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Seismic Assessment of a RHR Piping System

Carsten Block[1], Fritz-Otto Henkel[2], and Willi Messerer[3]

[1] Head Nuclear Technology, WOELFEL Beratende Ingenieure GmbH + Co. KG, Hoechberg, Germany (block@woelfel.de)
[2] Managing Director, WOELFEL Beratende Ingenieure GmbH + Co. KG, Hoechberg, Germany
[3] Project Manager, WOELFEL Beratende Ingenieure GmbH + Co. KG, Hoechberg, Germany

ABSTRACT

The main objective of this paper is to evaluate the seismic behavior of the Residual Heat Removal (RHR) piping system of the Kashiwazaki-Kariwa Nuclear Power Station for the 2007 Niigataken-chuetsu-oki earthquake. National rules and regulations are considered and different analysis methods including multi-support excitation analysis are investigated.

The analyses performed for the RHR piping system show that no substantial damage had to be expected for the occurred earthquake according to German national rules. In addition, the conservatism of the different analysis methods is shown.

INTRODUCTION

On 16 July 2007, a strong earthquake, the Niigataken-chuetsu-oki earthquake (NCOE), affected the Tokyo Electric Power Company (TEPCO) Kashiwazaki-Kariwa Nuclear Power Station (NPS), the biggest nuclear power plant in the world, located at about 16 km away from the epicenter. The large amount of observations and data collected led to the organization of the Kashiwazaki-Kariwa Research Initiative for Seismic Margin Assessment (KARISMA).

The earthquake was accompanied by very high peak ground accelerations of up to 0.68 g at the foundation, reaching the 1.1 to 3.6-fold design values of the NPS. The 3 blocks which were in operation and another block in the start-up phase were shut down. During and after the earthquake all reactors were in safe condition.

In view of the large number of data measured inside and outside the power plant – acceleration time histories in/at the ground, in the buildings and at plant components – the idea matured to evaluate within the scope of an IAEA-program the seismic behavior of the plant with consideration of national rules and regulations, i.e. the seismic safety of an existing plant on the basis of the measured data.

The recorded measurement data and the “reanalysis” thus make it possible to investigate the real behavior of the plant during earthquake, its design and structural changes. The damage or non-damage is evaluated in relation to the ground motions which were recorded by the seismic instrumentation and the occurrence of which could thus be confirmed, and to the accelerations measured in the plant itself.

The following paper summarizes the work done by the authors during the KARISMA benchmark Subtask 2.1. Subject of the investigations is the Residual Heat Removal (RHR) piping system which is responsible for the heat removal with boiling water reactor shut down – i.e. it must be available during and after the earthquake. Different analysis methods including multi-support excitation analysis are investigated. The investigations of the RHR piping system are carried out on the basis of the input documents made available by TEPCO.

NUMERICAL MODEL

For the analysis of the RHR piping a spatial beam model with equivalent beams with bending and shear elasticity is generated, taking into account the torsional impact from eccentricities between the center of mass and the center of stiffness. The analyses are carried out with the ROHR2 / R2STOSS software program. The numerical model of the RHR piping is shown in figure 1.

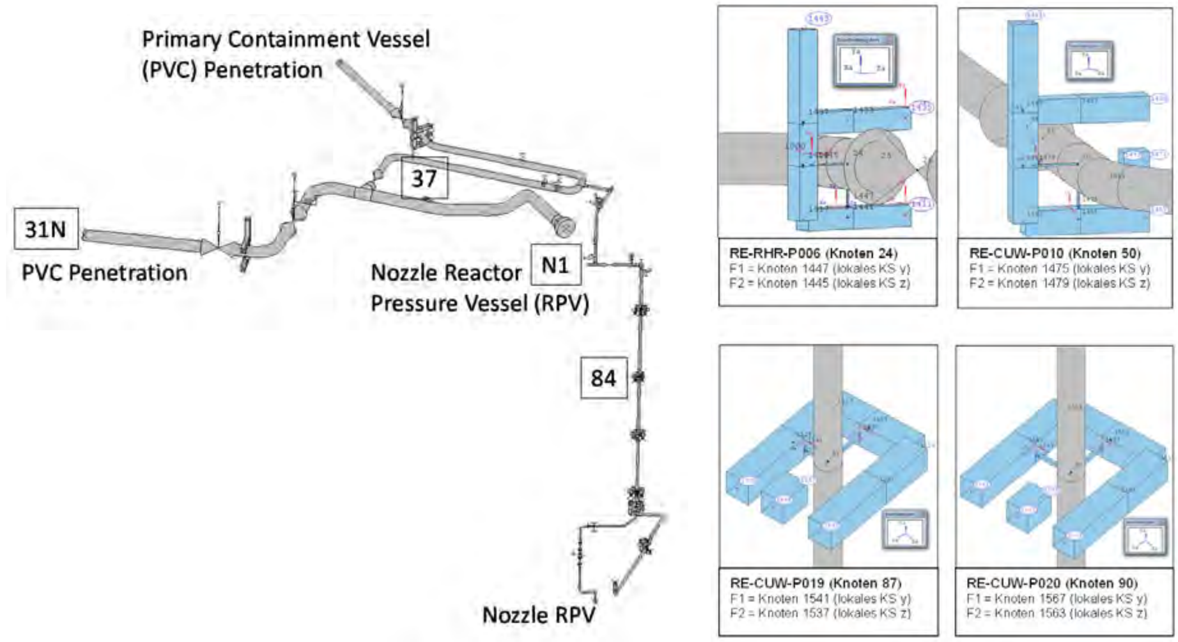


Figure 1. Numerical model of RHR piping

The material characteristics of the steel piping are taken from the input documents. Main parts of the piping are made of St 44.4 with minimum yield strength of 265 MPa and minimum tensile strength of 420 MPa at room temperature.

Anchors and mechanical snubbers are modeled with predefined stiffnesses. Some of the pipe supports are modeled with the corresponding steel support structure made of S235JR material as exemplarily shown in figure 1.

Gaps and clearances are not included in the calculation. Friction is considered in the time-history analyses only.

The analysis is performed according to the German nuclear code KTA 3211.2 code class A2/A3 for service level D which covers loading from earthquake. Due to a lack of detailed information in the beginning of the project service level D is chosen, which permits gross general deformations which may necessitate repair or replacement of the respective component. For the verification of stresses only primary stresses shall be taken into account.

The equivalent stress from primary stresses for service level D according to KTA 3211.2 code class A2/A3 is determined to:

$$S_{II} = B_1 \frac{d_a p_{max}}{2 \cdot s_c} + B_2 \frac{M_{iI} + M_{iII}}{W} \leq 3.0S \leq 2.0R_{p0.2T} \qquad (1)$$

or for components without B1, B2 specification to

$$S_{II} = \frac{d_a \cdot p_{max}}{4 \cdot s_c} + 0.75 \cdot i \frac{M_{iI} + M_{iII}}{W} \leq 2.4S \qquad (2)$$

with the following symbols:

S_{II} equivalent stress from primary stresses
B_1, B_2 stress factors according to KTA 3211.2
d_a outer diameter of pipe
s_c wall thickness minus corrosion allowance
W section modulus
p_{max} maximum operating pressure
The maximum operating pressure is p = 86.2 bar except for a small part of a DN50 pipe next to the RPV with p = 2.9 bar.
M_{iI} resultant moment due to dead weight
M_{iII} resultant moment due to occasional load earthquake
I stress intensification factors according to KTA 3211.2
S stress comparison value according to KTA 3211.2 ($S = R_{p0.2RT} / 1.6$)

The maximum allowable stress is 3.0 S, respectively 2.4 S, and shall not exceed 2 x yield strength $R_{p0.2T}$. For the piping material St 44.4 this leads to a maximum allowable stress of 249.4 MPa for service level D. Normal operational conditions are not in the scope of this paper.

For the earthquake loads the following analyses are carried out:

A1: Response Spectrum Modal Analysis (RSMA) with enveloped raw spectra

- The raw spectra used are calculated from measured acceleration time-histories and time-histories derived from the analysis of the reactor building (figure 2). The analysis of the reactor building is shown in a parallel paper, Block et al. (2013). The spectra are calculated for a damping of D = 2 %.
- The spectra are applied as enveloping spectra at all supporting points of the piping system. Figure 3 shows the spectra for the four locations and the enveloped spectrum exemplarily for the horizontal x-direction.
- The spectral peaks are not extended; the calculated spectra are not smoothed.
- For the modal combination the complete quadratic combination (CQC) rule is applied.
- The seismic excitation acts simultaneously in all three directions. The overall response is determined from the single directions (x, y, z) by a square-root-of-sum-of-squares (SRSS) superposition.
- The rest modes are considered in the analysis and are superposed SRSS.

A2: RSMA with enveloped and smoothed spectra

- The spectral peaks of the enveloping spectra generated for analysis A1 are extended and the raw spectra are smoothed – according to KTA 2201 new. The spectra thus determined are applied at all supporting points of the piping system. Figure 3 shows the enveloped and smoothed spectrum for the horizontal x-direction.
- Beside the spectra the same approach as for analysis A1 is chosen.

A3: RSMA with multi-support excitation with raw spectra

- The spectra used are calculated from the given acceleration time-histories (figure 2) at four different locations with a damping of D = 2 %.
- Supports are grouped to areas with the same excitation level.
- The spectra determined for the four groups are applied “acting out-of-phase” at the respective supporting points of the piping systems.
- The portions from the different excitations (“out-of-phase”) are superimposed with SRSS.
- Apart from the above points the same approach as for analysis A1 is chosen.

A4: Time-history analysis with multi-support excitation

- The analysis is carried out applying the direct integration method.
- The given time-histories for the four different excitation levels (figure 2) are applied at the respective supporting points assigned to the four groups.
- A Rayleigh damping with parameters α = 1.0 and β = 0.000123 is applied leading to a damping curve with D ≈ 4 % at 2 Hz and D ≈ 2 % at 50 Hz. Thus the substantial frequency range between 5 and 50 Hz is subject to a (conservative) damping D ≤ 2 %.
- The damping for the direct integration is selected in compliance with CODE CASE N-411-1. Accordingly, in the analysis the damping is split in global structural damping and discrete individual dampings (friction supports). The impact of the damping effect of the friction supports is not taken into account.

Beside the analyses described above static and modal analyses are performed for checking purposes.

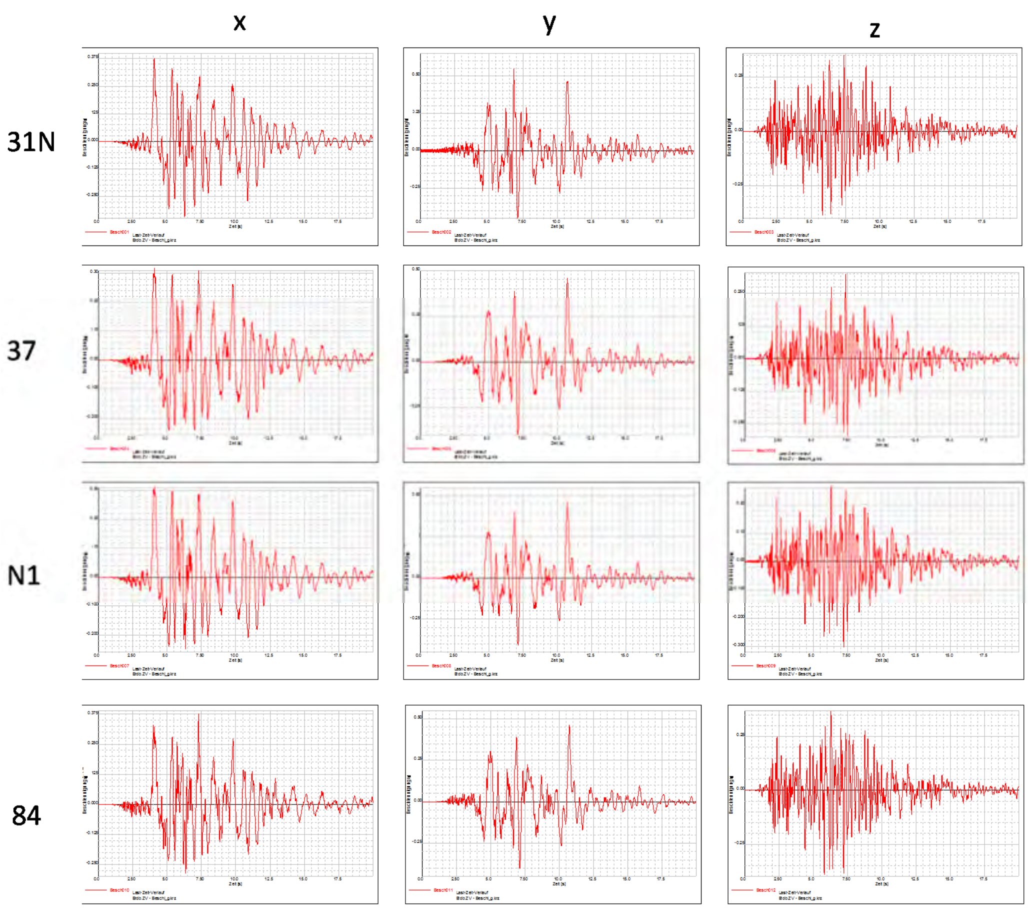


Figure 2. Acceleration time histories at four locations derived from reactor building analysis

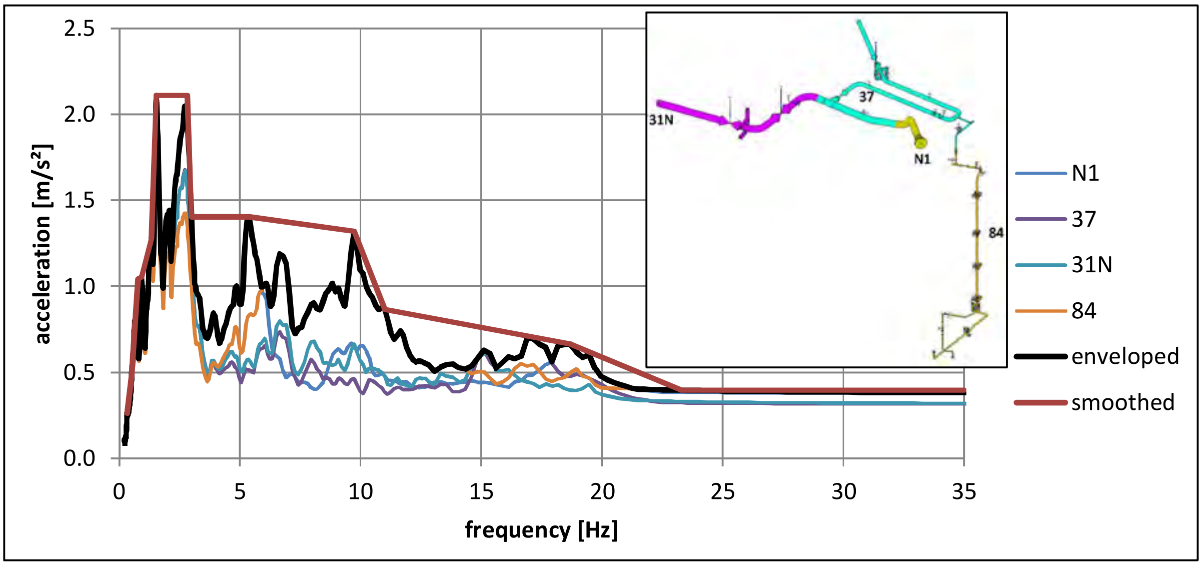


Figure 3. Spectra in horizontal x-direction for D = 2 %

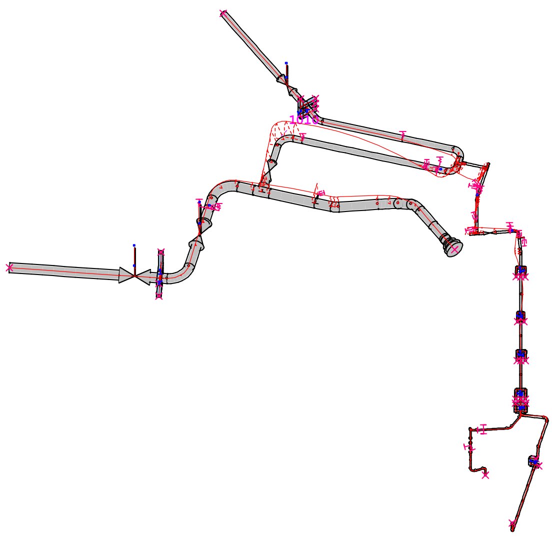
ANALYSIS RESULTS

Modal Analysis

Table 1 shows the first 10 modes up to 9.7 Hz of the RHR piping system. The first natural frequency is at 5.7 Hz and corresponds to a mode shape with the main portions in horizontal direction. The first main vertical mode is at 9.7 Hz.

Table 1: Summary of the first 10 modes of the RHR piping system

Mode	Frequency (Hz)	Modal participating mass ratios (%)			Mode 1
		UX	UY	UZ	
1	5.7	6.1	12.3	2.0	
2	6.0	0.3	1.1	0.0	
3	6.0	0.4	1.7	1.1	
4	7.0	1.3	7.7	0.2	
5	7.9	0.1	0.3	0.0	
6	8.6	0.0	1.1	1.2	
7	9.0	1.7	0.0	0.0	
8	9.1	0.7	0.8	0.2	
9	9.5	0.2	2.9	0.6	
10	9.7	0.0	1.9	8.0	



Service Level D incl. Earthquake Loads

For a comparison of the different analysis methods the maximum stress utilization factors are calculated according to KTA 3211.2 code class A2/A3 for service level D. The stress utilization factor is the ratio of existing equivalent stress to allowable stress. Table 2 summarizes the maximum stress utilization factors for the different analysis methods described in the previous section.

Table 2: Summary of stress utilization factors for different analysis methods

Analysis Method	Damping	Maximum Stress Utilization Factor U_{max}
A1: RSMA with enveloped raw spectra	D = 2 %	85.0 % (Fig. 4)
A2: RSMA with enveloped and smoothed spectra	D = 2 %	97.7 % (Fig. 5)
A3: RSMA with multi-support excitation with raw spectra	D = 2 %	72.2 % (Fig. 6)
A4: Time-history analysis with multi-support excitation	Rayleigh Damping ($D \leq 2$ %)	83.4 % (Fig. 7)

The results show that for all analysis methods the design criteria according to KTA 3211.2 code class A2/A3 for service level D are not exceeded at any location. The highest stresses occur as expected for analysis method A2 with enveloped and smoothed spectra. The location with the maximum utilization factor of 97.7 % is at a T-fitting with a relatively high stress intensification factor. This RSMA method with enveloped and smoothed spectra is standard practice for design analyses of nuclear systems, structures and components. The results show the conservatism of this approach.

The more sophisticated the analysis is the less conservative, respectively the lower the stress utilization factors are. The multi support response spectrum analysis results using four input motions are lower than the ones using enveloped response spectra. However, one would expect that the multi support time history analysis results would be even lower than the ones for multi support response spectrum analysis. The main reason for the higher maximum utilization factor for the multi-support time history analysis is the approach for the applied damping. With the chosen factors for the Rayleigh damping the damping factor corresponds to about D = 1.2 % at 10 Hz. Applying a damping of D = 2 % would reduce the stresses. Due to a limited time for the benchmark project this could not be studied in more detail.

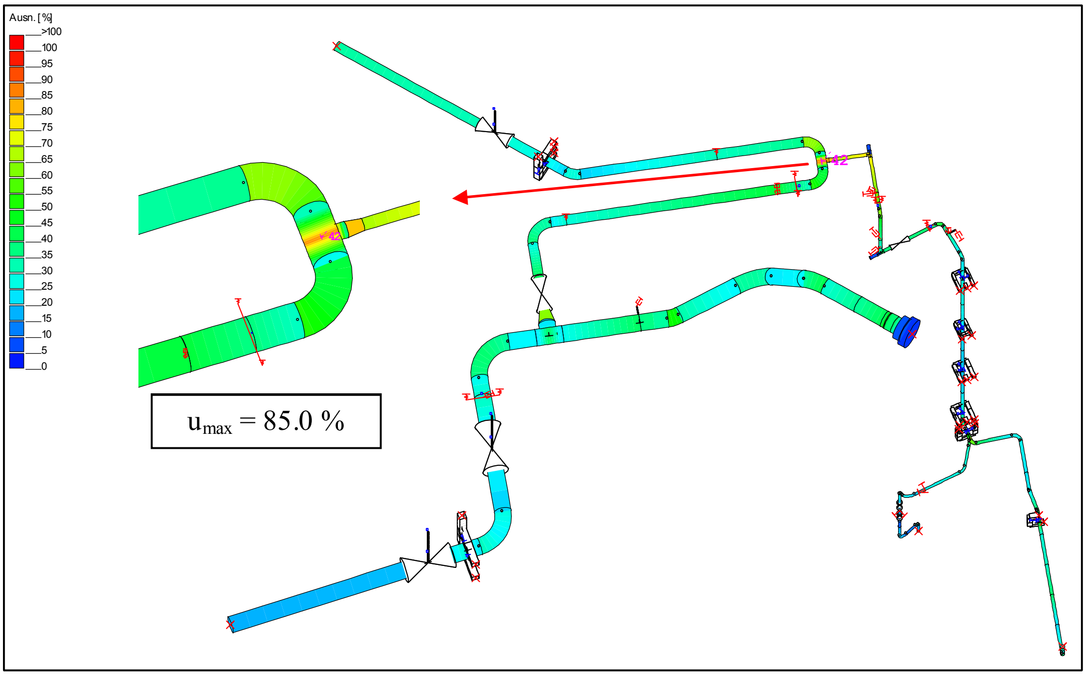


Figure 4. Stress utilization factors for analysis A1: RSMA with enveloped raw spectra

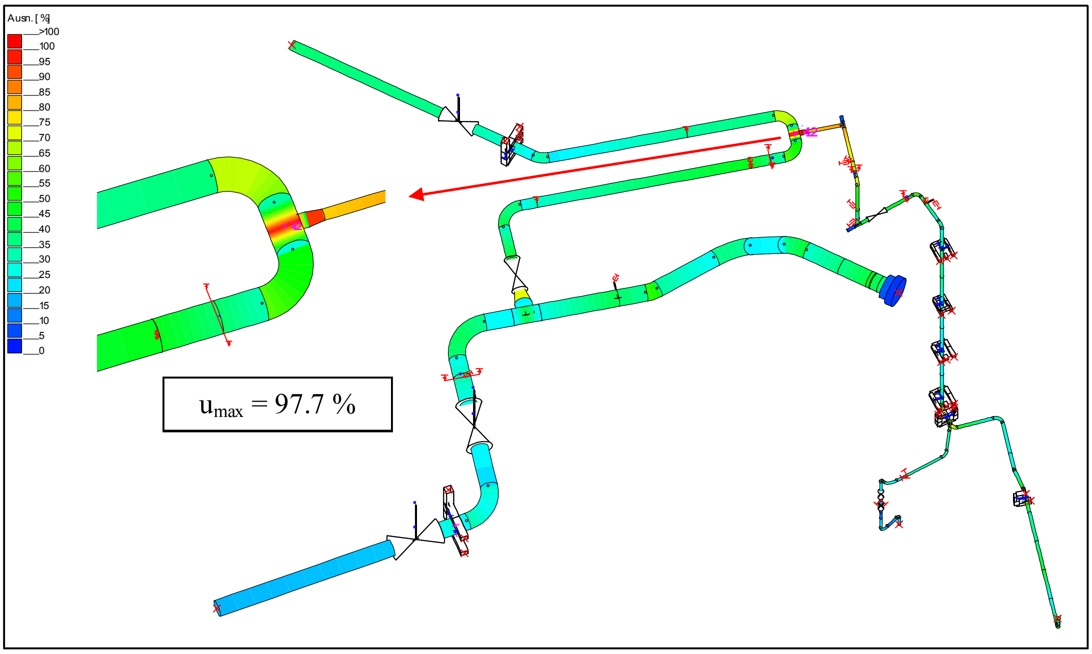


Figure 5. Stress utilization factors for analysis A2: RSMA with enveloped and smoothed spectra

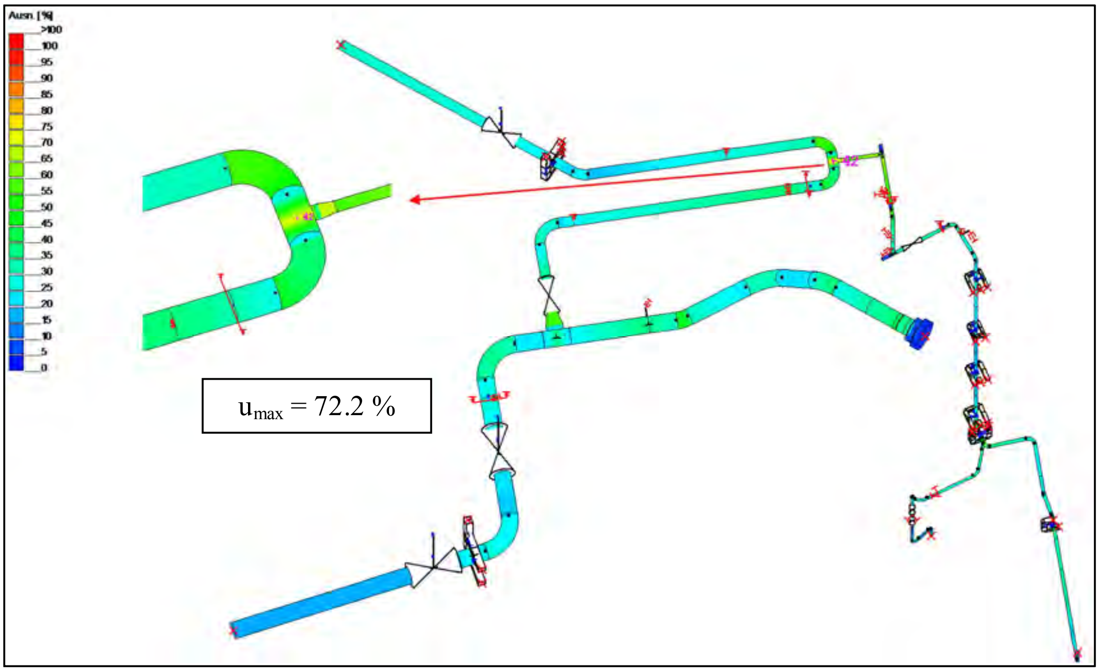


Figure 6. Stress utilization factors for analysis A3: RSMA with multi-support excitation with raw spectra

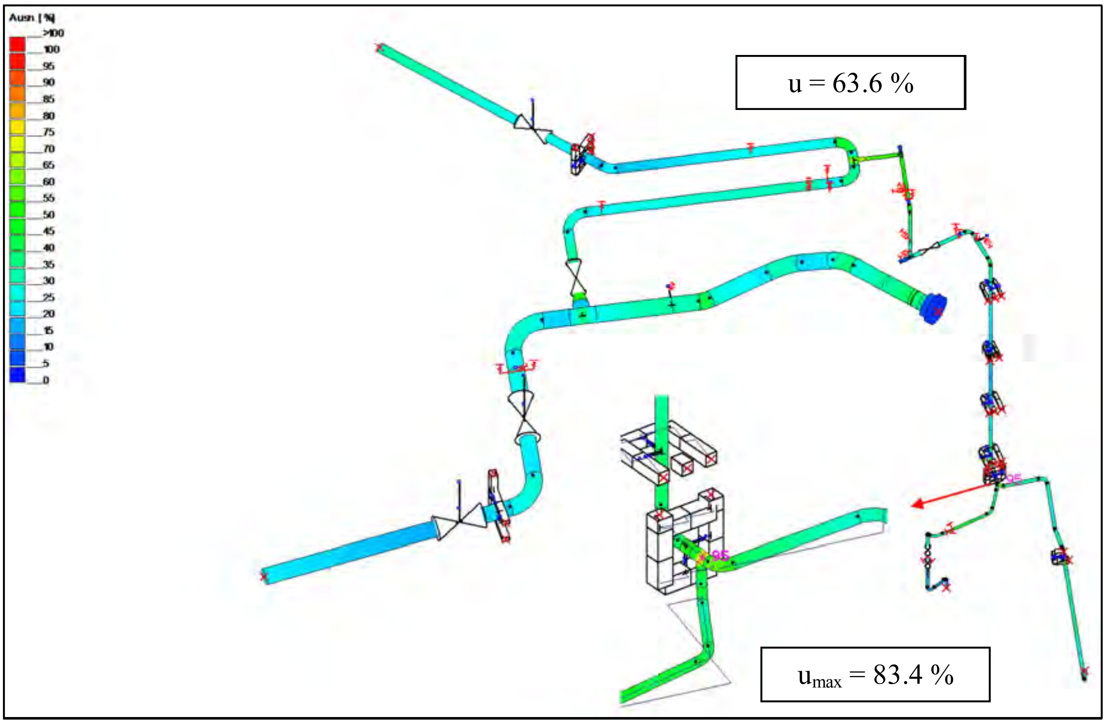


Figure 7. Stress utilization factors for analysis A4: Time-history analysis with multi-support excitation

CONCLUSIONS

The analyses performed for the RHR piping system show that no substantial damage had to be expected for the occurred earthquake according to German national rules. This result substantiates the experience from site that no damage had been observed at the piping after the earthquake.

Overall, the KARISMA benchmark gave a good opportunity to compare different analysis methods. The comparison showed the impact of e.g. smoothing the raw spectra concerning the conservatism of this approach.

Nevertheless, for the assessment of results of the multi-support time history analysis a whole series of analyses would actually be required to investigate in detail the various impacts of different parameters. The parameters which have an impact on the results and which should be investigated in a next step are:

- Impact of the frequency-dependent damping on the results (with the direct integration method modal damping is not possible)
- Variation of the time increment and assessment of the impact on the results
- Study of the impact of higher mode shapes (time increment) on the results
- Effects of the friction on the results
- Variation of the convergence criteria

REFERENCES

Block, C., Henkel, F.-O., Messerer, W. (2013) *Seismic Margin Assessment of a Reactor Building*, SMiRT-22, 18-23 August 2013, San Francisco, USA

Cases of ASME BOILER AND PRESSURE VESSEL CODE, Case N-411-1, Alternating Damping Values for Response Spectra Analysis of Class1, 2 and 3 Piping, Section III, Division 1. ASME-Code 1995 Section III, Division 1 APPENDICES, Appendix N-1000 Dynamic Analysis Methods.

Input documents handed over by IAEA – TEPCO

- Drawings (isometric data) and tables to the RHR-system (not listed in more detail).
- Tables of the material properties and system properties of the RHR-system
- Acceleration time-histories of the NCO-earthquake for the RHR piping system.

KTA 3211.2: Pressure and Activity Retaining Components of Systems Outside the Primary Circuit; Part 2: Design and Analysis. Safety Standards of the Nuclear Safety Standards Commision (KTA), June 1992

ROHR2, R2STOSS, Piping Analysis Software, SIGMA Ingenieurgesellschaft mbH

KTA 3211.2: Pressure and Activity Retaining Components of Systems Outside the Primary Circuit; Part 2: Design and Analysis. Safety Standards of the Nuclear Safety Standards Commision (KTA), June 1992