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Division V

KARISMA BENCHMARK STUDY OF THE SAFETY-RELATED NUCLEAR PIPING SYSTEM

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ABSTRACT

KARISMA is an abbreviation of KAshiwazaki-Kariwa Research Initiative for Seismic Margin Assessment. This International Benchmark Study was launched in the framework of the IAEA program on Seismic Safety of Existing Nuclear Power Plants to provide insight for the following topics: understanding the consequences of the Niigataken-chuetsu-oki (NCO) July 2007 earthquake in relation to dynamic response of structures and equipment; calibration of simulation methodologies and examining their ability to represent observed behavior and identify the main parameters influencing the response; evaluation of margins by quantifying what would happen in soil, structure and equipment, when input is increased.

This paper focuses on the results and experience gained by authors during this Benchmark Study with seismic analysis of Residual Heat Removing (RHR) piping. Scope of the Benchmark included different types and stages of analyses: static analysis has been performed for sustained loads, while calculation of the dynamic response was realized by means of response spectrum method (RSM) and Time History Analysis (THA). Moreover, dynamic response was requested to be defined with the use of two different approaches: uniform and independent support motion (ISM).

The paper discuses the peculiarities of different national rules for piping stress analysis, as well as the techniques of the various types of dynamic analysis: RSM and THA for uniform motion and the same approaches when seismic input is defined differently for different piping supports (independent support motion).

INTRODUCTION

KARISMA International Benchmark Study was launched in the framework of the IAEA program on Seismic Safety of Existing Nuclear Power Plants to provide insight for the following topics: understanding the consequences of the NCO July 2007 earthquake in relation to dynamic response of structures and equipment; calibration of simulation methodologies and examining their ability to represent observed behavior and identify the main parameters influencing the response; evaluation of margins by quantifying what happens both in soil, in structure, and for equipment, when input is increased.

The KARISMA exercise consisted from two general parts: Structure and Equipment. Reactor Building (RB) of Unit 7 Kashiwazaki-Kariwa Nuclear Power Plant was an objective of the first part, whereas equipment was represented by Residual Heat Removing (RHR) piping system, Spent Fuel Pool and Pure Water Tank.

It should be noted, that in spite of the high level of accelerations recorded during earthquake (1.25g for horizontal and 0.73g for vertical free field motion), the plant has demonstrated good seismic performance: IAEA inspection has reported only few insignificant failures for safety related Structures Systems and Components (SSC) and some failures for non-seismically designed SSC, IAEA (2007).

For engineering community NCO Earthquake has provided a unique opportunity for benchmarking of the dynamic response of the Reactor Building, taking into account soil-structure interaction and consequent consideration of the dynamic response of the equipment located in Reactor Building. From this perspective RHR piping was an excellent candidate for such kind exercise.

INPUT DATA AND REQUESTED SCOPE OF ANALYSES

Input data for benchmark was provided by Tokyo Electric Power Company (TEPCO) and presented all main characteristics needed to create piping model for static and dynamic analyses:

- description of the RHR piping system, including valves, reducers, nozzles, penetrations and tees: geometry (length, outside diameter, thickness etc.), material description (composition of the material, Young's modulus), insulation weights, etc.;
- description of supporting structures: geometry, directions of restraints, spring constants (translation and rotation) at supports and penetration points;
- design condition of the RHR piping system: maximum design pressure, maximum design temperature and operating temperature.

Several stages of the Benchmark were defined. During initial two phases it was requested to perform conventional static analysis under sustained loads and also dynamic response spectrum and time history analyses. Input signals for seismic excitation were defined as acceleration time histories derived from the simulation's records provided by TEPCO.

In Phase III seismic multi-support analyses were required. Input signals at four points for three directions were provided in terms of accelerations TH. At this time signals were obtained from the structural dynamic analysis of RB performed by other Benchmark participants.

RHR PIPING MODEL

A finite element model of RHR piping was developed in computer program dPIPE (2007). The analysis model representing the piping and other in-line components consists of a sequence of nodes connected by straight and curved pipe elements (circular uniaxial elements with tension, compression, torsion, and bending capabilities, which are able to incorporate flexibility and stress intensification factors in the formulation). Piping restraints and supports were idealized as springs with appropriate stiffness values for the restrained degrees of freedom. Spring hangers were taken into account as a pre-tensioned elements, carrying the piping weight in the hot state (since no specific data for springs was provided, spring's characteristics were selected from the LISEGA catalogue). Both: vertical spring's stiffness as well as horizontal due to swinging effect were taken into account for static and dynamic analyses. For static load case an additional consideration was made for the lateral spring hanger's loads due to pendulum effect. For static analysis piping weight (including the weight of material, medium and insulation) was distributed along the model. For dynamic analysis concentrated masses were lumped in nodes. At the same time size of FE mesh was defined by the requirements of an accurate modeling of dynamic behavior of the system over the frequency range significant for seismic event. The following formula was used to determine the spacing between two successive mass points:

$$L_{\max} \leq \frac{1}{2}\sqrt{\frac{\pi}{2 * FMAX}} * \sqrt[4]{\frac{E * I * g}{w}} \tag{1}$$

where: *FMAX* - cut-of-frequency, Hz; E - Young Modulus, N/mm^2, I - moment of inertia, mm^4, g - gravity constant, mm/sec^2, w - total piping weight per length, N/mm

Figure 1 shows dPIPE analysis model.

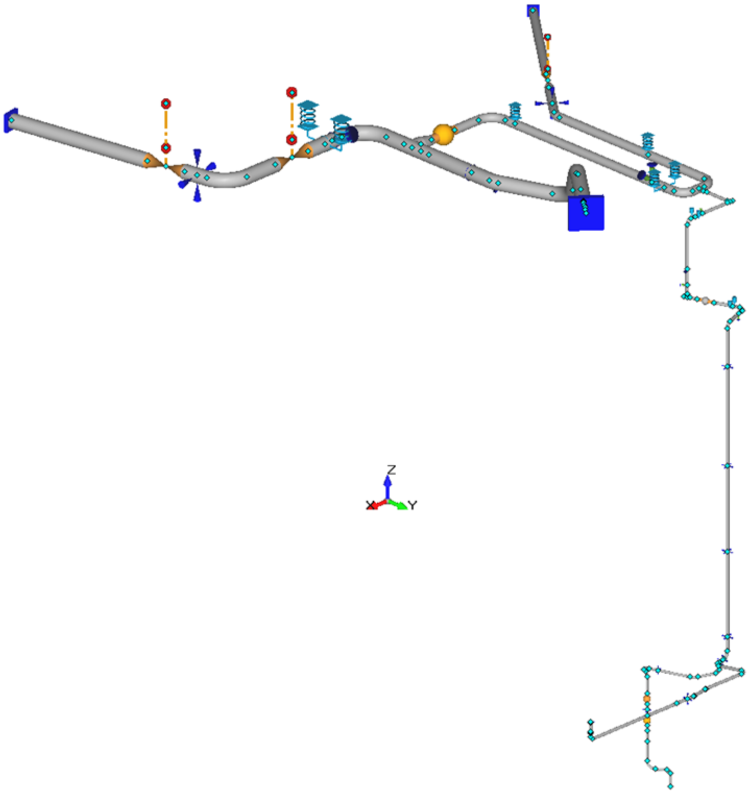


Figure 1. RHR piping dPIPE analysis model.

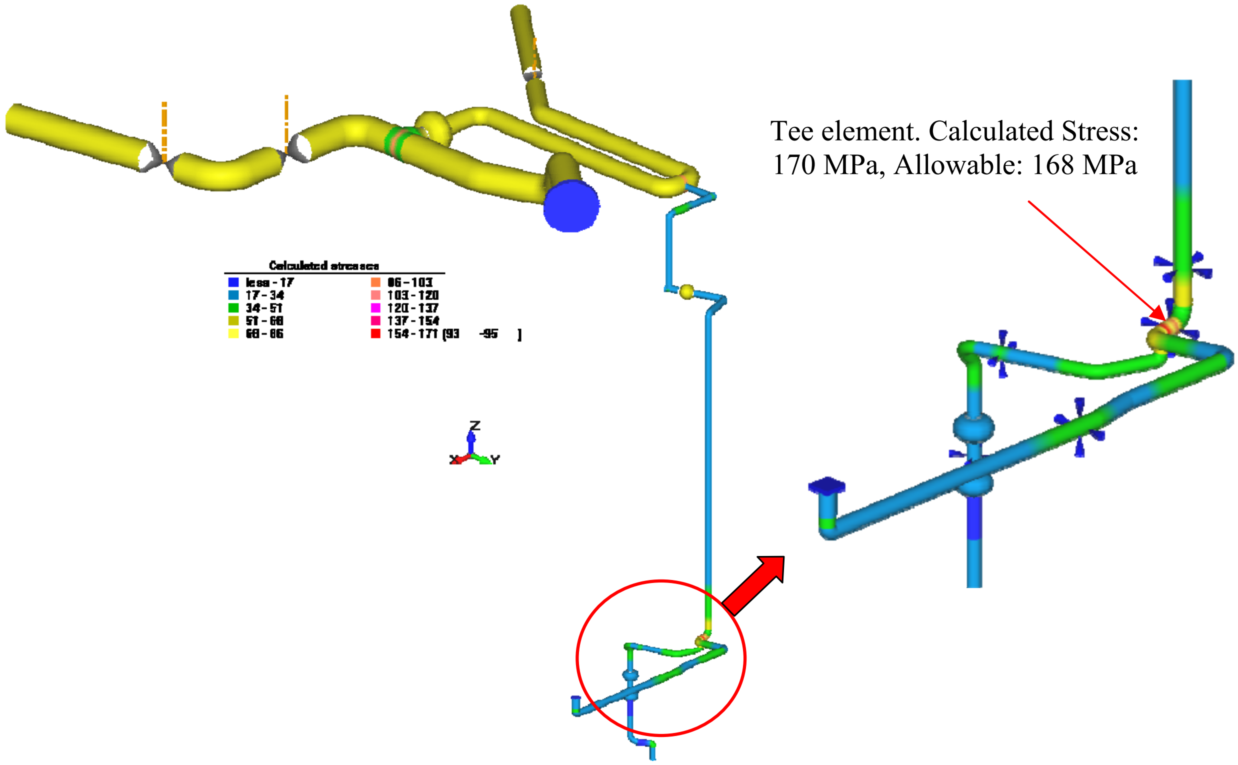
PIPING STRESS ANALYSIS WITH USE OF DIFFERENT NATIONAL NORMS

One of the requirements of the benchmark specification was to use a national norms for assessment of RHR piping. In this regard the first unexpected result appeared in the static analysis: according to Russian Code PNAE (1989) stress calculated in TEE element has exceeded an allowable value, Figure 2. To understand this phenomena a limited comparison of piping strength requirements was undertaken: PNAE vs. ASME NB-3600.

Table 1 shows details for stress calculation in the most loaded RHR piping element. It's evident that highlighted difference came from both sources: calculated stresses as well as allowable values. While the nominal allowable stresses for carbon steel according to both standards are identical (Table 2), the values for the allowable stresses consistent with Design Conditions are more conservative in case of PNAE: 1.3 vs. 1.5. At the same time the value of calculated stress is governed by stress index for the welded TEE element: PNAE gives 2.54 while ASME leads to 1.16.

But the most significant variations exist in the provisions for seismic design. Table 3 shows differences in the code defined values for allowable stresses and recommended damping that should be taken for seismic design. It should be noted that only consideration of these two factors (allowable stresses and damping) leads at least to double conservatism of PNAE vs. ASME.

For a numerical quantification of the effects discussed above a comparative analysis of RHR piping was performed with variation of parameters that have most significant influence on dynamic response. Table 5 presents a matrix for variation of parameters while figure 3 demonstrates results in terms of demand to capacity ratio.



Tee element. Calculated Stress: 170 MPa, Allowable: 168 MPa

Figure 2. Static Analysis (Results for PNAE Assessment)

Table 1: Details for stress calculation, TEE element, Static Analysis: pressure and weight

	PNAE	ASME BPVC NB-3600
1	Stress index for Primary Load: Kи(s) = 2.54	Primary Stress Indices: B2b = 1, B2r = 1.16 (Butt Welding Tee per ANSI B16.9 or MSS SP)
2	Calculated stresses: 170 MPa	Calculated stresses: 112 MPa
3	Allowable Stress: 168 MPa	Allowable Stress: 193 MPa

Table 2: Differences between PNAE and ASME Codes: Allowable Nominal Stresses
(for pipes working below the creep range)

Code	Symbol	Allowable Nominal Stress (Design Stress Intensity)
PNAE (for all types of pipes)	[σ]	for all steels: $\min\left\{R_m^T/2,6; R_{p0.2}^T/1,5\right\}$
ASME (Wrought or cast pipes)	S_m	ferrous steels: $\min\left\{S_T/3; 1,1S_T^T/3; S_Y^T/1,5\right\}$ austenitic steels: $\min\left\{S_T/3; 1,1S_T^T/3; S_Y/1,5; 0,9S_Y^T\right\}$
ASME (Welded pipes)		ferrous steels: $\min\left\{\frac{0,85}{3}S_T; \frac{1,1\times 0,85}{3}S_T^T; \frac{0,85}{1,5}S_Y^T\right\}$ austenitic steels: $\min\left\{\frac{0,85}{3}S_T; \frac{1,1\times 0,85}{3}S_T^T; \frac{0,85}{1,5}S_Y; 0,9\times 0,85S_Y^T\right\}$

Table 3: Differences between PNAE and ASME Codes: Allowable Stresses and damping

Parameter	Code	Document	Article N	Value
Allowable stresses	PNAE	PNAE G-7-002-86 NP-031-01 (2001)	5.11.2.11	1,8[σ]
	ASME	ASME BPVC Section II, Part D	NB-3656(b)	$\min\left\{3S_m; 2S_Y^T\right\}$
Damping	PNAE	PNAE G-7-002-86	5.11.2.4	0.02
	ASME	ASME BPVC, Appendix N	N-1230	0.05

Table 4: Matrix for Parametric Study

Parameters	Variants of Analysis						
	V1	V2	V3	V4	V5	V6	V7
Code	PNAE	PNAE	PNAE	PNAE	ASME	ASME	ASME
Hanger Stiffness	YES	YES	YES	NO	YES	YES	NO
Swing	YES	YES	YES	NO	YES	YES	NO
High Frequency	YES	YES	NO	YES	YES	YES	YES
Bend Flexibility	PNAE	PNAE	PNAE	PNAE	ASME NB	Code Case	ASME NB
Modal Combination	SRSS	CQC	SRSS	SRSS	SRSS	SRSS	SRSS

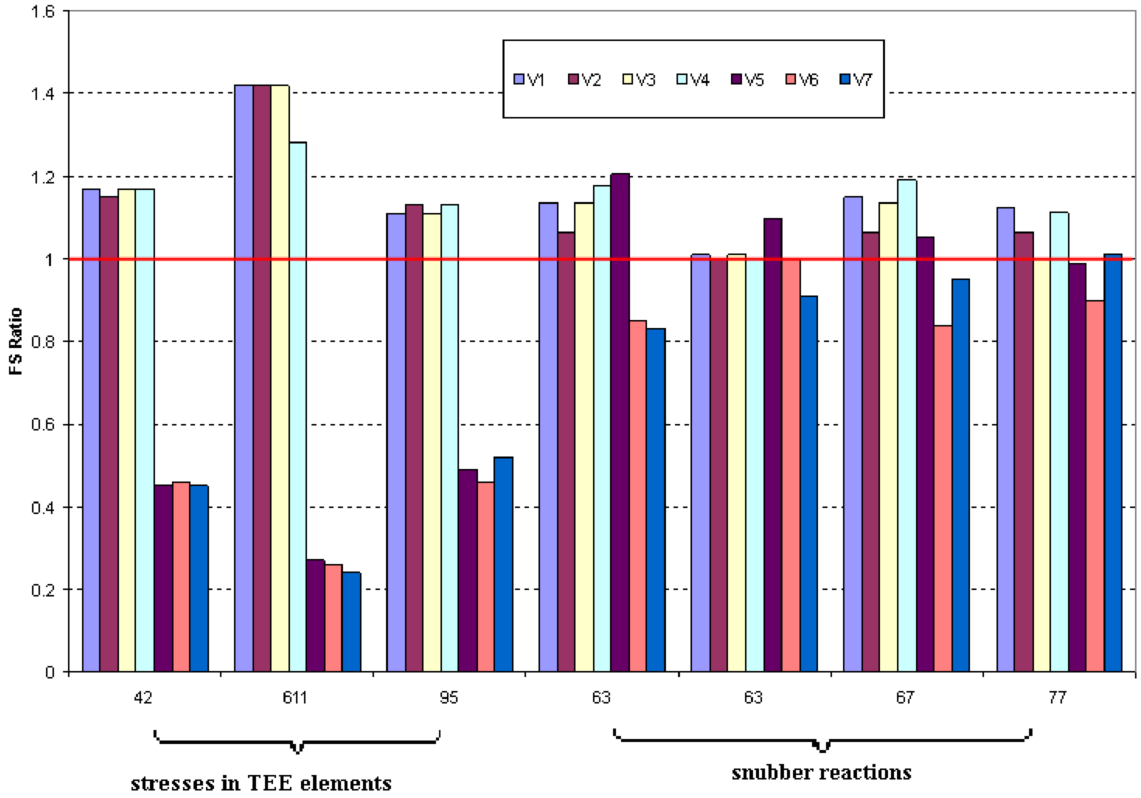


Figure 3. Results of Parametric Study (demand to capacity ratio)

INDEPENDENT SUPPORT MOTION ANALYSIS

Phase 3 of the benchmark was focused on the multi-support excitation analysis. For this stage seismic input was defined separately for four seismic groups associated with locations of RHR piping supports, Figure 4. Different types of analyses were requested: Response Spectrum Method Analysis and Time History Analysis. Computational technique for ISM RSM is well developed and realized in many Software Codes.

At the same time, multi-support THA is rather infrequent approach and there are no many samples of its implementation for piping design and analysis. Generally, a need for THA appears when the piping system contains nonlinearities that could not be correctly addressed in the frame of linear Response Spectrum Method. However, piping systems in nuclear power plants are highly complex nonlinear structures with a number of sources for non-linearity: ductile piping even under normal operation works far beyond an elastic range. Moreover, practically each type of the pipe support or seismic restraint exhibits more or less non-linear behavior under static or dynamic loads. Consideration of these effects under static loads is a normal design practice: engineer during design stage should handle with such effects as support's friction, one-way action, pendulum effect for spring and rod hangers, etc. Unlike that, seismic analysis on the design stage in the most cases is performed with use of RSM which utilizes only linear characteristics of supports. Such approach is quite justified, considering a safety factor inherent for the design. However, under severe earthquake loadings beyond design basis some type of nonlinear analysis is necessary to accurately predict the piping responses and seismic margins. Table 5 summarizes types and sources of nonlinearities existed in nuclear piping.

Table 5: Types and sources of local nonlinearities in piping systems

Nonlinear Effect	Static loads	Dynamic Loads	Type of Piping Supports
Friction	(1)	usually represented by the overall damping ratio or could be modeled explicitly in the frame of Time History Analysis (THA)	sliding supports, also some types of the constant spring hangers exhibit hysteresis friction in the mechanical parts
Gaps		could be represented with use of linearization technique in the frame of RSM (iteration procedure would be utilized as well), or could be modeled explicitly in the frame of THA	one-way static supports, rod hangers, some types of snubbers
Pendulum or Swing effects		could be included in dynamic analysis as equivalent lateral stiffness, or addressed explicitly in the frame of THA	variable and constant spring hangers, rod hangers
Large Displacements		could be addressed explicitly in the frame of THA	sway braces
local damping and energy dissipation	-	in the frame of RSM only approximate solution is available, however this effect could be represented explicitly in the frame of THA.	viscous dampers, energy absorbers

(1) practically all non-linear effects could be addressed in static analysis explicitly with use of iteration technique.

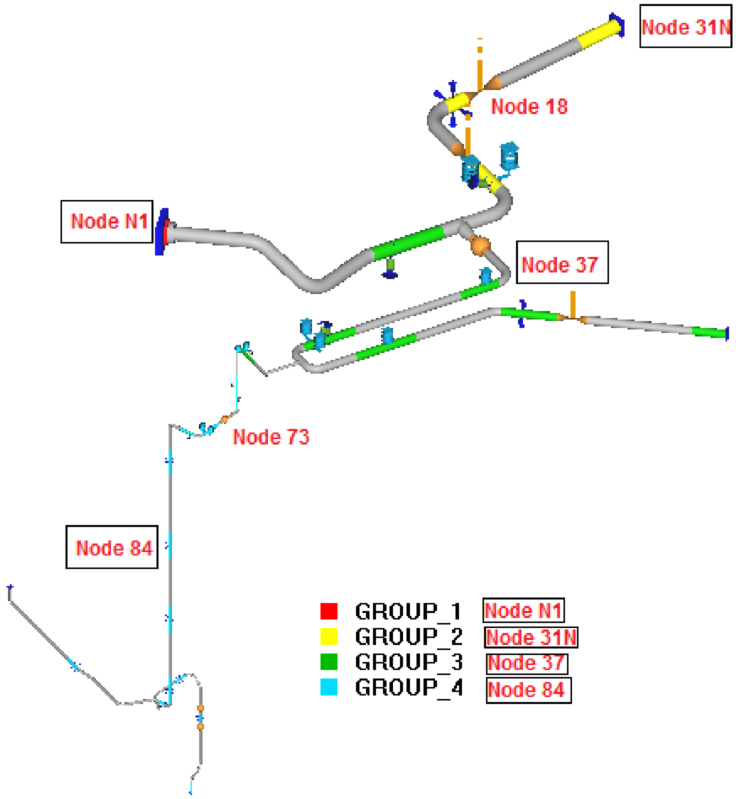


Figure 4. Support's Grouping for seismic input

In the frame of the ISM analysis a total piping response can be conditionally divided into two parts: inertial response and pseudo-static response due to differential movements of piping supports. Necessity of such separation comes from the different nature of these seismic loads: inertial loads are traditionally treated as a primary loads and thus they are combined with other mechanical loads (piping weight and pressure). Seismic Anchor Motion (SAM) loads are deformation-based and like thermal expansion loads they are considered as secondary.

The problem of seismic loads separation within RSM is solved in terms of input data, as well as by appropriate solution algorithm. Input seismic excitation is defined as sets of Floor Response Spectra (FRS), while maximal relative displacements for the piping supports are defined separately. Next, the certain rules for load's combination are applied within RSM to get total piping response:

- for Inertia or Dynamic Components:
    (1) Support's Group Responses for each direction are combined by absolute sum method;
    (2) Modal and directional responses are combined by the SRSS method without considering closely spaced frequencies;
- for the Pseudostatic Components:
    (1) for each group, the maximum absolute response is calculated for each input direction;
    (2) Group Responses are then combined by the absolute sum rule;
    (3) Combination of directional responses are carried out by the SRSS rule;
- Total Response is SRSS combination of Dynamic and pseudostatic responses.

In the case of ISM THA the problem looks more complex. To implement THA instead of conventional FRS a compatible set of accelerograms is needed. Typically these time histories are developed on the basis of the smoothed and broadened design FRS. Even if these signals match very well a target FRS, there are still left several significant issues specific for ISM THA:

- resulting displacements derived from the artificial accelerogram could be unphysical due to distortions and shifts of the signal's reference baseline;
- even a minor errors between calculated and target FRS in the low-frequency range could lead to the large response displacements.

These problems should be carefully addressed during developing of accelerograms, either being taken into account in ISM THA algorithm.

In the frame of KARISMA exercise this problem was solved by means of the "Large Mass" method (LMM) in conjunction with a modal transient procedure. To realize this approach the following steps were undertaken:

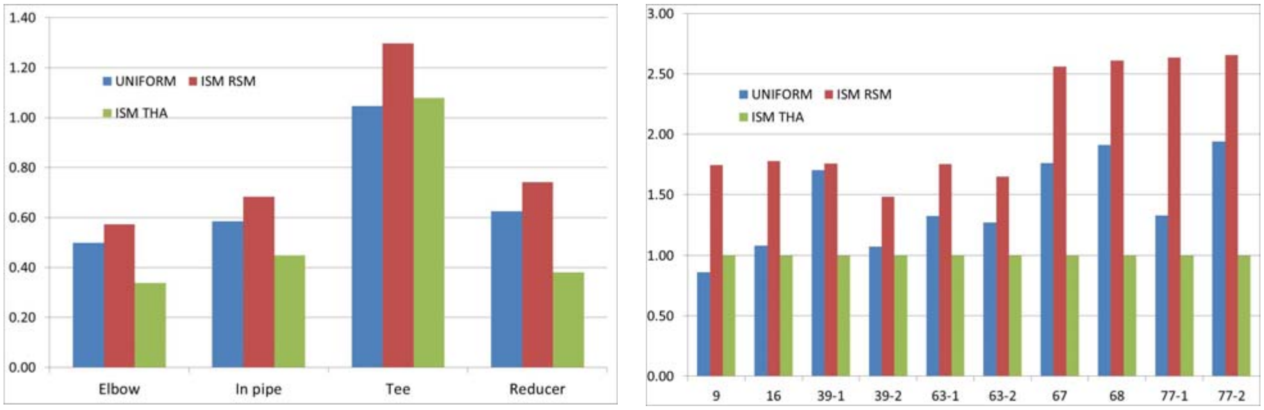
1. Conventional piping model was assembled to be suitable for ISM RSM analysis. Each piping support was assigned to one of the *N* predefined seismic groups.
2. *3xN* independent 1 DOF subsystems (*N* - number of seismic groups, *3* - number of spatial directions) were introduced in the model. Each such subsystem was constituted from the point large mass connected to the base through the spring. Value of the spring stiffness was selected to provide a natural frequency far below the first natural frequency of the considered piping. The point masses are several orders of magnitude larger than the total mass of piping.
3. All piping supports were reconnected to the appropriate point masses through the rigid links.
4. A transient dynamic forces numerically equal to the given acceleration time histories were applied at each mass point for each direction. At the same time magnitudes of these forces were scaled to reproduce given acceleration as response of the each mass point: F(t) = M*A(t)
5. Modal decomposition was performed for the modified model. As result there were obtained *3*N* mode shapes that solely correspond to the rigid body motion and *P* mode shapes related to unmodified piping model.

Now the total piping response R_{3*N+P} could be decomposed on two parts: inertial R_P and pseudostatic part R_{3*N}: $R_{3*N+P} = R_{3*N} + R_P$. Such approach allows to separate an inertial and pseudostatic response. In case of nonlinearities these procedure could be implemented in the following sequence:

1) calculate total response R_{3*N+P}, taking into account all nonlinearities;
2) calculate pseudostatic response R_{3*N}, also taking into account nonlinearities: it's identical to the displacement-based time history analysis of the weightless piping;
3) calculate an inertial response as $R_{3*N+P} - R_{3*N}$

Other benefit of this procedure: if the input accelerograms match well target FRS, but produce an unacceptable displacements, a pseudostatic or SAM part of seismic input can be defined independently from the accelerograms.

Figure 5 shows a comparative results: ISM THA vs. ISM RSM and Uniform RSM.



Stresses in piping elements (demand to capacity)

Snubbers Loads (loads are normalized)

Figure 5. Comparison of results for different dynamic methods

NOMENCLATURE

$[\sigma]$	- nominal allowable stress (PNAE)
S_m	- Design Stress Intensity (ASME)
R_m^T	- minimal tensile strength at temperature (PNAE)
$R_{p0.2}^T$	- minimal yield stress at temperature (PNAE)
S_T	- tensile strength (ASME)
S_Y	- yield strength (ASME)

CONCLUSIONS

This paper summarizes activities undertaken by CKTI-Vibroseism in the frame of KARISMA Benchmark study relating to the seismic analysis of the typical nuclear piping. Performed analyses have allowed to highlight several important topics inherent to the piping seismic analysis and design: differences in national regulations and modeling technique for the dynamic analysis. It's expected that IAEA will publish TECDOC with Review of Seismic Evaluation Methodologies for NPPs based on KARISMA Benchmark Results. Such publication certainly will be very helpful for the engineering community.

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