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An assessment of seismic margins in nuclear plant piping

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ABSTRACT: Interim results of an ongoing program to assist the U.S. Nuclear Regulatory Commission (NRC) in developing regulatory positions on the seismic analyses of piping and overall safety margins of piping systems are reported. Results of reviews of previous seismic testing, primarily the Electric Power Research Institute (EPRI)/NRC Piping and Fitting Dynamic Reliability (PFDR) Program (Guzy, 1988; EPRI, 1994), and assessments of the ASME Code, Section III, piping seismic design criteria as revised by the 1994 Addenda are reported. Major issues are identified herein only. Technical details are to be provided elsewhere.

1 INTRODUCTION

The Energy Technology Engineering Center (ETEC) is providing assistance to the U.S. NRC in developing regulatory positions on the seismic analysis of piping. As part of this effort, ETEC performed reviews of the ASME Code, Section III, piping seismic design criteria as revised by the 1994 Addenda. These revised criteria were based on the results of the PFDR Program.

The PFDR Program was implemented by General Electric (GE) and included simulated dynamic seismic, hydrodynamic, and water hammer testing and analyses of piping components and systems. Seismic tests were performed on 33 simple cantilever configurations of piping components and two prototypic piping systems. Material specimen tests were also performed. Based on these analyses and tests, revised criteria for the seismic design of ASME Code, Section III, Class 1, 2, and 3 piping systems were developed by EPRI and GE (Tagart & Ranganath, 1992; EPRI, 1994).

The revised ASME Code piping seismic design criteria in the 1994 Addenda were based on the rules developed by EPRI and GE (EPRI, 1994), and on evaluations by the ASME Special Task Group on Integrated Piping Criteria (STGIPC)** and the Technical Core Group (TCG) of the Advanced Reactor Corporation (ARC)**. The results of the PFDR Program were included in these evaluations.

* The views expressed in this paper are those of the authors and should not be construed to reflect the NRC position.

**These ASME and ARC/TCG evaluations are documented in reports of limited distribution.

This paper summarizes the current status of ETEC reviews of the revised ASME Code piping seismic design criteria in the 1994 Addenda and some of their bases. In addition, interim reviews by the Peer Review Group (PRG), which was established to provide an overview of the results of the ETEC reviews, are also summarized.

2 OVERVIEW OF PFDR TESTING

Results of 27 of the 33 PFDR seismic component tests were reevaluated as part of the program. These 27 tests are identified in the load margin table and involved 6-inch diameter, stainless and carbon steel components of varying thicknesses (Schedules 10 through 80).

A typical test configuration (EPRI, 1994) and a typical targeted test response spectrum are shown in Figures 1 and 2, respectively. During testing a single time history was utilized but the amplitude of the input was uniformly scaled to adjust the input load level and the time scale stretched or compressed to adjust the frequency of the peak response acceleration to be approximately 90% of the fundamental frequency of the test configuration. Typical test sequences involved initial low level characterization and verification tests and subsequent high level tests. Typically, the high level input was applied until a through-wall crack developed in the testing component or the test was terminated due to incipient instability of the test configuration as a result of ratcheting.

Results of the two PFDR seismic system tests were reevaluated by ETEC for the U.S. NRC as part of a separate program. Results of this reevaluation and other system tests will be reported separately.

The PFDR materials tests were intended to assess the effects of ratcheting on low cycle fatigue. Testing concluded that for low cyclic strains, shakedown occurred and failures were essentially due to fatigue. However, for large cyclic strains, sustained ratchet failures were observed.

3 REVISED ASME CODE PIPING SEISMIC DESIGN CRITERIA

The 1994 Addenda to the ASME Code, Section III, provide revised seismic design criteria for Class 1, 2, and 3 piping in Code Subsections NB/NC/ND-3600, respectively. The Addenda also provide alternate Class 1 criteria in Code Subsection NB-3200. For piping, the 1994 Addenda introduce the concept of reversing and nonreversing dynamic loads. For nonreversing dynamic loads and reversing dynamic loads in combination with nonreversing dynamic loads, the previous criteria are unchanged. However, conditionally higher allowable stresses are specified for reversing dynamic loads not required to be combined with nonreversing dynamic loads. Reversing dynamic loads include seismic loads.

Revised criteria are provided for both ASME Code Service Level B Operating Basis Earthquake (OBE) and Service Level D Safe Shutdown Earthquake (SSE) loads. The revised OBE criteria were not included in this review since regulatory changes in process will essentially eliminate the OBE from design considerations.

For the SSE, the revised Subsections NB/NC/ND-3600 criteria are the same for Class 1, 2, and 3 piping and require that the Code Equation (9) primary membrane plus bending stress load combination be less than 4.5 S_m. This criterion is similar to the previous Service Level D criterion except that: (1) the method of analysis to determine the seismic bending moments is specified, (2) the previous S_y-based allowable limit is eliminated, and (3) the previous S_m-based allowable limit is increased by 50%. The replacement of the previous

S_h-based allowable stress for Code Class 2 and 3 systems by a S_m-based allowable stress is noteworthy.

Conditions for application of the higher allowable stress limit require, in part, that:

1. The analysis be based on an elastic response spectrum solution utilizing 5% damping and peak broadening of no less than $\pm$ 15%.
2. B_2-based stresses due to weight effects be limited to 0.5 S_m.
3. C_2-based stress ranges due to SSE anchor motion effects be limited to 6 S_m.
4. Average axial stresses due to SSE relative anchor motion effects be limited to S_m.
5. Ratios of the outside diameter to wall thickness be limited to 50.
6. The ratio of the dominant load driving frequency to the lowest piping system natural frequency is greater than 0.5

The alternate piping criteria of Subsection NB-3200 of the revised criteria provide that, for the SSE, the average through-wall ratchet strain due to all simultaneously applied loads be limited to 5%, and the effective peak strain range due to all simultaneously applied loads be limited on the basis of the alternating stress intensity value at 10 cycles from the applicable Code Appendix I design fatigue curve.

4 TECHNICAL BASES FOR REVISED CRITERIA

The technical bases for the revised criteria provided in the 1994 EPRI, STGIPC and TCG reports concluded that the failure mode in piping systems due to reversing dynamic loads is ratchet-fatigue and not collapse and, consequently, that elimination of reversing dynamic loads from the ASME Code collapse criterion is justified. However, stresses due to these loads need to be limited to prevent failures due to ratcheting and/or fatigue. Thus, the limitation of the average through-wall ratchet strain as specified in revised Subsection NB-3200 is intended to provide that ratcheting effects on low cycle fatigue are negligible. In turn, empirical studies are claimed to demonstrate that the increased allowable stress limits in revised Subsection NB/NC/ND-3600 also provide that the ratchet strain limit of revised Subsection NB-3200 is satisfied.

The TCG and STGIPC evaluations were based primarily on the load margins, FM_r, demonstrated during PFDR component testing, where the load margin for a given set of design criteria is defined as the ratio of the minimum level of the seismic load expected to provide a through-wall crack in the piping system during one application of the load to the maximum level of the load permitted under the given set of design criteria. For the PFDR tests, FM_r was determined assuming that the fatigue failure stress was inversely proportional to $\sqrt{N}$ where N is the number of stress cycles. Load margins as evaluated by the STGIPC/TCG, ignoring weight and pressure stresses, are provided in column H of the accompanying load margin table.

5 REVIEW OF STGIPC/TCG LOAD MARGINS

Reviews of the revised piping design criteria and their bases identified issues relating to the SIGIPC/TCG evaluations of load margins demonstrated during PFDR component testing and the applicability of these margins to piping systems in general. Other issues included the inadequate technical support for the elimination from consideration of the collapse failure mode and the revised NB-3200 criteria, the inadequate consideration of concurrent seismic anchor motion and thermal expansion effects, and the underprediction of support loads by linear analysis methods.

However, in the following, only issues relating to the STGIPC/TCG load margins will be presented. These issues include the effects of:

1. R_w, the ratio of the frequency of the peak of the test input to the natural frequency of the test configuration (R_w values are provided in Column J of the table).
2. Broadening the peak of the test input in the load margin calculations.
3. The test temperatures.

In addition, ETEC reviews found that the B_2 stress indices utilized to obtain the STGIPC/TCG load margins for some of the straight-through piping products were based on failure characterizations which were inconsistent with Markl's tests (Markl, 1952). B_2 indices utilized by ETEC and by GE, if different, are provided in columns B and C, respectively, of the table. Corresponding stresses utilizing GE calculated response moments using 5% damping (M5) are provided in column D. Further, the number of high level tests to cause failure utilized by ETEC and by GE, if different, are provided in columns E and F, respectively. Finally, load margins calculated by ETEC and the TCG for PFDR component tests are provided in columns G and H, respectively.

Extrapolation of the results of PFDR testing to more critical conditions not tested were based on correction factors. Factors to account for the effects of test temperature, and the incorrect use of broadened vs unbroadened input spectra for load margin evaluations are provided in columns I and K, respectively, of the table. These R_w and unbroadened vs broadened correction factors are based on STGIPC/TCG evaluations reported during the September, 1993 ASME Code meetings. Resulting extrapolated load margins due to consideration of the above effects are provided in column L of the table. The minimum margin of 0.91 for Test No. 11 in column L is less than the minimum margins (approximately 2) for Test No. 36 reported during the September meetings.

The margins in column L of the table were based in part on STGIPC/TCG procedures for extrapolations for failure in a single event and STGIPC/TCG nonlinear analyses for corrections for R_w ratio effects. Use of these procedures and analyses were to evaluate the significance of the effects only and should not be construed to imply their approval. Further, the margins in the table do not include other effects evaluated by ETEC such as concurrent pressure and weight stresses and the actual geometry and material properties of the components tested.

6 PEER REVIEW GROUP REVIEWS

Based on its preliminary reviews, there was a consensus in the Peer Review Group that, even with resolution of obvious problems (e.g., limit on pressure during SSE, and use of S_m instead of S_h for Class 2 and 3 systems), the seismic margins associated with the 1994 Addenda design criteria may be too low to be deemed acceptable from a design standpoint.

Issues identified during these reviews included:

1. The inadequate technical basis for the revised Subsection NB-3200 rules.
2. The questionable elimination of the collapse failure mode from consideration and the use of the collapse failure criterion in NB/NC/ND-3600 to control fatigue failure.
3. The acceptability of the analytically derived margin correction factors for off-resonance conditions.
4. The definition of seismic margin utilized in the STGIPC and TCG evaluations and the lack of an established acceptable value for this margin.

5. The under-prediction of seismic system response by linear analysis method in piping systems designed in accordance with the revised rules.
6. The effects on failure modes of the presence of Code-allowed imperfections in piping systems designed in accordance with the revised criteria.

The Peer Review Group identified the need to resolve issues relating to:
1. The effects of input variability on margin, the effect of input scaling, and the true nature of the response of low frequency systems.
2. Component vs. system failure modes.
3. The under-prediction of system response by linear analysis in the evaluation of piping systems with increased allowable stresses.
4. Material related issues including dynamic strain aging and Code Section XI-allowed imperfection issues.

7 CONCLUSIONS

Results of the ETEC evaluations indicated that margins associated with the revised seismic design criteria in the 1994 Addenda to the ASME Code may be too low to be acceptable from a design standpoint and that some modifications to these criteria may be appropriate.

REFERENCES

EPRI 1994. *EPRI TR-102792-V1 through V5, Piping and Fitting Dynamic Reliability Program, Volume 1 through Volume 5.*

Guzy, D. 1988. Piping Design Criteria and Research, Current NRC Activities in Dynamic Design. *Nuclear Engineering and Design. 107: 161-167.*

Markl, A. R. C. 1952. Fatigue Tests of Piping Components. *ASME Transactions. 74:287-303.*

Tagart, Jr., S.W. & Ranganath, S. 1992. Proposed Dynamic Stress Criteria for Piping. *PVP 237-1: 133-137.*

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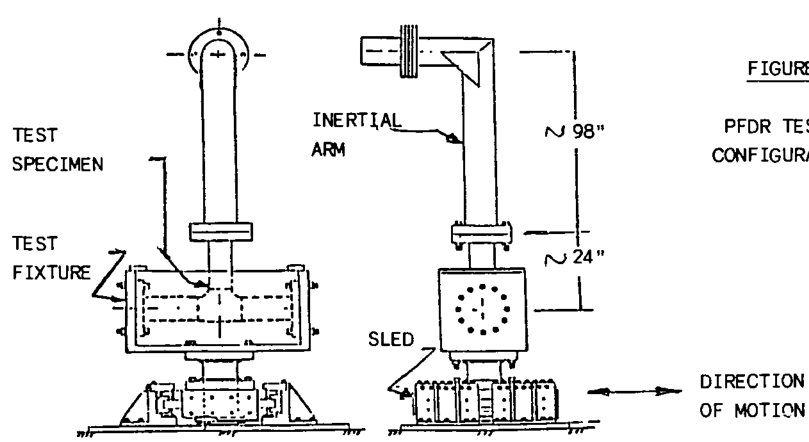
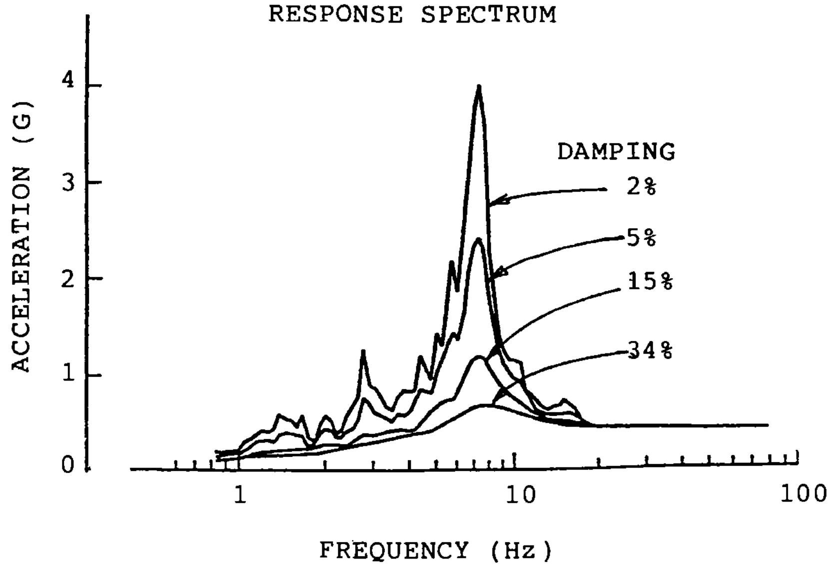


FIGURE 1

PFDR TEST 11 CONFIGURATION

FIGURE 2 TYPICAL TARGET TEST RESPONSE SPECTRUM



PFDR COMPONENT TESTING LOAD MARGINS

PFDR COMPONENT TEST MARGINS								EXTRAPOLATED TEST MARGINS			
NOMINAL B2M5/Z				# TST EVNT		SINGLE EVNT CORR		T ADJ	FREQ ADJ		MARGIN
A	B	C	D	E	F	G	H	I	J	K	L
ID	B2	GE B2 IF DIFF	B2M5 /Z	ETEC #	GE # IF DIFF	UNADJUST LOAD MARGN	TCG STATED MARGN	ER(T) NF(T) 650F/70F	RW	UNBR/BR RS AND RW ADJ	ADJSTED LOAD MARGN
ELBOWS											
1	2.37		544	5.50		14.18	14.00	0.82	0.833	0.34	3.90
2	2.37		499	9.50		17.09	18.50	0.82	0.859	0.31	4.31
3	5.51		752	3.25	3.50	15.07	15.70	0.76	0.900	0.33	3.75
4	3.27		645	2.50		11.33	11.40	0.82	0.806	0.37	3.44
5	3.27		670	3.50		13.94	15.70	0.82	0.900	0.33	3.75
6	3.27		631	3.50		13.11	14.20	0.76	0.900	0.33	3.27
7	3.27		752	4.50		17.73	19.50	0.76	0.714	0.44	5.97
8	3.27		772	4.87	5.00	18.92	21.40	0.76	0.917	0.34	4.92
13	4.29		679	4.41	2.50	15.83	13.90	0.82	0.897	0.33	4.23
19	3.27		704	2.65	3.00	12.73	15.20	0.76	0.956	0.37	3.59
30	5.51		354	3.33	3.00	7.17	6.90	0.76	0.972	0.38	2.08
31	5.51		740	3.92	3.50	16.26	17.20	0.76	0.875	0.30	3.74
35	3.27		584	4.58	5.00	13.89	16.10	0.82	0.932	0.35	4.03
37	5.51		373	1.85	2.00	5.64	5.60	0.76	0.972	0.38	1.63
41	3.27		811	2.00		12.74	14.10	0.82	0.929	0.35	3.67
STRAIGHT-THROUGH PIPING PRODUCTS											
9	1.00	2.03	331	1.50		4.50	10.30	0.76	0.900	0.33	1.12
10	1.00	2.02	336	2.50		5.90	13.30	0.76	0.900	0.33	1.47
11	3.35		599	0.35	0.50	3.93	4.50	0.76	0.862	0.30	0.91
12	1.00	2.02	402	2.50		7.06	17.00	0.76	0.875	0.30	1.62
14	1.00	2.02	304	1.50		4.14	8.80	0.82	0.875	0.30	1.03
15	1.00		428	5.24	5.00	10.89	11.60	0.76	0.875	0.30	2.51
16	1.00		1009	0.99	0.50	11.17	8.50	0.82	0.905	0.33	3.05
34	1.00		419	6.75	4.00	12.10	9.60	0.82	0.914	0.34	3.37
36	1.00	2.52	242	1.01	0.50	2.70	4.20	0.82	0.770	0.43	0.95
38	2.52	2.02	817	3.60		17.23	15.10	0.76	0.929	0.35	4.60
39	2.52	2.02	841	3.74	4.00	18.08	16.80	0.76	0.956	0.37	5.09
40	1.00		785	1.37	2.00	10.20	12.40	0.76	0.929	0.35	2.72