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GENERAL ELECTRIC

EXECUTIVE SUMMARY REPORT AND SUPPLEMENT

TECHNICAL BASES FOR THE SRSS METHOD OF COMBINING DYNAMIC RESPONSES

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OVERVIEW

Nuclear power plant structures and equipment are designed to accommodate many operational and transient type loads and load combinations. Included are such postulated events as the loss of coolant accident and high intensity earthquakes. In most cases for dynamic loadings, the peak structural dynamic response is calculated using linear elastic multi-degree of freedom system analysis. When two or more structural dynamic responses are considered, the peak response from each dynamic loading event is combined using the square root of the sum of square rule (SRSS). Subsequently, this combined peak dynamic response is added absolutely to the calculated static or slowly varying response. Use of the SRSS method for combining dynamic responses has been restricted to separate physical events which are postulated to occur together but for which the precise timing (phasing) is unknown. Furthermore, the use of the SRSS combinations of peak responses has also been limited to physical loading events and structural systems where the dynamic responses have rapidly varying amplitudes and short duration responses. Application of SRSS combination are limited to combining earthquake, LOCA and Safety Relief Valve (SRV) actuation dynamic responses.

To date, technical justification for the use of SRSS has centered around the facts that:

- the maximum peaks of individual responses are highly unlikely to coincide in time and
- the large conservatism in the total design process ensures sufficient structural design margin to protect against failure.

The purpose of this executive summary report is to highlight the significant results and conclusions of the Mark II SRSS study (Reference 37) and to present important information from subsequent technical studies described herein. A key result that quantitatively demonstrates the dynamic design margin inherent in nuclear plant structures designed to meet ASME Code (or equivalent) stress limits is shown to be related to the energy absorption capability of the component. For structures exhibiting even moderately

ductile behavior, this margin is significantly greater than the ratio of static failure stress to code allowable, and therefore assures sufficient additional margin to protect against structural failure even in the unlikely event that peak combined dynamic response exceeds the SRSS value.

Based on the material presented herein, it is concluded that the use of SRSS method is technically justifiable and represents a prudent and practical engineering approach for the combination of dynamic responses originating from earthquake, LOCA transients and SRV discharge loadings.

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1. INTRODUCTION

Structures and components of nuclear power facilities are designed for a large number of load combinations. Many of these load combinations include static loads combined with multiple dyamic loads. In most cases, peak responses from each of the dynamic loads are calculated elastically and are combined using the square-root-of-the-sum-of-the-square rule (SRSS). Then, the resultant peak combined dynamic response is added absolutely to the calculated static or slowly varying response. This combined maximum response is used to calculate component stresses. The maximum component stress must be shown to be lower than the code allowable values.

Since the phasing between simultaneous dynamic responses, such as earthquake and LOCA, is unknown, the SRSS rule provides a reasonable representation of resultant responses assuming their simultaneous occurrence. Combining the individual responses by direct addition of the individual response peaks by the so-called absolute sum (ABS) method is unnecessarily conservative because of the low probability of the peaks being coincident. Hence, this "probable" response combination, accounting for the low probability of coincidence, is appropriate and thus has been the most common practice. Such a probable response combination is provided by the SRSS rule.

The SRSS rule has been used in the following three distinct engineering applications (Reference 43):

- Combination of seismic modal responses,
- Combination of three responses along each of the three earthquake directions,
- Combination of two or more dynamic responses in a given direction.

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The justification for the use of SRSS in these applications is based on random vibrations and probability theory, and observation of:

- amplitude variations in time and uncertain phasing of the responses, and

- rapid variation and the short duration of the peak responses.

Thus, the maximum peaks of individual responses are unlikely to coincide. Furthermore, the probability of the actual response combination significantly exceeding the SRSS value is exceedingly small. Quantification of the above is given in Section 4.0 and Appendix A of this report.

In addition to the low probability of significantly exceeding the SRSS value, the consequences of exceedance are negligible because of:

- Existence of margins at all steps of the design process; e.g., dynamic load definition, structural models, damping parameters and allowable stress values in industry codes;

- The additional inherent structural dynamic reserve margins due to short duration of the peak responses and energy absorption capability of the structure.

These additional dynamic reserve margins are quantified in Section 5.0 of this report.

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2. CONCLUSIONS

The results of this summary report technically support the selective use of the SRSS rule for combining dynamic responses from seismic, SRV discharge and LOCA induced responses. This conclusion is based on the following factors:

1. Consistency with historical experience and technical bases. It is shown that using SRSS rule for combining multiple dynamic responses is not capricious but has substantial historical precedence and a valid technical basis.

2. There is a very low probability of the simultaneous occurrence of the individual events which produce the dynamic responses being combined.

3. The conditional probability level of not exceeding the SRSS response level, (based upon the condition that the simultaneous events and maximum calculated responses occur), has a mean non-exceedance value of 86 per cent for nearly the 600 combinations of BWR plant structural and equipment responses evaluated in this study. In addition, the conditional probability of the SRSS combined response being significantly exceeded is very small. The structural components selected for this evaluation were all significantly stressed and the response combinations chosen represent actual design cases for multiple event responses.

4. Structures have large additional dynamic reserve margins when dynamic stresses calculated by linear elastic analysis are held to ASME Code (or equivalent) allowable stresses (than when static stresses are held to this allowable stress). These additional dynamic margins provide assurance that no adverse consequence will result in the unlikely event that actual peak combined dynamic response exceeds the SRSS value and that static reserve margin are lower than expected.

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5. The very conservative design of a system for certain major dynamic loads is likely to make that system less reliable under normal operating conditions. This is especially true for piping systems and components subjected to thermal cycling. Therefore the SRSS approach leads to a balanced design, when considering both major dynamic and operational loads and is justifiable from a risk/benefit viewpoint.

6. The difference in calculated reliability of a component when designed by ABS and SRSS rules is very small.

Based on these factors, it is concluded that the use of SRSS is technically justified and represents a prudent and practical approach for design and evaluation of BWR plants.

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3. HISTORICAL APPLICATION OF SRSS

Several methods of dynamic analysis require the superposition of response components to obtain the peak responses to dynamic loading. When the phase relationships between the response components are unknown, an estimate of the net response is obtained using the SRSS rule for combining the maximum of each component response. Justification of the SRSS rule is based on statistical uncorrelation among the response components viewed as the output of a linear dynamic system to stochastic (random) input forcing functions. If the response components are essentially uncorrelated[(1)], then the variance of the total response is simply the sum of the variance of each component. Noting that the standard deviation, σ, is defined as the square root of the variance, the standard deviation of the total response is given by the SRSS of the essentially uncorrelated response component standard deviations, or

$$\sigma = \sqrt{\sum_{i=1}^{n} \sigma_i^2}$$

where the summation is over all n response components considered. Since the mean extreme-values R_i of response for each component of a narrow band system (i.e., a structural system with low damping) are proportional to their respective standard deviations (Reference 9), say $R_i = c_i \sigma_i$, it may be inferred that an estimate of the mean peak response is given by,

$$R = \sqrt{\sigma_{i=1}^{n} R_i^2}$$

which, of course, is the functional statement of the SRSS rule.

The heuristic development of the SRSS rule has prompted several empirical studies (Monte Carlo simulation) to assess the validity of the SRSS rule. Originally, the SRSS rule was suggested (Reference 28) as a means for combining modal maxima. Subsequently, the SRSS rule has had other applications

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(1) This means that it is very unlikely that peak values of the responses from all the components would occur at the same time.

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such as the combination of spatial response of a system subjected to independent excitation in three mutually orthogonal directions (Reference 8) and the combination of the effects of wave passage due to multiple support excitation of long structures (Reference 31). Most of the applications of the SRSS rule deal with the dynamic analysis of structures and equipment for earthquake ground motion. Other applications include the dynamic analysis of structures and equipment for nuclear weapons effects and shock loading for military and transportation applications. The following is a brief historical summary of the use of the SRSS rule as an estimator of peak response when the phase relationships of response components are unknown.

Rosenblueth (Reference 28) first suggested the SRSS rule for combining modal maxima in an unpublished Ph.D. thesis in 1951. The SRSS rule first appeared in published literature in 1953 (Reference 11). The justification was based on statistical analysis of earthquake ground motion viewed as a sequence of random velocity pulses. A more detailed presentation by Rosenblueth (Reference 29) followed in 1956. The use of the SRSS rule for combination of modal responses was noted by Housner (References 13, 14) for earthquake response spectrum analysis of multi-degree-of-freedom structures in 1959 and 1961. The SRSS rule was recommended for use in the modal analysis of structures subjected to nuclear weapons effects in 1961 (Reference 1). Since 1960, the SRSS rule has been the accepted method for combining modal responses in the earthquake design analysis of building structures using the response spectrum method (References 5, 16, 24, 26, 27 and 34).

A number of numerical studies have been conducted (References 7, 15, 18, 20, 21 and 23) which compare the effectiveness of the modal SRSS method as an estimator of peak response of multi-degree-of-freedom structures. Review of these studies indicates that the SRSS result tends to be a mean centered estimate of peak response for a variety of different types of input (ranging from single pulses to earthquake ground motion) to multi-degree-of-freedom structures. A general trend of the SRSS method toward more conservative estimates (i.e., above the mean) in lightly damped systems subjected to earthquake motion has also been noted (Reference 21).

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Consideration of random vibration theory has led several investigators to perform additional studies of the SRSS modal method (References 2, 4, 22, 25, 30 and 32). The use of the SRSS rule for modal analysis of light secondary systems has also been studied (References 3, 17, 33). The viewpoint of random vibration theory has provided the technical basis and limitations of the SRSS rule in modal analysis (Reference 36).

Additionally, consideration of random vibration theory indicates that the responses of a linear system to separate essentially uncorrelated input forcing functions are also essentially uncorrelated (Reference 9). Thus, the peak responses of separately applied dynamic loads may be combined by the SRSS rule to obtain an estimate of the peak response to the simultaneous applied loads if the loading conditions are essentially uncorrelated. Newmark and Rosenblueth (Reference 25) indicate that the SRSS rule is applicable for response components of systems that have negligible coupling between dynamic degrees-of-freedom even when there is some correlation between inputs. Studies (Reference 27) have indicated that the three orthogonal components of earthquake motion are essentially uncorrelated. The SRSS combination of modal response in independent directions using the response spectrum method has been demonstrated (Reference 6, 8, 10, 19) for earthquake loading. The SRSS combination of peak earthquake response in each of the three component directions is an accepted method for design analysis (Reference 12) and is reflected in the current NRC guidelines (Reference 35) as the preferred method for combination of spatial components of response for structures and equipment for earthquake effects. The SRSS combination of peak responses determined from any separate dynamic loading conditions is a valid procedure when the forcing functions are sufficiently uncorrelated.

Thus, the SRSS method of combining response components which are essentially uncorrelated has substantial historical precedence and a firm technical basis stemming from random vibration theory. The combination of multiple spatial dynamic effects due to earthquake by SRSS is the current regulatory position on the basis that the earthquake component motions (forcing functions) are essentially uncorrelated. From a technical viewpoint, the SRSS rule is equally applicable for the combination of any peak response components which are uncorrelated.

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From the above discussions, it is seen that the choice of using SRSS rule for combining multiple dynamic responses is not capricious but has substantial historical precedence and a valid technical basis.

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4. SRSS TECHNICAL STUDY SUMMARY

A technical study was conducted by GE in cooperation with the Mark II Owner's Group in 1977 to justify the use of the SRSS for combining dynamic responses. The results of this study, in the form of technical justifications for combining dynamic responses by SRSS were provided in Reference 37. Justification includes:

1. Quantification of the low probability of exceeding the SRSS values and the even lower probability of significant exceedance of SRSS (as shown in Figure 4-1) for Mark II dynamic responses,

2. Consistency with common engineering practice,

3. The low probability of the simultaneous occurrence of postulated events,

4. The negligible change in reliability when the most conservative rule (ABS) is used, and

5. Use of the SRSS combination leading to a balanced design.

Appendix A to this Executive Summary Report briefly summarizes all of the assumptions used and results generated in Reference 37 to justify the use of SRSS. The assumptions and results for each major step in the process are summarized in this Appendix. It is concluded in the study that the use of SRSS was technically justifiable and represents a prudent and practical engineering approach.

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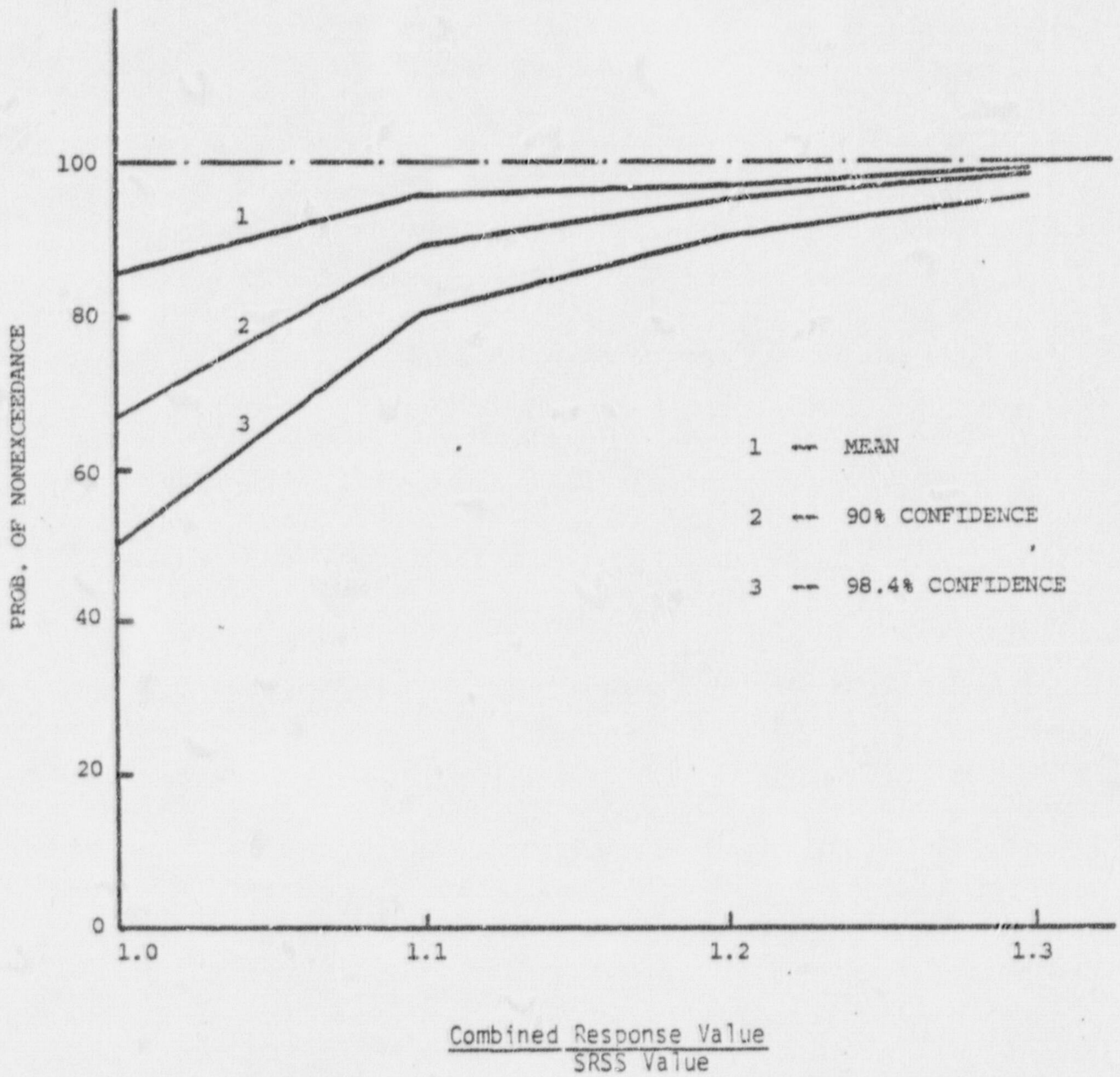

Figure 4-1. Combined Response vs. Probability of Non-Exceedance

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5. DYNAMIC RESERVE MARGINS

In addition to the technical bases covered in Reference 37, the consequences of design response exceeding SRSS response has been further considered by evaluating the actual reserve margins in structures subjected to dynamic loads and comparing them to the code design margin. This evaluation is discussed in this section.

The peak amplitudes of multiple dynamic responses of structures and components of nuclear power plants are calculated elastically and are combined using the SRSS rule. This section demonstrates that using this design method and limiting the combined stresses to ASME Code (or equivalent) allowable stress levels is very conservative. In fact, there is significant additional margin than in a design equivalent to combined static loadings and the same allowable stresses.

For static loads, holding calculated stresses to code allowable limit results in a static reserve margin (SRM) which is equal to the ratio of static load to cause failure (elastic-plastic analysis) to static load resulting in code stress limits calculated by linear elastic analysis. For dynamic loads, the dynamic reserve margin (DRM) is the ratio of the peak dynamic load to cause failure (elastic-plastic analysis) to peak dynamic load resulting in code stress limits calculated by linear elastic analysis. same as static load?

The DRM is related to the ratio of energy absorption capability at failure of the structure to its energy absorption at code allowable stress. For structures exhibiting even moderately ductile behavior, its DRM is generally many times greater than its SRM both for vibratory forcing functions and for pulsive forcing functions. The additional dynamic design margin, given by the ratio of DRM to SRM, is inherent in structures associated with transient dynamic responses such as those from earthquake, LOCA, and SRV discharge. Such additional dynamic design margin is significantly greater than that required to compensate for peak combined responses which could probabilistically exceed the SRSS value.

Examples of the additional dynamic reserve margin are quantified in this section through the study of single-degree-of-freedom (SDOF) systems with

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different natural frequencies subjected to triangular pulse and random oscillatory loadings. The results from this study are then shown to be consistent for complex structures through quantification of the design margin for a cantilevered beam subjected to oscillatory loadings.

5.1 SDOF SYSTEMS WITH TRIANGULAR PULSE AND EARTHQUAKE LOADS

This evaluation was first carried out using SDOF systems and triangular pulse type forcing functions to determine the ratio between the DRM to SRM at failure. The width of the applied pulse (t_d) was varied with respect to the fundamental period (T) of the SDOF system. The stress-strain curve for the material used is shown in Figure 5-1. Nonlinear analysis was carried out for different maximum strain levels to determine the DRM at each strain level. Results for maximum strains of 0.15 and 0.75 percent are given in Table 5-1. These results, which are typical for pulse type loading, indicate that for the maximum strain under consideration, the ratio between the DRM and the SRM is greater than 1.5, even for a very small ductility ratio[1] of 2.0.

Furthermore, from a number of nonlinear structural response analyses reported in the literature (References 39, 41) for SDOF systems with pulse type loads, it can be shown that structures even with a minimum ductility ratio of 2.0 have a DRM to SRM ratio of 1.5 or more for t_d/T values up to about 1.25. This is consistent with the results given in Table 5-1 and the conclusions drawn from it.

Following the triangular pulse analysis, SDOF systems were evaluated for earthquake loads to determine the additional dynamic reserve margin. This was achieved by reviewing and rearranging the dynamic response results to earthquakes contained in Reference 41. This indicated that structures with even moderate ductility nearly always have dynamic/static margins of at least 1.5 except at high structural frequencies.

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[1] Ductility ratio is defined as the ratio of the maximum acceptable deflection (or strain) to the deflection (or strain) at the effective yield point of the structure.

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5.2 SDOF SYSTEM WITH TYPICAL EARTHQUAKE AND SRV LOADS

This section describes some of the illustrative examples and the associated results utilized to show that even when the actual peak combined response exceed the SRSS combined response, the consequence of this exceedance is negligible because the DRM is much larger than SRM. For this purpose, SDOF models with natural frequencies of 5 and 16 Hz and material properties as shown in Figure 5-2 were subjected to a normal load (N) which would result in a static stress of 0.4 S_m and a combination of a design earthquake and safety relief valve (SRV) discharge loadings. These frequencies and material properties were chosen because they are representative of the frequencies and material of typical BWR components. The dynamic loadings were scaled such that the normal load response plus the SRRS combination of equal magnitude of earthquake (EQ) plus SRV responses would result in a total stress (S) equal to the Code limit for Level C Service, i.e.,

$$S = N + \sqrt{(EQ)^2 + (SRV)^2}$$

where S is the Code allowable stress for Level C Service.

For this system, four cases were analyzed. For the first case only the normal and earthquake loads amplified by the SRM (equal to 2.214 for Level C Service), were applied. This amplified load if applied statically would result in a stress which is 78.5 percent of ultimate static stress capacity of the structure. It is, however, shown in Table 5-2a that the calculated response from an elastic-plastic dynamic analysis, strain was nowhere near the failure strain. The 16 Hz model was the more critical with 36 percent of the ultimate capacity being reached. This indicates a substantially greater reserve margin under static plus dynamic earthquake loading than under static loading of equal magnitude.

For the second case, the dynamic loads (earthquake and SRV) were combined by direct addition (equivalent to ABS) with peak elastic response time phasing and then was added to the normal load (N). This combined load was used in dynamic inelastic analyses of the 5 and 16 Hz SDOF systems. The results are given in Table 5-2b. Evaluation of results given in this table shows

that peak strain response (ε_{max}) for the 5 and 16 Hz models subjected to worst case time phasing is only slightly higher than the yield strain and is only 1 percent of the ultimate strain. When comparing the strain increment (ε_{max} - ε_y) to the difference between ultimate strain (ε_{ult}) and strain corresponding to code allowable stress for Level C (σ_y), it is seen that only a very small fraction (≈0.3%) of the strain available beyond code limits is used to accommodate the worst combination of peaks.

For the third case, all loads (normal, earthquake, and SRV) were multiplied by the SRM for Level C Service and applied in the worst phase condition. These amplified loads (i.e., loads multiplied by SRM) would result in calculated strains equal to ultimate strains if applied statically. For this case, twenty four trials with different phasing between loads were used to determine the worst phasing conditions between the dynamic loads to produce the highest combined response and thus equivalent to using the ABS rule. A dynamic inelastic analysis was then performed. The results of this analysis are given in Table 5-2c. A comparison of the results of this case (Table 5-2c) and first case (Table 5-2a) show that for the load combination considered, most of the strain is due to earthquake with a small contribution from SRV loads. In addition, the results (Table 5-2c) showed that even for the worst phase combination case (this case is equivalent to increasing the SRSS of dynamic response peaks by a factor equal to 1.41) multiplied by a factor equal to the SRM, the maximum strain is less than half the ultimate strain (equal to 41 percent of the ultimate strain for the 16 Hz case).

The fourth case is same as the third except that the dynamic loads were multiplied by a factor equal to 1.25 for the inelastic analysis. The results given in Table 5-2d show that maximum strain for this case (which is equivalent to increasing the SRSS of dynamic response peaks by a factor equal to 1.77 times SRM), is still very much less than the ultimate strain (equal to 61 percent of the ultimate strain for the 16 Hz case).

This study as in the case of the pulse type loading (Section 5.1), illustrates the principle that DRM is much larger than SRM and as such the consequence of actual peak combined response exceeding the SRSS combined response is negligible. It is noted here that even higher additional dynamic reserve margin would exist for Level D Service limits.

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Hence, it is concluded that even if the SRSS combination of the peak dynamic responses is exceeded, the probability of reducing the ASME Code (or equivalent) reserve margin against failure is extremely low and hence the consequences of exceeding the SRSS combined responses are negligible.

In addition, results from Table 5-2b also show that only a very small fraction of the strain available beyond code limits is used to accommodate ABS combination of peaks. This is consistent with the ASME Section III design code philosophy which recognizes that some inelastic strain may occur at Level C Service allowable stress limits. Clearly this very small increment of inelastic strain is considered inconsequential to structural integrity.

5.3 BEAM SUBJECTED TO EARTHQUAKE AND SRV LOADS

The DRM was also evaluated for a multi-degree-of-freedom (MDOF) system in the form of a cantilever beam, subjected to earthquake and SRV type random loadings. The beam properties were chosen such that its fundamental frequency was 25 Hz. The material properties for the beam are the same as shown in Figure 5-2. This frequency and material properties are representative of some BWR components. The normal load (N) was chosen such that it produced a static stress of 0.4 times the allowable stress limits for ASME Level C Service. The procedure used to amplify the dynamic loads using the Code SRM was similar to that used in Section 5.2. The beam was analyzed with the computer program ANSYS (Reference 42) using the plastic beam element and the non-linear dynamic analysis option. The results of this analysis are given in Table 5-3 which shows that even when the dynamic loads are multiplied by 1.5, only about 44 percent of the ultimate strain of the material is used. It should be pointed out that considerably higher additional dynamic reserve margin would result if higher strain limits are utilized. Higher strain limits are permitted by the indicated material properties shown in Figure 5-2, but have not been used in this study.

Consistent with Section 5.1 and 5.2, the beam model also shows larger reserve margins under dynamic loads as compared to static loads. In fact, the additional dynamic reserve margins in this case was higher for complex structures (such as beams) than for the simple SDOF system.

5.4 CONCLUSIONS

It is shown that dynamic reserve margin inherent in nuclear power plant structures designed to meet ASME Code (or equivalent) stress limits is related to the energy absorption capability of the component and this margin is significantly greater than the static code design margin. Even for structures with minimal ductility ratios, the DRM is generally 50 percent greater than the SRM. This is true for both longer duration vibratory events such as those resulting from earthquakes as well as for short duration pulsive loads.

Table 5.2a

RESULTS FOR [N + K_1 (EQ)] SRM

Model Frequency (Hz)	ε_{max}	$\varepsilon_{max}/\varepsilon_{ult}$
5	0.0110	0.07
16	0.0537	0.36

Table 5.2b

RESULTS FOR [N + K_1(EQ) + K_2 (SRV)]*

Model Frequency (Hz)	ε_{max}	ε_y	$\varepsilon_{max}/\varepsilon_{ult}$	$\frac{\varepsilon_{max} - \varepsilon_y}{\varepsilon_{ult} - \varepsilon_y}$
5	0.0014	0.00104	0.01	0.242%
16	0.0015	0.00104	0.01	0.309%

Table 5.2c

RESULTS FOR [N + K_1 (EQ) + K_2 (SRV)] SRM**

Model Frequency (Hz)	ε_{max}	$\varepsilon_{max}/\varepsilon_{ult}$
5	0.0163	0.11
16	0.0621	0.41

Table 5.2d

RESULTS FOR $\left[N + 1.25\ [K_1\ (EQ) + K_2\ (SRV)]\right]$ SRM

Model Frequency	ε_{max}	$\varepsilon_{max}/\varepsilon_{ult}$
5	0.0255	0.17
16	0.0908	0.61

* Peak elastic response time phasing, equivalent to ABS

** Peak inelastic response time phasing

NOTE: K_1 (EQ) = K_2 (SRV); EQ = earthquake load.

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Table 5-1

RESULTS FOR SDOF SYSTEM SUBJECTED TO A TRIANGULAR PULSE

Width of Pulse/ Natural Period of SDOF	Reserve Margin* Static	Reserve Margin* Dynamic	Maximum Strain (ϵ_{max})-%	Dynamic Reserve Margin/ Static Reserve Margin	Ductility Ratio μ
0.1	1.15	4.52	0.75	3.93	10
0.2	1.15	4.52	0.75	3.93	10
0.3	1.15	4.47	0.75	3.89	10
0.4	1.15	4.34	0.75	3.77	10
0.5	1.15	4.23	0.75	3.68	10
0.1	1.03	1.75	0.15	1.70	2
0.2	1.03	1.75	0.15	1.70	2
0.3	1.03	1.75	0.15	1.70	2
0.4	1.03	1.74	0.15	1.69	2
0.5	1.03	1.71	0.15	1.66	2

For Service Level C, ASME Code allowable primary membrane stress limit at 550°F = S_y = 18.50 ksi (From Figure 4-1).

$$\text{Static Reserve Margin (at } \epsilon_{max} = 0.75\%) = \frac{S_{(\epsilon max = 0.75\%)}}{S_y} = \frac{21.25}{18.50} = 1.15$$

$$\text{Static Reserve Margin (at } \epsilon_{max} = 0.15\%) = \frac{19.0}{18.5} = 1.03$$

*Much higher static and dynamic reserve margins actually exist. The low static margins shown here are due to the selection of assumed low maximum strains (.75% and .15%).

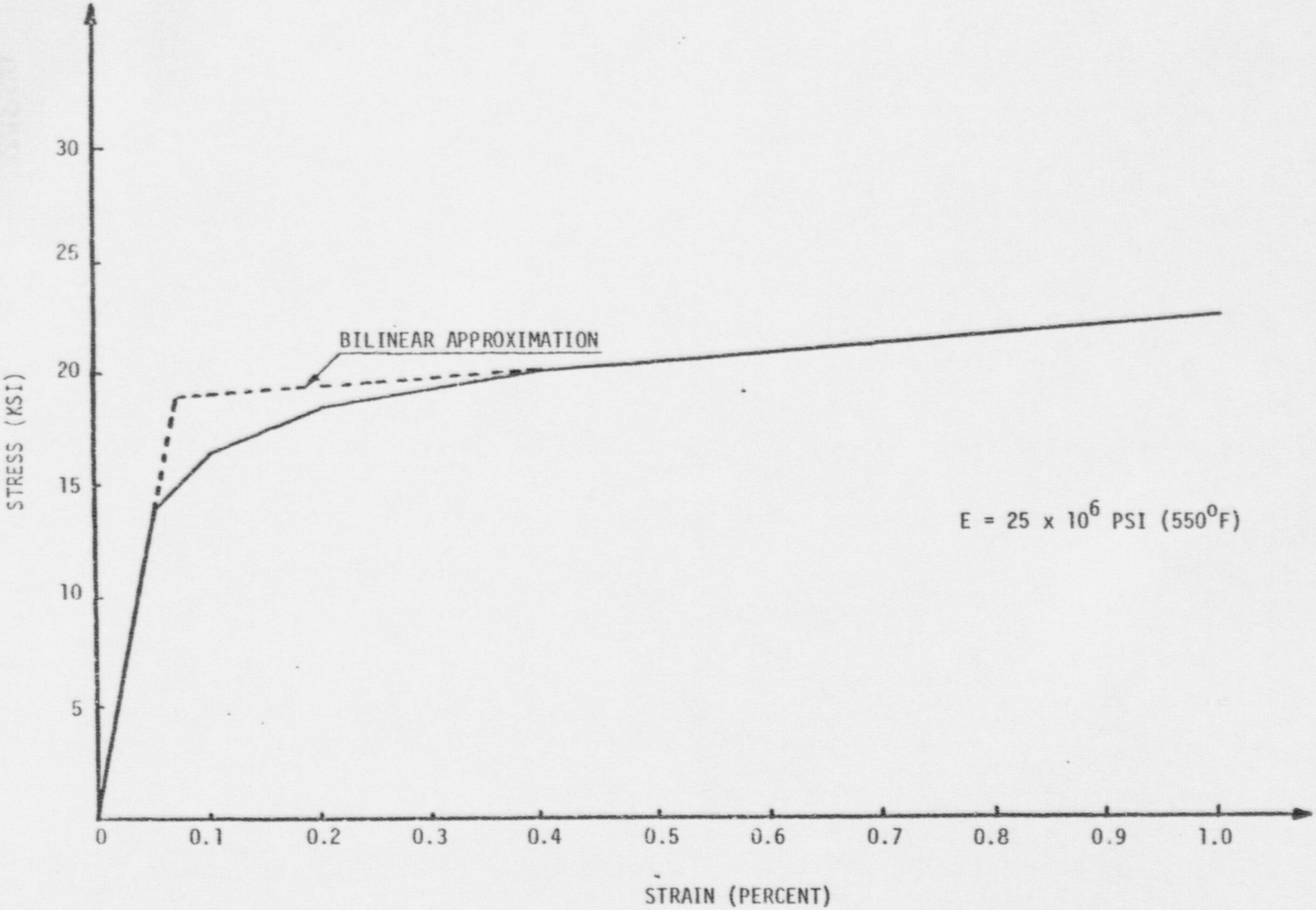

Figure 5-1. Code Minimum Stress-Strain Curve for 304 Stainless Stell at 550°F

Table 5-3

ANALYSIS RESULTS FOR MDOF (BEAM) SYSTEM

Description of Case	ε_{max}	$\varepsilon_{max}/\varepsilon_{ult}$
$[N + K_1(EQ) + K_2(SRV)]$ SRM	0.0351	0.23
$[N + 1.25[K_1(EQ) + K_2(SRV)]]$ SRM	0.0475	0.32
$[N + 1.5\,[K_1(EQ) + K_2(SRV)]]$ SRM	0.066	0.44

NOTE: $K_1(EQ) = K_2(SRV)$: SRM = Static Reserve Margin

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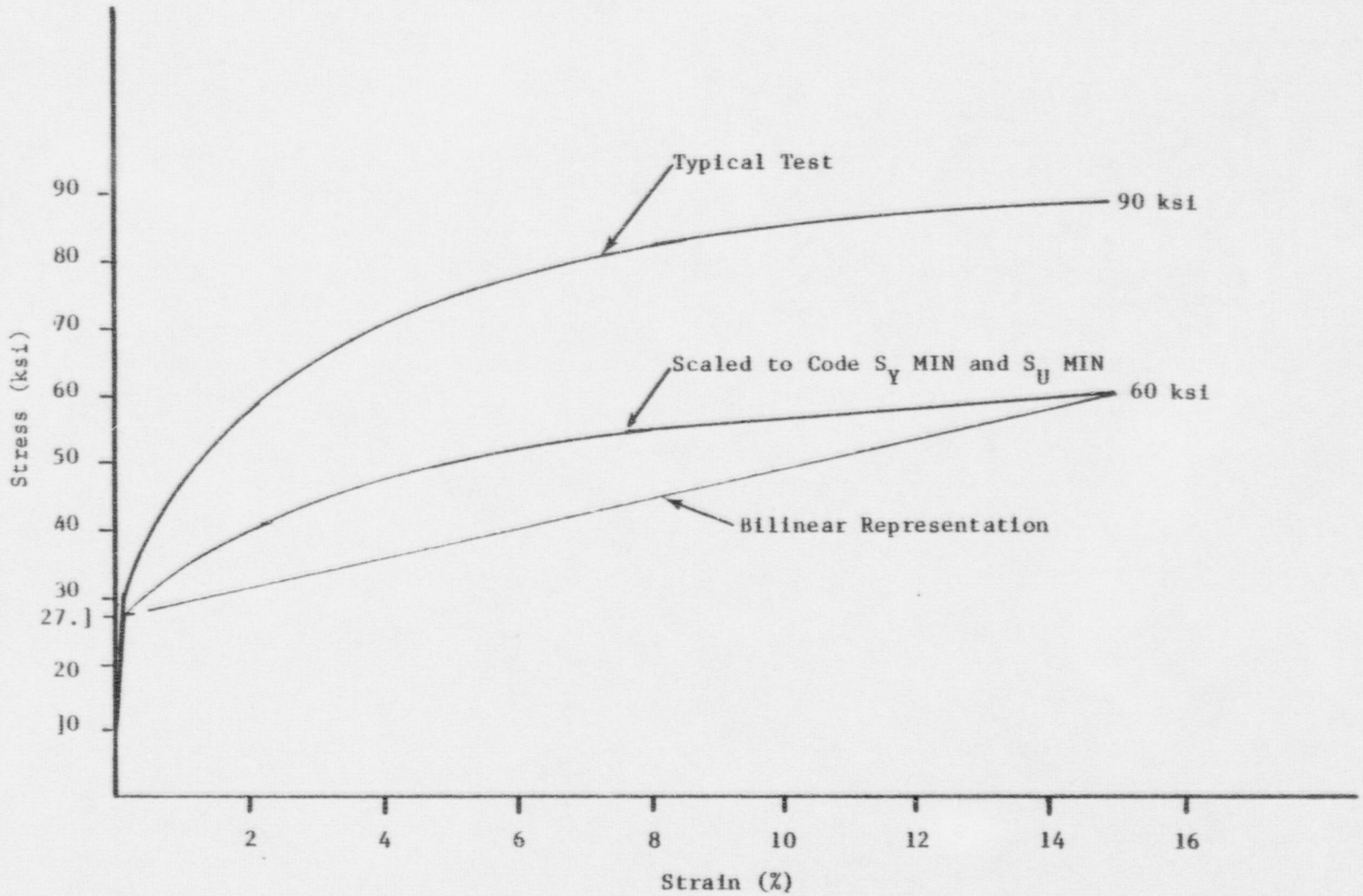

Figure 5.2 Stress-Strain Relationship SA-106B Material - 550 °F

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6.0 SRSS APPLICATION CRITERIA

On the basis of the material discussed in Sections 3, 4 and 5; which focuses on probabilistic concepts, the negligible structural consequences of exceeding SRSS value and consistency with accepted engineering practice, it is concluded that the selective use of the SRSS method for combining dynamic responses for earthquake, LOCA and SRV loadings is technically justifiable. The application criteria adopted for BWR plant design are:

1. The individual dynamic responses considered (earthquake, LOCA and SRV) are either from independent sources or, can be considered to have random peak phasing, and

2. The individual responses have rapidly varying amplitude and short duration peak responses.

Furthermore, it is shown that structures and components designed in accordance with ASME (or equivalent) code allowable stress limits, have inherent additional dynamic design margins to accommodate dynamic loads. This results primarily from the ductility ratios associated with structures designed and fabricated in accordance with applicable nuclear regulatory guides, industry codes and standards (Reference 44). Quantitative example of the additional dynamic design margin inherent in structures for a range of ductility ratios subjected to a short duration triangular pulse is shown in Figure 6-1. It can be seen from this figure that even in the event the SRSS value is exceeded, sufficient structural margin will exist to prevent failure.

Piping?

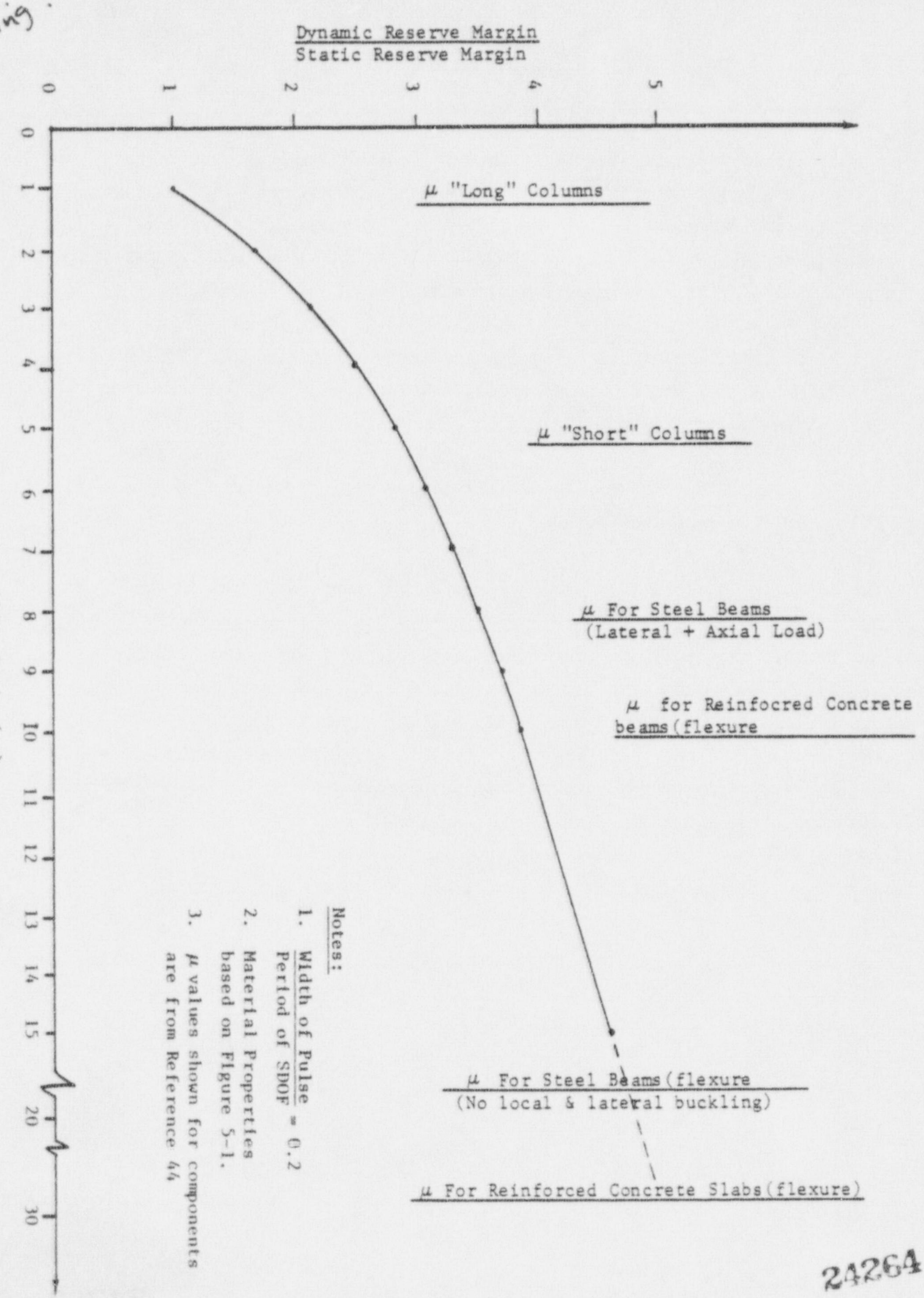

Figure 6-1. Typical Relationship of Ductility Ratio versus Additional Dynamic Margins for a Triangular Pulse

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Appendix A

SRSS TECHNICAL STUDY SUMMARY

This appendix briefly summarizes all the assumptions used and results generated in Reference 37 to justify the use of SRSS. Figure A-1 is a graphical display of the logic followed in the study and Figures A-2 through A-5 summarize the assumptions and results in each of these steps. In addition, these are also described below.

A.1 Individual Event Probability

A.1.1 Assumptions

The individual event probabilities, such as those for earthquake, safety relief valve (SRV) actuation, and LOCA events, are based on historical occurrences and operating plant data. These are required for computing the combined event probability for a given load combination.

Many of the individual event probability data were normalized to one-year encounter priods. In order to obtain combined probabilities for a 40-year plant life, a constant rate process (the Binomial process) was assumed for the individual probabilities.

A.1.2 Results

The individual event probabilities computed were compared with those given in the Rassmussen report (Reference 40) and were found to compare favorably with those in the Rassmussen report.

A.2 Combined Event Probability

A.2.1 Assumption

Individual event occurrence probabilities form the basis for determining joint event probabilities when the individual events

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are postulated to occur simultaneously. However, realistic joint event probabilities must be computed assuming some dependences of one event on another. For example, although not a licensing basis, in the reliability evaluation in this study, the LOCA event is assumed to be dependent on an earthquake event when simultaneous occurrences of both events are postulated. If such dependence is not accounted for where appropriate, the joint event probabilities would be incorrectly estimated. Combined events probability for a load combination is used in the reliability computations of a component.

A.2.2 Results

The study showed that the joint encounter probability of rare events, such as SSE and LOCA are less than 10^{-5} per 40 years. Such small encounter probabilities provide added assurance that the combination of structural responses due to dynamic loads will not be critical to safety evaluation.

A.3 Conditional Non-Exceedance Probability

A key basis for combining maximum dynamic responses using the SRSS rule is that the individual responses vary with time and thus it is highly unlikely that their maxima would coincide. This study quantifies the conditional probability P(SRSS) of non-exceedance of the SRSS value, given that the dynamic events, being combined are assumed to occur simultaneously.

A.3.1 Assumptions

Since the time phasing among dynamic events are unknown, they have been assumed to be randomly distributed. Consequently, by varying the time phasing randomly (for example through Monte Carlo trials) and summing the responses, the Probability Density Function and the Cumulative Distribution Function (CDF) of the maximum resultant

responses can be obtained. The CDF is the quantiative relationship between the maximum summed response and its non-exceedance probability.

A.3.2 Results

A.3.2.1 Conditional Non-Exceedance Probabilities

CDF calculations were performed for a large number (291 cases) of representative load combinations for the reactor pressure vessel (RPV), piping and containment structure of actual Mark II plants. Statistics of the conditional non-exceedance probability for different combined response levels have been evaluated and are shown in Figure 4-1 and in the table given below:

	Conditional Non-Exceedance Probability			
	SRSS	1.1 (SRSS)	1.2 (SRSS)	1.3 (SRSS)
Average value	86%	95.5%	96.5%	99%
Value above which 90% of cases fall	>67%	>89%	>95%	>98.5%
Value above which 98.4% of cases fall	>50%	>80%	>90%	>95%

The following points may be observed from the results given in the table and Figure 4-1.

*The SRSS value has an average non-exceedance probability of 86% for the Mark II plants.

*In 90 percent of the cases, the non-exceedance probability of the SRSS value is greater than 67%.

*In 98.4% of the cases, the non-exceedance probability of the SRSS value is greater than 50%.

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*In all cases the probability of non-exceedance is significantly increased for combined response values higher than the SRSS value.

The structural components selected for this evaluation were all highly stressed and encompass all significant events. The response combinations chosen represent actual design cases for multiple event responses. Although the analyzed responses themselves were for a specific plant, generic application of the results is justifiable since the evaluation included many structural systems with widely varying dynamic characteristics. This is further supported by the results of the sensitivity study described in Section A.3.2.2.

LOCATION FOR RESPONSES

Location	2 Dynamic Loads	3 or More Dynamic Loads	Total
Reactor and Internals	19	3	22
Piping	51	18	69
Structure	80	120	200
Response Combination	150	141	291

For each of these 291 cases tabulated, both[1] the negative and the positive cumulative distribution functions and the associated probability of non-exceedance of the SRSS value were determined. Thus, a total of 582 non-exceedance probabilities were computed.

A.3.2.2 CDF Parametric Sensitivity Studies

The various parameters that are likely to affect the CDF distribution and associated non-exceedance P(SRSS) are: time history duration, phase distribution between the time histories, frequency contents and the amplitude ratios of the time histories being combined. Consequently a sensitivity study was performed as a part of Reference 37 study to determine the effect of their variation on the CDF

(1) Since the earthquake direction is unknown, both the negative and positive peaks are considered separately when combining with another dynamic response.

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distribution and the P(SRSS). The results of the sensitivity study are summarized as follows:

(i) Change in duration of the reference (longest) time history by a ratio 10:1 resulted in a maximum decrease of P(SRSS) by 25 percent.

(ii) Changes in the assumed phase distribution between the time histories from uniform to triangular or sinusoidal, resulted in less than 10 percent change in P(SRSS).

(iii) Effect of amplitude ratios on P(SRSS) for piping was found to be the highest for two responses with near equal amplitude (important design case) and approached 50 percent for cases where one amplitude is significantly higher than the other. No other distinct response amplitude trends were evident.

(iv) The frequency contents of the responses being combined (ranging from 3 to 60 Hz) were generally quite random and did not exhibit any readily apparent effects on P(SRSS).

From these results, it was observed that the P(SRSS) values for the complex reactor plant structures subjected to the dynamic loading events included in Reference 37, are quite insensitive to those parameters which are likely to affect the CDF distribution. Therefore, it was concluded that the non-exceedance probabilities determined in Reference 37 are typical of those that would be evaluated for BWR plant structures.

A.4 Comparative Reliability Evaluation

A detailed discussion and method of analysis for evaluating the probability of failure of a component designed to meet the ASME code limits is given in Reference 37. For the purpose of this summary report, only the key ideas, assumptions and results of the study will be highlighted.

Conceptually, the probability of failure of a component can be thought of as the product[1] of three probabilities, i.e.,

$$P_f = P_1 \times P_2 \times P_3$$

where

P_1 = the probability of the simultaneous occurrence of the two or more events loading the components (see Sections A.1 and A.2).

P_2 = the conditional probability (given that the events have occurred simultaneously) of stress due to actual response exceeding the design stress (see Section A.3).

P_3 = probability of the actual stress exceeding the ultimate strength. In Reference 37, the classical strength vs. stress theory has been used.

P_f = failure probability, and $R = 1 - P_f$, where

R = reliability of a component.

The assumptions used in this analysis are:

1. Individual responses being combined are deterministic,

2. Material strength distribution is defined using the ASME III criteria.

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[1] In the strict mathematical sense, these are convoluted.

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3. Historical probability of structural failure data is known when the actual stress is less than or equal to the normal ASME stress limits.

More details on the validity of assumptions and on the reliability calculations are available in Reference 37 and also in Figures A-1 through A-5.

The reliability was calculated for several typical structural components using both SRSS and absolute sum (ABS) rules. Significant results are;

(i) P_2, the conditional probability value of non-exceedance, of SRSS per se, is not a significant contributor in terms of total reliability of a component.

(ii) The difference (gain) in reliability of a component designed to the ABS rule is considered negligible; for the cases considered, the range of reliability values are 0.99999425 to 0.99999750 for SRSS and, 0.99999680 to 0.99999750 for ABS rule

Thus, the negligible increase in reliability benefit for design to ABS instead of SRSS does not justify the potential cost increase by going from SRSS to ABS in the design.

A.5 Consistency with Accepted Engineering Practice

In addition to the consideration of the non-exceedance probability P(SRSS) and the negligible changes in reliability between the use of the SRSS and the ABS rule, justification of the use of the SRSS method also includes consistency with accepted engineering practice as outlined in Section 3.0.

A.5.1 Assumption

Accepted engineering practice is assumed to be those long standing procedures recommended in open literature by eminent engineers or

prominent industrial and national engineering organizations. This assumption is justified since structural dynamics is highly specialized, and until recently, no industry codes or standards existed.

A.5.2 Results

Reference 37, using established procedures in seismic analysis and probability theory, evaluated the conditional probability of non-exceedance associated with the applications of SRSS. The results of this evaluation are consistent with the historical basis for the use of SRSS as described in Section 3.0.

Furthermore, the procedure utilized to determine P(SRSS) and that for combining dynamic responses in this report is consistent with that recommended in Reference 43.

A.6 Balanced Design, Overall Reliability, and SRSS

Component design can encounter conflicting objectives. On the one hand, the design must be flexible so that thermal expansion does not cause excessive stresses under normal plant operation. On the other hand, the design needs to be sufficiently rigid so that primary dynamic stresses under extreme load, such as seismic, do not cause excessive inertial stresses. Since these two design considerations tend to work against each other, adding additional conservatism for the major dynamic loads will decrease the overall reliability due to the increased thermal cycling reaction forces and stresses. Structural systems tend to be somewhat forgiving of errors when they are designed to be too flexible, i.e., if higher than design dynamic loads occur, additional structural energy absorption capacity due to its flexibility would resist such load increases. Furthermore, structural systems tend to be less forgiving when they are designed to be too stiff, i.e., the expansion stresses in some local region due to constraints may severely reduce fatigue life below that considered

in the design. This discussion shows that component reliability may actually increase by the use of the SRSS rule rather than ABS rule for combining dynamic responses. This can be seen semiquantitatively in Figure A-6 (Reference 38), where it has been shown analytically that too little flexibility for piping is about 5 times more likely to cause failure than too much flexibility.

Thus, the application of SRSS rule for combining responses due to extreme loads in the design should result in a more balanced plant design when considering both normal operational transients and major dynamic loads.

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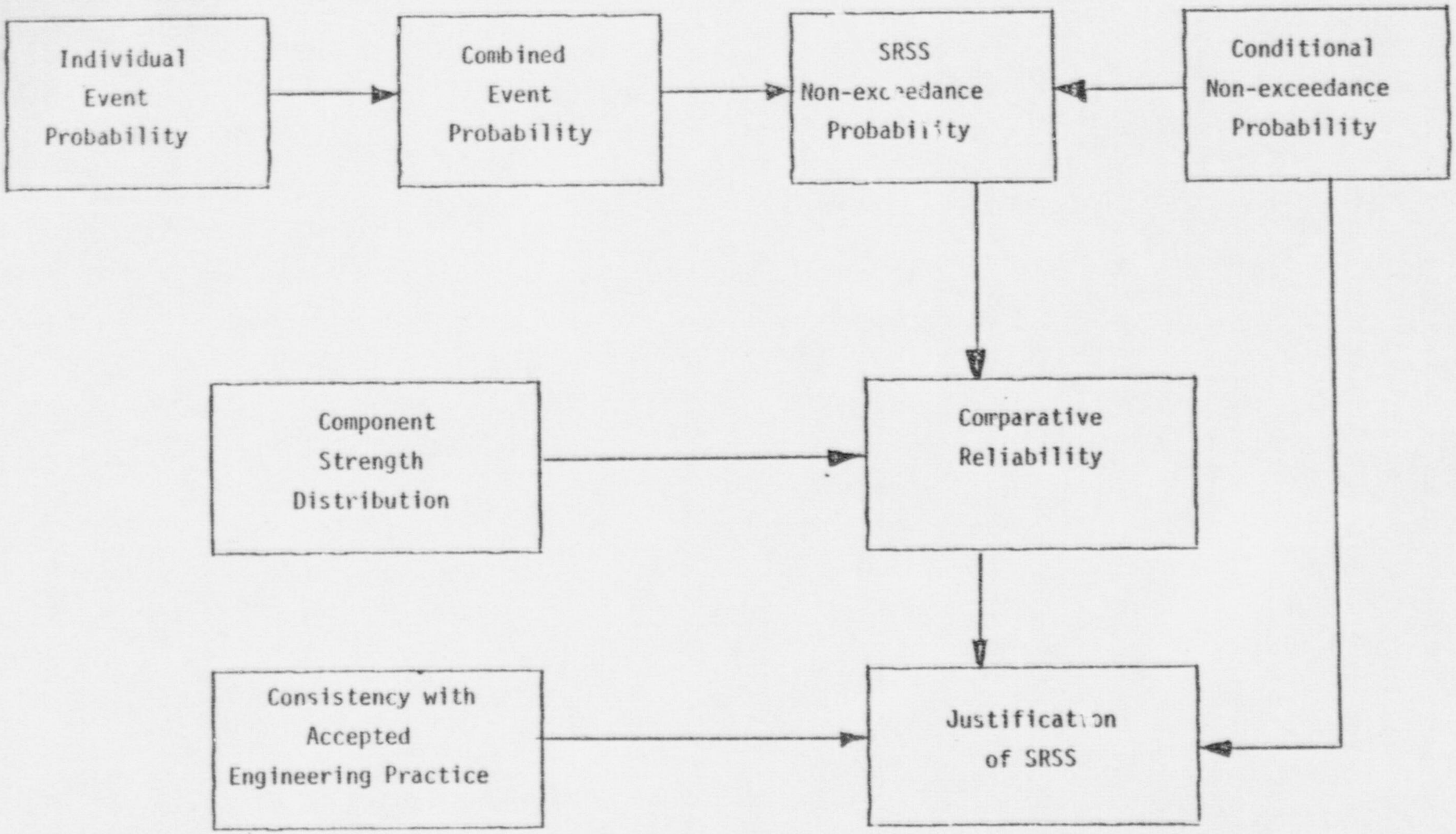

Figure A-1. Basis for SRSS Justification

INDIVIDUAL EVENT PROBABILITY

- Assumptions
  - + Past experience is the basis of assigning future event probabilities.
  - + Individual event probabilities follow a constant rate process.
- Result
  - + Calculated event probabilities are consistent with Rasmussen report.

COMBINED EVENT PROBABILITY

- Assumptions
  - + Event dependence required for quantification of realistic joint probability.
- Results
  - + Combined rare events encounter probabilities are small.
  - + Combined event probabilities are not overly sensitive to uncertainties in input parameters.

Figure A-2

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CONDITIONAL NON-EXCEEDANCE PROBABILITY

- Assumption
  - + Dynamic Responses to separate events have uncertain (random) phase relationship.
- Results
  - + Non-exceedance probabilities of SRSS-combined responses are large.
  - + Non-exceedance probabilities are not overly sensitive to response duration, phase distribution, and other parameters.

SRSS NON-EXCEEDANCE PROBABILITY

- Assumption
  - + Individual design responses have low exceedance probabilities
- Results
  - + SRSS total non-exceedance probabilities are close to unity.
  - + Non-exceedance probabilities are needed for reliability computation.

Figure A-3

COMPONENT STRENGTH DISTRIBUTION

- Assumptions
  - + Strength distributions can be described by a modified Weibull curves with three parameters.
  - + The nominal strength parameter in the Weibull distribution is the strength allowed by ASME Section III under service level A conditions.
  - + The maximum ultimate strength parameter is 3.6 times the service level A limits.
  - + The minimum ultimate strength parameter is 3 times the service level A limits.

- Results
  - + Comparative reliability results not sensitive to reasonable values of strength parameters.
  - + Assumed strength distribution consistent with failure data, normal code margins, and variations in code margins.

COMPARATIVE RELIABILITY

- Assumptions
  - + The plant life failure probability for each component under normal conditions can be based on field data and ranges between 2×10^{-4} and 2×10^{-5}.
  - + The failure probability of structures loaded to the minimum strength is 0.30.
  - + One-dimensional analysis adequate for comparative reliability calculations.
  - + Event classification given in GESSAR and ANS 50-WG2 are applicable.
- Results
  - + Comparative reliability results not overly sensitive to failure probability assumptions and other parametric values.
  - + No direct correlation exists between reliability and SRSS non-exceedance probability.
  - + Comparative reliabilities for components using SRSS and ABS rules are not significantly different.

Figure A-4

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CONSISTENCY WITH ACCEPTED ENGINEERING PRACTICE

- Assumption
  + Recommended procedures in open literature by eminent engineers constitute accepted engineering practice.

- Results
  + SRSS used in general earthquake engineering and nuclear weapon effects for modal analysis since 1951.
  + SRSS used for combining 3 directional earthquake effects since 1972.
  + SRSS used for combining different dynamic responses since 1973.

Figure A-5

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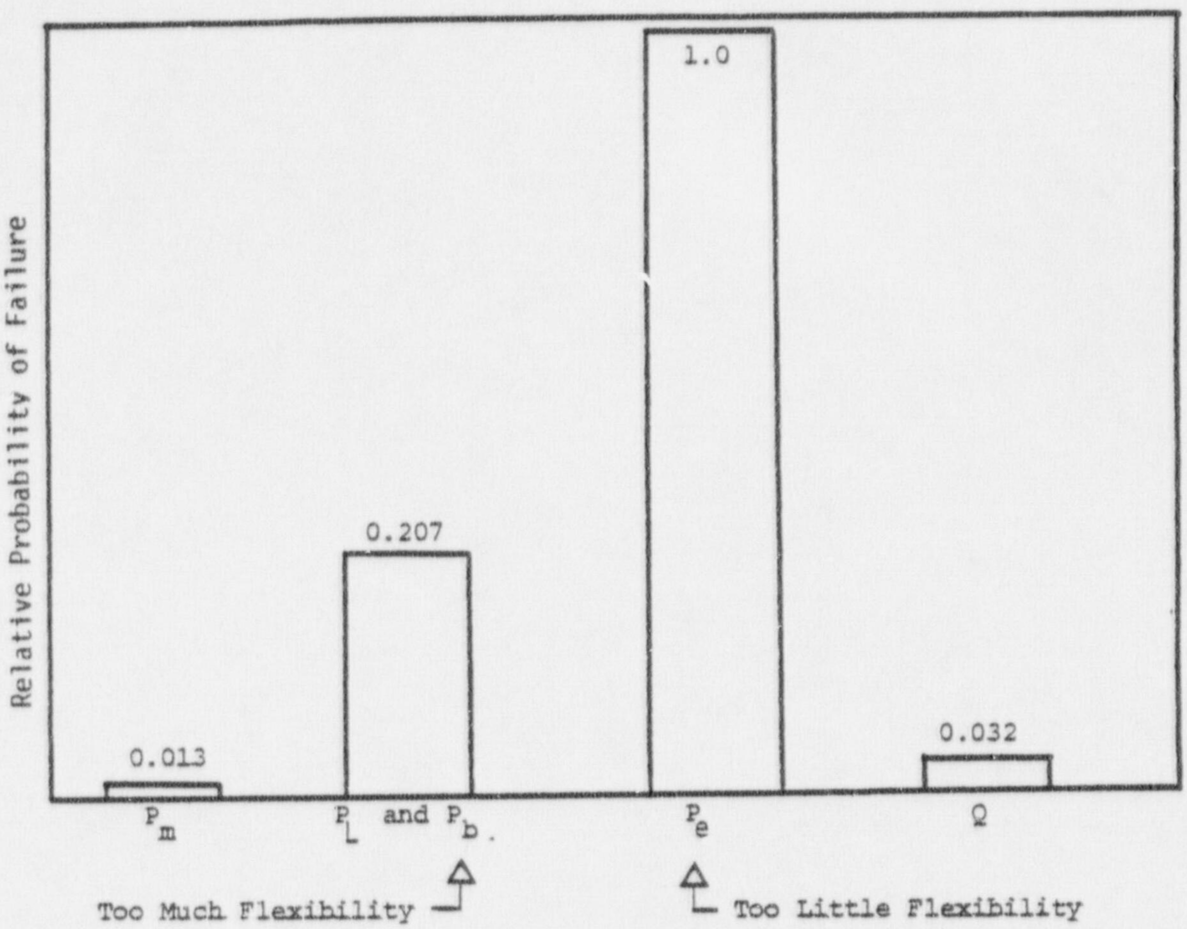

P_m - general membrane (primary) stress
P_L - local membrane (primary) stress
P_b - bending (primary) stress
P_e - expansion (secondary) stress
Q - membrane plus bending (secondary) stress

Figure A-6. Impact of Flexibility on Piping Reliability (Reference 38)

DISTRIBUTION

NAME	M/C
N. J. Biglieri	752
W. M. Davis	767
D. C. Ditmore	150
W. F. English	775
L. F. Fidrych	155
Ed Fuller	682
L. S. Gifford	Bethesda
W. D. Gilbert	685
W. A. Grafton	584
G. L. Gyorey	806
K. G. Hazifotis	681
R. A. Hill	682
R. D. Hoagland	150
P. W. Ianni	777
A. J. James	195
E. Kiss	145
L. K. Liu	775
J. E. Love	167
J. K. Martin	150
L. L. Myers	584
F. Reuter	666
R. R. Roof (7)	126
G. G. Sherwood	676
L. J. Sobon	681
P. P. Stancavage	195
J. Stapleton	150
S. J. Stark	195
C. V. Subramanian	775
E. O. Swain	760
T. A. Trumbull	602
G. E. Wade	767
B. E. Woodward	394
NEBG Library (5)	328
VNC Library (2)	VNC-102
CSSD File (5)	584

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