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Division V

ON THE APPLICABILITY OF NEW SEISMIC CRITERIA FOR NUCLEAR PIPING

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ABSTRACT

Most of the current Codes and Standards for piping stress analysis in nuclear and industrial fields consider inertial seismic loads as primary, causing not self-limiting stresses that can lead to gross plastic deformation and piping failure associated with a plastic collapse. At the same time, both the experience of past powerful earthquakes and numerous experimental campaigns carried out in Japan, USA, India and other countries have shown that the failure of piping during seismic impact occurs at loads that are many times higher than the design permissible level, and the modes of failure correspond to low cycle fatigue and ratchetting.

Conventional piping flexibility and stress analysis is based on elastic calculations. The fact that piping under intensive seismic loads will experience high plastic deformations is compensated in analysis by introducing in design increased damping, ductility factors, increasing the level of allowable stresses, and/or decreasing the corresponding stress indexes

At the same time, recently there were a number of publications and studies showing that a significant part of the inertial load can be classified as secondary, P. Labbé (2021) and, accordingly, the assessment of seismic stresses should be carried out in terms of fatigue strength, P. Sollogoub (2017).

The presented paper provides a comparison of the numerical results for the piping system under seismic loads achieving the level considered as permissible according to the new liberal seismic criteria. Two methods of analysis are considered: time history elastic-plastic dynamic analysis and conventional elastically-based beam model design approach.

On the basis of the results obtained, conclusions are drawn about both the degree of conservatism of the new criteria and the acceptability of results from elastic seismic analysis.

INTRODUCTION

Design of NPP piping systems must consider loading occurred during normal operation as well as occasional loads such as seismic and other dynamic events. From the very beginning of NPPs design and erection the strict seismic criteria have led to a great number of seismic restraints that became an issue for the plant’s cost and operation:

- an excessive number of seismic restraints leads to difficulty of access for inspection and maintenance of piping and equipment;
- increasing time required for the equipment's access may increase personnel' radiation exposure;
- some types of seismic devices can create an additional restraining for the piping thermal expansions compromising fatigue strength;
- additional devices increase the costs of the plant (they should be purchased), as well as additional expenses will be required for their operational maintenance and repairment.

Thus, since the mid-80s, plants and utilities have been looking for the way how to reduce conservatism of seismic analyses. At the same time the Snubber Reduction Program, EPRI (1987), was initiated and carried out in the USA, which gave the impulse to a deeper and more detailed study of the seismic performance of NPP's piping. A number of experimental studies has been carried out on individual piping components and whole piping systems installed on the powerful shaking table, NUREG (2008). At the same time, a database was collected and the past earthquakes experience was summarized, SQUG (2001). These studies have shown that plant's piping have a large margin of seismic capacity, and their possible failure under seismic load is caused not so much by the action of the primary inertial loads, but rather due to effect of low-cycle fatigue and ratcheting, P. Sollogoub (2017).

Gradually, less conservative approaches for seismic analysis were introduced in ASME BPVC: Code Case N-411 was adopted in 1986, allowing the use of increased damping (later it was accepted by Regulator and issued as RG 1.61 (2007)). Also, ASME BPVC Code, Section III, Division 1 introduced in 1992 the concept of Reversing (Seismic) Loads for piping system design allowing use reduced stress indexes for piping bends and tee/branch connections

CONTEMPORARY TRENDS AND APPROACHES FOR LIBERALIZATION OF SEISMIC CRITERIA

Several strain-based acceptance criteria methods for seismic assessment of NPP metallic piping have been proposed in recent years. Some of these methods are based on elastic-plastic analysis: ASME Code Case and JSME Code Case, some are based on conventional linear elastic analysis (MECOS). Below is a brief overview of these methods.

ASME Code Case N-900 (2019)

Applicability of this Code Case is subjected to a number of limitations for material, temperature, welded joints, and fabrication strains. Providing that all these limitations are met, Code Case installs strain-based acceptance criteria. Strain Limits for Reversing Dynamic Loads not Required to be Combined with Non-Reversing Dynamic Loads according to Code Case are (1) – (3):

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

where: $(\varepsilon_{eq}^{e})_{DWT}$ – the equivalent elastic membrane plus bending strain due to deadweight; ε_y – the true strain value corresponding to the Code specified yield stress at a temperature consistent with the loading under consideration. Satisfaction of this equation provides preventing of ratcheting effects influenced on seismic fatigue.

$$(TF)(\varepsilon_{eq})_{max} \leq \varepsilon_a \qquad (2)$$

where: TF – triaxiality factor; $(\varepsilon_{eq})_{max}$ – the maximum equivalent strain of the pipe: "the equivalent plastic strain is a cumulative, positive scalar quantity, nondecreasing strain measure that takes into account the entire deformation history", ASME Appendix EE (2021); ε_a - the allowable true strain amplitude;

$$\varepsilon_a = \frac{[S_a(N)]a}{E} \qquad (3)$$

where: $S_a(N)$ – allowable stress amplitude S a for N cycles of load and can be obtained from Figure I-9.1 or I-9.2 of Section III Appendices, Mandatory Appendix I; N shall not be less than 10; a – 2.3 or 1.5 for S_a values from Figure I-9.1 and I-9.2 accordingly; E – Young's modulus.

Code Case JSME NC-CC-008

Code Case "An alternative rule on seismic qualification of seismic S class piping systems by detailed inelastic FE response analysis" was proposed to JSME by a Task Group in order to establish an evaluation procedure in which the elastic-plastic behavior of piping systems is considered in a rational way. According to Morishita et. al (2020) Code Case consists from the Code Case itself, Mandatory Appendix SEGP-I "A guideline of inelastic response analysis methods for piping systems", Nonmandatory Appendix SEGP-A "A method of program verification and analysis data validation", Nonmandatory Appendix SEGP-B "A benchmark study on detailed inelastic response analysis of a piping system".

The Mandatory Appendix SEGP-1 provides very detailed guidance for the elastic-plastic FE analysis, including recommendations for the method and type of analysis, analysis code, finite element modeling, material properties, seismic input and damping ratio, etc.

Code Case uses two alternative acceptance criteria to evaluate seismic fatigue:

(1) a limit to the maximum value of equivalent strain amplitude $\bar{\varepsilon}_{max}$:

$$\bar{\varepsilon}_{max} = \frac{1}{2}\max[\Delta\bar{\varepsilon}_i, i = 1,2,3, \dots n-1] < S_a(N'_{eq})/E \tag{4}$$

where: $\Delta\bar{\varepsilon}_i$ – equivalent strain range for a number *n* of extreme points from the time history; E – Young's modulus; $S_a(N'_{eq})$ - the value of peak stress intensity determined from the design fatigue curve (in Japan practice it is defined in the JEAC4601-2015) read at the modified number of equivalent load cycles of earthquake N'_{eq}.

$$N'_{eq} = N_{eq}/(1 - U_{AB}) \tag{5}$$

where: N_{eq} – equivalent number of load cycles of an earthquake; U_{AB} – fatigue usage factor of operation conditions A and B.

(2) a limit to Fatigue Usage Factor:

$$U_f = U_{AB} + U_{Ss} \leq 1 \tag{6}$$

$$U_{Ss} = \sum_{1}^{n-1} \frac{1}{2N_i(S_p^i)} \tag{7}$$

where: S_p^i – a series of peak stress amplitude recalculated from the series of equivalent strain range $\Delta\bar{\varepsilon}_i$; $N_i(S_p^i)$ – the allowable number of load cycles in the design fatigue curve at the level *i*th peak stress amplitude. The factor of 2 is added in denominator to account the fact that $N_i(S_p^i)$ curve corresponds to a half cycle, not a full reversed cycle (in the original procedure a "range method" have been used that deals with half cycles, but authors (Morishita et. al (2020)) recommended to apply rain flow method as well)

MECOS Toward New Seismic Criteria Initiative

MECOS research program was undertaken under the Committee for the Safety of Nuclear Installations (CSNI) of the OECD Nuclear Energy Agency (NEA). It initiated the evaluation of margins inherent to the nuclear power industry design procedures, MECOS GE (2021).

One of the main MECOS outputs was understanding that a significant part of the seismic inertial load can be classified as a secondary load. Accordingly, the dominant failure mode specific for metallic piping is low-cycle fatigue. In this regard, MECOS suggested to use equation 10 from ASME BPVC NC-3600 and modify it in the following manner:

$$S_{SD} = i\frac{M_{SD}}{Z} \leq \frac{1958}{{N_{SD}}^{0.2}} \tag{8}$$

where: S_{SD} – stress range for Service Level D seismic loads, MPa; *i* – stress intensification factor (NC-3673.2); M_{SD} – range of resultant moments due to seismic loads specified for the Level D Service Limits, obtained from the linear-elastic analysis, N*mm; *Z* = section modulus of pipe, mm^3 (NCD-3653.3); N_{SD} = equivalent number of maximum stress cycles for Service Level D seismic loads;

Applicability of this equation is limited by above-ground carbon steel, low alloy steel, or stainless-steel piping systems subjected to limitations for the reversing dynamic loads, NCD-3655-(3)(b).

Additionally, it is assumed that number of stress cycles during Service Levels A and B conditions does not exceed 1000, and value of basic material allowable stress at cold and hot temperature (S_c and S_h) is below than 138 MPa.

Also, it was shown that equivalent number of maximum stress cycles N_{SD} for Service Level D seismic loads can be estimated according to the following equation, MECOS GE (2021), Chapter 6.2.2.8:

$$N_{SD} = 0.54\ (\mathrm{N_e^{0.6}} + 5) \tag{9}$$

where N_e = T/τ. T is the duration of the strong motion and τ is the eigen period of the piping predominant mode.

DESCRIPTION OF PIPING MODEL USED FOR BENCHMARKING

To investigate dynamic behavior of the piping under severe seismic input a prototype model was taken from the MECOS study, BARK (2015), Figure 1. This model was intensively tested on the seismic test rig and subjected to a number of analyses, NEA/CSNI (2018).

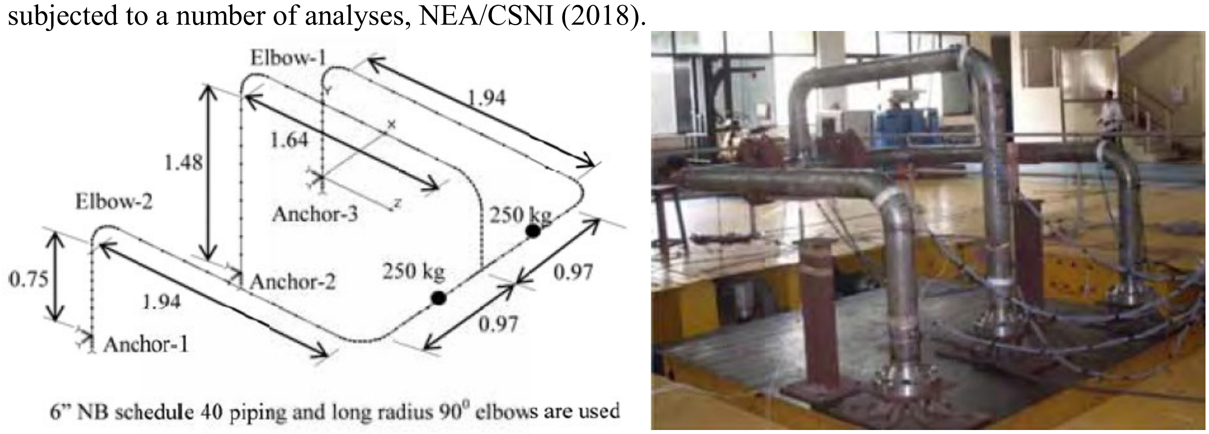

Figure 1. Benchmark Line, BARK (2015)

For the first step of analysis a conventional beam model was created and analyzed with use of dPIPE software, dPIPE (2017), Figure 2. As output from this analysis a natural frequencies and mode shapes were determined, Figure 3.

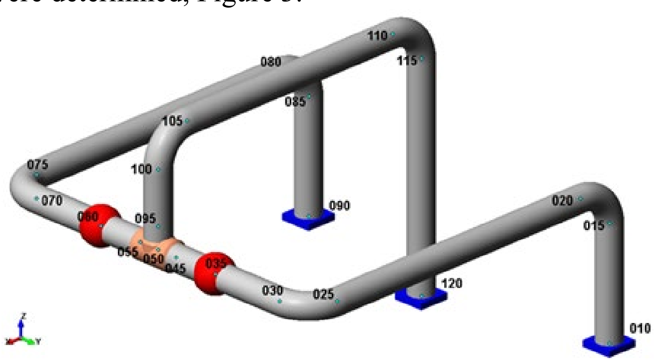

Figure 2. dPIPE Beam Model

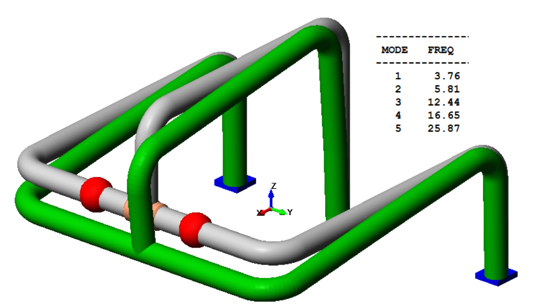

Figure 3. Beam Model natural frequencies and first Mode Shape

A hybrid FE model was developed according to JSME Code Case recommendations to undertake nonlinear elastic-plastic analyses. The model was created using the SHELL181 eight-node elements, PIPE16 two-node beam elements, COMBINE14 two-node spring elements and MASS21 one-node mass elements. SHELL181 elements were used for modeling of elbows and adjacent to elbows straight pipes and anchors. Natural frequencies of hybrid and beam models have been compared and being found well coincided (first natural frequency of the beam model is 3.76 Hz and hybrid models is 3.67 Hz).

The material properties used in the model correspond to carbon steel SA-333 Grade 6. Elastic properties were applied to pipe elements. According to JSME Code Case recommendations for elastic-plastic analysis, a bilinear kinematic hardening was applied to material of shell elements, Figure 4.

The benchmark line was composed of six 90° long radius elbows, one tee joint and two 250 kg lumped masses. The pipe had a 168 mm outer diameter and an average thickness of 7 mm. For the elbows, the radius of the bent portion was 228.6 mm. For the tee joint, the distance from the center to the end is equal to 143mm. Anchors were placed at three ends of the piping. Figure 5 shows the configuration of the model and the boundary conditions.

Implicit transient analysis was performed for all sets of calculations. Newmark time integration method was used. Loads were linearly interpolated for each sub-step. ANSYS automatically chooses the full Newton-Raphson method and whether or not to use line searching to solve any given time step. Large deflection analysis option was turned on.

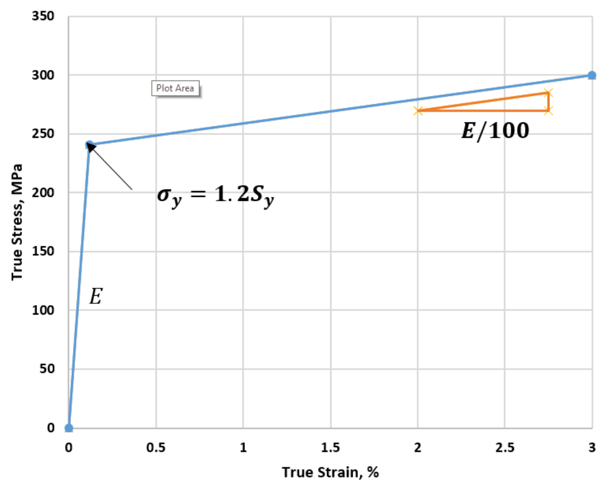

Figure 4. Bi-linear approximation of material's properties: SA-333 Grade 6 (Sy=240 MPa, E=2.04E+5 MPa)

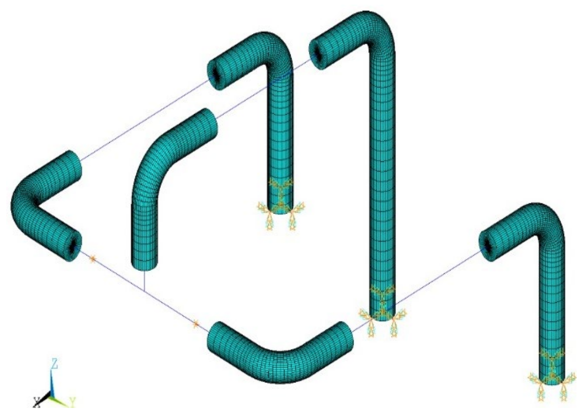

Figure 5. ANSYS Hibrid FE Model

Seismic Input and Loading Conditions

Analysis conditions were intentionally simplified for assessment of factors affecting the seismic response of the piping:

1) Seismic excitation was applied along Z axis only to excite the first mode shape of the line. Acceleration time history and its characteristics (Response Spectrum and Husid Plot) are shown in Figures 6 and 7. Initial level of seismic excitation was set at ZPA = 0.5g. In series of following calculations this Time History was scaled for higher ZPA levels.
2) Static loads (weight and pressure) were not considered in the dynamic calculations to exclude ratcheting effect.

Piping dynamic was evaluated for 4% critical damping (Rayleigh damping coefficients were calculated for minimum and maximum frequencies considered in the analysis: 3.67 and 30 Hz).

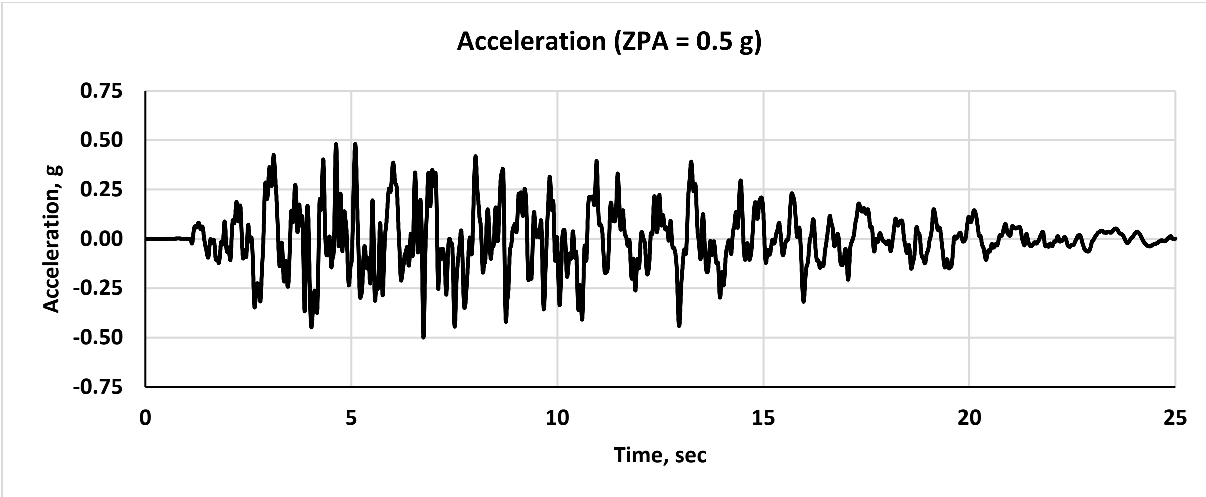

Figure 6. Acceleration Time History

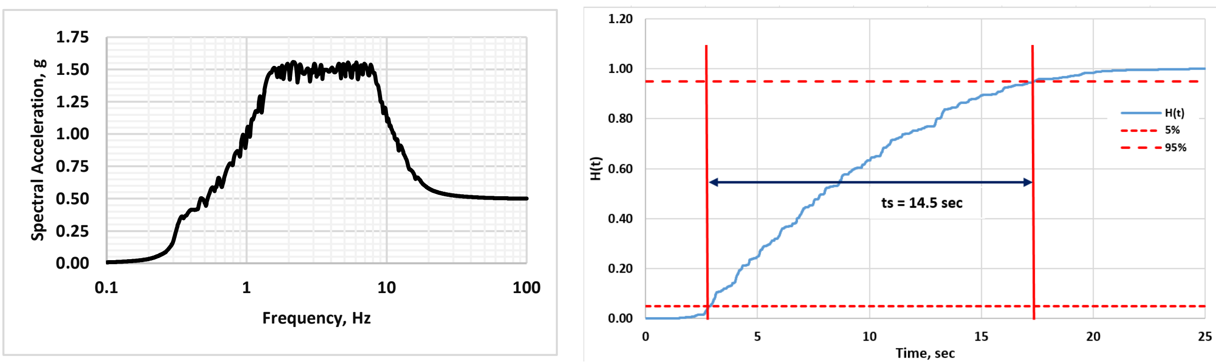

Figure 7. 4% Response Spectrum and Strong Motion duration (t_s = 14.5 sec)

RESULTS OF ANALYSES

Conventional ASME NB-3600 analysis

A normative linear elastic analysis was carried out on a hybrid model to establish the basic level of seismic input at which the stress in piping elements would reach the allowable value prescribed by ASME Code. For this purpose, the maximum resulting moment found in the elbow area (M_E), was substituted in the equation from NB-3656(b)(3): Level D Service Limits including reversing dynamic loads:

$$B_1 \frac{P_E D_O}{2t} + B_2' \frac{D_O}{2I} M_E \leq 3S_m \quad (10)$$

It was found that the level of $3S_M$ is reached when seismic input is scaled up to 1.6 g level. Similarly, for class 2 piping, NC-3655(b)(3), one gets the allowable level of ZPA=1.37 g. Greater conservatism is associated here with the use of lower values of nominal allowable stresses (S_h=118 MPa, instead of S_m=138 MPa).

Elastic vs. elastic-plastic analyses

The following set of nonlinear elastic-plastic analyses was undertaken with use of hybrid model under series of seismic Time Histories with ZPA scaled in the range from 1g to 4g. Figure 8 shows a hybrid model with marked zones of maximal response parameters: stress in elbow (ELBOW), anchor resulting moments (ANC(10) and ANC(120)) and vertical displacements (DISP).

Figure 9 shows results of these analyses in terms of ratios between elastic-plastic and elastic responses. Up to ZPA = 1g all responses are in the elastic zone. When ZPA reaches 1.6g, some local plastic zones appeared in the piping. But in general, the difference between nonlinear and linear calculations does not exceed 10%. With a further ZPA increase the moments in elements are decreased and displacements at the same time are increased. Thus, at certain level of the seismic intensity, the results of the linear elastic analysis can hardly be considered as representative. If the monotonic change in responses can be simulated in the frame of linear elastic calculation by means of additional damping, then after the ZPA level becomes greater than 2.5g, the system's stiffness is redistributed (for example due to formation of plastic hinges) and the dynamic response in the elastic analysis will no longer reflect the real response of the system.

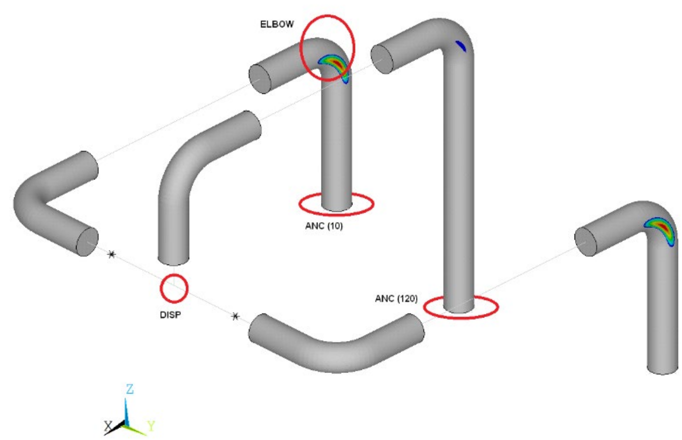

Figure 8. Hybrid model with zones of maximal response parameters

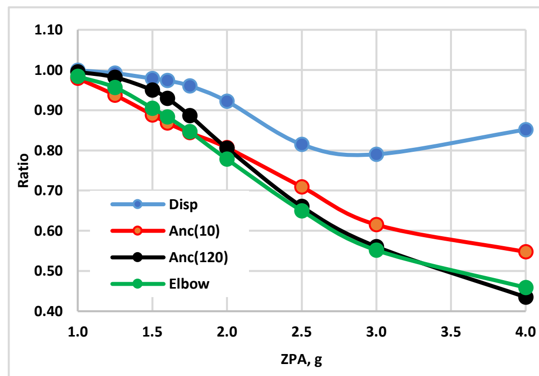

Figure 9. Influence of elastic-plastic behavior. Ratio = Res(plastic)/Res(elastic)

Assessment according to ASME Code Case N-900

Figures 10 and 11 show dependence of the accumulated equivalent plastic strain measured in the most stressed elbow form the level of ZPA.

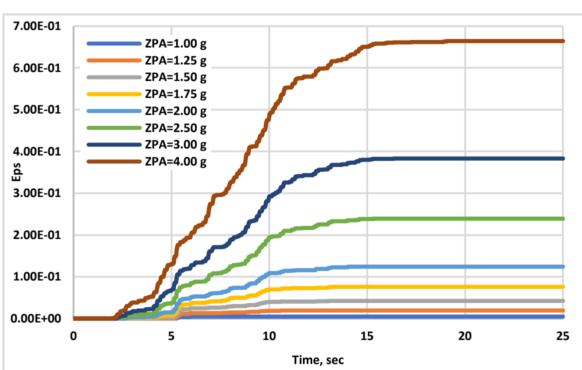

Figure 10. Accumulated equivalent plastic strain in time domain

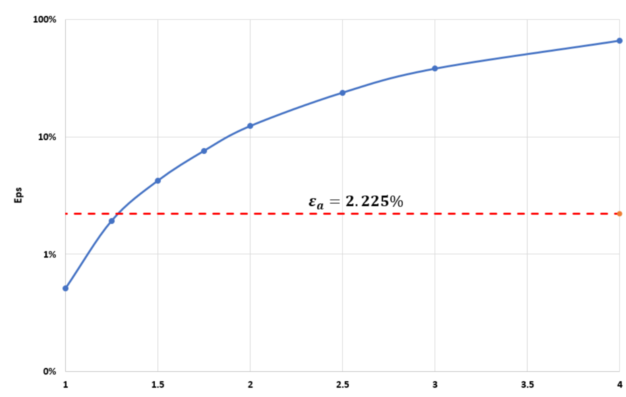

Figure 11. Accumulated equivalent plastic strain

If one takes N = 10 in equation (3), then from Figure I-9.1 (for UTS≤80 ksi) we get $\varepsilon_a = 4.45\%$. The maximum calculated value of the triaxial factor is TF ≈ 2, and, then the accumulated equivalent strain should not exceed 2.225%. As can be seen from Figure 10, the maximum ZPA allowed by the Code Case N-900 is 1.25g.

Assessment according to JSME Code Case NC-CC-008

According to JSME Code Case an assessment was made with use of equivalent strain amplitude, equations (6) and (7). The maximal strain range was defined from the strain time history, Figure 12. An equivalent number of cycles was defined from this plot by means of the rainflow method. Application of this approach is valid for this sample, because seismic response here is governed by first system's mode shape, so we have here practically proportional loading. Each column shown in Figure 13 corresponds to one cycle. Then, Cumulative Usage Factor CUF_{Ss} can be calculated with use of following formula (unlike equation (7), (11) does not contain 2 in the denominator, since in this case the summation is performed over full cycles):

$$CUF_{Ss} = \sum_{1}^{n} \frac{1}{N_i(S_p^i)} \tag{11}$$

It should be noted that in this procedure ASME fatigue curve Figure I-9.1 (for UTS≤80 ksi) was utilized. Dependence of CUF from ZPA is shown in Figure 14. This Figure shows that even for ZPA = 0.4g CUF reaches the value 0.5 only.

Figure 15 shows nonlinear change of the maximal equivalent strain depending on the increase in the intensity of the seismic excitation.

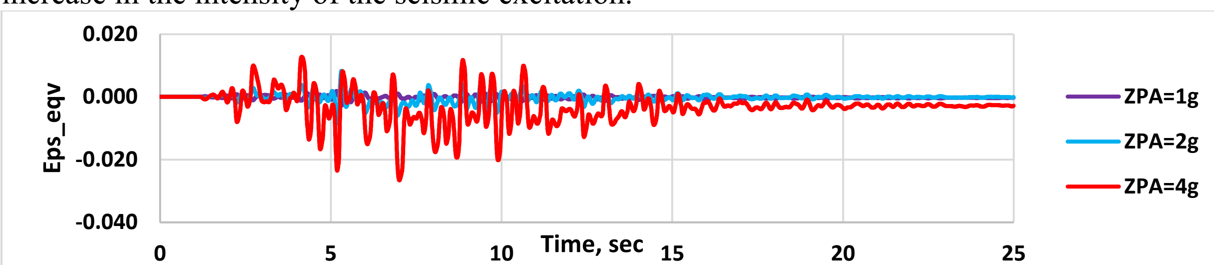

Figure 12. Equivalent total strain

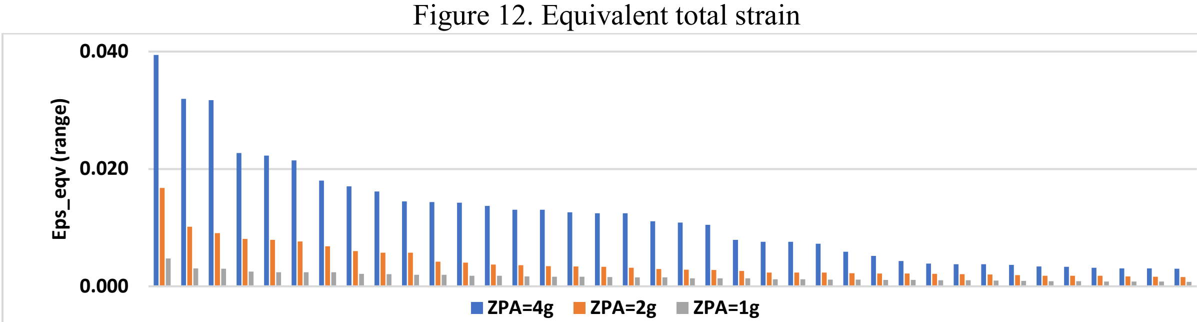

Figure 13. Rainflow Strain Cycles

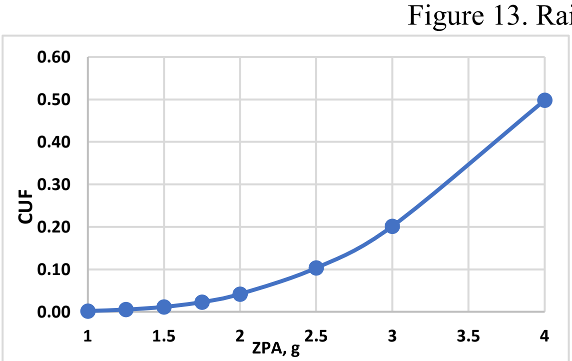

Figure 14. Usage factor

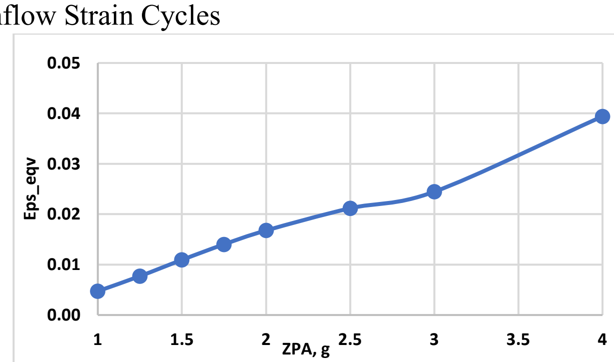

Figure 15. Maximal Range of Equivalent Strain

Assessment according to MECOS approach

Within this part of the study, the analysis was carried out according to the results of the elastic calculations of the hybrid model. Figure 16 shows time history of the equivalent stresses recalculated from the resulting moment in the Elbow zone, Figure 8. Further, based on this history and also using the rainflow method, the equivalent number of cycles was calculated, Figure 17 and the CUF is established accordingly. Figure 18 shows the change of the CUF depending on the intensity of excitation and a comparison of the elastic and elastic-plastic CUF depending on the increase of ZPA ("Markl" and JSME curves, respectively). It can be seen that CUF reaches unity at ZPA = 3.6 g when using the linear elastic analysis, while there is a significant margin for CUF obtained in the frame of elastic-plastic nonlinear calculation.

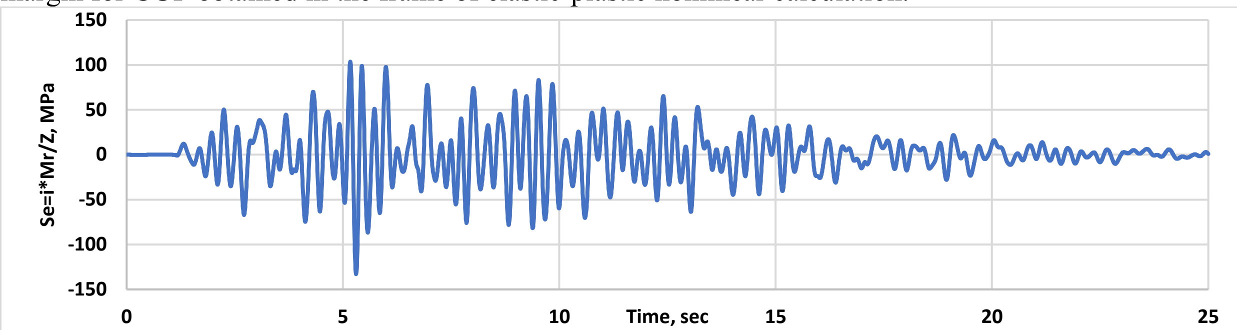

Figure 16. Time History of the equivalent stresses from elastic analysis (ZPA=0.5 g)

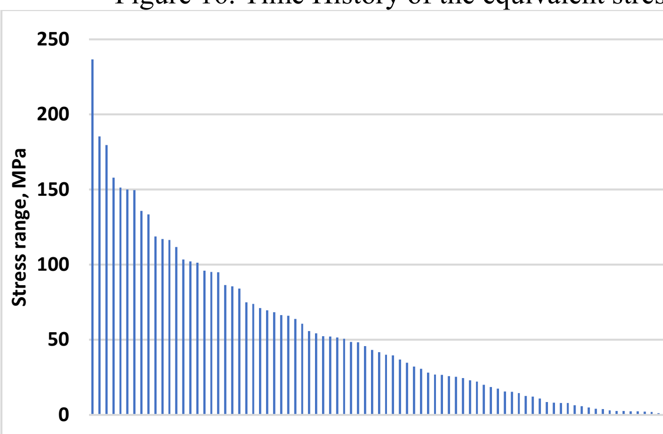

Figure 17. Rainflow cycles (ZPA=0.5 g)

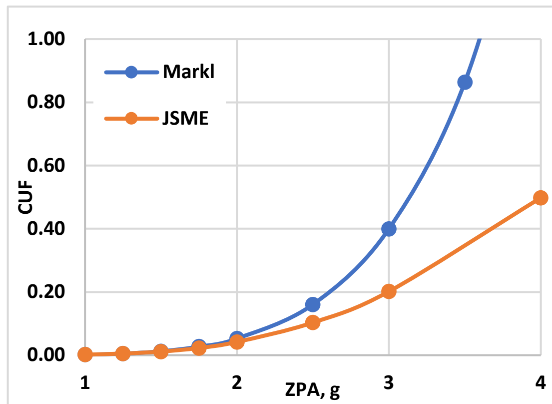

Figure 18. Usage factors

In the case of using a simplified calculation of the equivalent number of cycles according to equation (9), we get $N_{SD} = 0.54((14.5 * 3.7)^{0.6} + 5) = 8.59$, and equation (8) will be satisfied at ZPA=2.69g.

CONCLUSIONS

Figure 19 shows a comparison of the results in terms of highest ZPA values at which the seismic stress criteria is satisfied according approaches considered in this paper. It could be seen that highest conservatism reduction gives the use of JSME Code Case (even despite applying the fatigue curve with conventional safety factors: 2 for stresses and 20 for cycles). A questionable result is obtained for ASME Code Case: it looks more conservative then the direct use of Code equations. The use of the cumulative equivalent strain as a criterion allows eliminate work-expensive procedure for cycles counting, but apparently requires clarifying its relationship with fatigue failure. A simpler MECOS method does not require a nonlinear analysis and allows significantly reduce the conservatism at much lower analysis cost: this procedure may be utilized even in frame of the conventional linear response spectrum method.

It should be noted that in further studies it would be useful to evaluate the justified level of damping for elastic-plastic calculations (in this study, a normative 4% was used, which may be too optimistic). It would also be useful to assess how the identified trends will persist when analyzing a more representative set of piping systems, considering internal pressure, weight, seismic effects of different durations, etc.

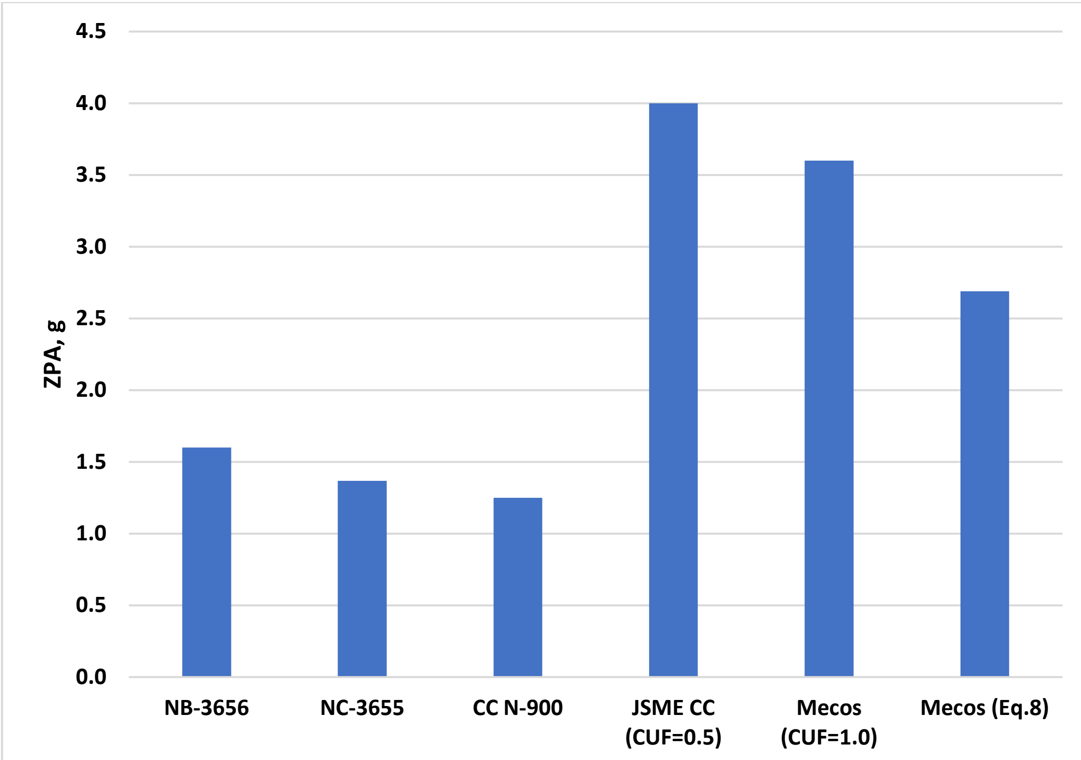

Figure 19. Comparison of different seismic procedures

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ASME Appendix EE (2021), ASME BPVC.III.A-2021, SECTION III Rules for Construction of Nuclear Facility Components, APPENDICES, Nonmandatory Appendix EE Strain-Based Acceptance Criteria Definitions and Background Information,