Transactions, SMiRT-26
Berlin/Potsdam, Germany, July 10-15, 2022
Special Session: MECOS initiative on Seismic design of piping systems - Towards improved design criteria

TOWARDS NEW SEISMIC CRITERIA. EXAMPLE OF NUMERICAL IMPLEMENTATION

Alexey Berkovsky[1]

[1] Principal, CKTI-Vibroseism, Saint Petersburg, Russia (aberkovsky@cvs.spb.su)

ABSTRACT

This paper presents an example of the numerical implementation for the seismic design procedure developed in the frame of MECOS initiative on seismic design of piping systems. New design approach is based on the following principles:

1. The seismic design rules should protect against the observed failure mode of piping components in seismic tests. This failure mode is the formation and propagation of a fatigue crack;
2. The design rules should protect against plastic instability;
3. The design rules should be based on elastic analysis, using standard elastic pipe stress analysis software, with pipes and fittings as beam and flexibility elements;
4. Since elastic stress analysis does not reflect precisely the plastic strain behaviour of pipe and fittings, the design rules should include safety factors on stress and cycles;
5. The strain rate during a seismic event is quasi-static, so that quasi-static fatigue principles may be applied

To achieve these goals the proposed procedure was developed with the following approaches and assumptions:

- Imposed limitations for sustained loads ensure exclusion of the ratcheting;
- Low cycle fatigue is described by Markl' equation for the best-fit fatigue curve;
- Appropriate safety factor was introduced in the developed fatigue-based equations;
- Applicability of the procedure is limited by above-ground carbon steel, low alloy steel, or stainless-steel piping systems subjected to limitations for the reversing dynamic loads.

The paper describes the proposed procedure in detail and provides numerical example developed on the basis of the WWER Feedwater line that was chosen as a prototype for evaluation and verification of new seismic criteria.

Comparison of analysis results between novel procedure and conventional approach allows to conclude the benefits of the procedure and the room for the further development.

INTRODUCTION

After the Fukushima Daiichi Accident in 2011 many institutions have undertaken numerous studies focused on increasing the nuclear safety in face of seismic impact. One of such organization was 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.

As part of this activity, the MECOS (**ME**tallic **CO**mponent margins under high **S**eismic loads) program was started in 2015 with intention to preform three parts studies:

1) collection information about current design practices and piping systems seismic tests that could be used for the following benchmarking
2) implementation of the benchmark analyses

3) development of proposals for new, improved seismic design criteria.

The results of parts 1 and 2 were published in 2018 in NEA/CSNI/R(2018) report, while the third part research was elaborated by the group of experts in 2018 – 2021 and corresponding report is planned for publishing in 2022 – 2023, MECOS GE (2021).

The proposed new design criteria formulated by the Group of Experts (GE) are based on the following considerations:

- Conclusions from earthquake experience: study of the extensive post-earthquake experience has shown that welded metallic piping systems exhibit high ruggedness in strong motion earthquakes. All known cases of piping seismic failures indicate that the causes of piping failure in strong motion earthquakes tend to result from a few common causes (large anchor motions, brittle material, non-welded joints, corrosion, failure of supports, interaction).
- Conclusions from seismic tests: numerous seismic tests performed in recent decades have clearly indicated that failure of pressurized piping components and systems occurred by through wall cracking resulting from low-cycle fatigue combined with accumulated plastic strain, designated as fatigue-ratchetting. The magnitude of excitation and number of seismic cycles used in these tests were well above existing seismic design parameters.
- Categorization of Seismic Stresses: in the course of this MECOS study it was shown that seismic stresses depending on the piping natural frequencies and frequency content of the seismic input could be split on primary and secondary parts, Labbé (2020, 2021).
- Primary stress contribution: in the proposed design approach the criteria for the primary part of the seismically induced stresses follow to the existing design practice and utilize conventional form of the Code equation for combination of sustained and occasional loads.
- Fatigue contribution: Those part of the seismic inertial load that classified as secondary, should be used in the seismic fatigue assessment. For this purpose, an equivalent number of cycles should be defined. An appropriate methodology was proposed in the MECOS GE activity. An appropriate procedure of a new design approach incorporating cyclic fatigue analysis, based on the modified Markl's fatigue equation, is presented in this paper. This approach does not require non-linear analysis. It consists of processing the outputs of a conventional linear elastic analysis.
- Seismic design margins: the intent of the new design criteria is to provide approach that is based on the Code equations and represent fatigue damage caused by seismic inertia cyclic loads. However, in contrast with an original Markl's approach with a safety factor equal to 2, the fatigue curve used for seismic fatigue is rebuilt with a reduced safety factor equal to 1.67 providing that piping materials and contribution of non-seismic loads will correspond to imposed limitations.
- Seismically induced ratchet strain: the use of proposed procedure assumes the same limitations that are inherent for the reversing loads defined according to NCD-3655 (b), ASME BPVC (2021). Such limitations should prevent fatigue-ratcheting failure.

ANALYSIS AND DESIGN APPROACH FOR CLASS 2-3 PIPING

Background for Implementation

The proposed procedure is based on the following approaches and assumptions:

1) Imposed limitations for sustained loads ensure exclusion of the ratcheting (Code limitations for reversing loads)
2) Low cycle fatigue is described by Markl' equation for the best-fit fatigue curve:

$$S_{range} = 3378 * N^{-0.2} \tag{1}$$

where S_{range} – stress range, MPa; N – number of cycles.

3) Safety factor for stresses derived from the low cycle part of Markl' fatigue curve sets to 1.67 that corresponds to B31.1 and B31.3 ASME Codes. Considering this safety factor, equation (1) could be re-written as:

$$S_{range} = \left(\frac{3378}{1.67}\right) * N^{-0.2} = 2020 * N^{-0.2} \qquad (2)$$

From the above, the cumulated usage factor for loads pertained to Levels A/B ($U_{A/B}$) and SSE (U_{SSE}) loads may be expressed as:

$$U_{A/B} + U_{SSE} = \frac{N_{A/B}}{\left(\frac{2020}{S_{A/B}}\right)^{5}} + \frac{N_{SSE}}{\left(\frac{2020}{S_{SSE}}\right)^{5}} \le 1 \qquad (3)$$

or:

$$S_{SSE} \le \frac{2020}{N_{SSE}{}^{0.2}} \left(1 - U_{AB}\right)^{0.2} \qquad (4)$$

According to NCD-3611.2, Allowable Stress Range for Expansion Stresses is

$$S_A = f(1.25 S_c + 0.25 S_h) \qquad (5)$$

where $f = 1$, if $N < 7000$;

S_c = basic material allowable stress at minimum (cold) temperature;

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

Considering NCD-3653.2 (c), the effects of pressure, weight, other sustained loads, and thermal expansion shall meet the requirements of equation (11), ASME BPVC (21):

$$S_{TE} \le (S_h + S_A) \qquad (6)$$

Introducing additional limitations for Level A, B Service Loads, namely: $N_{A/B} \le 1000$; S_c and $S_h \le 138$ MPa (this limitation comes from ASME B31.3 for materials with minimum tensile strength of over 480 MPa), one may derive from (6):

$$S_{TE} = S_{A/B} \le (S_h + S_A) = (S_h + 1.25 S_c + 0.25 S_h) = 1.25(S_h + S_c) = 1.25(138 + 138) = 345\ MPa$$

and

$$U_{A/B} = \frac{N_{A/B}}{\left(\frac{2020}{S_{A/B}}\right)^{5}} = \frac{1000}{\left(\frac{2020}{345}\right)^{5}} = \frac{1000}{6910} = 0.145$$

consequently:

$$S_{SSE} \le \frac{2020}{N_{SSE}{}^{0.2}} \left(1 - U_{AB}\right)^{0.2} = \frac{2020}{N_{SSE}{}^{0.2}} \left(1 - 0.145\right)^{0.2} = \frac{2020 * 0.97}{N_{SSE}{}^{0.2}} = \frac{1958}{N_{SSE}{}^{0.2}}$$

Limitation of Applicability

This procedure applies to above-ground carbon steel, low alloy steel, or stainless-steel piping systems subjected to limitations for the reversing dynamic loads

Prevention of Fatigue Failure

The stress range for Service Level D seismic loads shall meet the limit of eq. (7):

$$S_{SD} = i \frac{M_{SD}}{Z} \le \frac{2020}{N_{SD}{}^{0.2}} \left(1 - U_{AB}\right)^{0.2} \qquad (7)$$

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, in.-lb (N*mm)

Z = section modulus of pipe, in.^{3} (mm^3) (NC-3653.3);

N_{SD} = equivalent number of maximum stress cycles for Service Level D seismic loads;

U_{AB} = usage factor from all Service Level A and B loads:

$$U_{AB} = \frac{N_{AB}}{\left(\frac{2020}{S_{AB}}\right)^5} \tag{8}$$

where: N_{AB} = total equivalent number of cycles for all Service Level A and B thermal cycles, calculated in accordance with NCD-3611.2;

S_{AB} = maximum stress range for Service Level A and B thermal cycles, corresponding to N_E in NCD-3611.2, MPa.

If $N_{AB} \leq 1000$ cycles, and if S_c and S_h are below 138 MPa, then equations (7) and (7a) can be simplified and written as:

$$S_{SD} = i\frac{M_{SD}}{Z} \leq \frac{1958}{{N_{SD}}^{0.2}} \tag{9}$$

Prevention of Plastic Instability

The primary stress limits of NCD-3653 eq. (9a) or (9b) shall apply for the primary stress adjusted seismic response spectra.

Adjusted Seismic Response Spectra $S^*(f)$ may be obtained from the given Seismic Response Spectra $S^*(f)$ on the following manner:

– for the frequencies in the range $f \leq f_{peak}$: $S^*(f) = c^*S(f)$, *where* $c^* = (S_{peak}/S_{ZPA})$

– for the frequencies above f_{peak}: $S^*(f) = S_{ZPA}$

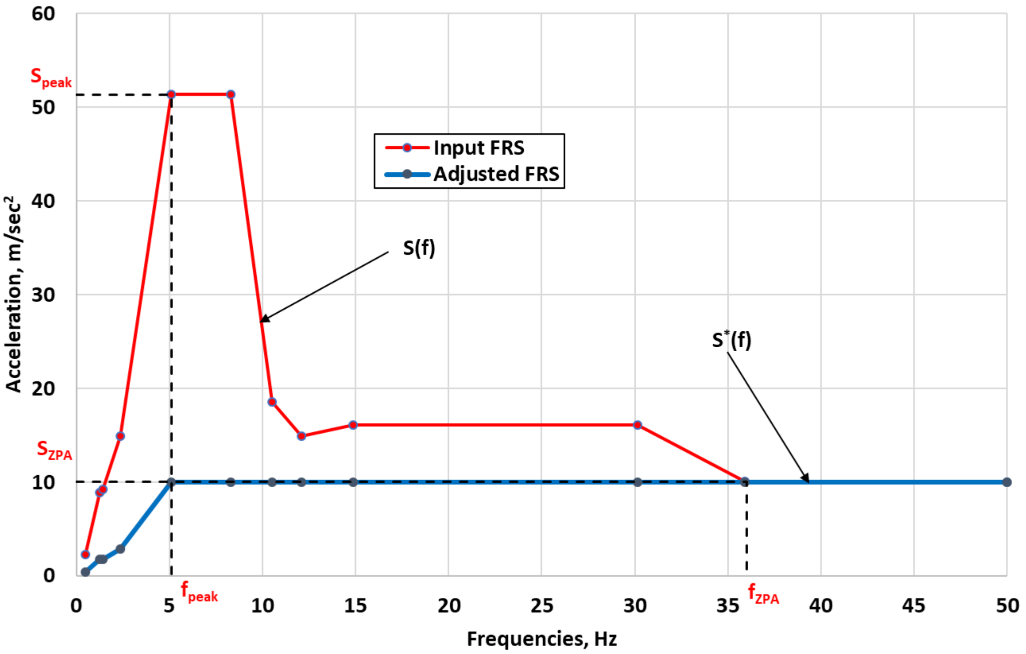


Figure 1. Extraction of the FRS' primary part

NUMERICAL EXAMPLE

In order to validate the proposed criteria, they should be checked for completeness, coherence and resulting margins on examples. A representative line was selected on purpose, which is presented in this section as well as some associated results.

Description of the Line

WWER Feedwater line was chosen as a prototype for evaluation and verification of new seismic criteria. Original seismic design of this line assumed additional horizontal restraining, but for the purposes of this analysis, it was removed from the model. Details of this line are presented in Figure 2 as well as in Table 1. Figure 3 provides data to be used as seismic input: three-component floor response spectra. Figure 4 presents first mode shapes and natural frequencies of the line calculated with use of dPIPE Software.

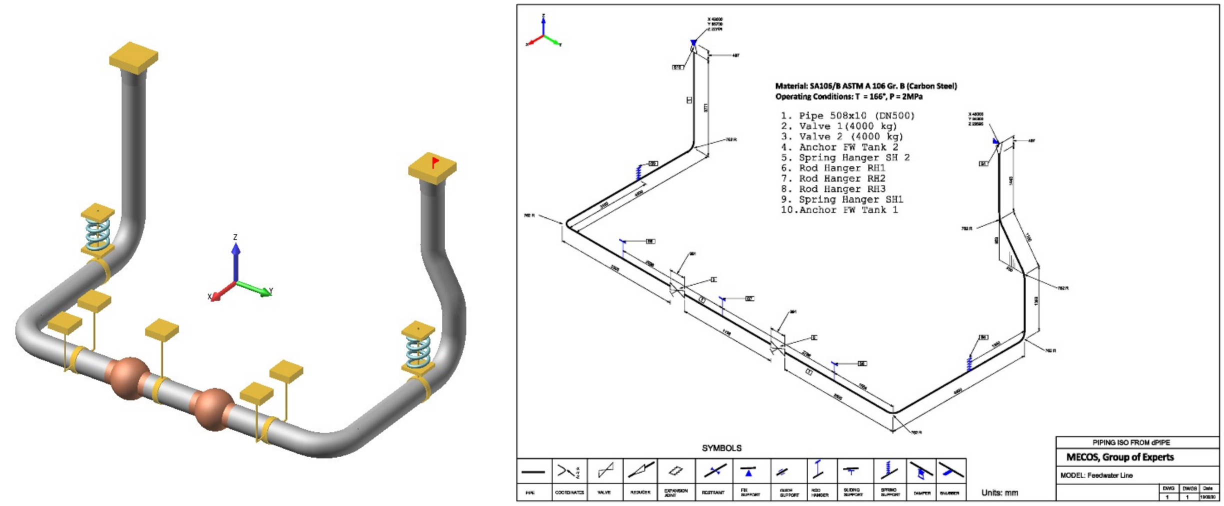
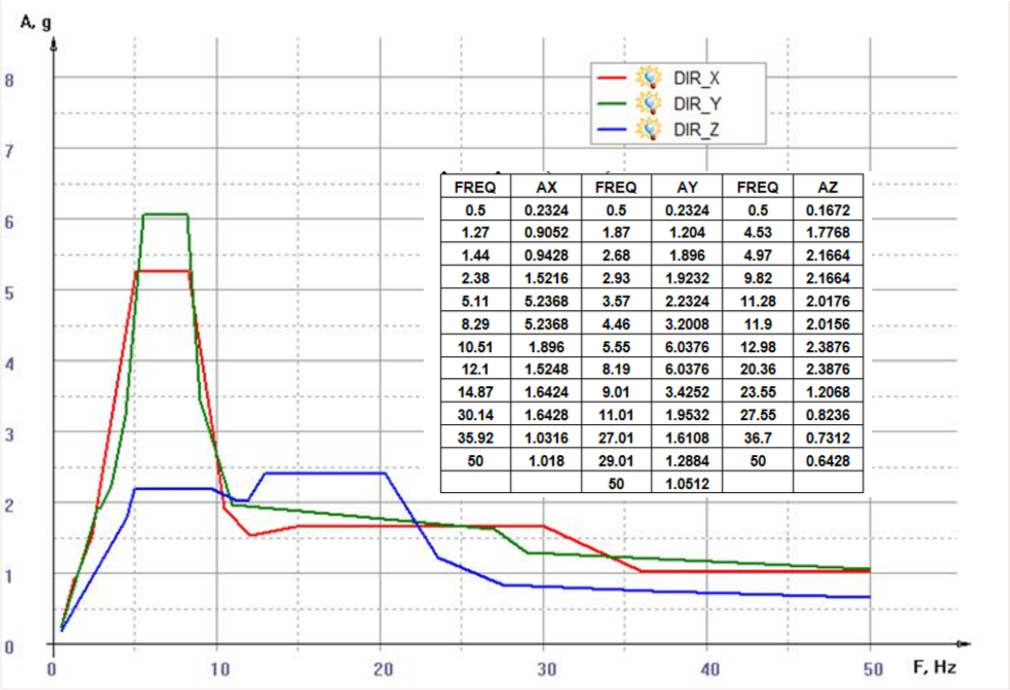


Figure 2. Piping Model General View and Main Dimensions

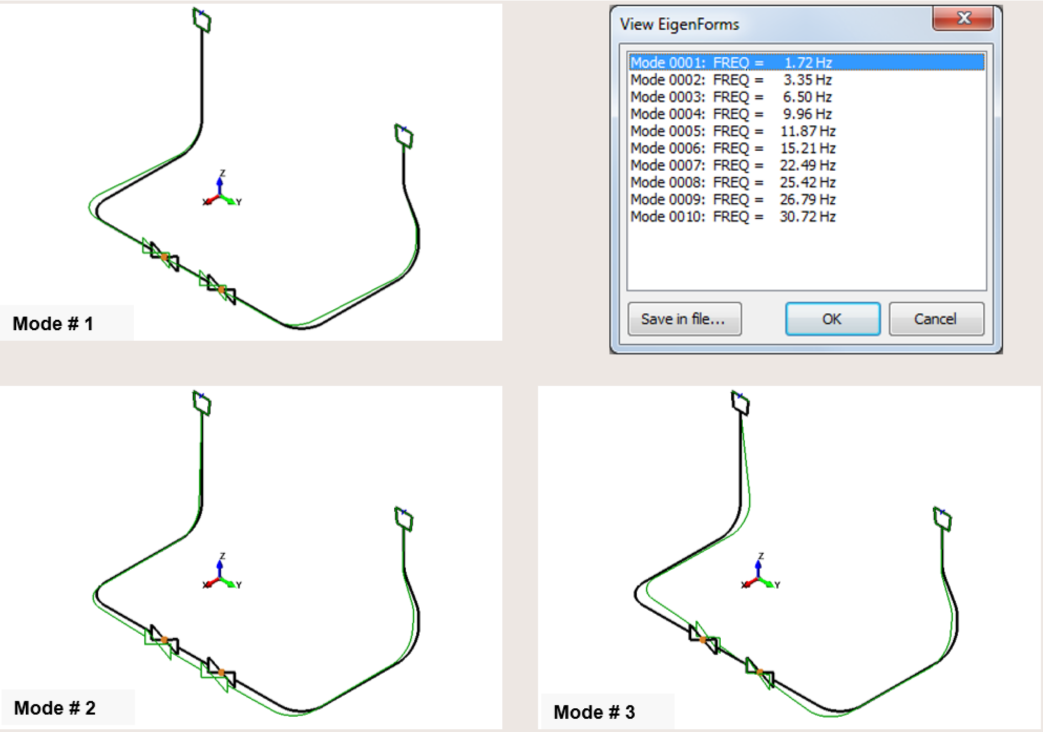


FREQ	AX	FREQ	AY	FREQ	AZ
0.5	0.2324	0.5	0.2324	0.5	0.1672
1.27	0.9052	1.87	1.204	4.53	1.7768
1.44	0.9428	2.68	1.896	4.97	2.1664
2.38	1.5216	2.93	1.9232	9.82	2.1664
5.11	5.2368	3.57	2.2324	11.28	2.0176
8.29	5.2368	4.46	3.2008	11.9	2.0156
10.51	1.896	5.55	6.0376	12.98	2.3876
12.1	1.5248	8.19	6.0376	20.36	2.3876
14.87	1.6424	9.01	3.4252	23.55	1.2068
30.14	1.6428	11.01	1.9532	27.55	0.8236
35.92	1.0316	27.01	1.6108	36.7	0.7312
50	1.018	29.01	1.2884	50	0.6428
		50	1.0512		

Figure 3 Input Floor Response Spectra

Table 1 General Data for the material and pipe's operation conditions

Parameters	Designation	Units	Expression	Value
outside diameter of pipe	D_o	mm	-	508
nominal wall thickness	t_n		-	9.53
inside diameter	D_i		$D_o - 2\ t_n$	488.94
mean radius of pipe	r		$(D_o - t_n)/2$	249.24
nominal bend radius of pipe bend	R		-	762
flexibility characteristic of the bend	h	-	t_nR/r^2	0.117
moment of inertia	I	mm^4	$0.0491(D_o^4 - D_i^4)$	4.64E+08
reducer's cone angle	α	deg	-	15
section modulus of pipe	Z	mm^3	$2*I/D_o$	1.83E+06
operating (hot) temperature	T_{hot}	°	-	166
cold temperature	T_{cold}		-	20
service Level D coincident internal pressure	P	MPa	-	0.77
Material	**Carbon Steel SA106B**			
basic material allowable stress at hot temperature, MPa	S_h	MPa		118
basic material allowable stress at cold temperature, MPa	S_c			118
material yield strength at a temperature consistent with the loading under consideration	S_y			212
Service Level D allowable stresses	S_{allw}^D		$\min(3S_h; 2S_y)$	354



```
Mode 0001:  FREQ =     1.72 Hz
Mode 0002:  FREQ =     3.35 Hz
Mode 0003:  FREQ =     6.50 Hz
Mode 0004:  FREQ =     9.96 Hz
Mode 0005:  FREQ =    11.87 Hz
Mode 0006:  FREQ =    15.21 Hz
Mode 0007:  FREQ =    22.49 Hz
Mode 0008:  FREQ =    25.42 Hz
Mode 0009:  FREQ =    26.79 Hz
Mode 0010:  FREQ =    30.72 Hz
```

Figure 4. First mode shapes and natural frequencies of the piping

Conventional Analysis in Compliance with ASME BPVC NCD-3600

Results of the conventional analyses with use of Response Spectrum Method are provided in the tables and figures below. Three different piping fittings with maximal seismic moments were selected for the further processing, namely: straight pipe between nodes “250” and “260”, bend element between nodes “30” and “40” and reducer between nodes “260” and “270”. Figure 5 shows node numbering and location of the mentioned elements.

Equation (9) for Service Level D, NCD-3655 will be considered further:

$$B_1 \frac{P * D_0}{2t_n} + B_2 \frac{M_A + M_B}{Z} \leq S_{allw}^{D} = \min(3S_h; 2S_y) \qquad (10)$$

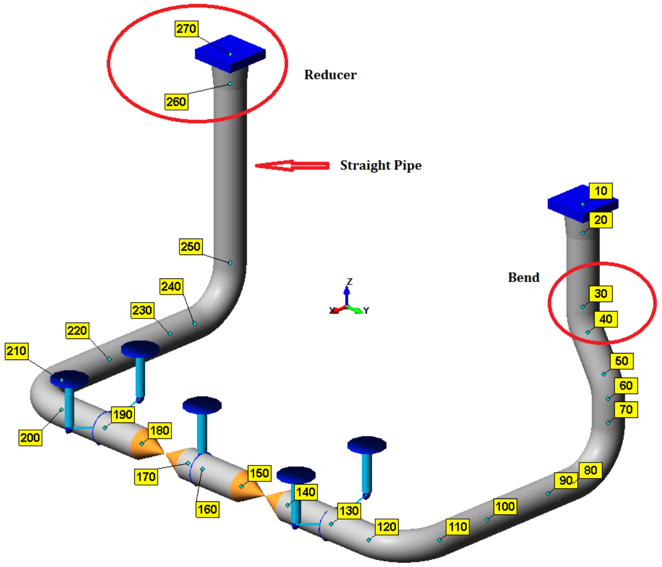


Figure 5 Piping FE model and Nodes numbering

Summary of calculations are given below in the Table 2.

Table 2 Stress Assessment of pipes and fittings (conventional approach)

Parameters	Designation	Units	Expression	Value
primary stress indices				
straight pipe (nodes “250” – “260”)	B_1	-	-	0.5
	B_2		-	1
bend (nodes “30” – “40”)	B_1		$0.4*h-0.1 \leq 0.5$ and ≥ 0	0
	B_2		$1.30/h^{2/3}$	5.44
reducer (nodes “260” – “270”)	B_1		-	0.5
	B_2		-	1
resultant moment loading on cross section due to weight loads				
straight pipe (nodes “250” – “260”)	M_A	N*mm	-	4.026E+05
bend (nodes “30” – “40”)				1.217E+06
reducer (nodes “260” – “270”)				4.026E+05
resultant moment loading on cross section due to seismic loads				
straight pipe (nodes “250” – “260”)		N*mm	-	6.343E+08

Parameters	Designation	Units	Expression	Value
bend (nodes "30" – "40")	M_B			3.445E+08
reducer (nodes "260" – "270")				6.343E+08
Equation (9) resulting stresses				
straight pipe (nodes "250" – "260")	EQ9_D	MPa	$B_1 \frac{P * D_0}{2t_n} + B_2 \frac{M_A + M_B}{Z}$	358
bend (nodes "30" – "40")				1030
reducer (nodes "260" – "270")				358
Demand to capacity ratio				
straight pipe (nodes "250" – "260")	FS_{E9D}	-	EQ9_D/S_{allw}^{D}	1.01
bend (nodes "30" – "40")				2.91
reducer (nodes "260" – "270")				1.01

Seismic Analysis According to the Proposed Code Case. Prevention of Fatigue Failure.

Let's assume that the total equivalent number of cycles for all Service Level A and B thermal cycles is less than 1000. Also considering that $S_h = S_c = 118$ MPa < 140 MPa, then the simplified form of the fatigue's prevention equation (9a) may be used.

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:

$$N_{SD} = \mathrm{n_e} = 0.54\ (\mathrm{N_e^{0.6}} + 5) \qquad (11)$$

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

According to NUREG/CR-5347 the strong motion duration may vary from 6 to 15 seconds. For the considered benchmark line, we may assume T being equal 12 sec. and predominant mode is first eigen mode with natural frequency 1.72 Hz. Then: $\tau = 1/1.72 = 0.58$ sec. The following calculations are summarized in the Table 3.

Table 3 Stress Assessment for Prevention of Fatigue Failure

Parameters	Designation	Units	Expression	Value
duration of the strong motion	T	sec	-	12
eigen period of the predominant mode	τ		-	0.58
seismically induced number of cycles of various amplitudes	$\mathrm{N_e}$		T/τ	20,64
equivalent number of maximum stress cycles for Service Level D seismic loads	N_{SD}	-	$0.54\ (\mathrm{N_e^{0.6}} + 5)$	6.02
allowable stress for seismic fatigue evaluation	S_{allw}^{SF}	MPa	$\frac{1960}{{N_{SD}}^{0.2}}$	1369
section modulus of pipe	Z	mm^3	$2*I/D_o$	1.83E+06
Range of resultant moments due to seismic loads:				
Straight pipe	M_{SD}	N*mm	2*M_B from the Table 6.3.3	1.269E+09
Piping Bend				6.890E+08
Reducer				1.269E+09
stress intensification factor				
Straight pipe	i	-	-	1.00
Piping Bend			$0.9/h^{2/3}$	3.76

Parameters	Designation	Units	Expression	Value
Reducer			$0.5+0.01\alpha(D_2/t_2)^{0.5} \leq 2$	1.60
Straight pipe	S_{SD}	MPa	$i\dfrac{M_{SD}}{Z}$	695
Piping Bend				1419
Reducer				1112
Demand to capacity ratio				
Straight pipe	FS_{SF}	-	$\dfrac{S_{SD}}{S_{allw}^{SF}}$	0.51
Piping Bend				1.04
Reducer				0.81

Seismic Analysis According to the Proposed Code Case. Prevention of Plastic Instability.

For the prevention of plastic instability, the same approach as for the conventional seismic analysis is used, but for the seismic input a reduced FRS is used as it was shown in Figure 1. For the considered case, initial Spectra are reduced as it is shown in in Figure 6 below. The reduction coefficient c^* is calculated as $c^* = S_{peak}/S_{ZPA}$

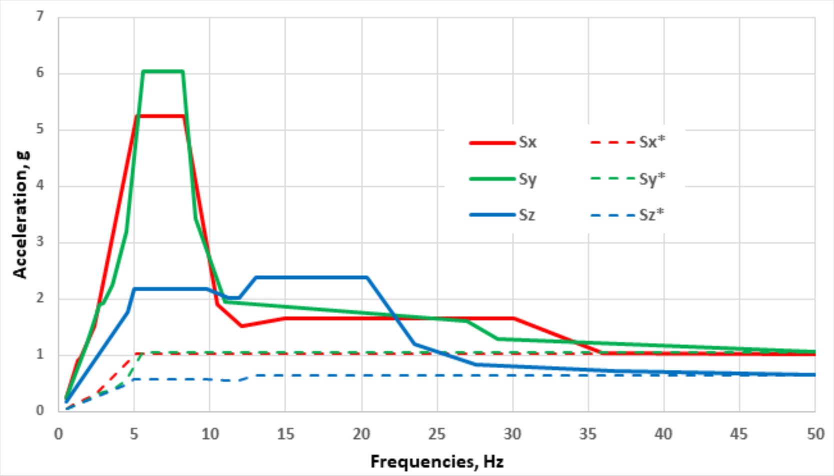


Figure 6 Reduction of the input FRS to the primary part

The table 4 shows the results of the seismic analysis for reduced FRS. Obtained results may be compared with allowable stresses installed depending on the assigned levels of Service Limits (B, C or D).

Table 4 Stress Assessment of pipes and fittings based on the reduced FRS

Parameters	Designation	Units	Expression	Value
Service Level D allowable stresses	S_{allw}^{D}	MPa	$\min(3.0S_h; 2.0S_y)$	354
resultant moment loading on cross section due to primary part of seismic loads				
straight pipe (nodes “250” – “260”)	M_B	N*mm	-	1.235E+08
bend (nodes “30” – “40”)				6.502E+07
reducer (nodes “260” – “270”)				1.235E+08
Equation (9) resulting stresses				
straight pipe (nodes “250” – “260”)	EQ9	MPa		78
bend (nodes “30” – “40”)				197

Parameters	Designation	Units	Expression	Value
reducer (nodes “260” – “270”)			$B_1 \frac{P * D_0}{2t_n} + B_2 \frac{M_A + M_B}{Z}$	78
Demand to capacity ratio				
straight pipe (nodes “250” – “260”)	FS_{E9D}	-	$EQ9/S^D_{allw}$	0.22
bend (nodes “30” – “40”)				0.56
reducer (nodes “260” – “270”)				0.22

CONCLUSION

Proposed seismic design procedure allows more realistically and less conservative reflect piping failure modes under extreme seismic impact and may be recommended for seismic design or requalification of metallic ductile piping classified as Safety Class 2 and 3. Figure 7 demonstrates the benefits of the proposed procedure: demand to capacity ratios for different piping elements and appropriate failure modes.

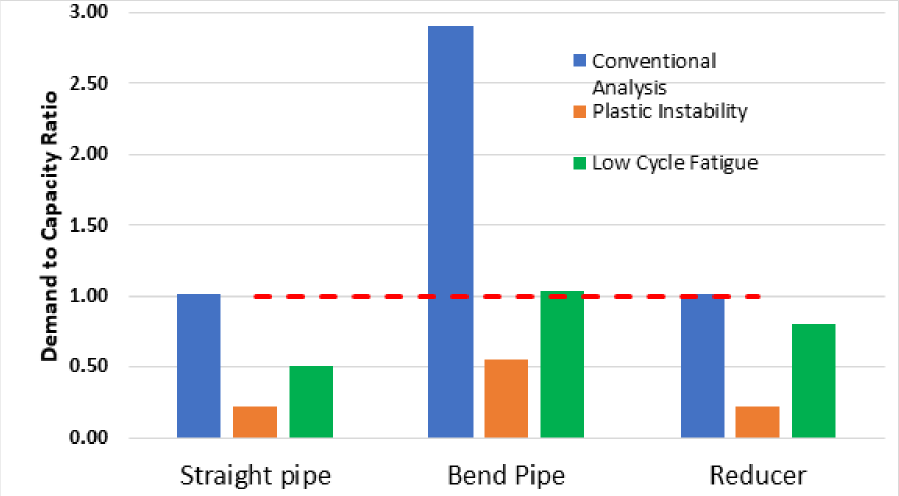


Figure 7 Comparison of margins when applying new approach

REFERENCES

ASME BPVC (2021), SECTION III, *Rules for Construction of Nuclear Facility Components, Division 1 - Subsection NCD, Class 2 and Class 3 Components*

NEA/CSNI (2018), *Final Report of the Project on Metallic Component Margins Under High Seismic Loads (MECOS)*.

MECOS GE (2021), Towards New Approach for Seismic Design of Piping Systems, Final Report, endorsed for publishing by seismic subgroup of Working Group on Integrity and Ageing of Components and Structures (IAGE WG), NUCLEAR ENERGY AGENCY COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

P. Labbé (2020), *On Categorization of Seismic Load as Primary or Secondary for Multi-Modal Piping Systems*, ASME 2020 PVP Conference, PVP2020-21065, July 2020,Minneapolis, USA

P. Labbé (2021), *Modified Response Spectrum Accounting for Seismic Load Categorization as Primary or Secondary in Multi-Modal Piping Systems,* ASME 2021 PVP Conference, PVP2021-61395, July 2021, Virtual, Online