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THE RESULTS OF A NONLINEAR INELASTIC ANALYSIS ON A PIPING SYSTEM IN A BASE ISOLATED PLANT USING AN INELASTIC MATERIAL MODEL

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ABSTRACT

A novel concept for a Nuclear Power Plants in high seismic regions is to provide base isolation for the nuclear island. Nuclear power plants designed as a base isolated plant face many difficult design problems. The Nuclear Island (containment building and auxiliary building) are based isolated while the balance of the plant is not. As a result, the piping systems that initiate in the nuclear island and terminate in the adjacent buildings will be subjected to extremely high relative seismic anchor displacements. Classic linear elastic design methods may result in extremely complex designs. A solution to this design problem is the use of nonlinear inelastic analysis. This study provides a detailed nonlinear piping analysis using an inelastic material model to qualify the piping system. This system initiates in the auxiliary building and terminates in the turbine building crossing over the seismic gap, which experiences relative anchor displacements of 24". The study provides the detailed method used to analyse the system along with the results of the piping analysis. A strain based and a stress-based acceptance criteria is explained and used to qualify the piping system.

ANALYSIS BACKGROUND

A novel concept for a Nuclear Power Plants in high seismic regions is to provide base isolation for the nuclear island. Base isolated nuclear power plants face unique design challenges for piping systems that cross between the base isolated portion and the portion that is not base isolated. This is due to the extremely high relative seismic anchor displacements between these sections. When analysing such a system, classic linear elastic design methods may result in extremely complex designs. To avoid these complex design solutions, a study was completed to determine if the use of non-linear inelastic analysis approach could be used to streamline the design process and reduce complexity.

The main steam line was chosen as the piping system to be analysed for this study. The analysed piping line initiates in the auxiliary building and terminates in the turbine building after crossing over the seismic gap (from the base isolated building to the non-base isolated building). Thus, the piping system is subject to the high seismic anchor displacements between buildings due to the auxiliary building being base isolated. The model of this piping system is shown in Figure 1 below. An initial linear elastic finite element analysis (FEA) of this section of piping resulted with primary pipe stresses failing to qualify under Subsection NC of the ASME BPVC. Using a traditional linear elastic design method, the next step would typically be to try rerouting piping or adding and modifying pipe supports to try and qualify the pipe stresses. However, for the purposes of this study, the goal was to qualify the pipe stresses utilizing only non-linear inelastic methods.

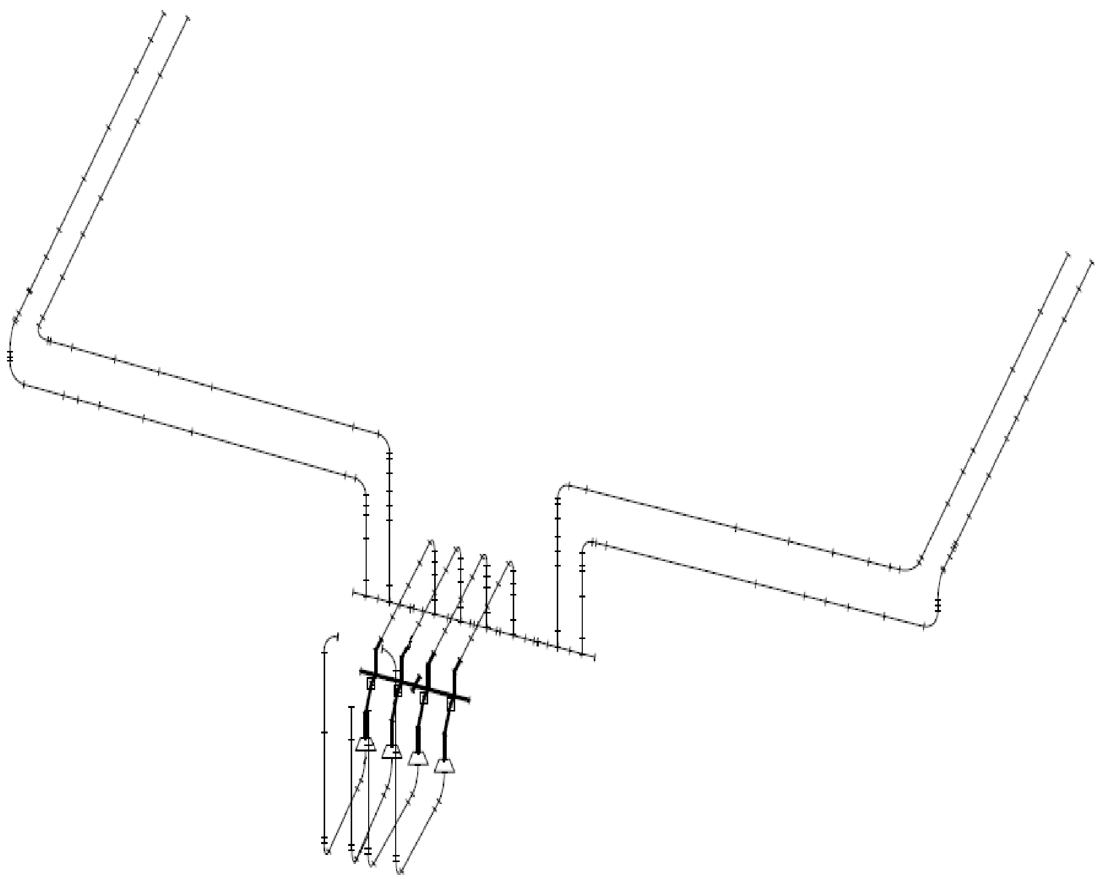

Figure 1. Main Steam Piping Model

METHODOLOGY

The nonlinear time history analysis performed on the main steam model for this study includes pressure, deadweight, seismic inertial loads, seismic anchor motion loads, and fluid transient loads. The seismic inertial loads and seismic anchor motion loads are expressed as a single displacement time history representing both portions of the SSE event. The fluid transient loads are represented by a set of force time history data applied at specified points along the main steam piping. For simplicity this analysis assumes that both the SSE and fluid transient event occur at the exact same time, which is conservative but for design purposes it would be necessary to determine when both events start in relation to each other.

In this nonlinear analysis inelastic material properties are used to model the main steam line. Bilinear Kinematic Hardening model is used as the inelastic material model because this is a transient analysis and kinematic hardening is required to properly model the materials ability to relax when the load is removed or reversed. The plastic strain in the inelastic material is not additive, therefore to obtain an accurate strain load the primary and secondary loads must be considered simultaneously.

ACCEPTANCE CRITERIA

When conducting this non-linear inelastic analysis, a combination of both a stress based, and strained based criteria was used to qualify the piping system. All the piping with a Von Mises stress exceeding the yield stress is qualified to the strain-based criteria and all other is qualified to the stress-based criteria. The following criteria are described in the following sections.

Strain Based Criteria

When conducting an inelastic time history analysis, the pipe which the Von Mises stress exceeds yeild is qualified using a strain-based acceptance criterion that is currently in development as a Code Case for ASME BPVC, Section III, Division 1. The current proposal is used in this evaluation as follows.

In applying the inelastic criteria, first, the true strain in the plastic region is determined. This strain should be calculated simultaneously for concurrent loads. The equivalent plastic strain ε_{eq}^{P} is a cumulative, positive scalar quantity and defined in Nonmandatory Appendix EE, paragraph EE-1110, the fourth paragraph. Appendix EE paragraph EE-1100 defines the true strain as:

$$\varepsilon_{eq}^{P} = \int_{0}^{t} \left(\frac{2}{3}\dot{\varepsilon}_{ij}^{p}\dot{\varepsilon}_{ij}^{p}\right)^{1/2} dt \qquad in/in\left(\frac{mm}{mm}\right)$$

where

ε_{eq}^{P} = Equivalent plastic strain
$\dot{\varepsilon}_{ij}^{p}$ = Plastic strain rate tensor with *ij* reflecting tensor notation
t = Time interval

The strain criteria are limited to a small number of materials which include A106 grade B, but not A106 grade C. Grade C is very similar to grade B that the strain criteria are judged to apply to both materials. In ANSYS, both A106 grade B and A106 grade C are modelled using very slightly different bilinear kinematic hardening stress-strain curves. Both materials are taken as having the elastic moduli listed in the ASME BPVC until they reach a yield stress of 36000 psi, at which point they switch to a tangent modulus of 1000000 psi, as listed in Figure 1.2 of the USS Steel Design Manual.

Strain Limits for Membrane Plus Bending Strain due to the Sustained Loads:

The equivalent membrane plus bending strain due to pressure and all sustained loads, $(\varepsilon_{m+b}^{e})_{P+D}$ calculated by elastic analysis and averaged across the pipe wall shall be limited as follows:

$$(\varepsilon_{eq}^{e})_{SL} \leq \varepsilon_{y}$$

Where

ε_y = true strain at yield

Conservatively, in this study, maximum principal elastic strain is used instead of elastic membrane plus bending strain:

$$(\varepsilon_{eq}^{e})_{SL} = \sqrt{\frac{1}{2}[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2]}$$

Where

ε_1, ε_2 and ε_3 = principal strains

Strain Limits for Non-Reversing Dynamic Loads or Non-Reversing Dynamic Loads Combined with Reversing Dynamic Loads:

(1) The requirements of Section 5.3 (3) and (4) shall be met for the reversing dynamic loads.
(2) The requirements of Section 5.1 shall be met.
(3) The average equivalent total strain $(\varepsilon_{eq}^{P})_{ave}$ across the pipe section shall be limited as follows:

$$(\varepsilon_{eq}^{P})_{ave} \leq \frac{.35n}{(TF)} \tag{3}$$

Where
TF = Triaxiality Factor, see Section 5.4.
n = = strain hardening exponent per Table NB-3228.5(b)-1 for the applicable material

(4) The maximum equivalent strain $(\varepsilon_{eq}^{P})_{max}$ shall be limited as follows:

$$(\varepsilon_{eq}^{P})_{max} \leq 0.45 \left\{ \frac{\sinh\left[\frac{\sqrt{3}}{3}(1-n)\right]}{\sinh\left[\frac{\sqrt{3}}{3}(1-n)(TF)\right]} \right\} \varepsilon_f \tag{4}$$

Where
TF = Triaxiality Factor, see Section 5.4.
ε_f = the true strain at fracture, defined in Nonmandatory Appendix EE

Strain Limits for Reversing Dynamic Loads Not Required to be Combined with Non-Reversing Dynamic Loads:

The following strain limits shall apply:

(1) The number of cycles of reversing dynamic load exclusive of earthquake is limited to 20.
(2) The requirements of 5.1 shall be met.

(3) The equivalent elastic membrane plus bending strain $(\varepsilon_{eq}^{e})_{DWT}$ due to the deadweight shall be limited as follows:

$$(\varepsilon_{eq}^{e})_{DWT} \leq {}^{1}\!/_{3}\varepsilon_y$$

Where:
ε_y = the true strain at yield

$$(\varepsilon_{eq}^{e})_{DWT} = \sqrt{\frac{1}{2}[(\varepsilon_1-\varepsilon_2)^2 + (\varepsilon_2-\varepsilon_3)^2 + (\varepsilon_3-\varepsilon_1)^2]}$$

Where
ε_1, ε_2 and ε_3 = principal strains

(4) The maximum equivalent total strain $(\varepsilon_{eq}^{P})_{max}$ shall be limited as follows:

$$(\varepsilon_{eq}^{P})_{max} \leq \frac{\varepsilon_a}{(TF)}$$

$$\varepsilon_a = \frac{S_a(N)a}{E} = \frac{410ksi * 2.3}{30000ksi} = 0.0314$$

Where

ε_a = the allowable strain amplitude as defined in equation (8)

E = Young's modulus, obtained from Figure I-9.1 of Appendix I. Figure I-9.1 lists Young's modulus as 30000 ksi for A106 grade B and grade C.

N = number of cycles of dynamic load. N is taken as 20 for the main steam line.

$S_a(N)$ = allowable stress amplitude S_a for N cycles of load and can be obtained for A106 Gr. B and C in Figure I-9.1 of Appendix I; N shall not be less than 10 or greater than 20. Both A106 Gr. B and A106 Gr. C have ultimate tensile strength less than 80 ksi, so for N=20 cycles, $S_a(N)$ is 410 ksi.

a = 2.3 for Sa values from Figure I-9.1.

Triaxiality Factor:

The Triaxiality Factor is determined in accordance with non-mandatory Appendix FF-1143. The maximum TF is conservatively used in the analysis to determine the strain limit.

Stress Based Criteria

The seismic event being considered for this study is a Level D SSE event, to which can be applied the elastic analysis criteria of ASME BPVC Appendix F. Appendix F states that for Ferritic steel, the general primary membrane stress intensity Pm shall be less than .7Su, and that the primary membrane plus bending stress intensity shall be less than .9Su. This leads to equations (8) and (9) below.

$$P_m \leq 0.7S_u$$

$$P_m + P_b \leq 0.9S_u$$

Where P_m is the primary membrane stress, S_u is the tensile strength of the material, and P_b is the bending stress

The stress that is used to identify the point of transition from elastic to plastic is determined using the Von Mises equations as follows:

$$\sigma_e = \frac{1}{\sqrt{2}}\left[(r_2 - r_1)^2 + (r_2 - r_3)^2 + (r_3 - r_1)^2\right]^{1/2}$$

$$\sigma_e = \frac{1}{\sqrt{2}}[VM]$$

Where $[VM] = \left[(r_2 - r_1)^2 + (r_2 - r_3)^2 + (r_3 - r_1)^2\right]^{1/2}$

Transition occurs when $\sigma_e \geq \sigma_y$

Per the Von Mises criteria (page 49, D' ISA):

$$\tau_{oct} = \frac{1}{3}\left[(r_2 - r_1)^2 + (r_2 - r_3)^2 + (r_3 - r_1)^2\right]^{1/2}$$

Or

$$\tau_{oct} = \frac{1}{3}[VM]$$

If we substitute the Von Mises theory for the Tresca theory as permitted by the new Mandatory Appendix, the maximum stress intensity is: $2 \times \tau_{oct}$ or

$$S_{max} = 2\left(\frac{1}{3}[VM]\right)$$
$$= \frac{2}{3}[VM]$$

From above

$$[VM] = \sqrt{2}\sigma_e$$

And therefore, the maximum stress intensity S_{max} is

$$S_{max} = \frac{2\sqrt{2}}{3}\sigma_e$$

If σ_e is less that σ_y, then the element will remain elastic. Therefore, if the element remains elastic then,

$$S_{max} \leq \frac{2\sqrt{2}}{3}\sigma_y$$

The σ_{yp} value used is the actual estimated yield stress of 46 ksi. The Code allowable yield stress is 30 ksi. Therefore

$$\sigma_{yp} = \frac{46}{30}(S_C) = 1.53S_C$$

Therefore, for all points that remain elastic

$$S_{max} = \frac{2\sqrt{2}}{3}(1.53)(S_C)$$

$$= (.942)(1.53)(S_C)$$

$$= 1.44(S_C)$$

The allowable Code stresses per the New Appendix are:
Primary Membrane is .7Su
Maximum Primary stress is .9Su
S_{max} = (1.44)(30) = 43.2 ksi (where the material goes plastic)
.7Su = 42 ksi
.9Su = 54 ksi

The maximum stress values σ_e, determined includes all stress classifications, which conservatively enveloped the P_m+P_b stress. Further, the analysis includes seismic anchor motion effects which are secondary stress. Per the new Mandatory Appendix, -1300(b) only primary stresses need to be considered. Also, per the updated Appendix XIII for piping seismic anchor motion stresses are considered separate from inertial stress and have a higher stress limit.

Therefore, the stresses being used to determine σ_e are conservative relative to the Stress Intensity determination of P_m+P_b. Therefore, if an element does not go plastic, then the P_m+P_b of .9Su is met by default.

The results are therefore post-processed to generate the Pm (Primary Membrane) stresses and include the effect of Pressure, weight, seismic inertial loads, fluid transient loads, and seismic anchor motion effects.

The study does include seismic anchor motion effects, which are secondary stresses and typically secondary stresses are not considered for Level D events per Appendix F. However, since both the seismic inertial and seismic anchor motion effects are represented by a single time history, there is not an effective way to separate the results into primary and secondary stresses. However, if the combined primary and secondary stresses meet the Pm and Pm+Pb limits, the higher primary plus secondary stress limit for P_m+P_b+Q would be met. It is also important to note that Appendix F only requires evaluation of primary stresses. Secondary stresses are not required to be evaluated.

then by definition the primary and secondary stresses considered alone would meet the limits and the thus resulting design is conservative and the pipe stresses acceptable.

ANALYSIS RESULTS

Table 1 contains a summary of all the elements reaching the plastic range on the stress-strain curve for the main steam analysis for Level D loads. Note that a linear FEA analysis was performed as part of the initial system evaluation, but not directly as part of this study and the system was unable to meet the ASME BPVC Level D acceptance criteria.

Table 1-1-: Main Steam – Plastic Elements Strain Results: Deadweight Strain

Rank	Element	Location of Highest Stress	Strain	Allowable Strain Ratio
1	190	28” LR Elbow	1.14E-05	0.03
2	189	28” LR Elbow	1.07E-05	0.02
3	188	28” LR Elbow	9.96E-06	0.02
4	187	28” LR Elbow	9.34E-06	0.02

Table 1-1-: Main Steam – Plastic Elements Strain Results: Deadweight + Pressure Strain				
Rank	Element	Location of Highest Stress	Strain	Allowable Strain Ratio
1	190	28” LR Elbow	4.747E-04	0.37
2	189	28” LR Elbow	4.745E-04	0.37
3	188	28” LR Elbow	4.743E-04	0.36
4	187	28” LR Elbow	4.741E-04	0.36

Table 1-3: Main Steam – Plastic Elements Strain Results: Average Strain (P+DW+SSE+WH)				
Rank	Element	Location of Highest Stress	Strain	Allowable Strain Ratio
1	190	28” LR Elbow	1.66E-04	0.0024
2	189	28” LR Elbow	1.66E-04	0.0024
3	188	28” LR Elbow	1.65E-04	0.0024
4	187	28” LR Elbow	1.64E-04	0.0023

Table 1-4: Main Steam – Plastic Elements Strain Results: Maximum Equivalent Strain(P+DW+SSE+WH)				
Rank	Element	Location of Highest Stress	Strain	Allowable Strain Ratio
1	190	28” LR Elbow	1.481E-03	0.00104
2	189	28” LR Elbow	1.484E-03	0.00104
3	188	28” LR Elbow	1.481E-03	0.00104
4	187	28” LR Elbow	1.468E-03	0.00103

Table 2 compares the top 5 highest support loads in each orthogonal direction from the non-linear inelastic analysis done to the corresponding support loads from the linear time history analysis. The comparison of the support loads show that analysing the system with inelastic material properties doesn’t have a large impact on the loads that the pipe support must withstand.

Table 2-1: MS Support Loads: Top 5 Highest Loads, X -direction				
[redacted]			ANSYS Nonlinear	ANSYS Linear
Support No.	Node	Level	Force (lbf)	Force (lbf)
HMS205-006G	405	D	249515	208413
HMS205-017S	605	D	-196049	-213254
HMS205-011G	505	D	-195826	-189290
HMS205-025S	210	D	168638	173357
HMS205-032G	3075	D	145692	145484

Table 2-2: MS Support Loads: Top 5 Highest Loads Y -direction				
[redacted]			ANSYS Nonlinear	ANSYS Linear
Support No.	Node	Level	Force (lbf)	Force (lbf)
SUPPORT MS-1	5025	D	1202750	1037493
SUPPORT MS-4	5040	D	1190669	1029910
HMS205-009R	20	D	475599	428975
HMS205-007R	100	D	472964	461986
HMS205-028R	275	D	107007	108975

Table 2-3: MS Support Loads: Top 5 Highest Loads Z -direction

			ANSYS Nonlinear	ANSYS Linear
Support No.	Node	Level	Force (lbf)	Force (lbf)
HMS205-010G	1075	D	-576009	-531732
HMS205-032G	3075	D	-570101	-525345
HMS205-008G	2075	D	-569094	-527607
HMS205-031G	4075	D	-554034	-647931
HMS205-024X	205	D	345161	366700

CONCLUSION

The purpose of this study was to qualify the main steam piping system using a combination of a Strain Based Acceptance Criteria and the new mandatory appendix for level D loads. All pipe elements that the Von Mises stress exceeds yeild were analysed with the strain-based acceptance criteria described earlier in this calculation. The mainstream model analysis had 4 elements reach plastic strain and those can be found in Table 1. As described earlier in this paper, if the element did not go plastic then by default the $P_m + P_b$ stresses met the limit of $0.9S_u$. It can be concluded from this analysis and the acceptance criteria from the ASME Boiler Code, Section III that the main stream system pipe can be qualified.

This study also contains a comparison of the support loads from the non-linear time history analysis to the support loads of a linear time history analysis. These loads can be found in Table 2. It can be seen from the comparison that most of the loads are with 10-15% of each other. Therefore, it can be concluded from this study that for this system whether the analysis is a linear time history analysis or a time history analysis with non-linear inelastic material properties the support loads are unaffected by the analysis type. The use of detailed nonlinear time history analysis is very useful in this scenario and it allows us to qualify pipe what otherwise would not qualify with standard linear analysis methods.

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