Evaluation of Seismic Resistance of a Fire Protection Riser Pipe System with a Line Segment Analysis Approach

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Abstract *— Effective stresses due to a seismic occurrence are prevented in piping systems by means of seismic bracings and piping supports. A line segment analysis determines if each pipe segment in a pipe system has enough flexibility to survive the target seismic event with a calculated, optimal use of supports. These ideal support locations, or anchor points, are determined by modeling the stresses at each pipe segment and using several iterations based on different anchor locations. From these iterations, the combined stress from the pipe system is compared against a predetermined seismic stress. If the combined stress is less than the seismic stress, then the pipe system is capable of surviving these seismic stresses with a calculated amount of supports. This evaluation gives designers the confidence that the resulting support layout for a given pipe system meets the demanded resistance for a modeled seismic event. This study was made in hopes that this approach becomes a standard procedure for engineers everywhere. It allows the successful positioning of seismic supports in a pipe system in order to satisfy its seismic design criteria by lending the right amount of flexibility to the system.*

Key Terms *— Anchor Point, Effective Stress, Line Segment Analysis, Pipe System.*

INTRODUCTION

Due to previous seismic events, guidelines and codes of design are continuously changing to adapt piping systems to newly acquired knowledge. Their purpose is to avoid significant damage to fire protection pipe systems and permitting them to remain functional following a seismic event.

In order to assess a location in the world subject to high frequencies of earthquake events, the U.S. Geological Survey (USGS) provides maps, like the one in Figure 1, that show areas of probability of exceedance of the peak ground acceleration in a 50-year period. This helps determine the relative probability of a seismic occurrence and the relative demand on structures in different parts of a country [1].

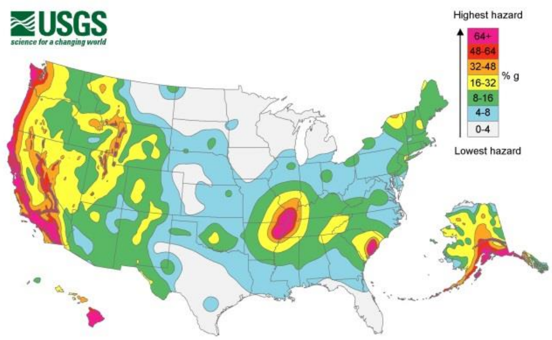

Figure 1
Seismic Hazard Map of the United States of America

Standards such as the "National Fire Protection Association (NFPA) 13: Standard for the Installation of Sprinkler Systems" provide the industry a benchmark for design and installation of automatic fire sprinkler systems, and addresses sprinkler system design approaches, system installation, and component options to prevent fire deaths and property loss [2]. The NFPA allows the use of alternative methods of providing earthquake protection of sprinkler systems based on seismic analysis [1]. With this, the piping system is expected to have the same seismic resistance performance as the building structure it is installed in. Piping systems are required to be protected to minimize or prevent pipe breakage in areas subject to earthquakes. This is accomplished through techniques, such as:

- Making the piping flexible to minimize stresses produced by differential building movement;

- Attaching the piping directly to the building structure with sway bracings for minimum relative movement; and,
- Optimizing brace/support placement in piping system.

A line segment analysis does just that. It forms an organized, step-by-step procedure for calculating the combined stress of a pipe segment in a piping system in order to optimize brace/support placements through adequate pipe segment flexibility. It separates each pipe segment and evaluates them individually for the following:

- Pipe segment properties
- Bending moment
- Bending Stress
- Torsional Stress
- Shear Stress

When having all this information, the analysis becomes a simple, comparative procedure between the combined stress of the segment versus a predetermined seismic stress. In the following sections, a six (6)-inch diameter, carbon steel fire protection riser will be evaluated for seismic resistance using a line segment analysis.

Objective

The main objective is to determine what modifications to the piping arrangement and its brace/support placement will assist the system in maintaining its integrity. This innovative methodology and step-by-step procedure lets designers confirm that the piping flexibility allows the pipe system survive the target seismic event.

METHODOLOGY

The calculation procedure was structured so as to model the stresses occurring at each anchor point of each pipe segment and comparing that combined stress result against an agreed upon predetermined seismic stress. This multistep calculation was organized as follows.

Initial Assumptions

- The pipe to be analyzed is made to Carbon Steel ANSI Schedule 40 specifications [3] [4], and therefore conforms to those dimensions.
- For the system's weight, pipes were assumed to be filled with water.
- Pipe insulation was not included in calculations since fire risers do not contain pipe insulation.
- Pipe system is assumed to be rigid, with no flexibility components like seismic couplings or flexible loop installations. For the sake of this analysis, the only source of flexibility is provided by a minimum pipe segment length later discussed.
- The fire protection system shall be designed to meet all of the requirements of NFPA 13 latest edition [2] and Factory Mutual (FM) Datasheet 2-8 recommendations [5].
- The seismic design forces that shall be used to retrofit the existing piping system and design the new piping system and its supports shall be expressed as the seismic factor for a 475-year MRP spectra, multiplied by an operating pipe weight safety factor, as follows:

$$F_p = 2.125 \; x \; W_p \qquad (1)$$

Where 2.125 is the seismic factor and W_p shall be taken as 1.15 times the weight of water-filled pipe as per NFPA 13, Section 9.3.5.6. This gives F_p a value of 2.444.

- A pipe expansion (Δ) of 0.8 in is to be assumed. This is taken from factors such as: expansion coefficient of carbon steel, the span length of pipe, and the fluid temperature running through it.
- Finally, the use of half the yield strength as the allowable working stress is to be attributed to this pipe system. So the combined stress of the pipe system cannot go over 15,450 psi of allowable stress. If it does, the pipe system will rupture and can no longer be in service.

Procedure

The following is a step-by-step procedure in how to calculate the combined stress of the piping system shown in Figure 2, using a line segment analysis.

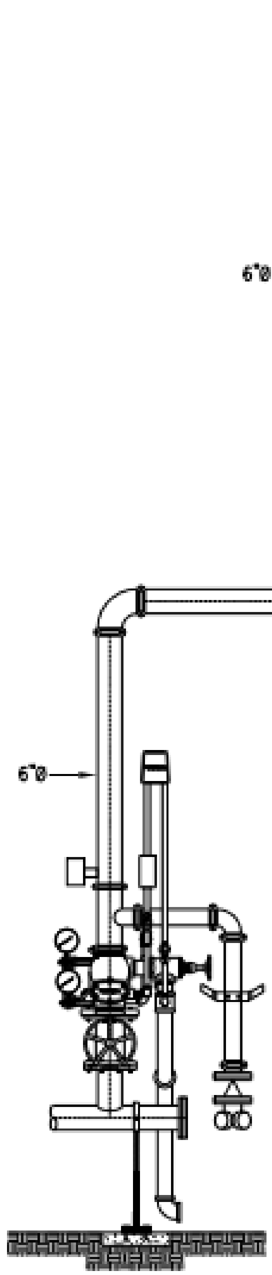

Figure 2
Detail of Fire Protection Riser to be Evaluated

The first stage of this procedure is to establish the pipe system properties of the fire protection riser to be evaluated. The results from said procedure are shown in Table 1. The following is the step-by-step procedure for each pipe property:

1. Obtain carbon steel pipe properties. These properties include: nominal diameter, outside diameter (O.D.), inside diameter (I.D.), wall thickness, and wall metal area. Wall thickness is expressed as:

$$Wall\ Thickness = \frac{O.D. - I.D.}{2} \quad (2)$$

And wall metal area is calculated as:

$$Wall\ Metal\ Area = \frac{\pi}{4} * (O.D.^2 - I.D.^2) \quad (3)$$

2. Determine the moment of inertia (I) for each pipe size/diameter with:

$$I = \frac{\pi}{64} * (O.D.^4 - I.D.^4) \quad (4)$$

3. Determine the polar moment of inertia (J) for each pipe size/diameter as follows:

$$J = 2 * I \quad (5)$$

4. Determine the pipe weight per unit length for each pipe diameter using Carbon Steel ANSI Schedule 40 specifications [3] [4].
5. Determine the contribution of the water weight per unit length for each pipe diameter using Carbon Steel ANSI Schedule 40 specifications [3] [4].
6. Determine the total weight per unit length for each pipe diameter. This is the sum of the tube weight plus the fluid weight inside tube.
7. Calculate minimum length of pipe for flexibility (L_{min}) for each pipe diameter. This value describes the minimum length required in order to provide the appropriate flexibility to the piping system. This is calculated as follows:

$$L_{min} = \sqrt{\frac{Expansion * O.D. * 10^6}{1.6 * Allowable\ Stress}} \quad (6)$$

Where Expansion (Δ) = 0.8 in, and Allowable Stress = 15,450 psi.

Table 1
Properties for a 6-Inch Diameter Fire Protection Riser

For a 6" Diameter Fire Protection Riser													
Material	Nominal Diameter [in]	Outside Diameter [in]	Inside Diameter [in]	Wall Thickness [in]	Wall Metal Area [in^2]	Moment of Inertia, I [in^4]	Polar Moment of Inertia, J [in^4]	Tube + Fluid Weight [lb/ft]	Insulation Weight [lb/ft] *	Total Weight [lb/ft]	Minimum Length for Flexibility [ft] **	c [in] (Distance from ℄ to Outer Fiber)
Carbon Steel	6	6.625	6.065	0.280	5.581	28.142	56.284	31.500	0	31.500	14.642	3.313

The second part of the procedure involves creating sketches of the present conditions of the pipe system:

1. Prepare sketch of the general assembly of pipe system, including: orientation of pipe system in space, length of segments and pipe properties. Sketch can be seen below in Figure 3:

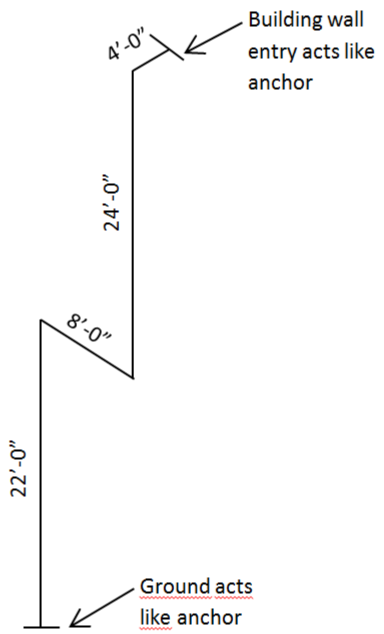

Figure 3
Pipe System Sketch of Fire Protection Riser to be Evaluated

2. Prepare diagram of each pipe segment showing: orientation of pipe system in space, length of pipe segments, proposed anchor points, and pipe properties. Here is where the iterations of anchor point placements occur. Trials of anchor placements are done so that when the combined stresses of a specific pipe segment are calculated, they do not exceed the pre-determined allowable stress of 15,450 psi. If they do exceed it, anchor placement within the pipe system is changed.

The following is the sketch of a trial of anchor placements within the piping system:

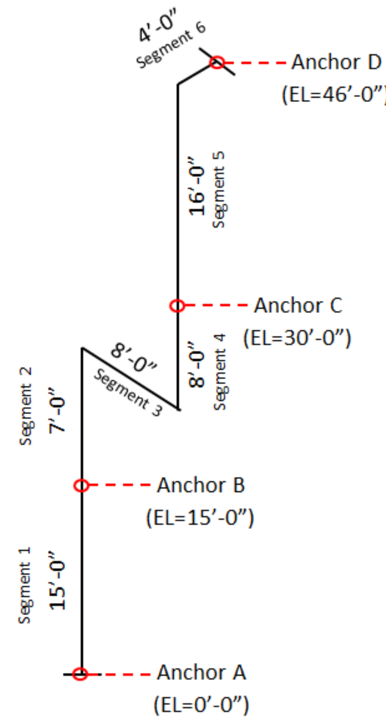

Figure 4
Sketch of Anchor Placement Trial in Pipe System

Anchors B and C represent new four (4)-way longitudinal and transverse seismic sway bracings anchored to a wall structure. These bracings are preferred so as to limit pipe movements in all directions, leaving the segment lengths flexible enough (more than 14.642 ft, as seen in Table 1) to distribute the seismic stresses.

Next is the actual calculation of the bending moment, bending stress, torsional stress, and the shear stress for each segment. These are calculated for the purpose of adding them to get the combined stress of the pipe system. Process is shown in Tables 2, 3 & 4, and explained subsequently.

Table 2
Combined Stress Calculations for Segment #1

F_p = 2.125 * 1.15 = 2.444

Proporsional Force @ A = $\frac{\text{Segment Length Closest to Anchor B}}{\text{Segment Length Closest to Anchor A+Segment Length Closest to Anchor B}}$ = 0.50 %

Proporsional Force @ B = $\frac{\text{Segment Length Closest to Anchor A}}{\text{Segment Length Closest to Anchor A+Segment Length Closest to Anchor B}}$ = 0.50 %

					Anchor A						Anchor B					
					x (North-South)		y (East-West)		z (Vertical)		x (North-South)		y (East-West)		z (Vertical)	
Segment	ϕ [in]	lb/ft	ft	lb	Distance [in]	Moment [lb-in]	Distance [in]	Moment [lb-in]	Distance [in]	Moment [lb-in]	Distance [in]	Moment [lb-in]	Distance [in]	Moment [lb-in]	Distance [in]	Moment [lb-in]
1	6	31.500	15	472.500	90	42525.000	90	42525.000	0	0	90	42525.000	90	42525.000	0	0.000
			ΣF =	472.500	ΣM_x =	42525.000	ΣM_y =	42525.000	ΣM_z =	0.000	ΣM_x =	42525.000	ΣM_y =	42525.000	ΣM_z =	0.000

Given:		
A =	5.581	in^2
I =	28.142	in^4
J =	56.284	in^4
c =	3.313	in

Anchor A Stress Calculation (Allowable Stress = 15,450 psi)

Bending Stress:

$$\sigma_x = \frac{\sum M_x * c * P.F. * Fp}{I} = 6116.987 \text{ psi}$$

$$\sigma_y = \frac{\sum M_y * c * P.F. * Fp}{I} = 6116.9873 \text{ psi}$$

$$\sigma_z = \frac{\sum M_z * c * P.F. * Fp}{I} = 0 \text{ psi}$$

Torsional Stress:

$$T_z = \frac{\sum M_z * c * P.F. * Fp}{J} = 0 \text{ psi}$$

Shear Stress:

$$\tau = \frac{\sum F * P.F. @ A * Fp}{2A} = 51.723 \text{ psi}$$

Combined Stress A = 8,650.88 psi

RESULT = OK

Anchor B Stress Calculation (Allowable Stress = 15,450 psi)

Bending Stress:

$$\sigma_x = \frac{\sum M_x * c * P.F. * Fp}{I} = 6116.9873 \text{ psi}$$

$$\sigma_y = \frac{\sum M_y * c * P.F. * Fp}{I} = 6116.9873 \text{ psi}$$

$$\sigma_z = \frac{\sum M_z * c * P.F. * Fp}{I} = 0 \text{ psi}$$

Torsional Stress:

$$T_z = \frac{\sum M_z * c * P.F. * Fp}{J} = 0 \text{ psi}$$

Shear Stress:

$$\tau = \frac{\sum F * P.F. @ B * Fp}{2A} = 51.723 \text{ psi}$$

Combined Stress B = 8,650.88 psi

RESULT = OK

Table 3
Combined Stress Calculations for Segments #2, #3 & #4

F_p = 2.125 * 1.15 = 2.444

Proporsional Force @ B = $\frac{\text{Segment Length Closest to Anchor C}}{\text{Segment Length Closest to Anchor B+Segment Length Closest to Anchor C}}$ = 0.53 %

Proporsional Force @ C = $\frac{\text{Segment Length Closest to Anchor B}}{\text{Segment Length Closest to Anchor B+Segment Length Closest to Anchor C}}$ = 0.47 %

					Anchor B						Anchor C					
					x (North-South)		y (East-West)		z (Vertical)		x (North-South)		y (East-West)		z (Vertical)	
Segment	ϕ [in]	lb/ft	ft	lb	Distance [in]	Moment [lb-in]	Distance [in]	Moment [lb-in]	Distance [in]	Moment [lb-in]	Distance [in]	Moment [lb-in]	Distance [in]	Moment [lb-in]	Distance [in]	Moment [lb-in]
2	6	31.500	7	220.500	42	9261.000	42	9261.000	0	0	96	21168.000	96	21168.000	96	21168.000
3	6	31.500	8	252.000	84	21168.000	84	21168.000	48	12096.000	96	24192.000	96	24192.000	48	12096.000
4	6	31.500	8	252.000	84	21168.000	84	21168.000	96	24192.000	48	12096.000	48	12096.000	0	0.000
			ΣF =	724.500	ΣM_x =	51597.000	ΣM_y =	51597.000	ΣM_z =	36288.000	ΣM_x =	57456.000	ΣM_y =	57456.000	ΣM_z =	33264.000

Given:		
A =	5.581	in^2
I =	28.142	in^4
J =	56.284	in^4
c =	3.313	in

Anchor B Stress Calculation (Allowable Stress = 15,450 psi)

Bending Stress:

$$\sigma_x = \frac{\sum M_x * c * P.F. * Fp}{I} = 7916.741 \text{ psi}$$

$$\sigma_y = \frac{\sum M_y * c * P.F. * Fp}{I} = 7916.7409 \text{ psi}$$

$$\sigma_z = \frac{\sum M_z * c * P.F. * Fp}{I} = 5567.8178 \text{ psi}$$

Torsional Stress:

$$T_z = \frac{\sum M_z * c * P.F. * Fp}{J} = 2783.9089 \text{ psi}$$

Shear Stress:

$$\tau = \frac{\sum F * P.F. @ B * Fp}{2A} = 84.596 \text{ psi}$$

Combined Stress B = 12,810.44 psi

RESULT = OK

Anchor C Stress Calculation (Allowable Stress = 15,450 psi)

Bending Stress:

$$\sigma_x = \frac{\sum M_x * c * P.F. * Fp}{I} = 7713.7475 \text{ psi}$$

$$\sigma_y = \frac{\sum M_y * c * P.F. * Fp}{I} = 7713.7475 \text{ psi}$$

$$\sigma_z = \frac{\sum M_z * c * P.F. * Fp}{I} = 4465.8538 \text{ psi}$$

Torsional Stress:

$$T_z = \frac{\sum M_z * c * P.F. * Fp}{J} = 2232.9269 \text{ psi}$$

Shear Stress:

$$\tau = \frac{\sum F * P.F. @ C * Fp}{2A} = 74.022 \text{ psi}$$

Combined Stress C = 11,997.46 psi

RESULT = OK

Table 4
Combined Stress Calculations for Segments #5 & #6

$F_p = 2.125 * 1.15$ = 2.444

$$\text{Proporsional Force @ C} = \frac{\textit{Segment Length Closest to Anchor D}}{\textit{Segment Length Closest to Anchor C+Segment Length Closest to Anchor D}} = 0.20\ \%$$

$$\text{Proporsional Force @ D} = \frac{\textit{Segment Length Closest to Anchor C}}{\textit{Segment Length Closest to Anchor C+Segment Length Closest to Anchor D}} = 0.80\ \%$$

Segment	ϕ [in]	lb/ft	ft	lb	Anchor C x (North-South) Distance [in]	Anchor C x (North-South) Moment [lb-in]	Anchor C y (East-West) Distance [in]	Anchor C y (East-West) Moment [lb-in]	Anchor C z (Vertical) Distance [in]	Anchor C z (Vertical) Moment [lb-in]	Anchor D x (North-South) Distance [in]	Anchor D x (North-South) Moment [lb-in]	Anchor D y (East-West) Distance [in]	Anchor D y (East-West) Moment [lb-in]	Anchor D z (Vertical) Distance [in]	Anchor D z (Vertical) Moment [lb-in]
5	6	31.500	16	504.000	96	48384.000	96	48384.000	0	0	48	24192.000	96	48384.000	48	24192.000
6	6	31.500	4	126.000	192	24192.000	192	24192.000	24	3024.000	24	3024.000	0	0.000	24	3024.000
			ΣF =	630.000	ΣM_x =	72576.000	ΣM_y =	72576.000	ΣM_z =	3024.000	ΣM_x =	27216.000	ΣM_y =	48384.000	ΣM_z =	27216.000

Given:		
A =	5.581	in^2
I =	28.142	in^4
J =	56.284	in^4
c =	3.313	in

Anchor C Stress Calculation (Allowable Stress = 15,450 psi)

Bending Stress:

$$\sigma_x = \frac{\sum M_x * c * P.F. * Fp}{I} = 4175.863 \text{ psi}$$

$$\sigma_y = \frac{\sum M_y * c * P.F. * Fp}{I} = 4175.8633 \text{ psi}$$

$$\sigma_z = \frac{\sum M_z * c * P.F. * Fp}{I} = 173.99431 \text{ psi}$$

Torsional Stress:

$$T_z = \frac{\sum M_z * c * P.F. * Fp}{J} = 86.997153 \text{ psi}$$

Shear Stress:

$$\tau = \frac{\sum F * P.F. @ C * Fp}{2A} = 27.586 \text{ psi}$$

Combined Stress C = 5,908.83 psi

RESULT = OK

Anchor D Stress Calculation (Allowable Stress = 15,450 psi)

Bending Stress:

$$\sigma_x = \frac{\sum M_x * c * P.F. * Fp}{I} = 6263.795 \text{ psi}$$

$$\sigma_y = \frac{\sum M_y * c * P.F. * Fp}{I} = 11135.636 \text{ psi}$$

$$\sigma_z = \frac{\sum M_z * c * P.F. * Fp}{I} = 6263.795 \text{ psi}$$

Torsional Stress:

$$T_z = \frac{\sum M_z * c * P.F. * Fp}{J} = 3131.8975 \text{ psi}$$

Shear Stress:

$$\tau = \frac{\sum F * P.F. @ D * Fp}{2A} = 110.343 \text{ psi}$$

Combined Stress D = 14,570.30 psi

RESULT = OK

Each table represents free pipe segments from one anchor to another. So for Table 2, the combined stress is calculated for the segment between Anchor A and Anchor B. For Table 3, the segments correspond to the ones between Anchor B and Anchor C. Finally, Table 4 represents the combined stress calculation for the segments between Anchor C and Anchor D.

For each table, the following steps are made for the calculation of the combined stress generated in those portions of the piping system:

1. Determine the proportion of force applied to each anchor, based on geometry of system. Formulas for these proportional forces are shown in each table. These are factors applied for the calculation of each stress.
2. Determine moments between each anchor point in three-dimensional space. Depending from which anchor point and around which direction in space the moment is calculated, different results are given.

For example, in Table 2, and verifying Figure 4, between Anchor A and B there is the vertical Segment 1 of fifteen (15) feet of length. When calculating the moment from Anchor A, around the x-axis (North-South direction), the result is given as the multiplication of the pipe segment force and the distance from Anchor A to this force.

Pipe segment force is calculated by multiplying the total weight (found in Table 1) and the segment length.

$$Segment\ Force = 31.5\frac{lb}{ft} * 15ft \qquad (7)$$

$$= 472.5\ lb$$

Distance from Anchor A to segment force is taken as half the segment length, and converting it from feet to inches.

$$Distance = \frac{\left(15ft * \frac{12in}{1ft}\right)}{2} = 90\ in \qquad (8)$$

Then the moment generated in that pipe segment is calculated by multiplying the segment force by the distance.

$$M_x = 472.5lb * 90in = 42{,}525\ lb - in \qquad (9)$$

When calculating the moment from Anchor A, around the y-axis (East-West direction), the result is the same as around the x-axis. But when calculating the moment from Anchor A, around the z-axis (Vertical direction), the result is zero (0) since the pipe segment is vertical.

3. Determine bending stresses between each anchor point, as seen in Tables 2, 3 and 4.
4. Determine torsional stress between each anchor point, as seen in Tables 2, 3 and 4.
5. Determine shear stress at pipe, as seen in Tables 2, 3 and 4.
6. Combine stresses to determine resultant stress on pipe between each anchor point. This is the result of adding the results for bending stress, torsional stress and shear stress at pipe.
7. Compare the resultant combined stress against the allowable stress. If resultant stress is less than the allowable stress, then the pipe is expected to survive the projected seismic event.

After finishing this step-by-step procedure, certainty that the pipe system will resist the predetermined seismic stresses is achieved. With these results, the reactions for the new anchor brace supports can be calculated, giving the engineer/designer the peace of mind that those supports will carry a more than necessary strength to dissipate any seismic stress it is exposed to.

CONCLUSIONS

After performing several rounds of calculations in which iterations based on different brace anchors locations were used, we arrived at the conclusion that with judicious anchor placement, the pipe assembly was capable of surviving the stresses that would result from the assumed seismic event. In Segment 1, as seen in Table 2, the combined stress result from Anchor A and Anchor B were both 8,650.88 psi. Since 8,650.88 psi is less than the allowable stress of 15,450 psi, the pipe segment can withstand the seismic stresses. In Segments 2, 3 and 4, as seen in Table 3, the combined stress from Anchor B is 12,810.44 psi and from Anchor C is 11,997.46 psi. Both resulted less than 15,450 psi so anchor points are arranged in an acceptable distance from each other. Lastly, Segments 5 and 6, as seen in Table 4, have a combined stress from Anchor C of 5,908.83 psi and from Anchor D of 14,570.30 psi. This difference in combined stress is due to the proportional force at Anchor D being a lot larger than at Anchor C. Why? Because from Anchor D, Segment 6, from which the moment distance is calculated, is four times less than Segment 5. Anyway, both combined stresses resulted less than the allowable stress, making the whole fire protection system stable from the predetermined seismic stresses. When this is confirmed, the new anchor supports illustrated in Figure 4 can now be installed confidently.

The seismic resistance gained in the piping system by the use of this line segment analysis is not the most important feature of this evaluation. This methodology introduces designers and engineers everywhere the right tool to create a seismic compliant piping system by confidently knowing where exactly supports/anchors are to be placed. With this, vertical and horizontal forces in each anchor point can be calculated easily, and the choosing process of new supports has the right backup and supporting data behind it.

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