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STRUCTURAL INTEGRITY OF SMALL-DIAMETER PIPING DURING SEISMIC LOADING

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ABSTRACT

Small-diameter piping subjected to the load case Safe Shutdown Earthquake (SSE) plus operational loads have been investigated and re-evaluated. The paper gives an impression of the expenditure for re-evaluation regarding small-diameter piping and seismic loading.

Site-specific seismic loading is of particular importance for design of structures and components located therein. The seismic event leads to loads that can exceed those of normal operation and may be relevant to failure. During seismic events, power plants are subjected to horizontal and vertical vibrations. Components such as piping systems are often mounted to massive concrete constructions like floors and shear walls using post-installed anchors. Post-installed (PI) fastening constructions with anchor plates and anchors are required to transfer the forces resulting from the interactions between structure and component.

Therefore, size and location of Tresca-stresses regarding the investigated small-diameter piping systems were calculated and compared to the allowable stresses of the ASME Code. The calculations were performed by means of the Finite Element method using the response spectra method. The FE-model uses elbow-elements instead of flexibility factors as it is common in conventional piping codes. Due to unknown piping-support stiffness values, several assumptions were necessary to estimate these values. Hereby, many extreme value estimations and parameter studies were carried out. Even three soil parameter assumptions were considered for calculating the floor response spectra.

Some piping supports of the past, made of long cantilever beams with up to 13 piping supports on it, were re-designed for better resisting seismic loads. The new design consists of one cantilever beam with a square profile welded to a square anchor-plate which is fixed to the reinforced concrete wall by means of four PI anchors. This design can become a new standard support for the regarded small-diameter piping at Kernkraftwerk Gösgen (KKG).

INTRODUCTION

Small-diameter piping in nuclear power plants many times are constructed according to standard installation guidelines like the "ANALOGIE-MODELL" of the nuclear power plant (NPP) Gösgen or guideline like the KSD 7045 for small piping. For the ANALOGIE-MODELL used as installation guideline in KKG for the excitation phase of the supporting distances along the piping were determined with stress intensification factors for bends and tees. The proof of the correctness of this kind of assessment was attested by several analyses. The correct distances were also attested by the regulator in the erection phase of the plant. The piping built according to this installation guidelines were not demanded an explicit assessment of all the loads on it and on the supporting structures according to the low stated loads calculated for several examples of small-diameter piping. The load level was low also for SSE loads combined with the highest operational loads. As the rules taking the SSE into account changed in the last years according to new earthquake information gained out of national and international projects the spectra for the SSE had to be changed and several lines of the small piping were assessed according to the new spectra considering not only the pipes but also the supporting structures, plates and anchors connecting the piping to the buildings. Taking into account the inherent margins when using more realistic excitation of the considered piping the loads are lower than according to the standard response spectra of the piping according to standard numerics using for example Rohr2 for calculation of the response of the structure only.

OBJECTIVE AND BACKGROUND

In the present work, several small-diameter piping systems were re-evaluated according to state-of -the-art code ASME BPVC Section III and 5 standard support structures with plates and anchors were designed.

For re-evaluation small-diameter piping was excited and measured by vibration diagnosis. The aim was to get more realistic models for the following calculations. Model updating was done based on vibration measurements. Although new SSE-spectra were taken into account which are higher than a factor of two compared to the old ones the herein followed assessment led to low usage factors of the small-diameter piping and the possibility to design several standard supports with plates and anchors. The anchors were dimensioned according to the European standards.

The supports were dimensioned according to ASME NF and the pipes were also re-evaluated according to the state of the art of ASME BPVC.

For several representative small-diameter piping in the NPP Gösgen the load case SSE was considered. The maximum Tresca-stress and its occurrence in place were evaluated. Furthermore, the loads at the supports of the structure were evaluated considering the Safe shutdown earthquake SSE in combination with deadload G, temperature T and inner pressure Pi.

MODELL OF THE IVESTIGATED PIPING SYSTEMS AND BOUNDARY CONDITIONS

A small number of piping systems with model character for re-evaluation seismic loading have been investigated. The largest diameter of these piping systems with a nominal diameter DN15 amounts 21-22 mm with a wall thickness of 3 mm. The torus radius of the elbows is around 90 mm. One end of the construction is a fixpoint (FP) and the other one a connection of piping branches to a steel construction, see Figure 1. Since stiffness parameters at these connection points are unknown estimations are necessary. Therefore, two systems were calculated: One assumption consists of a hinged connection and the other one of a stiff connection. The according FE-models are named “System Hinged” and “System Fixpoint”. In one case, when the stress utilization was greater than 100% a rather weak degree of freedom which is an out-of-plane movement of the T-piece activating the torsional spring with the stiffness c_d around the Y’-axis at the connection point (Figure 1) was investigated in more detail by means of model-updating (see below).

The Finite Element Model (FE-Model) of the piping consists of ELBOW31-Elements using the Finite Element Code Abaqus (2018). The straight piping segments were modelled with ELBOW31-Elements as well considering ascending and descending cross section ovalization. A local coordination system was used for each piping system oriented to the direction of walls.

SEISMIC LOADING

From the building model pre-specified calculated time history functions and corresponding floor response spectra for the load case Safe Shutdown Earthquake (SSE) are available for two points P1 and P2 of the floor (Figure 2) where all investigated piping system are installed. For each position P1 and P2 three independent time history functions resp. floor response spectra exist named Spectrum 1, Spectrum 2 and Spectrum 3. For each spectrum three different soil parameters varied from “soft” via “medium” to “stiff”. That means for the points P1 and P2 altogether 2 x 3 x 3 spectra exist for each of the global excitation direction X, Y and Z. Due to the very small mass per piping length (about 1.5 kg/m) the expected reaction forces at the supports are rather small. Before performing 2 x 3 x 3 x 3 = 54 calculations, the consideration of creating as much as possible envelope spectra came up. This is a first assumption for delivering conservative results.

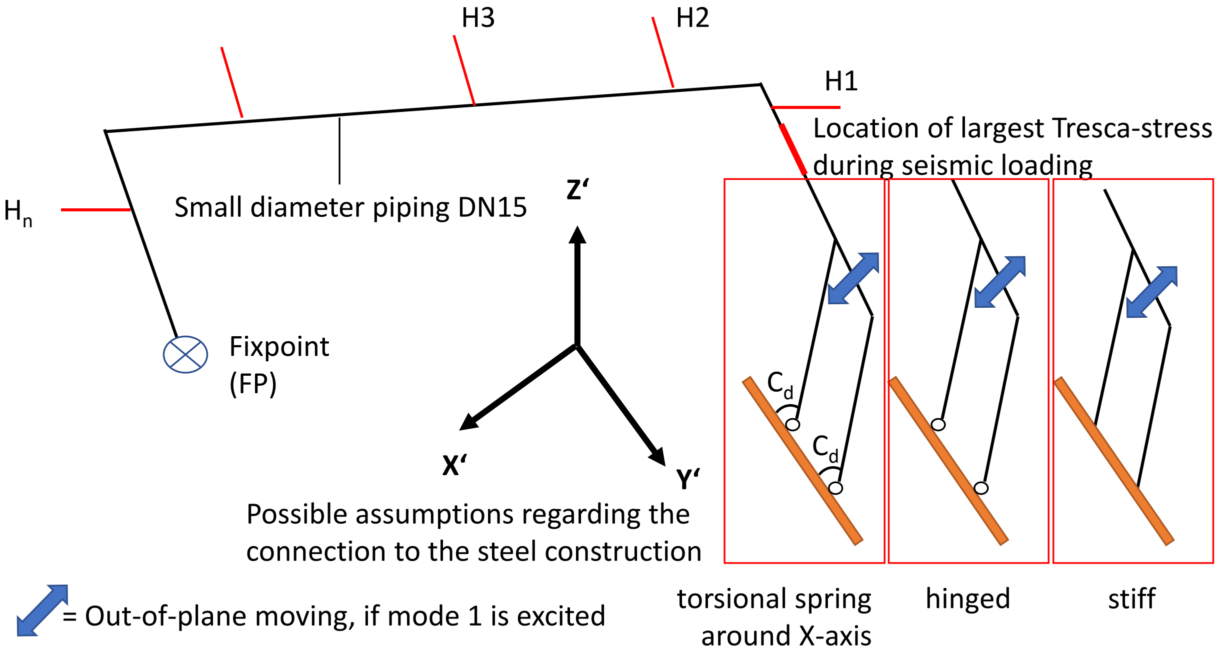


Figure 1: Schematic diagram of a piping system typical for the investigated small-diameter piping systems with n supports H1 to H_n mostly consisting of cantilever beams bearing up to 13 small-diameter piping

The next step after reviewing the level of the spectra regarding the parameter soil shows that only the parameter “stiff” is essential for creating an envelope spectrum.

Figure 3 shows this result - but only for spectrum 3.

A further step of evaluating the local response spectra brought about that Spectrum 3 yields the highest level for Direction X (Figure 4), that Spectrum 2 yields the highest level for Direction Y (Figure 5), and that Spectrum 1 yields the highest level for Direction Z (Figure 6). The final definitions of only three envelope – one for each direction – are given in these three figures as well.

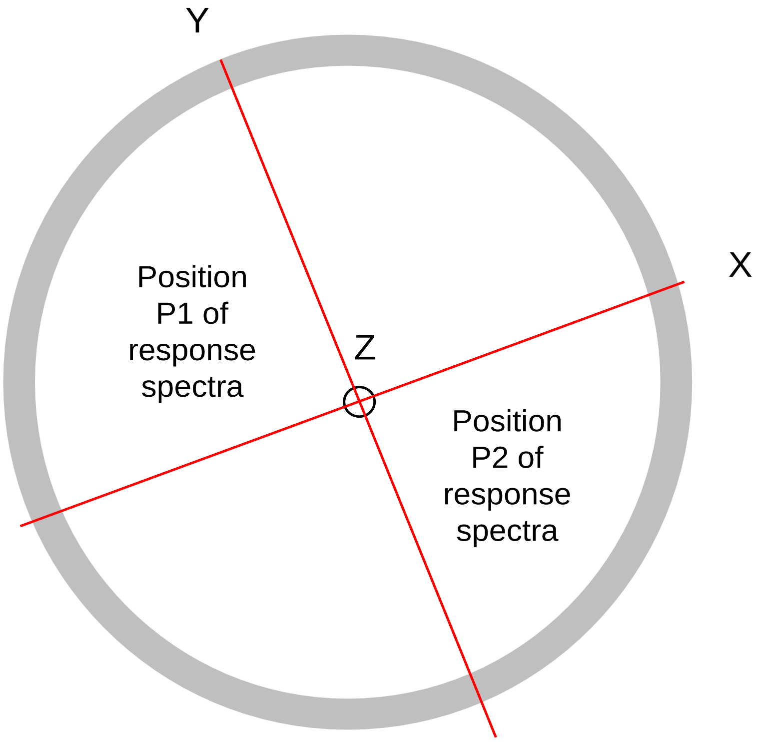


Figure 2: Global directions of the applied floor response spectra

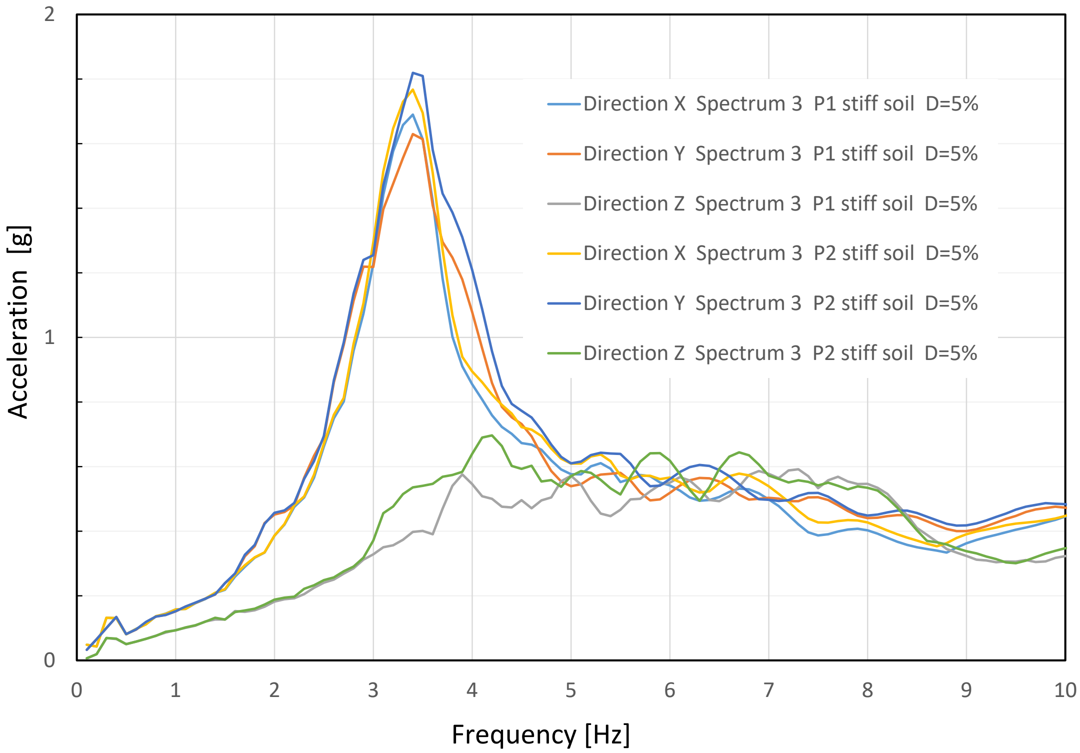


Figure 3: Local floor response spectra essential for creating envelope spectra

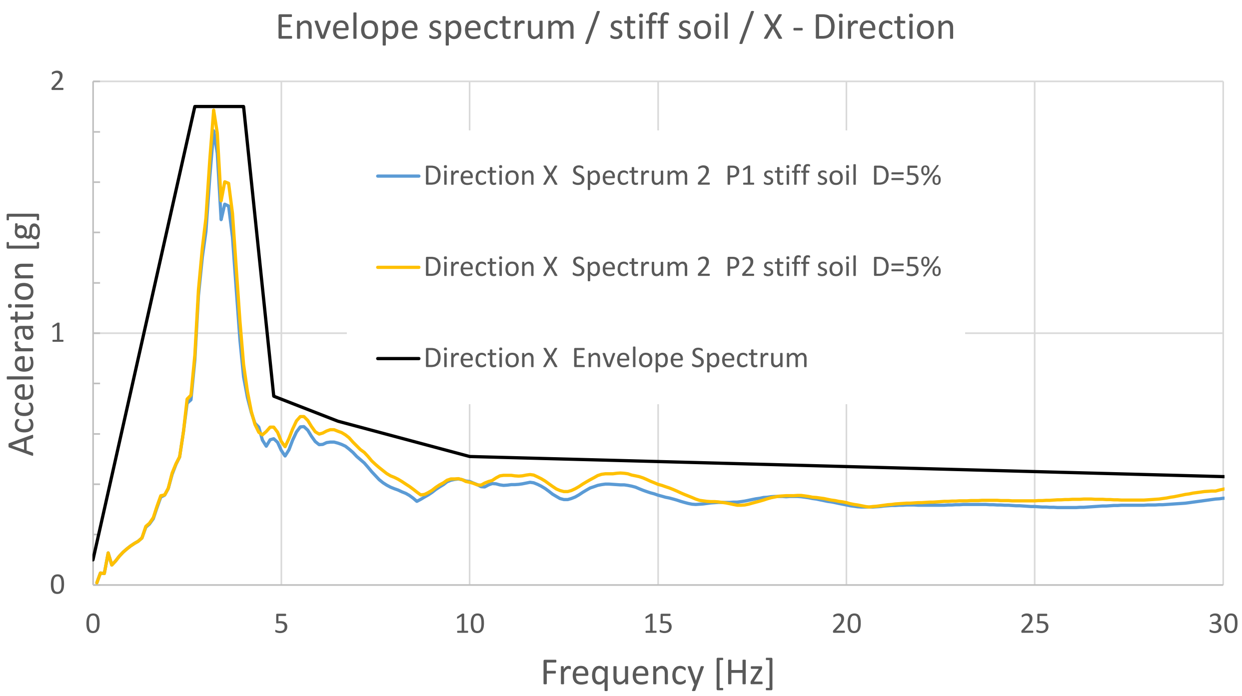


Figure 4: Relevant local floor response spectra of point P1 and P2 for creating one envelope spectrum for the whole floor in global X-direction

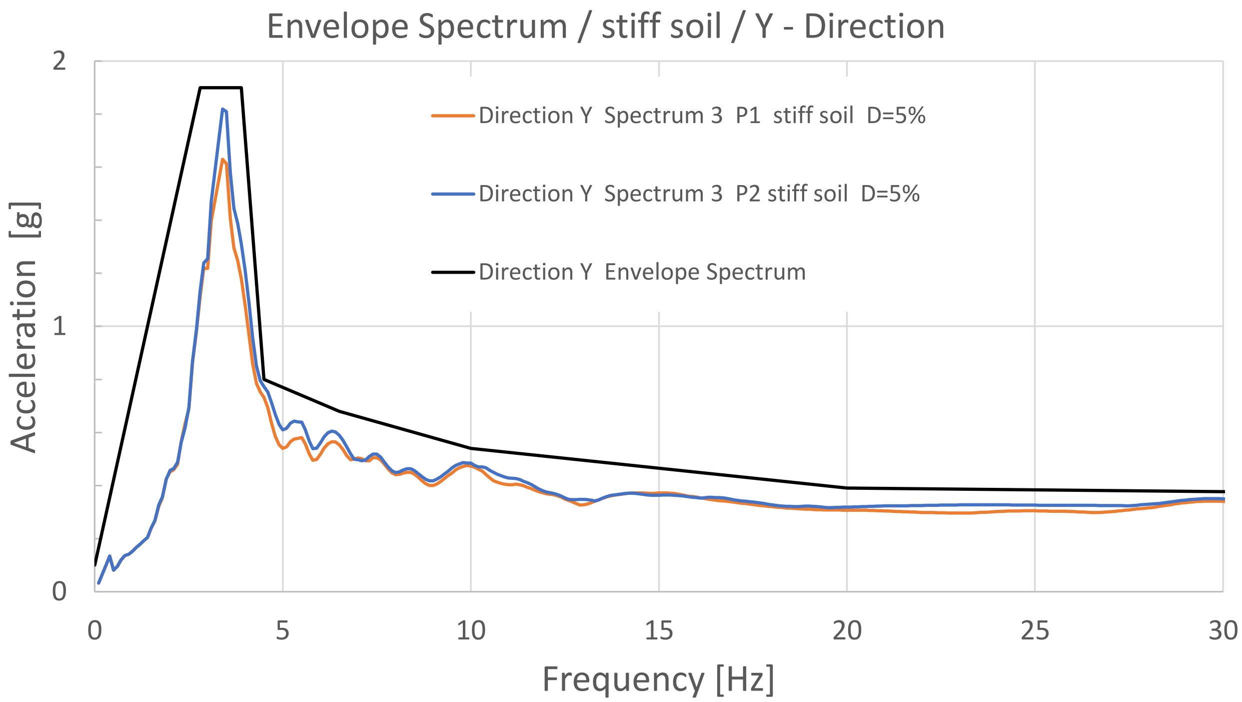


Figure 5: Relevant local floor response spectra of point P1 and P2 for creating one envelope spectrum for the whole floor in global Y-direction

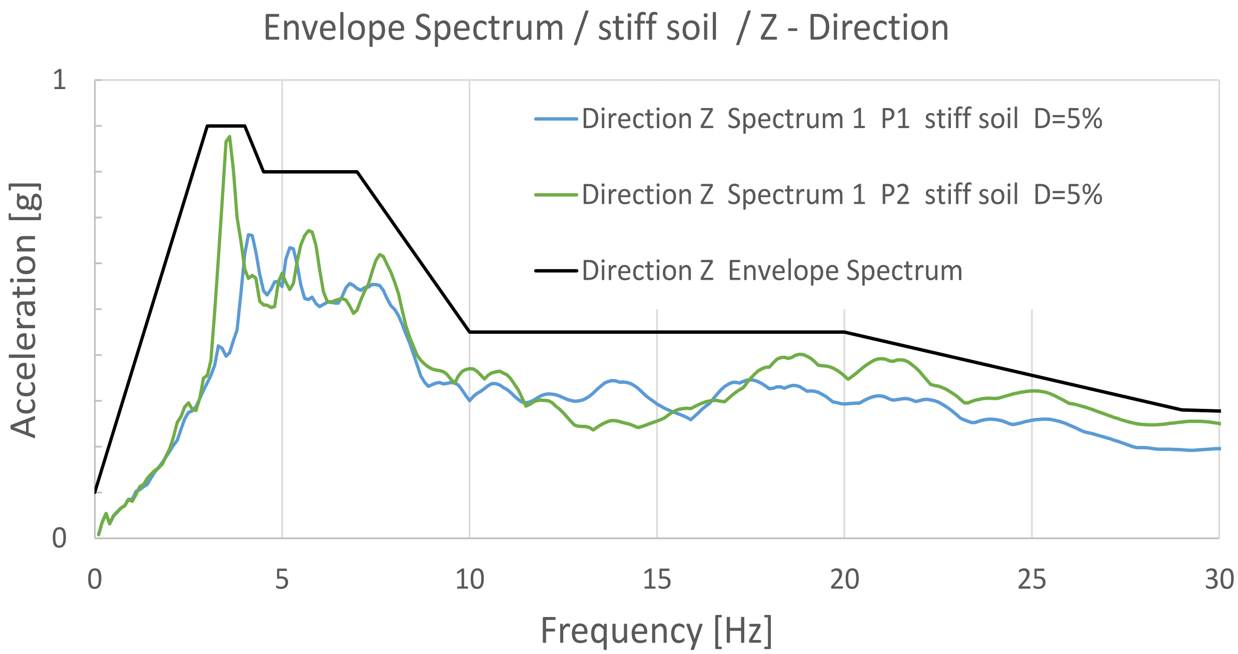


Figure 6: Relevant local floor response spectra of point P1 and P2 for creating one envelope spectrum for the whole floor in global Z-direction

CALCULATIONS CONCSIDERING SSE PLUS DEAD LOAD, TEMPERATURE AND INTERNAL PRESSURE

The system response of the investigated piping systems was calculated for the hot systems (higher than 350 °C) and the load cases SSE+G+Pi+T (SSE plus gravity load G (dead load) plus internal pressure Pi) with $P_i = 17.5$ MPa. The calculations were carried out in the local coordination system only by means of the three determined envelope spectra which is a further (second) assumption for delivering conservative results. The response spectra method with the summation method CQC (Complete Quadratic Combination) was used. According to the ENSI Note (2012) all three seismic loading directions X, Y, and Z were combined simultaneously. This procedure is third assumption for delivering conservative results.

The given seismic loading in the global coordination system was transformed into the local X'-, Y'- and Z'-coordination system which is defined by the directions of walls where the fastening are installed. The limit value assumption for the connection of the piping to the steel construction using either the “Hinged System” or “Fixpoint System” is a fourth assumption for delivering conservative results.

Since stiffness parameters for the supports H1 to Hn are missing, spring stiffness parameters for three translatory directions were assessed via guideline VDI 3842 (VDI 2004). This guideline offers empirical values depending only on the size of the piping: For nominal diameter DN15 stiffness values for translatory directions are given with $Cw_{x'} = Cw_{y'} = Cw_{z'} = 100$ N/mm. These three values were used for each point on the cantilever beam bearing a piping, see Figure 7.

Regarding maximum stresses, the results of the FE-calculations for both, the “Hinged System” and the “Fixpoint System” yield with one exception:

- **60% stress utilizations** comparing the maximum calculated with the lowest allowable values of Tresca-stresses regarding ASME Boiler and Pressure Vessel Code (2013)

The largest results of support forces Hn in each direction for those fastening constructions bearing up to 13 pipes on a cantilever beam are rather small:

- in X‘ – direction $\mathbf{H_{nX}}$ = **43 N**,
- in Y‘ – direction $\mathbf{H_{nY}}$ = **28 N** and
- in Z‘ – direction $\mathbf{H_{nV}}$ = **65 N**.

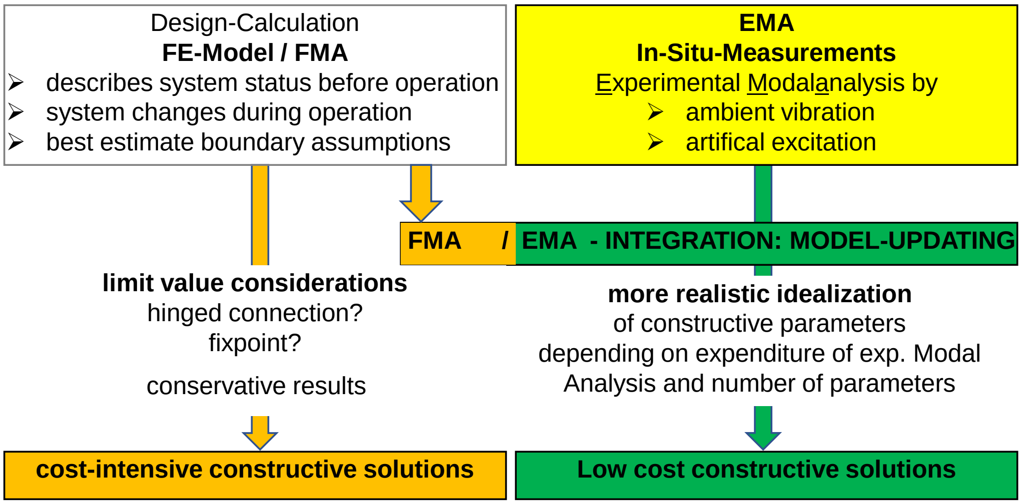
Exception: In two cases (“Hinged System”) the stress utilization lies slightly below resp. above 100%. Here, the calculated first eigenvalues amount less than 5 Hz (4.0 Hz and 3.6 Hz). Regarding the envelope spectra it is obvious that these frequencies are located in the plateau of seismic excitation. The corresponding modes show large out-of-plane movements of the tee, ref. to Figure 1, leading – if excited – to large bending stresses close to the first support H1. A vibration analysis was performed to check, whether these small frequencies are present in reality:

VIBRATION ANALYSIS AND MODEL UPDATING

A vibration analysis was performed in the area of the tee. The piping was excited in out-of-plane direction of the tee, ref. to Figure 1. During fading of the vibration the experimental determination of the first natural frequency yielded a value of 8.9 Hz – much larger than the calculated one. The calculation model was then updated step by step. Besides a slightly increasing of other support stiffness a torsional stiffness of $C_d = 30 \times 10^6$ Nmm/rad yielded a good coincidence between the measured und calculated first natural frequencies, Table 1. Consequently, the maximum Tresca equivalent stress changed after model-updating to a value close to that one of the “Fixpoint System”. A stress utilization of only 66% was obtained by means of the updated FE-model.

The same experience with small-diameter piping was made in the past during the seismic safety assessment for nuclear power plant KKP1(Kernkraftwerk Philippsburg 1). Present stiffness parameters were greater than the parameters assumptions of the design calculation. This brought about conservative results: The frequency shift to higher values after model-updating caused, that the first natural frequency runs out of the high-level plateau of the applied response spectra. This is described in Kerkhof et al. (2015).

Table 1: Model-updating and expected advantages



NEW STANDARD DESIGN OF SUPPORT BY MEANS OF PI ANCHORS

The fifth assumption for delivering conservative results is the simplification using always the same internal forces between piping and cantilever namely always the maximum calculated values in each direction: $H_{nX} = 43$ N, $H_{nY} = 28$ N and $H_{nV} = 65$ N, cf. to Figure 7. This is the final and only loading for the new design of the four PI anchors regarding the load case seismic loading, dead load, temperature and internal pressure. Hereby the design loading is given for a new standard fastening approved for nuclear conditions. On this basis Schmieder et al. (2020) created a new design for the fastening with PI anchors:

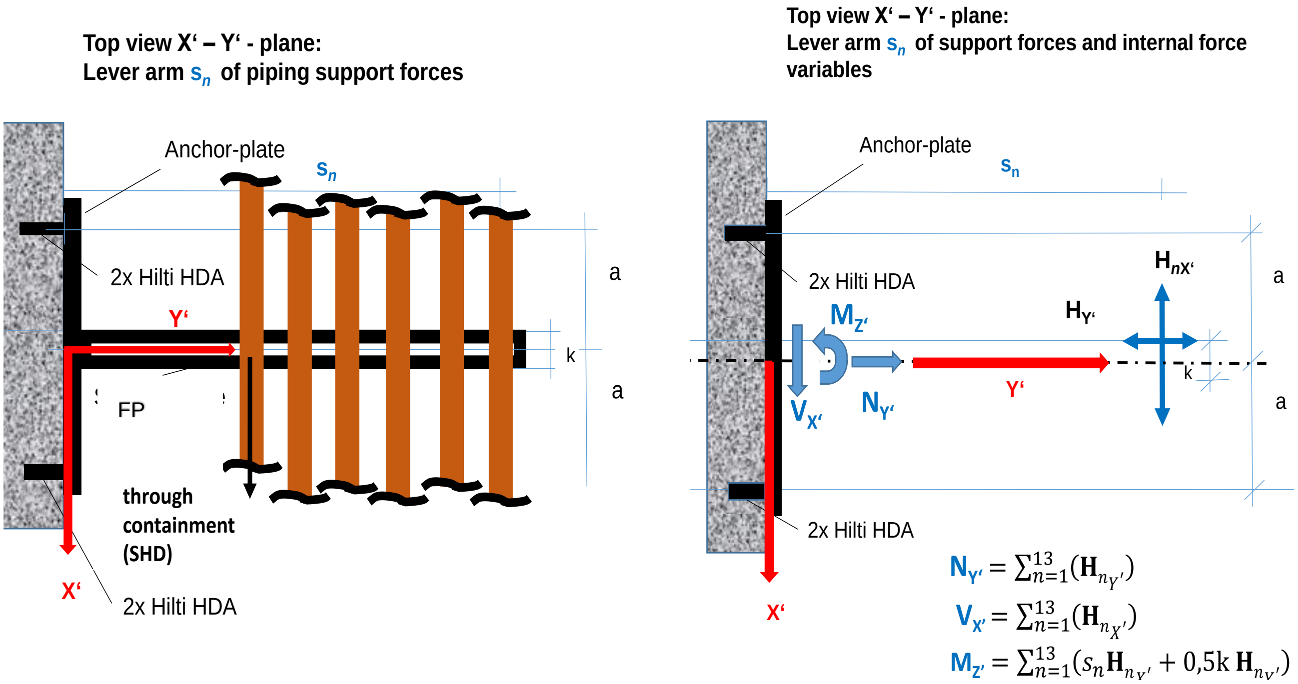
The fastening consists of four anchors of the type HDA-P(R) M10 with a minimum distance of 120 mm and a cantilever beam with a quadratic cross-section and a side length of k = 70 mm. Hereby the seismic safety assessment is conducted regarding the load case SSE + G + Pi + T.

Since the loads are acting in combination, the safety case for combined loading must be carried out due to equation (1) showing that **I < 1** applies. The results are given in Table 2: Equation (1) was verified for six beam types of cantilever beams bearing 9 resp. 13 small-diameter piping in different distances to the anchor-plate. The largest value of I was I = 0.8.

$$\mathbf{I} = \left(\frac{N_{Ed}}{N_{Rd}}\right) + \left(\frac{V_{Ed,y}}{V_{Rd,y}}\right) + \left(\frac{V_{Ed,z}}{V_{Rd,z}}\right) + \left(\frac{M_{Ed,x}}{M_{Rd,x}}\right) + \left(\frac{M_{Ed,y}}{M_{Rd,y}}\right) + \left(\frac{M_{Ed,z}}{M_{Rd,z}}\right) \leq 1 \qquad (1)$$

with

$M_{x'} = M_{Ed,y}$ $\quad M_{y'} = M_{d,x}$ $\quad M_{z'} = M_{Ed,z}$ $\quad V_{x'} = V_{Ed,y}$ $\quad N_{y'} = N_{Ed,y}$ $\quad V_{z'} = V_{Ed,y}$


Top view X' – Y' - plane:
Lever arm s_n of piping support forces

Top view X' – Y' - plane:
Lever arm s_n of support forces and internal force variables

$$N_{Y'} = \sum_{n=1}^{13} (\mathbf{H}_{n_{Y'}})$$
$$V_{X'} = \sum_{n=1}^{13} (\mathbf{H}_{n_{X'}})$$
$$M_{Z'} = \sum_{n=1}^{13} (s_n \mathbf{H}_{n_{Y'}} + 0{,}5\mathrm{k}\, \mathbf{H}_{n_{Y'}})$$

Figure 7: Design and nomenclature for the new design of the fastening with four PI anchors and anchor-plate

Table 2: Safety case for combined loading of the investigated fastening construction with four PI anchors and anchor-plate, see Figure 7.

Comparison of design-loads (Ed) und maximum design-resistance values (Rd) for the calculated internal forces and bending moments as well as safety case for combined loading (Interaction-value I < 1)								max. Loads H_n and directions		
beam type / number n of piping	Loading						**I < 1**	X’	Y’	Z’
	Nmm	Nmm	Nmm	N	N	N	%	N	N	N
VI / 13	$M_{x'}$	$M_{y'}$	$M_{z'}$	$V_{x'}$	$V_{x'}$	$V_{z'}$	**80**	43	28	65
V / 13							**63**			
IV/ 9							**44**			
III / 9							**55**			
II / 9							**50**			
I / 9							**55**			
Max. resistance	$M_{Rd,y}$	$M_{Rd,x}$	$M_{Rd,z}$	$V_{rd,y}$	N_{Rd}	$V_{rd,z}$				
	1.7×10^6	3.6×10^6	1.7×10^6	42800	28000	42800				

CONCLUSION

Safety assessments regarding several constructions of the past as well as the new design with post-installed anchors finally show stress utilizations clearly lower than 100% when maximum calculated Tresca-stresses were compared with the allowable stresses of the ASME code. Experimental modal analyses and model-updating document that actual present stiffness values must have been higher than estimated values from guidelines. Measured natural frequencies were significantly higher than calculated eigenfrequencies.

Some piping supports of the past, made of long cantilever beams with up to 13 piping supports on it, were re-designed for better resisting earthquake loads. The new design consists of one cantilever beam with a square profile welded to a square anchor-plate which is fixed to the reinforced concrete wall by means of four PI anchors. This design can become a new standard support for the regarded small-diameter piping at the investigated floor of the KKG - building.

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