Evaluation of Seismic Margins for an In-Plant Piping System

C. A. KOT, M. G. SRINIVASAN, B. J. HSIEH
Argonne National Laboratory, Argonne, IL USA

ABSTRACT

The excess seismic capacities or margins of a prototypical in-plant piping system and its components are evaluated by comparing measured inputs and responses from high-level simulated seismic experiments with design loads and allowables. Large excess capacities are clearly demonstrated against pipe and overall system failure with the lower bound being about four. For snubbers the lower bound margin is estimated at two and for rigid strut supports at five.

1. INTRODUCTION

Earthquake experience as well as experiments indicate that, in general, piping systems are quite rugged in resisting seismic loadings (EQE 1988; Chen et al. 1987). Therefore there is a basis to hold that the seismic margin against pipe failure is very high for systems designed according to current practice. However, there is very little data, either from tests or from earthquake experience, on the actual margin or excess capacity (against failure from seismic loading) of in-plant piping systems.

Design of nuclear power plant piping systems in the U.S. is governed by the criteria given in the ASME Boiler and Pressure Vessel (B&PV) Code (Slagis 1990), which assure that pipe stresses are within specified allowable limits. Generally linear elastic analytical methods are used to determine the stresses in the pipe and forces in pipe supports.

The objective of this study is to verify that piping designed according to current practice does indeed have a large margin against failure and to quantify the excess capacity for piping and dynamic pipe supports on the basis of data obtained in a series of high-level seismic experiments (designated SHAM) on an in-plant piping system at the HDR (Heissdampfreaktor) Test Facility in Germany. Note that in the present context, seismic margin refers to the deterministic excess capacities of piping or supports compared to their design capacities.

2 SHAM TEST CONFIGURATIONS

A detailed description of SHAM experiments has been given by Kot et al. (1990). Figure 1 shows a sketch of the test object in the SHAM tests, the VKL (Versuchskreislauf) piping system. It consists of multiple stainless steel pipe branches of 100 to 300 mm diameter. Its two main flow loops are connected to the HDU vessel and the DF16 manifold. The piping system was excited directly by means of two displacement controlled servohydraulic actuators. As shown in Fig. 1 both actuators were acting in the horizontal x direction at H5 and H25. They were operated together and in phase, and were programmed to apply to the pipe identical displacement excitation histories.

While six different dynamic support systems of the VKL piping system were designed for the SHAM tests, only two are considered here. The first of these, the NRC configuration shown in Fig. 1, was designed by the Idaho National Engineering Laboratory. It was a stiff system that used snubbers and struts. The other system, denoted the KWU configuration, had no snubbers at all, was more flexible, and had one strut less than the NRC configuration, with H3 being removed. It was designed by Siemens, AG Unternehmensbereich Kraftwerk Union, Offenbach, Germany.

All configurations used the same dead-weight hanger systems, shown in Fig. 1. Similarly, all configurations employed the same rigid struts in the horizontal z direction at locations H4 and H23, which served to stabilize the input motions of the actuators along the x direction.

3 SUPPORT SYSTEM DESIGN

The seismic excitation for the design of both the systems considered here was based on the HDR floor response spectrum, shown in Fig. 2, for a prescribed SSE (Safe Shutdown Earthquake) floor response with a ZPA (Zero Period Acceleration) of 0.6 g. A *displacement* history of 15 s duration was generated from this spectrum to control each of the two actuators for 100% SSE excitation.

For the NRC configuration, the design objective was to determine, for a given piping layout, the location and sizes of snubbers and struts as in a typical U.S. nuclear power plant design. The provisions of ASME B&PV Code (1980), Section III, Division 1 - Subsection NC (for Class 2 Components) governed the design with Level C Service Limits assumed and damping in accordance with PVRC criteria. Analyses were performed (using the Response Spectrum Method with the NUPIPE II program) assuming hot conditions (288°C) and the actual operating pressure of 7 MPa with the SSE excitation applied both in three directions at all supports and also only at the two actuator locations along x direction, thus representing the test loading conditions. The enveloped stress resultants from these analyses were used to ensure that Equation 9, NC-3650, was satisfied. The supports themselves were sized to have the design capacity to sustain the forces determined only from the analysis for the two-point SSE excitation of the tests.

For the KWU configuration the struts H9, H10, and H11 were located such that the pipe stresses, computed per ASME Code Equation 9, are within allowables that correspond to Level B Service Limits for material properties at ambient temperature. The design analysis was performed only for the actual test conditions for the 100% SSE loading. Time history analysis was performed with the KWU-ROHR program assuming proportional damping for the system. The struts were sized very conservatively using nominal load capacities for Level B Service Limits.

Table 1 gives a summary of the pipe stress results at selected locations showing the values obtained by ASME Code Equation 9. The locations at which the stresses are calculated are shown schematically in Fig. 3. Note that the allowable stresses used for the KWU system (Level B Service Limits, cold pipe) are higher than the ones for the NRC configuration (Level C Service Limits, hot pipe) even though the Equation 9 stresses are actually smaller for the KWU configuration for most locations.

Table 2 gives a summary of the design results for the support forces. The rated Level C capacity for the supports is also shown in the table. The nominal capacity given for the Grinnell Size B strut in the KWU configuration actually corresponds to Level B Service Limits.

4 MARGINS TEST RESULTS

Table 3 shows the relevant tests used for margins evaluation which covered the range from 100% to 800% SSE loading level. For the higher levels of loading, the amplitudes of the displacement histories were simply scaled up. Because of apparent defects in Anchor Darling snubbers, all of them were replaced with equivalent rated Pacific Scientific snubbers (see Table 2) for tests T41.31.2, T41.31.3, and T41.31.5. For the higher level loading tests, the NRC configuration was modified (strengthened) to prevent an atypical engineered failure of the Elbow 3 (see Fig. 3). Using a new set of Anchor Darling snubbers for the 600% and 800% SSE tests, all snubbers except H6 were changed to conform to the support configuration shown in Table 2. The snubber H6 was changed to the size PSA 1.

In the high level loading tests there was significant local plastification when strains at many locations exceeded the nominal strain at yield (0.3%). The highest strain recorded (KWU configuration, 800% SSE) reached about 1.3%. In general the pipe stresses at 100% SSE loading were on the order of one–half of the code limits for the NRC configuration and somewhat less for the KWU configuration. Allowable stress limits were reached only at load levels of 300% SSE. At the extreme loadings (800% SSE), the equivalent elastic peak stresses in the pipe material were about three times the allowable value; however, no failure of piping occurred.

Table 3 gives the peak forces experienced by the supports. Note that for some snubbers, the actual size used might be different from that shown in Table 2. The design calculations in general underpredicted the peak dynamic support forces as may be seen by comparing the peak forces measured in the 100% SSE (Table 3) with those from the design calculations (Table 2). The forces in three snubbers, H6, H7, and H8, in the NRC configuration had already exceeded the rated capacity (for Level C Limits) at the design load of 100% SSE. At 200% SSE almost all of the peak snubber forces exceeded the rated capacity, in some cases by as much as a factor of three.

Two snubbers, H6 and H8 (both PSA 1/2), failed to function during the 300% SSE level test. The snubbers H8, H12, and H22 failed due to overload at the 600% SSE test. They were not replaced for the 800% SSE test in which the snubber H7 failed. No failures of rigid struts occurred even at load levels of 800% SSE.

5 MARGINS AGAINST FAILURE

The safety margin against failure may be defined as the ratio of the loading at failure to the design loading, or as the ratio of capacity at failure to rated or design (i.e., allowable) capacity. Failure is defined here as rupture for the pipe, mechanical malfunctioning or rupture for the snubber and rupture for the rigid strut.

All definitions of margins also involve some design parameter as the basis. The use of different service, temperature and loading conditions in the design of the NRC and KWU configurations makes it necessary to redefine a common basis for comparison purposes. The most appropriate basis for the 100% SSE, ambient temperature test condition are Level C Service Limits. Based on material properties given in the German DIN standard, the allowable Equation 9 pipe stress for Level C Service Limits is 285 MPa for the steels used. The rated capacities for struts and snubbers are the Level C Capacity values given in Table 2.

From Tables 1 and 2, we note that the systems are overdesigned to some extent even for the design loading. Therefore it seems appropriate to adjust the margins based on the loading level by an overdesign factor, this factor being the ratio of the allowable stress/force to calculated maximum stress/force at design loading. From Table 1, we see that the stress overdesign factor for the NRC configuration is 1.62 (i.e. 285/176), and that for the KWU configuration is 1.70 (i.e. 285/168). For snubbers the overdesign factors ranged from 1.1 to 2.07, and for struts in the NRC configuration the range was from 1.90 to 2.71. The KWU struts were greatly overdesigned with the factor ranging from 3.56 to 4.05. Based on loading level alone the lowest level at which any snubber failure occurred was at 300% SSE. Similarly, based on the loading level, all the struts had *at least* a margin of 8, since none failed even at the 800% SSE level. However, more realistic margin values for struts and snubbers adjusted by the overdesign factors are listed in Table 4.

Using a different definition of margin, i.e., the ratio of the peak force in a support at or before failure to its rated Level C Capacity, Table 4 again gives the margins calculated from the peak values listed in Table 3 . For supports that did not fail at all, the highest force it experienced divided by its rated capacity is defined as the lower bound of the margin.

Generally the margins based on force ratios are higher than those defined on the basis of loading level. Since some supports were not tested to capacity and for others the first exposure was at a high load level, the margins based on load level are less reliable than those based on force ratios. Taking this into account the lowest margin against snubber failure is only about 2. On the other hand, the struts have a large margin, in the range of 5.66 to 6.74.

Considering the margin against pipe failure based on loading levels, in both the configurations no pipe failure occurred even at the 800% SSE loading level. However, since the NRC configuration was modified after the 300% SSE test one can only state that the lower bound for margin against pipe failure is at least 3 for the NRC configuration and at least 8 for the KWU configuration. If we adjust these values by the overdesign factors, the lower bounds drop to 1.85 for the NRC configuration, and 4.71 for the KWU configuration.

Because of pipe plastification at high loading levels, difficulties arise in defining the pipe margin as the ratio at failure (or maximum stress reached in case of no failure) to allowable stress. Using expressions valid only for elastic behavior (such as Equation 9) margins of 300% are estimated but are questionable. Hence it seems more appropriate to use the peak strains recorded during the tests as an indicator of excess capacity. The highest strain recorded in the 800% SSE test for the KWU configuration was 1.3%. For the pipe materials, the total strain at nominal yield is about 0.3%. Thus, the peak pipe strains exceeded four times the strain at yield. While this is not defined as the margin for pipe, it shows that the ductility of the pipe provides a large margin against pipe failure.

6 CONCLUSIONS

The simulated seismic experiments conducted on the prototypical VKL in–plant piping system clearly demonstrate the inherent ruggedness of piping systems under extreme earthquake loadings. However, the nonprototypical loading and not consistent design procedures make the quantification of seismic margins problematical. If input loading level is used as a basis, then a seismic margin of *at least* eight can be deduced for the entire piping system. If allowance has to be made for possible overdesign, the lower bound for the margin may drop to about four. It should be emphasized that since there was no pipe failure, the above figures are merely lower bounds and that the real margin could far exceed them.

ACKNOWLEDGMENT

This work was performed under the sponsorship of the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research.

REFERENCES

Chen, W. P., Onesto, A. T., and DeVita, V. (1987). "Seismic Fragility Test of a 6-Inch Diameter Pipe System," Energy Technology Engineering Center, NUREG/CR-4859.

EQE Engineering Inc. (1988). "Piping Seismic Adequacy Criteria Recommendations Based on Performance During and After Earthquakes," EPRI NP-5617.

Kot, C. A., Srinivasan, M. G., Hsieh, B. J., Malcher, L., Schrammel, D., Steinhilber, H., and Costello, J. F. (1990). "SHAM: High-Level Seismic Tests of Piping at the HDR," *Nuclear Engineering and Design*, Vol. 118, pp. 305-318.

Slagis, G. C. (1990). "Linear Elastic Piping Seismic Analysis – Help or Hindrance?" Seismic Engineering - 1990, ASME Pressure Vessels and Piping Division Publication, Vol. 197, pp. 69-76.

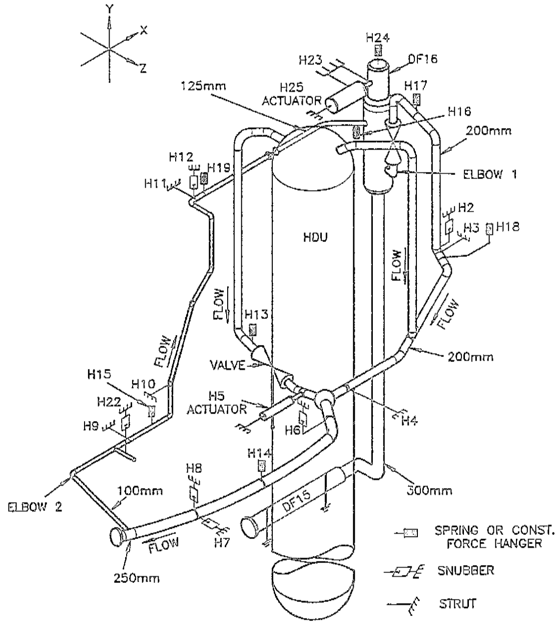

Fig. 1 VKL Piping System with NRC Support Configuration

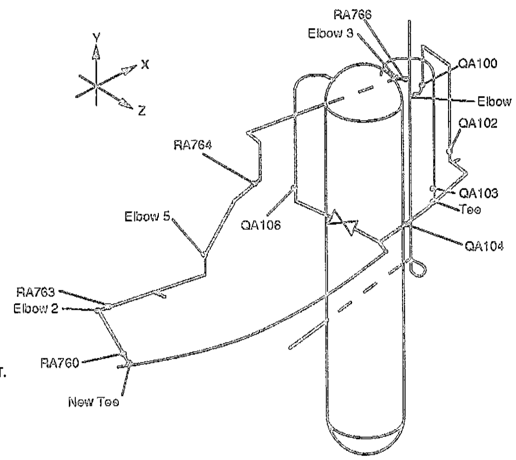

Fig. 3 Strain Measurement Locations Selected for Stress Comparisons

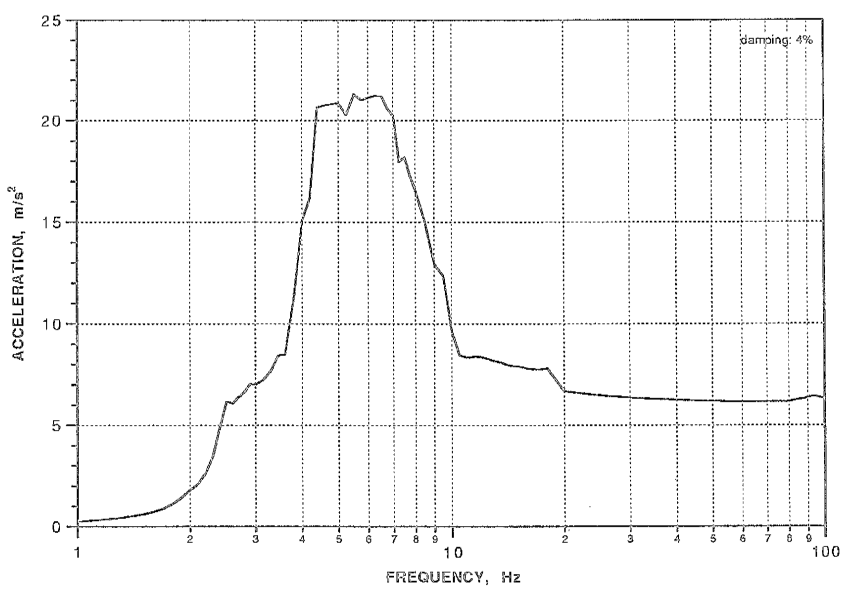

Fig. 2 Floor Response Spectrum for the HDR 100%–SSE Excitation

Table 1. Design Stresses (in MPa) per Equation 9 of ASME Code

	NRC Configuration		KWU Configuration	
Location	ASME Eq. 9	Allowable Stress	ASME Eq. 9	Allowable Stress
RA766	99	208	83	
Elbow 3	119	208		
QA100	132	208	103	247
Elbow 1	176	208	168	247
QA102	93	217	76	
QA103	73	217	64	
QA106	52	217	57	
QA104	65	217	62	
RA764	85	217	73	
Elbow 5	103	217		
RA763	81	217	88	247
Elbow 2	91	217	121	247
RA760	134	217	87	
New Tee	165	171		

Table 2. Support Forces (in kN) from Design Calculations (for 100% SSE)

	NRC Configuration			KWU Configuration		
Support Type and Designation	Calculated Force	Manufacturer and Size	Level C Capacity	Calculated Force	Manufacturer and Size	Nominal Capacity
Strut H3	4.6	Grinnell, B	8.9			
Strut H9	1.9	Grinnell, A	3.8	2.5	Grinnell, B	6.7
Strut H10	1.4	Grinnell, A	3.8	2.3	Grinnell, B	6.7
Strut H11	2.0	Grinnell, A	3.8	2.2	Grinnell, B	6.7
Snubber H2	6.3	PSA , 1	9.3			
Snubber H6	3.3	PSA, 1/2	3.9			
Snubber H7	4.5	AD, 150	9.3			
Snubber H8	2.7	AD, 70	3.9			
Snubber H12	1.2	AD, 40	2.2			
Snubber H22	2.0	PSA, 1/4	2.2			

Table 3. Seismic Margins Tests, Peak Support Forces (in kN)

Support	KWU Configuration Loading % SSE/Test Designation						NRC Configuration % SSE/Test Designation			NRC – Modif. % SSE/ Test Designation	
	100 T41.21.1	200 T41.21.3	300 T41.21.2	400 T41.21.4	600 T41.21.5	800 T41.21.6	100 T41.31.2	200 T41.31.3	300 T41.31.5	600 T41.81.2	800 T41.81.3
Strut H3							6.7	21.1	29.3	45.5	60.0
Strut H9	2.8	5.99	9.4	11.0	17.0	17.5	1.7	2.8	3.8	9.5	18.0
Strut H10	3.5	8.43	11.8	14.2	18.0	26.0	2.3	5.3	8.6	14.0	21.5
Strut H11	4.5	7.11	10.5	11.0	14.6	18.0	4.2	7.3	9.6	14.1	20.3
Snubber H2							3.3	9.2	13.5	22.5	21.0
Snubber H6							5.6	8.3	1.8	24.0	42.0
Snubber H7							11.1	18.1	29.0	51.5	60.0
Snubber H8							6.1	10.6	4.5	7.6	Absent
Snubber H12							1.1	3.4	5.5	5.0	Absent
Snubber H22							1.9	5.1	5.6	8.0	Absent

Table 4. Margins for Support Members

	Force, in kN			Load Level, % SSE			
Support Type and Designation	Peak Meas.	Level C Capacity	Configuration	for peak	for failure	Adjusted Load Level Margin	Force Ratio Margin
Strut H3 (Grinnell B)	60.0	8.9	NRC	800		4.15	6.74
Strut H9 (Grinnell B)**	17.5	8.9	KWU	800		2.28	1.97
Strut H10 (Grinnell B)**	26.0	8.9	KWU	800		2.07	2.92
Strut H11 (Grinnell B)**	18.0	8.9	KWU	800		1.98	2.02
Strut H9 (Grinnell A)	18.0	3.8	NRC	800		4.00	4.74
Strut H10 (Grinnell A)	21.5	3.8	NRC	800		2.95	5.66
Strut H11 (Grinnell A)	20.3	3.8	NRC	800		4.21	5.34
Snubber H2 (PSA 1)	22.5	9.3	NRC	600		5.41	2.42
Snubber H6 (PSA 1/2)	8.3*	3.9	NRC	200	300	2.54	2.13
Snubber H6 (PSA 1)	42.0	9.3	NRC	800		2.84	4.52
Snubber H7 (PSA 1)**	29.0	9.3	NRC	300		1.45	3.12
Snubber H7 (AD 150)	60.0*	9.3	NRC	800	800	3.86	6.45
Snubber H8 (PSA 1/2)	10.6*	3.9	NRC	200	300	2.08	2.72
Snubber H8 (AD 70)+	7.6*	3.9	NRC	600	600	4.17	1.95
Snubber H12 (PSA 1/4)**	5.5	2.2	NRC	300		1.64	2.50
Snubber H12 (AD 40)+	5.0*	2.2	NRC	600	600	3.28	2.27
Snubber H22 (PSA 1/4)+	8.0*	2.2	NRC	600	600	5.45	3.64

* indicates value to be the peak ever reached before snubber failed

** not tested to full capacity

+ first test at high load level (600% SSE)