3-D view of the existing interference condition can be seen in figure 3.

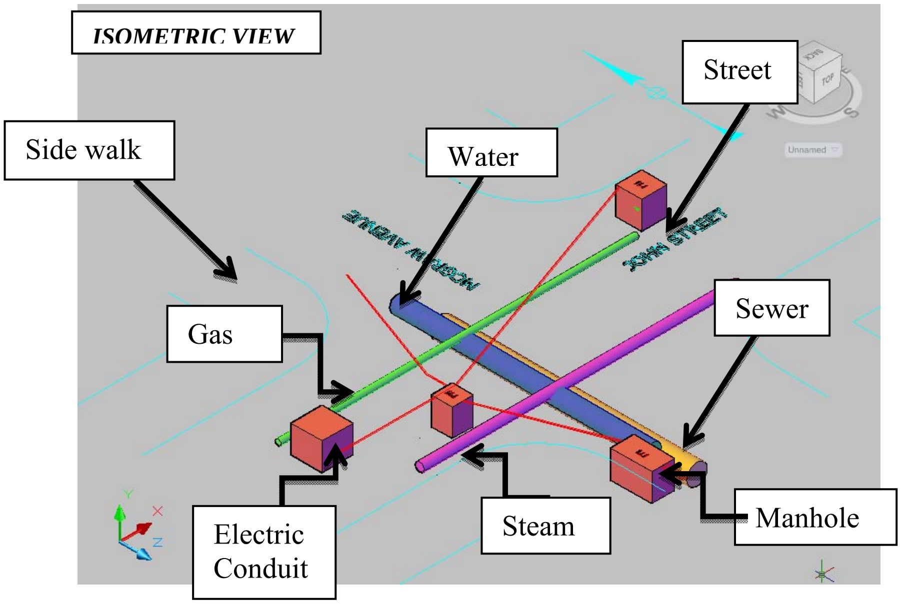


Fig. 3: AUTOCAD 3D model Projection of the existing case of the steam pipe with interference

3. MATHEMATICAL FORMULATION

There are different forces and stresses acting on the steam distribution system. In order to design a high value engineering solution it is necessary to define the fundamental equations governing the problem. The steam pipe can be modeled as a cylindrical element. If the radius to thickness ratio is greater than 10, we can safely assume a thin wall pressure vessel where *t* is uniform and constant. Below is a free body diagram showing the stresses and combined loadings acting on the cylindrical element.

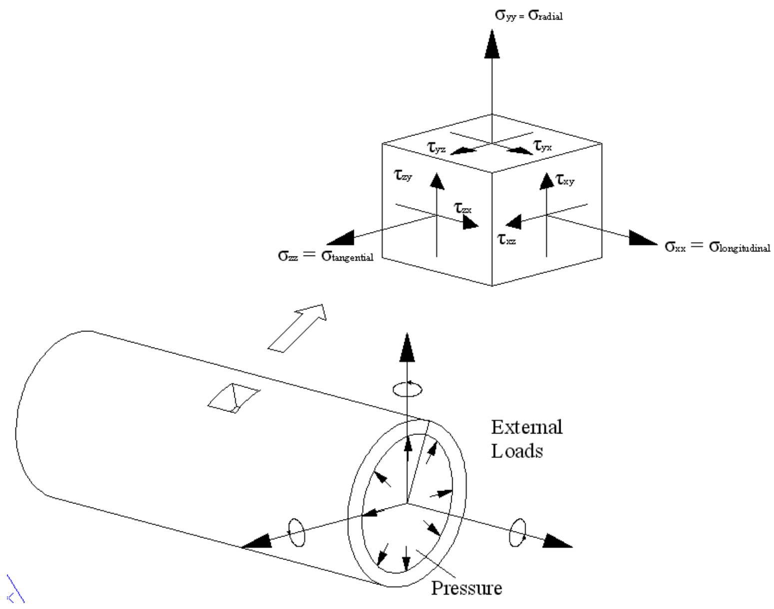


Fig. 4: Free body diagram showing the combined loading and stresses acting on a body

When a cylinder body is subjected to an internal pressure, *p*, it will experience 3 types of principal stresses. Along σ_{xx} it will experience a longitudinal stress, along σ_{zz} it will experience a tangential stress, and along σ_{yy} it will experience a radial stress. Since we are assuming a thin wall pressure vessel the radial stress is assumed to be zero. Therefore,

Tangential Stress $= \sigma_{\theta} = \frac{PD}{2t}$ (1) Longitudinal Stress $= \sigma_L = \frac{PD}{4t}$ (2)

3.1 MOMENT STRESSES

The moment stress on the pipe cross-section caused by an external load is

$$\sigma_M = \frac{M}{Z} \quad (3), \qquad where\ Z = \frac{\pi D^2 t}{4} \quad (4)$$

Where
M = flexural moment
Z = section modulus expressed in terms of the pipe diameter, D, and the wall thickness

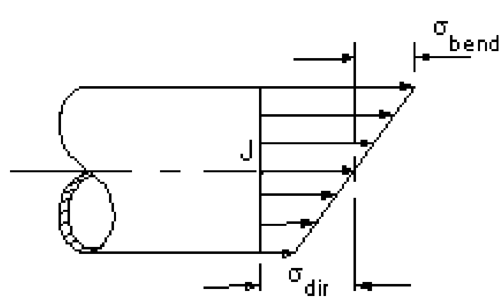


Fig. 5: Bending stress diagram

It becomes evident that the steam distribution system will involve complex loadings and stresses that are introduced into the system by the varying loads (i.e., heat, pressure, weight, etc.) being imposed on the system. Although it is important to analytically analyze and investigate the nature of the stresses found acting on the system a comprehensive mathematical derivation will not be presented in this paper. Instead we hope to analyze the stresses in the system by using the CAEPIPE program (piping stress program) which uses the following equations taken from the ASME B31.1 code and from the Piping Design & Analysis CAEPIPE Workshop book specifying sustained stress, occasional stress, and expansion stress range.

3.2 Sustained Stresses

The stress (S_L) due to sustained loads (pressure, weight and other sustained mechanical loads) is calculated as

$$S_L = \frac{PD_o}{4t_n} + \frac{0.75iM_A}{Z} \leq S_h \quad (5)$$

Where,

P = maximum of CAEPIPE pressures P1, P2, and P3

D_o = outside diameter

t_n = nominal wall thickness

i = stress intensification factor. The product of 0.75i shall not be less than 1.0

M_A = resultant bending moment due to weight and other sustained loads

Z = uncorroded section modulus; for reduced outlets, effective section modulus

S_h = hot allowable stress (basic material allowable stress at maximum temperature)

*stress intensification factor is used to account for discontinuity in the geometric shape of the pipe. (i.e., welds, weldolets, etc.)

3.3 Occasional Stresses

The stress (S_{LO}) due to occasional loads is calculated as the sum of stress due to sustained loads (S_L) and stress due to occasional loads (So) such as earthquake or wind. Wind and earthquake are not considered concurrently.

$$S_{LO} = \frac{P_{peak}D_o}{4t_n} + \frac{0.75iM_A}{Z} + \frac{0.75iM_B}{Z} \leq 1.2S_h \quad (6)$$

Where,

M_B = resultant bending moment on the cross-section due to occasional loads such as thrust from relief/safety valve loads, from pressure and flow transients, earthquake, wind, etc.

P_{peak} = peak pressure = (peak pressure factor in CAEPIPE) × *P*

3.4 Expansion Stress range (i.e., Stress due to Displacement Load Range)

The stress (SE) due to thermal expansion is calculated as

$$S_E = \frac{iM_c}{Z} \leq S_A \quad (7)$$

Where,

M_c = resultant moment due to thermal expansion

S_A = $f(1.25S_c + 0.24S_h)$

f = cyclic stress range reduction factor where $6/N^{0.2} \leq 1.0$ and $f \geq 0.15$ with N being the total number of equivalent reference displacement stress range cycles expected during the service life of the piping

S_c = allowable stress at cold temperature

Displacement Stress Range S_E shall not exceed the allowable stress range S_A which is calculated by

$$S_A = f(1.25S_c + 0.25S_h) \quad (8)$$

Where: $f = 1$ (in our case)

4. Thermal Stress Analysis

The existing configuration was modeled in CAEPIPE and analyzed through the thermal stress simulation. The analysis showed the stresses of the presently designed pipe to have minimal thermal stresses.

In order to accommodate the water main two configurations have been designed to reroute the steam pipe. The first configuration employed the use of two reducers that decreased the diameter of the steam pipe from 20” to 12” in order to fit the steam pipe in-between the street surface and the water main. Although the reducers succeeded in creating space for the 36” diameter water main it was still in direct interference with the steam main, therefore a thermal loop was designed to go above the proposed water main running north to south along McGraw Avenue. The second configuration is similar to the first configuration except it does not make use of reducers since the thermal loop was designed to go below the proposed 36” water main.

4.1 CASE I: THERMAL LOOP ABOVE WATER MAIN

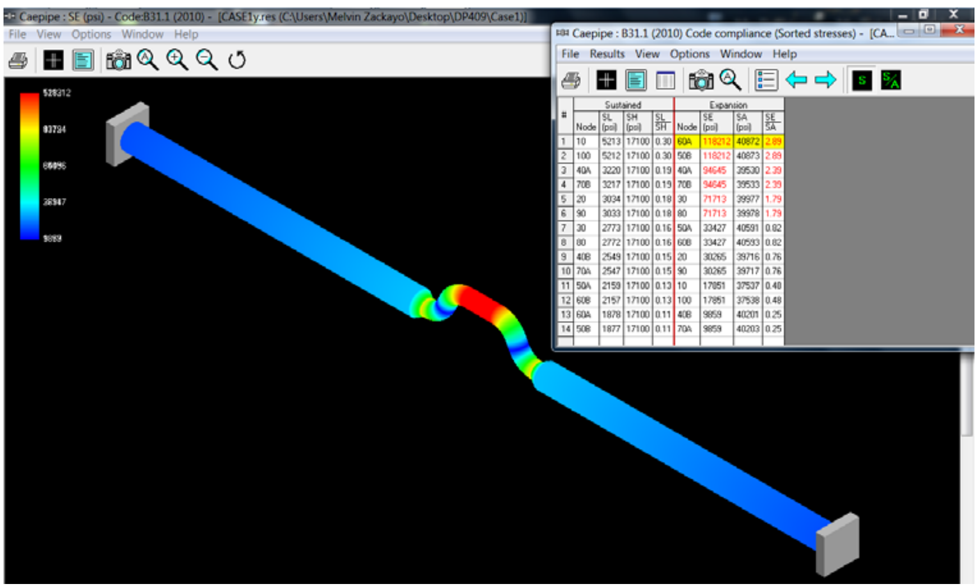
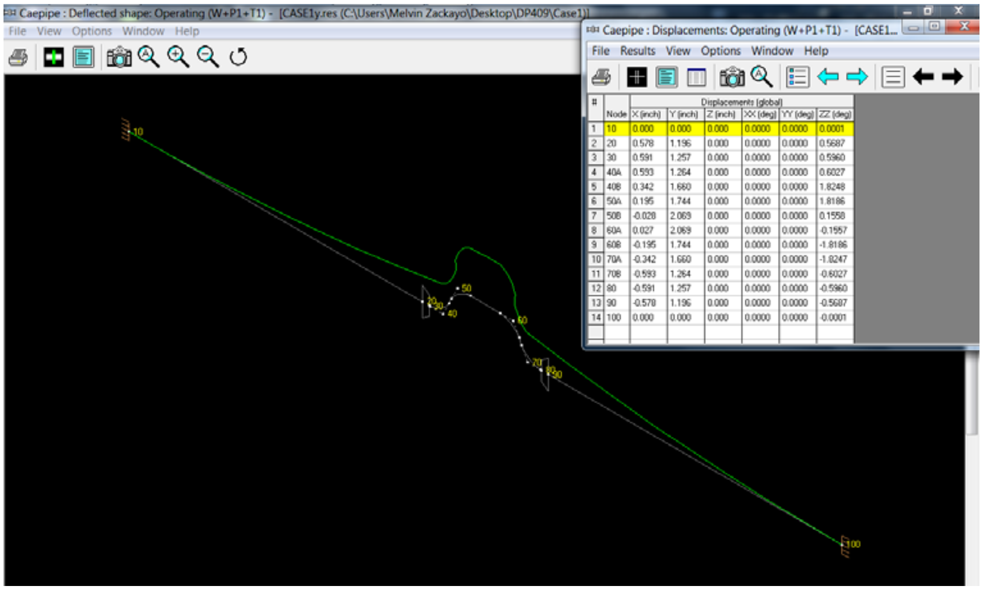


Fig. 6 Case I: Results after running analysis

Case I was modeled with two eccentric reducers and two 45° bends. This was done in order to fit in-between the water main and the street surface. Knowing that the water main has a depth of 4’-4” from the top of the pipe to the street surface it was found that only 2’-10” was available to develop a thermal loop after employing the restriction of having a clearance of 12” from the street surface to the steam housing and a 6” clearance between the steam housing and the water main. After running the analysis with the thermal loop, it was found to have excessive thermal stresses along the 45° bends. It failed approximately three times the recommended allowable stress specified in the ASME B31.1 code. The maximum stress experienced in the system was 118, 212 psi at nodes 60A and 50B. It is clear that the thermal loop developed is too rigid and is inadequate to flex during operating mode.

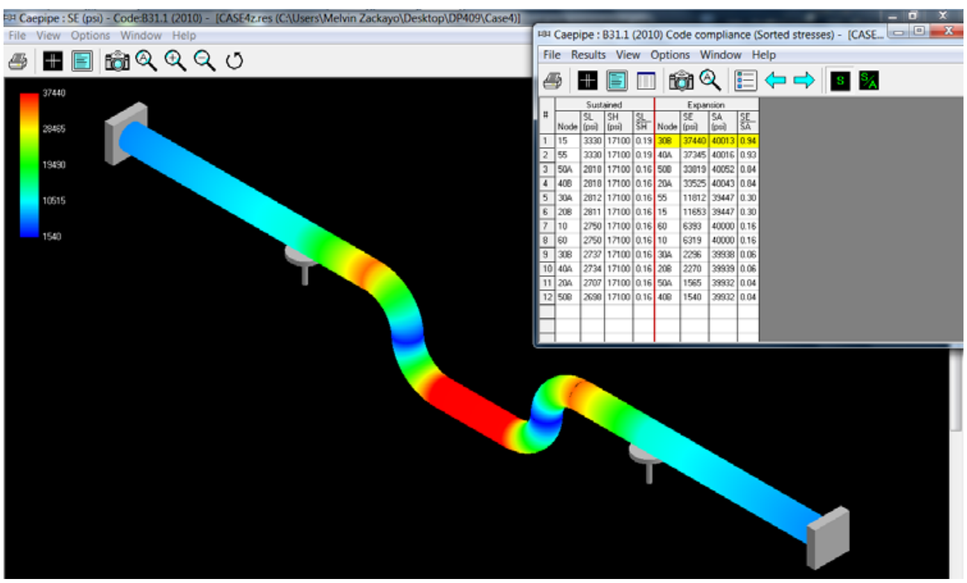


#	Node	Displacements (global) X (inch)	Y (inch)	Z (inch)	XX (deg)	YY (deg)	ZZ (deg)
1	10	0.000	0.000	0.000	0.0000	0.0000	0.0001
2	20	0.578	1.196	0.000	0.0000	0.0000	0.5687
3	30	0.591	1.257	0.000	0.0000	0.0000	0.5960
4	40A	0.593	1.264	0.000	0.0000	0.0000	0.6027
5	40B	0.342	1.660	0.000	0.0000	0.0000	1.8248
6	50A	0.195	1.744	0.000	0.0000	0.0000	1.8186
7	50B	-0.028	2.069	0.000	0.0000	0.0000	0.1558
8	60A	0.027	2.069	0.000	0.0000	0.0000	-0.1557
9	60B	-0.195	1.744	0.000	0.0000	0.0000	-1.8186
10	70A	-0.342	1.660	0.000	0.0000	0.0000	-1.8247
11	70B	-0.593	1.264	0.000	0.0000	0.0000	-0.6027
12	80	-0.591	1.257	0.000	0.0000	0.0000	-0.5960
13	90	-0.578	1.196	0.000	0.0000	0.0000	-0.5687
14	100	0.000	0.000	0.000	0.0000	0.0000	-0.0001

Fig. 7: CAEPIPE results: Operating displacement.

Another important factor, besides reviewing the thermal stresses, is to look at the displacement in the pipe due to the heat transfer of the steam to the pipe. The heating creates thermal growth in the pipe. The maximum deflection experienced in the pipe was found to be at nodes 50B and 60A with a deflection of 2.069" in the vertical direction. This configuration would be impacting the concrete housing that surrounds the pipe and could possibly cause structural damage to the housing due to their only being a 2" air gap inside the concrete steam housing.

4.2 CASE II: THERMAL LOOP BELOW WATER MAIN



#	Sustained Node	SL (psi)	SH (psi)	SL/SH	Expansion Node	SE (psi)	SA (psi)	SE/SA
1	15	3330	17100	0.19	30B	37440	40013	0.94
2	55	3330	17100	0.19	40A	37345	40016	0.93
3	50A	2818	17100	0.16	50B	33819	40052	0.84
4	40B	2818	17100	0.16	20A	33525	40043	0.84
5	30A	2812	17100	0.16	55	11812	39447	0.30
6	20B	2811	17100	0.16	15	11653	39447	0.30
7	10	2750	17100	0.16	60	6393	40000	0.16
8	60	2750	17100	0.16	10	6319	40000	0.16
9	30B	2737	17100	0.16	30A	2296	39938	0.06
10	40A	2734	17100	0.16	20B	2270	39939	0.06
11	20A	2707	17100	0.16	50A	1565	39932	0.04
12	50B	2698	17100	0.16	40B	1540	39932	0.04

Fig. 8 Case II: Results after running the analysis.

The pipe was configured similar to case I, as shown earlier, but instead the thermal loop was modeled below the water main with 90° bends. This would provide adequate spacing between other utilities and the water main itself. In order to eliminate pipe sag (which occurs due to its own weight), supports were modeled in the analysis at node 15 and 55. It was found that the maximum stress experienced during operating mode was 37, 440 psi at node 30B with a stress ratio S_E/S_A of 0.94. Case II was found to be within acceptable limits according to the ASME B31.1 code. Modeling the thermal loop below the water main provided ample space to make the thermal loop wider and longer, thus significantly reducing the thermal stress in the pipe.

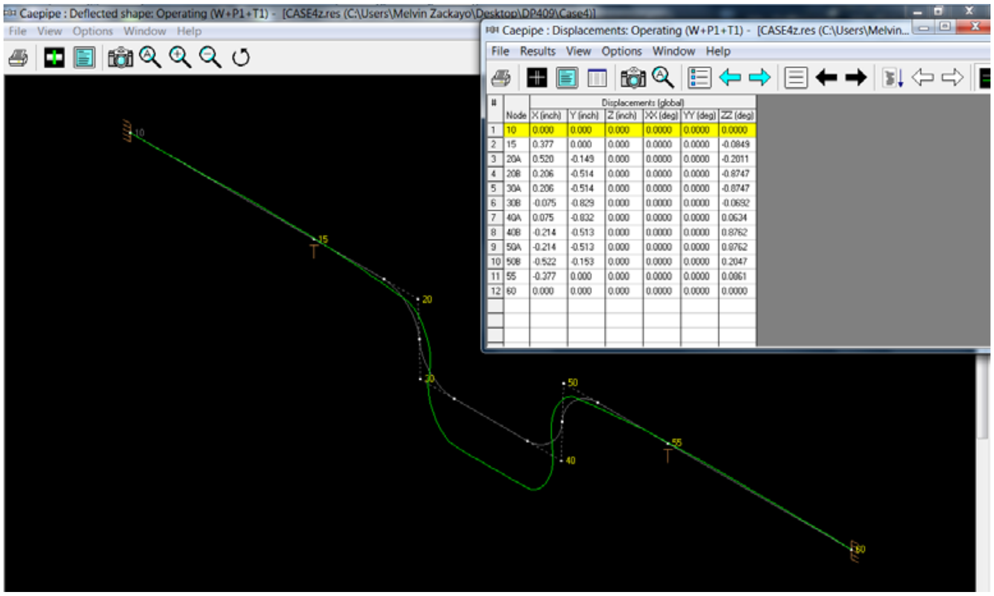


Fig. 9: CAEPIPE results: Operating displacement.

A maximum deflection of 0.832" is experienced at node 40A in the negative vertical direction. The minimum thermal movement that the pipe will experience will be safely contained in the concrete housing.

5. WATER HAMMER

Although we were able to have a configuration free of any direct interference with the new water main, the configuration poses a dangerous problem if not properly designed. The large thermal loop will be acting as a low point in which condensation will rapidly buildup over time. Without proper drainage this could lead to a phenomenon called water hammer. Water hammer is the violent reactions occurring in a fluid pipeline. Some basic facts about water hammer are listed below:

- Water hammer can occur in both hot and cold water lines.
- Water hammer is not always accompanied with noise.
- Water hammer is the result of dynamic changes by a moving fluid inside a fixed conduit (piping network).
- Water hammer is more prominent in bi-phase flows.
- The severity of water hammer would peak (piping breakdowns and fatal accidents) whenever the system dynamics is changed or disturbed.

5.1 TYPES OF WATER HAMMER

The following are some types of water hammer that a piping system can experience

1. Hydraulic shock

   These are disturbances in the water pipeline caused during a change in state, typically from one steady or equilibrium condition to another. Occurs when closing and opening of liquid users. Typically happens in water distribution networks.

2. Thermal shock

   These are disturbances in steam pipeline caused when steam condenses to water when the system is closed. Due to the condensation, there is formation of a vacuum. As a result, the steam forces the condensate to fill the vacuum when the system is open. This occasion, when steam bubbles are trapped between sub-cooled condensate inside the pipeline, results in thermal shock in the pipeline system.

Water hammer can be resolved by using draining station or traps to remove condensation as shown in Fig. 10 below.

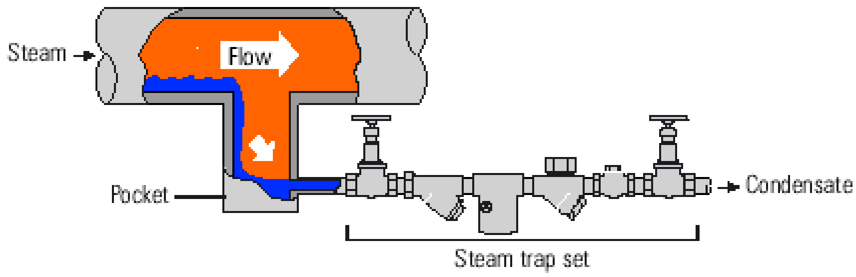


Fig. 10: Properly sized trap pocket

The damage caused by not having and maintaining proper drainage of condensation in a steam distribution system can be seen in the figure below.

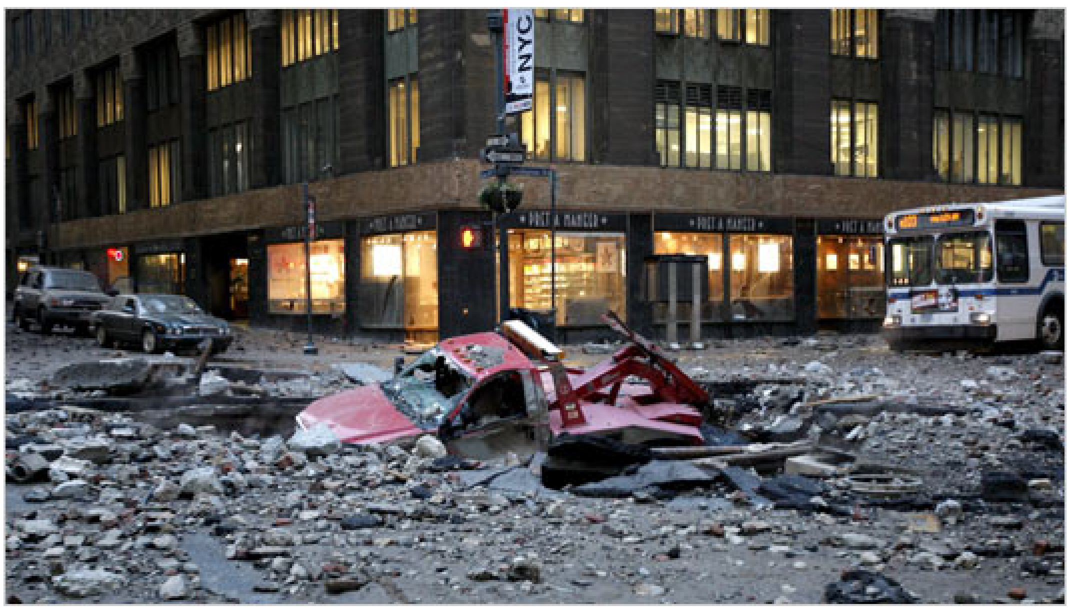


Fig. 11: Steam explosion on Lexington Avenue caused by water hammer

6. CONCLUSION

The proposed piping configurations were designed to not be in direct interference with the new water main being installed. Once this was achieved a stress analysis was done in order to comply with the ASME B31.1 Power Piping code standards.

Case I failed the thermal stress analysis at an operating temperature of 413˚F and a pressure of 200 psi. The stress being experienced was approximately three times the acceptable value. Despite satisfying all the geometric constraints, the thermal loop was too rigid to allow adequate thermal growth of the pipe. Different alterations were used in this case in order to reduce the stress experienced in the thermal loop. An angle of 45˚ was used in the thermal loop which experienced a high thermal stress of $S_E = 118,212\ psi$ and a stress ratio of $\frac{S_E}{S_A} = 2.89$ at nodes 50B and 60A. Another configuration was modeled and analyzed using 30˚ bends which experienced an even higher thermal stress of $S_E = 143,769\ psi$ and a stress ratio of $\frac{S_E}{S_A} = 3.49$ at nodes 50B and 60A. Upon realizing that increasing the angle in the thermal loop minimizes the thermal stress in the pipe, we decided to try a loop with 90˚ bends. This configuration experienced less thermal stresses when compared to the 30˚ and 45˚ bends. Although the 90˚ bends helped minimize the stress, we could not make the loop any larger due to having only 2'-10" of clearance in the vertical direction. Therefore we decided to go below the water main which would provide us with greater clearance to make the thermal loop larger.

In case II we modeled and analyzed several thermal loops. One loop was modeled as a 6'x6' loop which experienced a stress of $S_E = 37,109\ psi$ and a stress ratio of $\frac{S_E}{S_A} = 0.94$ at nodes 30B and 40A. We then modeled and analyzed an 8'x8' wide loop. This loop experienced a stress value of $S_E = 35,336\ psi$ and a stress ratio of $\frac{S_E}{S_A} = 0.92$ at node 30B. By increasing the thermal loop we increased the pipes ability to absorb more thermal movement thus resulting in a lower thermal stress. Our last configuration involved having a 10'x10' loop. This loop experienced a stress value of $S_E = 35,538\ psi$ and a stress ratio of $\frac{S_E}{S_A} = 0.90$ at node 30B which is lower than the first two iterations. It is concluded that the best pipe configuration is one with a wide thermal loop with 90˚ bends. In order to account and minimize possible pipe sag during sustained mode, we installed pipe supporting elements called limit stops along our pipe at nodes 15 and 55. These limit stops did not significantly change the stress experienced in the piping system.

For the iterations done in case II, any of the configurations could be used since they all achieved a stress ratio lower than 1.0 and the thermal movements are constrained within the encased concrete housing. Although a large thermal loop is beneficial in lowering the thermal stresses experienced in the pipe, it is not always practical to have such a large thermal loop because of the cost and the underground space being taken up plays a major role in deciding which thermal loop to use. A design configuration that is cost efficient and that can take the least amount of volumetric area without failing stress wise would be the ideal design.

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