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Realistic Seismic Design Margins of Pumps, Valves, and Piping

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ABSTRACT

Seismic design margins indicate the adequacy for earthquake resistance of pumps, valves, piping, and their supports used in nuclear power plants. The margins that exist with the allowable stresses given in applicable codes and standards are reviewed in this report. Nuclear industry practice with respect to concrete expansion anchor bolts and operability of pumps and valves are also reviewed. Examples of specific applications are included to illustrate the significant seismic design margins which are present in the systems and equipment in nuclear power plants.

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EXECUTIVE SUMMARY

(1) Allowable Stresses and Margins

In Safety Evaluation Reports, the adequacy of some items is often expressed in the form:

$$\text{Seismic Margin} = \frac{\text{Allowable Stress}}{\text{Calculated Stress}} = \frac{S_A}{\sigma_c}$$

The allowable stress is based on an applicable industry standard or code that always has a built-in margin of safety on ultimate strength. The calculated stress is determined by an analysis of the loads, including operating loads, dead weight, and earthquake loadings.

The Seismic Margin must be equal to or greater than 1.00. However, for some items, the Seismic Margin may be close to 1.00. The question arises: If the loads are underestimated such that σ_c is actually higher than calculated, will the item fail?

The question can be answered in terms of Nominal Margins defined as S_u/S_A or S_y/S_A, where S_u and S_y are the tensile and yield strength of the material, respectively. Nominal Margins indicate the reserve strength that is available when the Seismic Margin is 1.00. Nominal Margins depend upon the source of the allowable stress, S_A, which in turn depends upon the material and temperature. For a representative range of materials and temperatures, Nominal Margins on breaking range from

3.0 to 10.4, ASME Code Level B Stress Limits
1.43 to 5.2, ASME Code Level D Stress Limits
2.6 to 3.1, AISC Manual Basic Stress Limits
2.0 to 2.3, AISC Manual Seismic Stress Limits

These represent lower bounds on the margin of safety available for seismic-induced stresses that might be larger than those used in calculating the stress σ_C. They are lower bounds because σ_C is the result of all loads, not just the seismic-induced stresses.

The ASME Code Level B stress limits, and the AISC Manual basic and seismic stress limits preclude gross yielding. However, the ASME Code Level D stress limits do not necessarily preclude gross yielding; conceptually under Level D stress limits, yielding may occur but not breaking.

The preceding discussion applies directly to failure by tensile loads. Limitations in the ASME Code and AISC Manual on other types of loads--such as compressive loads with elastic or elastic-plastic instability, shear loads, bending moments and combinations of those loads--give about the same Nominal Margins as cited above for tensile loads.

(2) Concrete Expansion Anchor Bolts

Available test data indicate that, by using 1/4 of average strength as a design basis, the probability of failure at two times the design load is about 0.023 and at the design load, is less than 0.001. These estimates are based on the assumption that the anchor bolts are installed with the skill and care that is at least equivalent to that used in preparing the test installations.

(3) Operability

Operability of pumps and valves may be evaluated, in part or whole, by checking such aspects as bearing loads, impeller clearance, and shaft deflections for pumps, and yoke and/or stem lateral displacements for valves. Because limits for such aspects are established by the manufacturers with their specialized knowledge of their equipment, we cannot generically quantify the capacity of their equipment to exceed their limits.

Seismic qualification of complex mechanisms such as valve operators may be achieved by testing of the type described by Institute of Electrical and Electronic Engineers standards. Most test results are from "proof" tests; that is, the item operated during and after the test. That item may have been able to pass a test of several times the g-load used in the test. Accordingly, a Seismic Margin of 1.00 based on proof tests may correspond to a Nominal Margin significantly greater than 1.00, but not necessarily.

(4) Specific Applications

Examples of the development of Seismic Margins and Nominal Margins for pumps, valves, and piping bring out the aspect that σ_c used in defining Seismic Margins and Nominal Margins is seldom accurately known. Rather, because of the large number of complex items that must be evaluated, simple but conservative models and criteria are established. In the early stages of evaluation, loads may not be accurately known (for example, floor response spectra and piping loads on equipment). In their absence, conservative and sometimes very conservative estimates are made. The Seismic Margins given in final safety analysis reports may have substantial embedded conservatisms. In such cases, the Margins identified in (1) of this summary will only indicate lower bounds.

(5) Aspects Not Included in Nominal Margins

Portions of this report may convey an unintended impression that pumps, valves, and piping in nuclear power plants always perform satisfactorily. Actually, of course, there is an extensive history of valve operators which do not always operate and of piping which develops leaks. These have nothing to do with earthquakes, but the potential of "something (being) wrong" at the time an earthquake occurs is a concern. The "not included aspects" are discussed in the report and include such concerns as design or fabrication errors, fabrication defects, and corrosion or stress corrosion cracking.

The Nominal Margins in (1) of this summary are based on the assumption that quality control, preservice inspection, and inservice inspection are sufficient to minimize the importance of these "not included aspects".

1. INTRODUCTION

In Safety Evaluation Reports prepared by utilities in support of applications for nuclear power plant licenses, the adequacy of some items (for example, the hold down bolts on a pump) is often expressed in the form:

$$\text{Seismic Margin} = \frac{\text{Allowable Stress}}{\text{Calculated Stress}} = \frac{S_A}{\sigma_C} \qquad (1)$$

The allowable stress is based on an applicable industry standard or code that always has a built-in margin of safety on ultimate strength. The calculated stress is determined by an analysis of the loads; including operating loads, dead weight load and earthquake loadings.

For the item to be acceptable, the Seismic Margin must not be less than 1.00. However, for some items, the Seismic Margin may be close to 1.00; for example, 1.01. The question arises: If the loads are slightly underestimated such that, for example, σ_C is actually slightly higher than calculated, will the item fail?

To answer the question, it is necessary to define what is meant by "failure", and look in detail at the basis of the allowable stress, S_A.

Section 2 gives a brief description of design procedures which are used for pumps, valves, and piping in nuclear power plants.

Seismic Margins, as defined by Equation (1), are then considered and the concept of a "Nominal Margin," corresponding to a Seismic Margin of 1.00, is introduced. Nominal Margins indicate the reserve strength that is available when the Seismic Margin is 1.00. This portion of the report is summarized in Section 3.3.

The important aspect of securing pumps, valves, piping and their supports to the building structure is discussed in Section 4, "Concrete Anchor Bolts."

Operability aspects are then discussed in Section 5: these lead to a form of Seismic Margin that is different than Equation (1).

Sections 2, 3, 4 and 5 of the report deal with Seismic Margins and Nominal Margins on a generic basis. Section 6 of the report, "Specific Applications," describes in detail the basis for several specific Seismic Margins. The detailed data for these specific examples were furnished through the generosity of Virginia Electric Power Co. and Stone and Webster, Inc.; we wish to express our appreciation for the data furnished.

2. BACKGROUND OF DESIGN PROCEDURES

The construction of metal structures is a technology that has gradually evolved over the last two centuries. In the past 60 years or so, this technology has been standardized in the form of codes, design manuals, specifications, and so forth. These standards reflect the accumulated experience (successful and unsuccessful) over many years. The standards are continuously revised to reflect the introduction of new techniques or improvement of existing techniques. (For example, one of the most significant changes in the technology has been the introduction of welding as a method of joining metals.) These standards reflect such aspects as the quality and quality control of metals, fabrication techniques and their control, inspection techniques (x-ray, ultrasonics), the accuracy with which loads can be predicted (a particular problem for earthquakes), and the capability to evaluate the response of the structure to anticipated loads. In addition, the standards reflect a consensus position on cost-to-benefit ratios of the technology.

At the present time, nuclear power plant components such as pumps, valves, piping, and their supports are covered by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Div. 1 "Nuclear Power Plant Components" [1]; (ASME Code). However, prior to the 1974 edition the ASME Code did not cover supports, and, hence, most of the nuclear power plants that are in operation and may be in operation in the next few years contain supports that were designed in accordance with the American Institute of Steel Construction (AISC) "Manual of Steel Construction" [2], (AISC Manual). In the following sections aspects of the ASME Code and the AISC Manual that are pertinent to the evaluation of seismic margins are briefly discussed.

Several general aspects of both the ASME Code and the AISC Manual are:

(1) The design procedures are applicable to ductile steel materials (that is, to material which yield and stretch by about 15 percent or

more before it breaks). The procedures are not applicable to brittle materials such as cast iron.

(2) The design procedures are applicable to operating temperatures such that time-dependent phenomena(for example. creep at high temperatures) are not significant. The design procedures are not,for example, applicable to a ferritic steel structure that operates at 900 F.

(3) The design procedures give allowable stresses for base materials, not weld materials or weldments. However, the welding procedures and qualifications are such that the basic properties of the weldment (yield strength, ultimate tensile strength, and ductility) are at least as good as the base materials.

(4) The design procedures do not provide for severe environmental effects such as stress-corrosion cracking.

2.1 ASME Code

The ASME Code gives rules for the construction of pumps, valves, and piping under subsections NB for Class 1, NC for Class 2, and ND for Class 3. The rules under these subsections are intended to ensure the integrity of the pressure boundary, but not operability or functional capability. Under these rules, yielding of the material is permitted*, provided that the yielding does not cause leakage through or rupture of the pressure boundary.

Since 1974, the ASME Code has included Subsection NF, which gives rules for component supports. The subsection NF design approach is related to that of the construction of steel buildings. It is based on the prevention of excessive deformations; yielding is a primary consideration.

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*Deformation limits, if any are necessary, must be included in the Design Specification. These may impose limits on the amount of yielding.

The ASME Code includes provisions for four categories of loadings and associated limits:

(1) Design/Level A
(2) Level B
(3) Level C
(4) Level D

Level A is intended for normal conditions that are expected to occur. For example, a boiling water reactor (BWR) pressure vessel is expected to be loaded by its normal operating pressure of (about) 1050 psi. Further, this pressure is expected to be reduced to zero and reapplied quite often during the life of the plant, hence, fatigue as a result of this cycle of loading must be evaluated.

Level B is intended for upset conditions that probably will occur. For example, the relief valves in a BWR plant may be set so that the pressure rises to 1150 psi. Level B conditions are expected to occur often enough so that they should and are included in the fatigue evaluation. The operating basis earthquake (OBE) is usually considered a Level B loading.

Level C is intended for infrequent conditions. The occurrence of stress to Level C limits may necessitate the shutdown of the plant and removal of components for inspection and repair or replacement.

Level D is intended for conditions which probably will never occur, but there is a small chance they will. The safe-shutdown earthquake (SSE) and large loss-of-coolant accident (LOCA) are usually considered as Level D loadings. Level D limits are intended to assure that the plant can be brought to a safe-shutdown condition. For example, if a large LOCA occurs, Level D limits are intended to assure that the break of the large pipe does not cause failures of other piping or of other components (vessels, pumps, valves) essential to reach and maintain the safe-shutdown condition.

The ASME Code does not rule on which loading is considered to be in which category of loading, nor does it determine what combinations of loads should be in the various Code categories. These determinations are, in effect, established by NRC (for example, Regulatory Guide 1.48, "Design Limits and Loading Combinations for Seismic Category 1 Fluid Systems Components" [3]). An important consideration is whether a component is essential to obtain safe shutdown and whether it is active or passive. As a specific example, consider a PWR plant in which the main feedwater pumps (and/or the building in which they are located) are not designed to withstand the SSE. In principle, the main feedwater pumps could become useless following the SSE. The NRC requires that auxiliary feedwater pumps and their buildings be designed to withstand the SSE. These auxiliary feedwater pumps are considered as "essential" for safe shutdown. Further, they are "active" because they must operate following the SSE. Their normal function is to operate during and following various accident conditions including SSE. Accordingly, Regulatory Guide 1.48 [3] suggests that the auxiliary feedwater pumps be designed to Level B limits, not Level D.

2.2 AISC Manual

The AISC Manual is significant to this report because support structures in operating nuclear power plants and those that are to operate in the near future were designed before the development of ASME Subsection NF, "Component Supports." They were designed according to the AISC Manual.

The AISC Manual is much simpler than the ASME Code in the sense that it has no "classes," or "Categories of Loadings/Limits." However, it does contain one provision which is crudely analogous to the ASME Code Loading/Limits Level D. That provision is contained in Par. 1.5.6 of the AISC specification for the Design, Fabrication, and Erection of Structural Steel for Buildings (included in the AISC Manual). Par. 1.5.6 states, in effect, that allowable stresses may be increased by one-third in evaluating calculated stress produced by earthquake loadings combined with "normal" loadings.

In following portions of this report, we will discuss the relevance of the AISC Manual rules to Seismic Margins. We refer to the AISC Manual allowab'e stresses without the one-third increase as "basic allowable stresses;" those with the one-third increase are referred to as "seismic" allowable stresses.

In contrast to the ASME Code Subsections NB, NC, and ND, which are concerned with pressure boundary integrity, the AISC Manual rules are directed toward structural stability. This concern is appropriate for supports where, of course, there is no pressure boundary.

ASME Code Subsection NF, "Component Supports," follows rather closely the design philosophy of the AISC Manual. Indeed, much of the detailed guidance is identical to that given in the AISC Manual. Because the AISC Manual was developed solely for room temperature applications and covers a limited range of materials, NRC has provided additional guid[illegible] in Regulatory Guides 1.124 [4] and 1.130 [5].

3. ALLOWABLE STRESSES

Seismic Margins which use stress as a parameter are expressed in the form of Equation (1). In this portion of the report we discuss, on a generic basis, the relationship of Seismic Margins to Nominal Margins on yielding or breaking. We assume, in effect, that the calculated stress, σ_C due to the loadings is accurate, and we address the question: Given that the Seismic Margin, defined as S_A/σ_C, is 1.00, what is the margin on yielding or breaking?

We address the question first for tensile loads because the concepts involved are directly related to material tensile properties which, in turn, are used to establish the allowable stress, S_A. We then discuss other kinds of loadings, their stress limits, and how the Nominal Margins compare with those for tensile loads.

3.1 Tensile Loads/Allowable Stresses

3.1.1 ASME Code (Pressure Boundary)

To illustrate the significance of the allowable stress, S_A, in its simplest form, we consider the tensile load F_t in Figure 1 (a) and assume that F_t is such that $\sigma_c = S_A$. The Seismic Margin would be 1.00, the lowest value permitted by the ASME Code.

Table 1 indicates the basis used for establishing the ASME Code allowable stresses. These are fractions of the tensile properties of the material. These particular fractions were developed with due consideration of the many interacting aspects discussed above ("Background of Design Procedures").

Table 2 shows, for some typical materials, the Nominal Margins on yielding or breaking for tensile loaded items. The Nominal Margins are defined as:

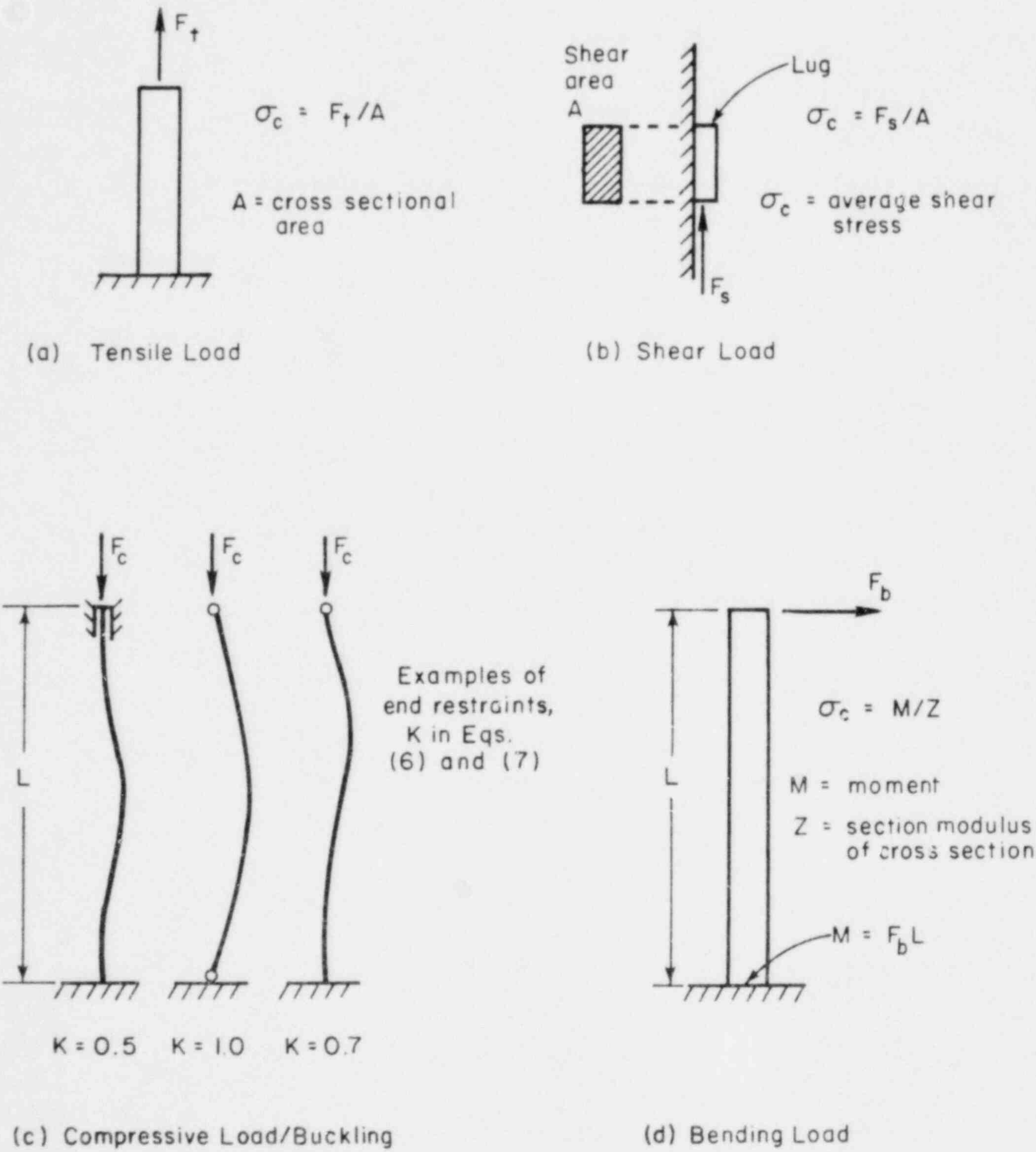

FIGURE 1. EXAMPLES OF TYPES OF LOADS

TABLE 1. ASME CODE FACTORS[a] USED IN ESTABLISHING ALLOWABLE STRESSES IN TENSION (for Pressure Boundary Integrity)[b]

Material	Class I		Class 2/3	
	S_y(c)	S_u	S_y(c)	S_u
Any, except bolting	2/3	1/3	2/3	1/4
Bolting (d)	1/3	---	2/3	1/4

(a) Allowable stress = factor times the material property S_y = tensile yield strength or S_u = ultimate tensile strength. Where factors are shown under both S_y and S_u, the lower of the two criteria is used to establish the allowable stress.

(b) This table is abstracted from Article III-3000 of the ASME Code and is specifically for ferrous materials.

(c) For austenitic stainless steels, the allowable stress may be up to 90% of the yield strength at temperature.

(d) For Class 2/3 heat treated bolting material, the allowable stresses do not exceed 1/5 of the specified minimum tensile strength or 1/4 of the specified minimum yield strength.

TABLE 2. NOMINAL MARGINS FOR TENSILE LOADINGS, ASME CODE LEVEL B OR AISC MANUAL BASIC ALLOWABLE STRESSES[a]

Material	Temp. °F	Material Property S_y, ksi (b)	Material Property S_u, ksi (b)	Class 1 S_A ksi (b)	Class 1 Nominal Margin on: Yield S_y/S_A	Class 1 Nominal Margin on: Break S_u/S_A	Class 2/3 S_A ksi (a)	Class 2/3 Nominal Margin on: Yield, S_y/S_A	Class 2/3 Nominal Margin on: Break, S_u/S_A	AISC Manual Nominal Margin on: Yield, S_y/S_A	AISC Manual Nominal Margin on: Break, S_u/S_A
SA-285-A	100	24.0	45.0	15.0	1.60	3.00	11.2	2.14	4.02	1.67	3.12
	500	19.4	45.0	12.9	1.50	3.49	11.2	1.73	4.02		
SA-516-55	100	30.0	55.0	18.3	1.64	3.00	1[illegible].7	2.19	4.01	1.67	3.06
	500	24.5	55.0	16.2	1.50	3.40	13.7	1.79	4.01		
SA-106-B	100	35.0	60.0	20.0	1.75	3.00	15.0	2.33	4.00	1.67	2.86
	500	28.3	60.0	18.9	1.50	3.17	15.0	1.89	4.00		
SA-216-WCC	100	40.0	70.0	23.3	1.72	3.00	17.5	2.29	4.00		
	500	34.5	70.0	21.6	1.60	3.24	17.5	1.97	4.00		
SA-240-304L	100	25.0	70.0	16.7	1.50	4.19	15.7	1.59	4.46		
	500	16.3	57.8	14.8	1.10	3.91	14.4	1.13	4.01		
SA-351-CF8M	100	30.0	70.0	20.0	1.50	3.50	17.5	1.71	4.00		
	500	19.9	67.0	17.9	1.11	3.74	16.8	1.18	3.99		
SA-240-304N	100	35.0	80.0	23.3	1.50	3.43	20.0	1.75	4.00		
	500	20.8	71.2	18.7	1.11	3.81	17.8	1.17	4.06		
SA-36	100	36.0	58.0	----	----	----	----	----	----	1.67	2.59
SA-307-B	100	33.3[c]	60.0				7.0	4.76	8.57		
	500	24.0[c]	60.0	----	----	----	7.0	3.43	8.57		
SA-325	100	81.0	105.0	----	----	----	20.2	4.01	5.20	2.02	2.62
	500	68.3[d]	105.0	----	----	----	20.2	3.38	5.20		
SA-193-B7	100	105.0	125.0	35.0	3.00	3.57	25.0	4.[illegible]	5.00		
(diam. ≤ 2-1/2")	500	88.5	125.0	29.5	3.00	4.24	25.0	3.54	5.00		
SA-193-B8	100	30.0	75.0	10.0	3.00	7.50	18.7	[illegible].60	4.01		
	500	19.4	63.5	6.1	3.18	10.41	12.1	1.60	5.25		

(a) See text for discussion of ASME Code Level D and AISC Manual "Seismic" allowable stresses and corresponding nominal margins.

(b) S_y = minimum specified tensile yield strength at 100 F, minimum expected tensile yield strength at 500 F.
S_u = minimum specified ultimate tensile strength at 100 F, minimum expected ultimate tensile strength at 500 F.
S_A = allowable stress per ASME Code or AISC Manual.

(c) Yield strengths for SA-307-B are not specified. These are estimates.

(d) Yield strengths for SA-325 at 500 F are not listed in the ASME Code. This is an estimate.

$$\text{Nominal Margin} = \frac{S_y}{S_A} \text{ for yielding} \tag{2}$$

$$\text{Nominal Margin} = \frac{S_u}{S_A} \text{ for breaking} \tag{3}$$

where σ_c is assumed to equal S_A, corresponding to a Seismic Margin of 1.00. It can be seen in Table 2 that, for this basic and significant case, a Seismic Margin of 1.00 corresponds to Nominal Margins on breaking ranging from 3.00 to 10.41.

The values of S_A derived as indicated in Table 1 and used in Table 2 to develop Nominal Margins are basic stress limits; they are used for Design, Level A and Level B loadings. In present practice, the operating basis earthquake (OBE) is considered to be a part of Level B loadings; hence the Nominal Margins shown in Table 2 are directly applicable.

However, the safe-shutdown earthquake (SSE) may be considered to be part of Level D loadings. For Class 2/3 pumps and valves, and piping, the allowable membrane tensile stress for Level D loading is two times the values of S_A shown in Table 2. Accordingly, the Nominal Margins on breaking range from 1.5 to 5.2. For Class 1 components and all classes of component supports, the allowable membrane tensile stress given in the non-mandatory Appendix F of the ASME Code cannot exceed 0.7 S_u, corresponding to a Nominal Margin on breaking of 1.43 for Level D. The ASME Code Level D stress limits do not necessarily preclude gross yielding; conceptually under Level D stress limits, yielding may occur but not breaking.

The material properties S_y and S_u used to establish Code allowable stresses at 100 F are the specified minimums at room temperature. At elevated temperatures, the ASME Code material specifications (SA specifications) do not establish minimum values of S_y or S_u. They are obtained from elevated-temperature tensile tests on representative samples of the material to obtain a plot of S_y or S_u as a function of temperature. A line representing the average of the test data is called a "trend curve"; this establishes a ratio of the properties at elevated temperatures to the properties at room temperature (70 F). This ratio is then multiplied by the specified minimum S_y or S_u to obtain the value of S_y or S_u at elevated temperatures. For example, for SA-516-55, which has the minimum specified yield strength of 30 ksi, the ratio of S_y at 500 F to S_y at 70 F is about 0.817, hence, S_y at 500 F is listed (see Table I.2-1 of the Code) as 30 x 0.817 = 24.5 ksi.

The Code procedure for establishing allowable stresses involves a fraction times the minimum expected S_y or S_u given in the SA specification; and tends to be a fraction of the minimum expected S_y or S_u at elevated temperatures. A pertinent aspect of Seismic Margins is the statistical characteristics of S_y or S_u for a given SA specification. Such statistical data are very sparse; available data are summarized and discussed in Appendix A. For materials which fall under the general description of "hot finished carbon steel," the available data indicate that (1) the mean value of S_y or S_u is about 20 percent higher than the minimums used in Table 2 and (2) the probability of obtaining a material with S_y or S_u less than those used in Table 2 is of the order of 0.01. Accordingly, the average Nominal Margin on breaking corresponding to a Seismic Margin of 1.00 ranges from about 3.6 to 12.5 for Design, Level A, and Level B loadings; and from about 1.8 to 6.2 for Level D loadings.

It can be seen in Table 2 that the Nominal Margin on yielding for Level B is as low as 1.10. For Level D loadings, the Nominal Margin on yielding is as low as 0.55. Accordingly, for a Seismic Margin of 1.00, yielding will occur. However, note that the Nominal Margin against breaking is high; for example, for SA-240-304L at 500 F, the Nominal Margin against yielding is 0.55, but the Nominal Margin against breaking is not less than 1.43. With the loadings due to an SSE (combined with other concurrent loadings), yielding is possible, but (in concept) not breaking of the pressure boundary.

3.1.2 AISC Manual (Supports)

For tensile loads, such as F_t in Figure 1(a), the basic allowable stress is 0.6 S_y, where S_y is the specified minimum yield strength of the material. Accordingly, the Nominal Margin on yielding is:

$$\text{Nominal Margin} = \frac{S_y}{S_A} = \frac{S_y}{0.6 S_y} = 1.67$$

The Nominal Margins on breaking are shown in the last two columns of Table 2 for materials that might be used under the AISC Manual and for the two bolt materials which are directly covered under the AISC Manual.

It may be observed in Table 2 that, for SA-325 bolting material, the basic general allowable stress limit of 0.6 S_y is not applied; the allowable stress is 40 ksi, not 0.6 x 81 = 48.6 ksi.

As in the ASME Code method, the AISC allowable stresses are based on minimum specified material properties; Appendix A data indicate that mean values of S_u and S_y are about 20 percent higher than minimum specified.

As previously mentioned, AISC permits allowable stresses to be increased by one-third when earthquake loadings are included. If used, this reduces the Nominal Margins by a factor of (3/4).

In summary, the Nominal Margins corresponding to a Seismic Margin of 1.00 are:

	On Yielding	On Breaking
Basic Limits	1.67 or greater	2.62 or greater
Seismic Limits	1.25 or greater	1.97 or greater

3.1.3 Margin on Seismic-Induced Stresses

The Seismic Margin has been defined by Equation (1) as S_A/σ_c , where σ_c is the calculated stress due to all loads. That is, $\sigma_c = \sigma_{cs} + \sigma_{cn}$, where σ_{cs} is the stress due to seismic loads and σ_{cn} is the stress due to non-seismic loads. Because seismic loadings are subject to large uncertainties, it is pertinent to evaluate the margin that exists for seismic-only loads when the Seismic Margin is 1.00 and therefore, $\sigma_{cs} + \sigma_{cn} = S_A$. We define this seismic-only margin as $M_s = \sigma_{cs}^*/\sigma_{cs}$, where σ_{cs}^* is that magnitude of seismic stress which causes σ_c to exceed S_u. To the extent that σ_{cs} is proportional to earthquake magnitude, M_s indicates how many times the magnitude of the earthquake assumed in obtaining σ_{cs} would have to increase in order for an item to break.

The value of M_s will obviously depend upon what proportion of the total stress is due to seismic loads; we define k by the relation $\sigma_{cs} = kS_A$ where the value of k ranges from 1.00 for all seismic loads to zero for no seismic load. The seismic-only margin, M_s, can be obtained by the equation:

$$M_s = \frac{\frac{S_u}{S_A} - (1-k)}{k} \tag{4}$$

Noting that S_u/S_A is what we have defined as Nominal Margin on breaking Equation (4) can be written as:

$$M_s = \frac{1}{k}(NM-1) + 1 \tag{5}$$

where NM = nominal margin on breaking.

As a specific example, let us consider SA-307-B bolts with S_A established by the Code Level D allowable stress of $0.7S_u$, and assume that k = 0.5. For this example, Equation (5) gives:

$$M_s = \frac{1}{.5}\left(\frac{1}{.7} - 1\right) + 1 = 1.86$$

In this example, the reserve strength is sufficient to permit up to 1.86 times the seismic stresses used in calculating the Seismic Margin of 1.0.

For pressure boundaries, the probability is relatively high that stresses due to internal pressure will be a significant part of the total calculated stress, σ_c; that is, k will be quite a bit less than 1.0. This directs attention to items which are not pressure boundaries such as hold-down bolts on pumps and supports for piping.

3.1.4 Probability Aspects

In the preceding, we have mentioned one probability aspect; that is, the statistical characteristics of material tensile properties as related to the specified or, at elevated temperature, expected minimum properties. However, this is a minor aspect of the probability of failure as a whole, and we here touch on other aspects. This will, of necessity, be on a speculative basis because hard data are not available.

Some loads, such as internal pressure for pressure boundary evaluation or weight for supports, are quite accurately known for normal operating conditions. The capacity of structures to withstand such loads has been thoroughly investigated. For example, there are many hundreds of tests on the capacity of piping products (straight pipe, elbows, branch connections, and so forth) to withstand internal pressure. Further, many years of experience with such loads and structures are available for guidance.

Not much is known about either the seismic loadings on pumps, valves, piping, and their supports or the capacity of those structures to withstand seismic loadings. Some relevant experience exists in that nonnuclear power plants and plants such as oil refineries have been subjected to severe earthquakes. However, it is not apparent that the existing experience is used in evaluation of seismic loadings for pumps, valves, piping, and their supports in nuclear power plants.* Rather, seismic loadings are estimated by starting from an assumed ground motion and proceeding through a complex series of theoretical

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*A recent report, "Equipment Response at the El Centro Steam Plant During the October 15, 1979 Imperial Valley Earthquake", NUREG/CR-1665, October 1980, constitutes a highly significant document with respect to seismic design of nuclear power plants. Unfortunately, the details of pumps, valves, piping and their supports are not covered sufficiently. The report, p. 38, includes a suggestion: "An analysis of Unit 4 to current design criteria would indicate the levels of conservatism inherent in these design-related procedures." This work, if undertaken, would provide a realistic perspective to seismic design of nuclear power plants.

calculations to estimates of loadings on pumps, valves, piping, and their supports. In this process, a number of probably conservative assumptions are made, such as:

(1) selection of low-probability OBE and SSE magnitudes
(2) use of conservative damping values
(3) use of elastic analysis
(4) peak widening of floor response spectra

The total effect of such conservatisms might be at least partially quantified by applying the procedures to plants that have been subjected to earthquakes. However, in so far as we are aware, this has not been done. Until it is done, we can only speculate on what conservatism (or lack of conservatism) exists in methods now being used to evaluate seismic loadings. Our speculation is that the methods used are conservative.

Having the seismic loadings, it is a relatively straightforward task to determine the stress, σ_c, due to those loadings.

Another aspect of margins corresponding to a Seismic Margin of 1.00 is the matter of structural redundancy. Examples are a pump held to the floor by 8 bolts, a piping system supported by 20 hangers, or most any kind of truss-like support. The Seismic Margin is usually related to the most highly stressed of the redundant items. For example, in the piping system with 20 supports, one of them may have a Seismic Margin of 1.00, while the others may have significantly lower stresses. The failure of one member of a redundant structure does not necessarily mean that the entire structure will fail. There is a good chance that the remaining members will have sufficient reserve strength to withstand the additional load shed by the failed member.

In the preceding, we have discussed aspects which indicate that the Nominal Margins, as we have defined them, tend to underestimate the actual reserve margins of load-carrying capacity. We now discuss aspects which could cause the Nominal Margins to overestimate actual reserve margins.

In our evaluations of Nominal Margins, we have ignored the possible presence of fabrication defects and/or deterioration in service, such as those caused by stress corrosion or fatigue. These aspects can, of course, cause significant reductions in actual margins. Indeed, numerous instances of leaks in piping in nuclear power plants have occurred. It is obvious then, that there can be conditions such that even a minor earthquake could be the "last straw" leading to a failure. Evaluation of the safety significance and probability of such a condition involves the probability of defect detection (both as-fabricated and in-service), in-service inspection coverage and frequency, the consequence of failure (for example, leak versus break of a pressure boundary), and redundancy of shutdown systems. However, consideration of such aspects is beyond the scope of this report.

In our evaluations of Nominal Margins, we have made an implicit assumption that σ_c is an accurate evaluation of stresses. This assumption may not always be true. First, the designer may simply make a numerical error, and the checker may miss that error. Second, the designer and checker may not have a complete description of everything relevant to the analysis, or the analysis may not fully reflect the dimensions of the as-built structure. Third, the designer may be using a method of stress calculation which is not valid. These aspects could, of course, lead to smaller actual margins than the Nominal Margins given in this report. The Nominal Margins given in this report are based on the assumption that quality control, pre-service inspection and in-service inspection are sufficient to minimize the importance of these aspects.

3.2 Other Types of Loads

3.2.1 Shear Loads

The load F_s in Figure 1(b) produces an average shear stress $\sigma_c = F_s/A$, where A is the cross-sectional area of the lug.

Yielding due to a shear stress occurs at a shear stress magnitude that is less than that stress required to produce yielding by a tensile stress. Because material properties are characterized in terms of tensile yield strength, relationships between shear yielding and tensile yielding were developed. These "theories of yielding" were developed roughly a century ago; the two theories still generally used are the maximum shear (Tresca) and the distortion energy (Mises). These theories indicate that shear yielding occurs when the shear stress is about one-half (precisely 0.5 by maximum shear theory, 0.577 by distortion energy theory) of the tensile yield strength of the material.

The maximum shear theory is the basis for the stress intensity concept used for Code Class 1; these rules limit a shear stress to one half of that permitted for a tensile stress. Accordingly, the Nominal Margin on yielding is theoretically the same as that for tensile loads (for example, those shown in Table 2). The shear stress required to cause breaking is not well established; however, it is not less than about 0.6 times the ultimate tensile strength. Accordingly, the Class 1 Nominal Margin on breaking is about the same or slightly higher than those shown in Table 2.

For Code Classes 2 and 3, shear stresses are limited by specific rules such as those in NC-3359(b) of the ASME Code. The shear allowable stresses range from 0.49 to 0.70 times the tensile allowable stress, depending upon the material that is subjected to shear (for example, for a fillet weld, the factor is 0.49). Accordingly, the Nominal Margins on yielding or breaking are about the same as those shown in Table 2.

The AISC Manual allowable shear stress is 0.40 S_y, whereas the allowable tensile stress is 0.60 S_y. The allowable stress in shear is 0.67 times the allowable stress in tension. Accordingly, the Nominal Margins on yielding or breaking are about the same as those on tensile loading.

3.2.2 Compression Loads/Buckling

Figure 1(c) illustrates the basic aspects of design for compression loadings. When L is small compared to the cross-sectional dimensions, yielding occurs when $F_c/A = S_y$. For ductile materials, breaking is not the controlling aspect of design. However, when L is large compared to the cross sectional dimensions, the beam fails by "buckling." The load which causes buckling is dependent upon the modulus of elasticity of the material but not on its yield strength or ultimate tensile strength. There is an intermediate regime of L where gross displacements can occur by combinations of yielding and buckling. The type of design guidance developed over the last century or so for compressive loads is illustrated by the following equation from the AISC Manual:

$$\sigma_c = \frac{\left[1 - \frac{1}{2}\left(\frac{KL/r}{C}\right)^2\right] S_y}{\frac{5}{3} + \frac{3}{8}\frac{KL/r}{C} - \frac{1}{8}\left(\frac{KL/r}{C}\right)^3} \tag{6}$$

where: K = a factor which depends upon the end restraints of the beam (see Figure 1(c) for examples)

L = beam length (see Figure 1(c))

r = radius of gyration = $(I/A)^{1/2}$, where I = moment of inertia and A = area of the beam cross section

C = $(2\pi^2 E/S_y)^{1/2}$

E = modulus of elasticity of the material

S_y = tensile yield strength of the material

Equation (6) is applicable when KL/r is less than C. When KL/r is greater than C:

$$\sigma_c = \frac{12}{23}\,\frac{\pi^2 E}{(KL/r)^2} \tag{7}$$

It may be noted that when KL/r is small (the quantitative definition of when the length L is small compared to the cross sectional dimensions), the limit on σ_c is $0.6S_y$, the same as for tensile stress. When (KL/r)/C is 1.0 or greater, Equation (7) is used. Equation (7), without the (12/23) factor, is the Euler theoretical elastic column buckling theory. The factor of (12/23) = 0.522 can be regarded as an inverse factor of safety on the theoretical elastic buckling stress.

The nominal factor of safety varies from 1/0.6 = 1.67 for small L on yielding to 23/12 = 1.92 for large L on buckling. A larger margin for buckling than for yielding is desirable because buckling is dependent upon fabrication tolerances (such as initial straightness of the beam) and the exact loading conditions (such as, a slightly off-center load).

The Nominal Margins under compressive loads, with a Seismic Margin of 1.00, are the same as the factor of safety, ranging from 1.67 to 1.92. For small L, an additional margin exists to the extent that average yield strengths are higher than the minimum yield strength used in design.

If the AISC Manual "Seismic" allowable stresses are used, then the Nominal Margins for a Seismic Margin of 1.00 become 1.67/1.33 = 1.25 to (23/12)/1.33 = 1.44.

3.2.3 Bending Loads

Figure 1(d) shows a load F_b that produces a bending moment $M = F_bL$ and a corresponding bending stress, $\sigma_c = M/Z$, where Z is the section modulus of the bar. A single application of the bending load is not limited by concern about breaking; rather, the concern is to limit the deformation to acceptable magnitudes. This aspect is more relevant to supports than to the pressure boundary integrity of pumps, valves, and piping. Accordingly, we will discuss the AISC Manual first.

The basic AISC Manual allowable bending stress is 0.66 S_y, whereas the allowable tensile stress is 0.60 S_y. It might seem that the Nominal Margin on yielding for bending stresses is a bit lower than for tensile loading.

Actually, this is not the case. Gross plastic deformation can occur only when the load is sufficiently high to produce a plastic hinge. For a solid rectangular cross section, the plastic hinge moment is 1.5 times the first-yield moment. Accordingly, for this cross section, the Nominal Margin on yielding is 1.5/0.66 = 2.35.

The AISC Manual also covers more complex cross sections such as I-beams and box-beams. In such beams, buckling on the compression side of the beam must be and is considered. In general, the limits are such as to ensure margins on bending loads that are about equal to or greater than the margin on tensile yielding.

For pressure boundary integrity evaluation, the ASME Code also gives allowable stresses for bending; these are not as conservative as the AISC Manual. For Class 1, the allowable stresses in bending are α times those in tension, where α-ratio is a generalization of the specific value of $\alpha = 1.5$ for a rectangular cross section cited previously. Conceptually, the margin on gross plastic yielding for bending loads is the same as the margin for tensile yielding. However, as discussed under tensile loading, for austenitic steels at 500 F the Nominal Margin on yielding is only about 1.1, and for Level D loadings, the Nominal Margin on yielding is 0.55. It is important to note (1) that these are pressure boundary integrity rules, and (2) that yielding does not mean a leak-through, or break of, the pressure boundary.

The ASME Code Classes 2 and 3 permit bending stresses of 1.5 S_A, 1.65 S_A, 1.8 S_A, and 2.4 S_A for Levels A, B, C, and D, respectively, where S_A is the allowable stress in tensile loading. For Level D loadings on a solid rectangular cross section, and with material like SA-240-304L at 500 F, the Nominal Margin on gross yielding due to bending loads is 16.3 x 1.5/(14.4 x 2.4) = 0.71. Again, it is important to note that these are rules for pressure boundary integrity.

3.2.4 Combined Loadings

The loadings on pumps, valves, piping, and their supports often consist of combinations of tensile, shear, and bending loads, or compression, shear and bending loads. For most combinations of loads, the ASME Code and AISC Manual give explicit rules. Some examples are:

(1) ASME Code 2 Classes 2 and 3, tension plus bending

$$\sigma_C = (\sigma_t + \sigma_b) \leq k\ S_A$$

where σ_t = tensile stress, σ_b = bending stress, and k = 1.5, 1.65, 1.8, and 2.4 for Levels A, B, C, and D, respectively.

(2) AISC Manual, tension plus bending

$$\frac{\sigma_t}{0.6\ S_y} + \frac{\sigma_b}{0.66\ S_y} \leq 1.0$$

(3) AISC Manual, shear and tension, SA-307-B bolts.

$\sigma_t \leq 28.0 = 1.6\ f_v$, but not greater than 20 ksi
where f_v = shear stress.

In general, the ASME Code and AISC Manual allowable stresses for combined loadings are such that Nominal Margins on combined loads are about the same as for the individual loads.

3.3 Summary of Allowable Stresses and Nominal Margins

Nominal Margins indicate the reserve strength that is available when the Seismic Margin is unity. Nominal Margins for tensile loadings are summarized in the following table.

Failure Criteria	Nominal Margins			
	ASME Code, for Pressure Boundary Integrity		AISC Manual, for Supports	
	OBE (Level B)	SSE (Level D)	Basic	Seismic
Break	3.0 to 10.4	1.43 to 5.2	2.6 to 3.1	2.0 to 2.3
Yield	1.1 to 4.8	0.55 to 2.4	1.67	1.25

The margins for seismic loading only are related to the Nominal Margins by the Equation:

$$M_S = \frac{1}{k}(NM-1) + 1$$

where M_S = margin on seismic loading

$k = \sigma_{cs}/S_A$

σ_{cs} = portion of calculated stress due to seismic loading

S_A = allowable stress

NM = Nominal Margin.

The ASME Code and AISC Manual also contain rules for other loadings. They are

(1) shear loads (Figure 1(b))
(2) compressive loads (Figure 1(c))
(3) bending loads (Figure 1(d))
(4) combinations of loads.

In general, the rules are such that Nominal Margins for these other loadings are about the same as for tensile loads.

In detail, the Nominal Margin corresponding to a Seismic Margin of 1.00 depends upon the following.

(1) material
(2) operating temperature
(3) type of loading
(4) failure criteria
(5) exact source of the allowable stress, S_A. For example, ASME Code, Level B allowable stress for pressure boundary integrity, or AISC Manual, basic allowable stress.

In addition, to establish the margins on seismic loading only, that portion of the calculated stress due to seismic loading must be identified.

The Nominal Margins cited herein are related to minimum material properties (see Appendix A). An assumption is made that calculated stresses, σ_C, are accurate. Present methods for estimating seismic loadings are deemed to be such that σ_C is probably higher than will actually occur, leading to further increase in actual margins over the Nominal Margins.

Fabrication defects and/or deterioration in service (for example, those due to stress-corrosion or fatigue) were not considered in the evaluations of Nominal Margins. These aspects can cause significant reductions in actual margins. Indeed, numerous instances of leaks in piping in nuclear power plants have occurred without any significant seismic loadings.

4. CONCRETE ANCHOR BOLTS

A major aspect of seismic capability of pumps, valves, and piping is to assure that they are adequately held to the building structure. For pumps, this involves hold-down bolts. For piping, supports such as hangers are involved. Valves are usually supported by the attached piping; hence, piping supports are significant to valves.

Bolting connections to concrete can be made either by installing the bolts before pouring the concrete or by drilling a hole in the concrete and inserting an anchor bolt.

Bolts installed before the concrete is poured have not produced any known field-installation problems. The embedded ends of the bolts can be hooked or installed with large washers; thereby, the tensile and shear strength of bolting like SA-307 grade B can be developed. However, anchor bolts installed after pouring the concrete have given field-installation problems, and the NRC IE Bulletin 79-02 [6] was issued to address the problems.

Considerable skill and care in the installation process are required to consistantly obtain anchor bolts that, as installed, develop the tensile and shear strength indicated by Manufacturers' catalogs.

References [7] and [8] are two recent ASME publications concerning anchor bolts. The data given in Reference [9] have been abstracted in Appendix B to this report. From our review of Reference [9] data, it appears that (with one exception*) the tensile and shear strength of anchor bolts given in Manufacturers' catalogs can, with appropriate skill and care, be achieved in field installations.

Manufacturers commonly recommend (1) that design loads for anchor bolts should not exceed one-quarter of the manufacturer's tensile or shear strength, and

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*Discussed in Appendix B.

(2) that a linear interpolation should be used for combinations of tension and shear. If the recommendation is used for both SSE and OBE and associated loadings, the average Nominal Margin would be 4.0. However, this Nominal Margin is not the same as the Nominal Margins for allowable stresses; these are related to minimum material properties, whereas the Nominal Margin of 4.0 is related to average strengths.

Judging from the data given in Reference [9], there is a substantial scatter of data above and below the average, even though all of these results presumably come from tests where skill and care had been used in the installations. The statistical evaluation described in Appendix B indicates that if design loads are taken as one-quarter of average loads, the probability of failure at the design load is less than 0.001, provided the expansion anchor bolts are installed with skill and care at least equivalent to that used in preparing the test installations.

5. OPERABILITY

We have mentioned that operability considerations for active pumps and valves may influence the choice of appropriate allowable stresses (for example, the use of Level B limits rather than Level D). In this section of the report, we discuss other operability aspects of pumps and valves.

5.1 Operability Parameters

The Seismic Margins of pumps may be limited by such aspects as bearing loads, impeller clearance. or shaft deflections. For valves, the yoke and/or stem lateral displacements may limit operability. The Seismic Margins are then definable as:

$$\text{Seismic Margin} = \frac{P_m}{P_s} \qquad (8)$$

where P_m is a parameter limit (for example, minimum impeller clearance) established by the manufacturer and P_s is the calculated value of that parameter under service conditions, including the OBE or SSE.

We might speculate that the manufacturer would tend to specify a low value for any parameter significant to operability of his equipment and that the analyst establishing P_s would tend to select loads and calculations methods that would lead to overestimates of P_s. If that were true, then a Seismic Margin of 1.00, as defined by Equation (8) would correspond to a Nominal Margin significantly greater than 1.00. However, beyond that speculation, there is no way we can generically quantify the significance of a Seismic Margin as defined by Equation (8).

5.2 Seismic Qualification by Testing

Seismic qualification of complex mechanisms such as valve operators may be achieved by the testing method described by Institute of Electrical and

Electronic Engineers Std. 344-1975 [10]. This testing involves mounting the item on a "shake table" in a manner that simulates the mounting of the item in service. Input motions are then applied to the shake table. In general, the seismic simulation input waveforms

(1) produce a test response spectra that envelops the service response spectra
(2) have a peak acceleration equal to or greater than the zero period acceleration, except at low frequencies
(3) do not include frequencies above the zero period acceleration asymptote (typically, include 1 to 33 Hz)
(4) have a duration that simulates eartnquake durations (for example, 30 seconds)

The input motion should, to the extent feasible, also simulate the three-axis aspect of earthquake ground motions. The operability of the item should be verified during and after the test.

Once an item has been tested, its Seismic Margin can be expressed as:

$$\text{Seismic Margin} = \frac{g_t}{g_s} \tag{9}$$

where g_t = zero period test acceleration
g_s = zero period service acceleration (calculated for anticipated service conditions, including the OBE or SSE).

In developing Nominal Margins corresponding to Seismic Margins based on allowable stresses, we assumed that σ_c was accurate. The analogous assumption for Seismic Margins defined by Equation (9) is that g_s is accurate. Now, to the extent that the test is an accurate simulation of what happens to the item during an OBE or SSE, a Seismic Margin of 1.00 corresponds to a Nominal Margin of 1.00.

Most of the test results we have seen are from "proof" tests; that is, the item operated satisfactorily during and after the test. That item may have been able to pass a test of several times the q_t that was used. Accordingly, a Seismic Margin of 1.00 based on proof tests <u>may</u> correspond to a Nominal Margin significantly greater than 1.00, but not necessarily.

6. SPECIFIC APPLICATIONS

In the preceding, we have discussed Seismic Margins, as defined by Equation (1), and Nominal Margins, as defined by Equations (2) and (3), under the hypothesis that σ_C is an accurately known stress. In actuality, σ_C is seldom accurately known. The major reason for this is the magnitude of the task of accurately determining σ_C for the large number of complex items that must be evaluated in the process of licensing a nuclear power plant.

Ordinarily, to reduce the magnitude of the task to a practical level, simple but conservative models and criteria are established. In the early stages of evaluations, data such as floor response spectra and piping loads on equipment may not be accurately known. In the absence of this information, conservative and sometimes very conservative estimates are made. These methods usually show that most items evaluated meet criteria that are acceptable to NRC. For those items, there is no need to conduct a more accurate evaluation, and Seismic Margins that appear in final safety analysis reports may have substantial embedded conservatisms. For those particular items which do not meet the initially established criteria, the model and conservatisms embedded in the evaluation are reviewed and, with more realistic assumptions, the criteria usually can be met. In relatively rare instances, some design change is made so that the criteria can be met.

The examples were selected to illustrate the aspects discussed above. They also illustrate the types of evaluations performed on pumps, valves, and piping.

6.1 Pumps

For pumps, we will evaluate the anchor bolts on a motor-driven auxiliary feedwater pump. The pump/motor is shown in Figure 2. This pump (8-stage centrifugal pump, Ingersoll-Rand 3HMTA8) develops a rated flow of 375 gpm at 1220 psi discharge pressure. The pump has a 6-in. flanged suction with

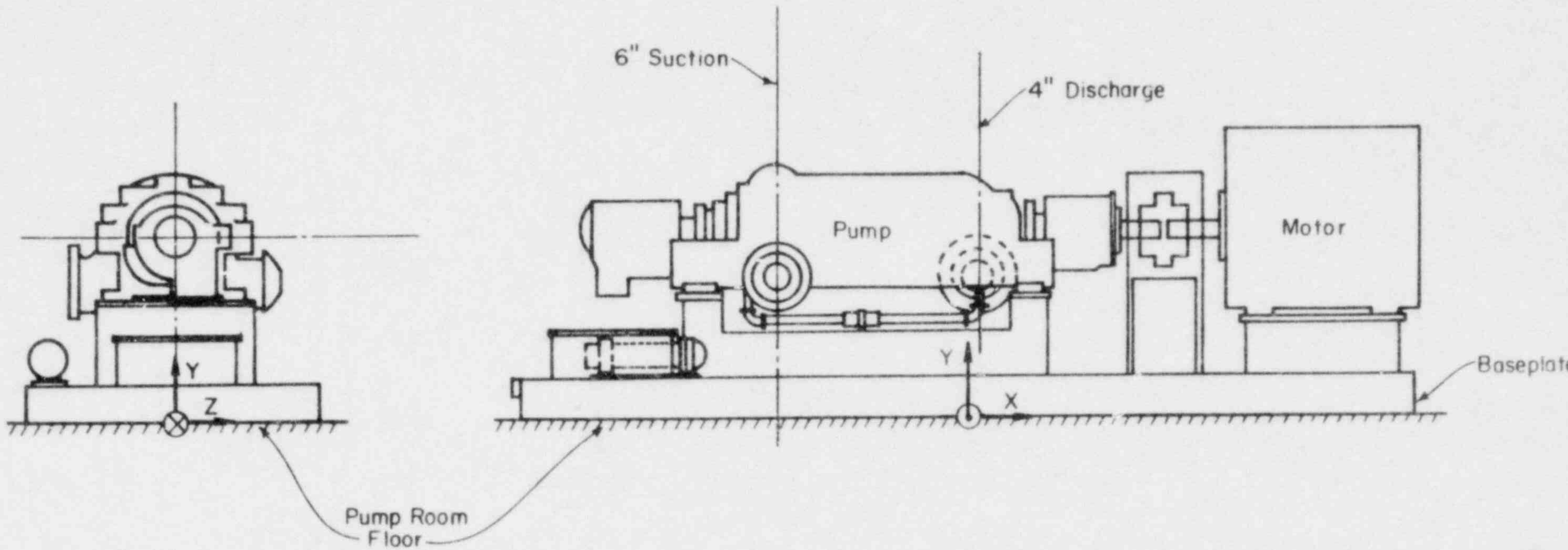


FIGURE 2. LAYOUT OF MOTOR DRIVEN AUXILIARY FEEDWATER PUMP

Schedule 40 piping and a 4-in. welded discharge with Schedule 80 piping. The pump weighs about 4000 lb. The motor is rated at 450 hp at 3600 rpm. The motor weighs about 3900 lb.

The evaluation starts with an evaluation of natural frequencies. Because of operability considerations at 3600 rpm, the first mode natural frequency of the pump and motor internals (for example, shafts) must have a first mode frequency greater than about 70 Hz. Further, the anchoring framework (pump and motor feet, pedestals, baseplate, and bolting) must be sufficiently rigid so that resonances do not occur within the operating speed of 0 to 60 Hz. Accordingly, for evaluation of seismic loadings, the pumps, motors and their connections to the pump room floor can be evaluated by application of low period (0.02 second or smaller) seismic accelerations of the pump floor.

For seismic analysis for the DBE, accelerations are taken to be 1.5 g horizontal and 0.48 g vertical. Figure 3 shows representative horizontal and vertical response spectra for the pumphouse floor. For periods of 0.02 second or less, the acceleration does not exceed 0.2 g; accordingly the accelerations used for evaluation of the anchor bolts of 1.5 g horizontal and 0.48 g vertical are very conservative.

6.1.1 Motor Feet Bolting

The model for the bolting for the motor feet is shown in Figure 4(a). The pump is anchored to the pedestal with four 7/8 in. A307 Grade B bolts. The shear stress is simply the horizontal 1.5 g loading (1.5 x 3900 lb weight of motor) divided by the cross sectional area of the four bolts. The cross-sectional root area of 7/8-in.-NC bolts is 0.419 in.^{2}, hence the bolt shear stress, τ, is:

$$\tau = \frac{1.5 \times 3900}{4 \times 0.419} = 3490 \text{ psi}$$

The maximum tension on the bolts is obtained by summing the moments about A. (It can readily be verified that moments about B will give lower bolt loads.)

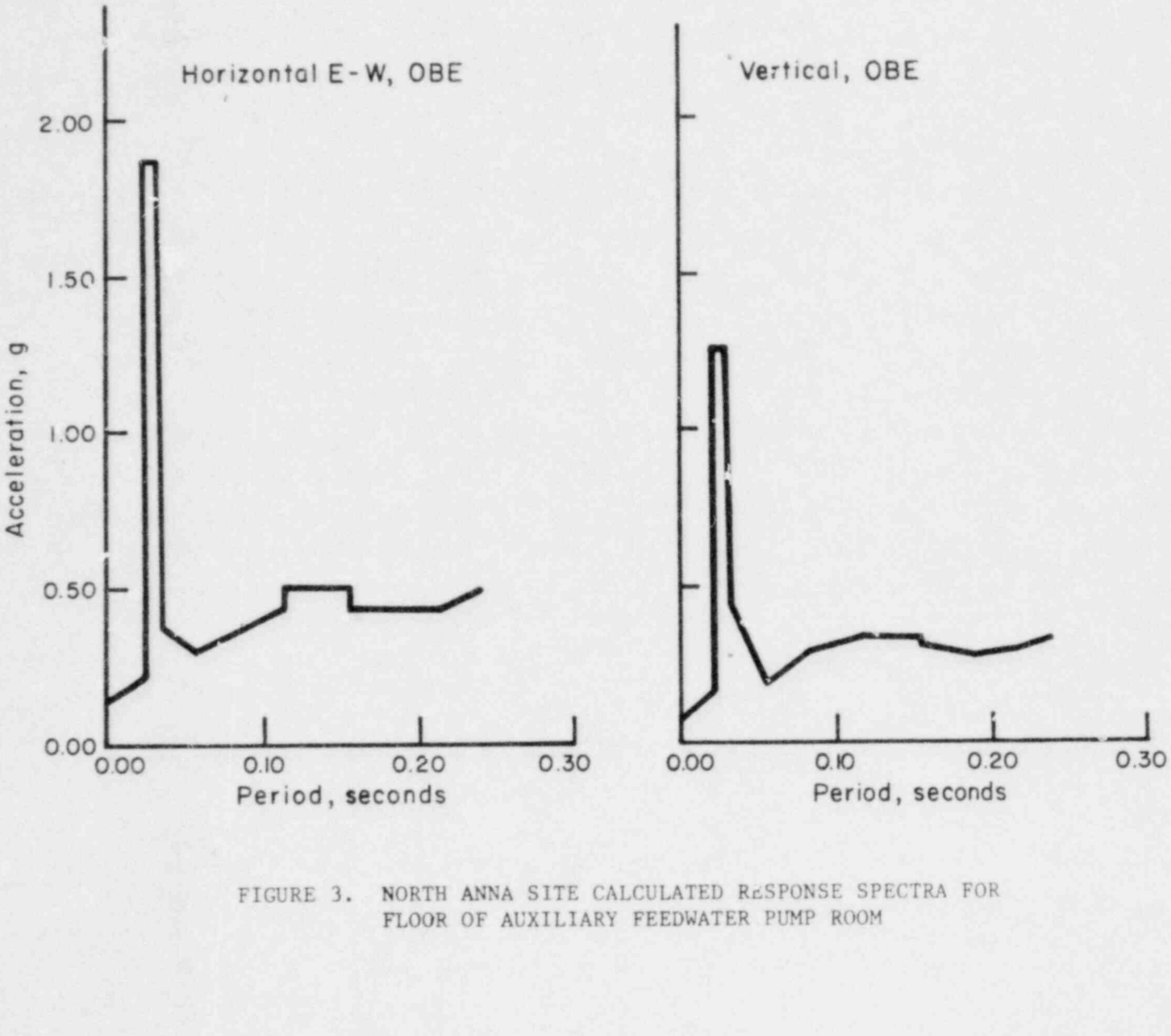
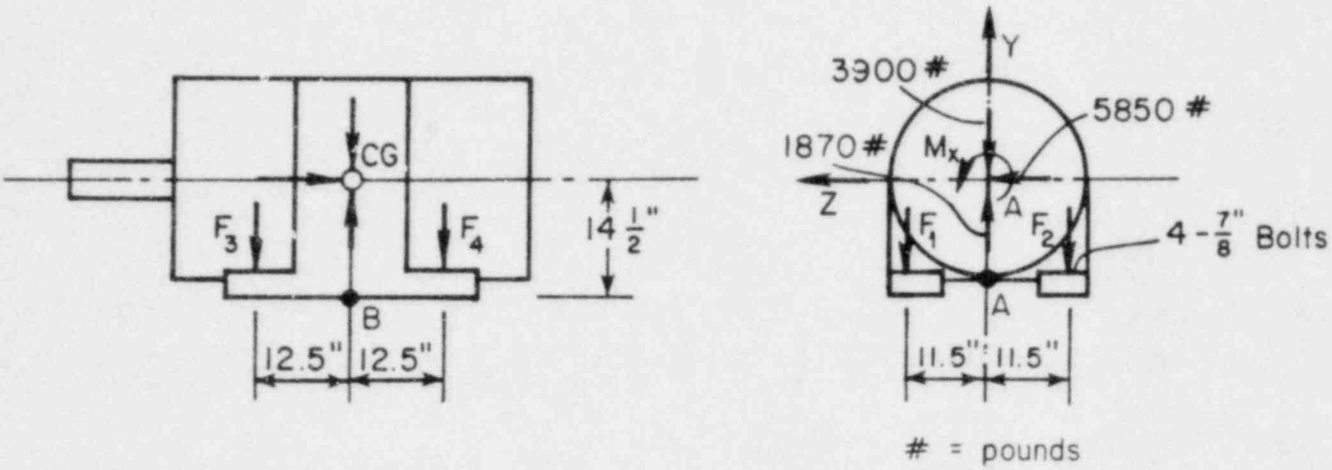
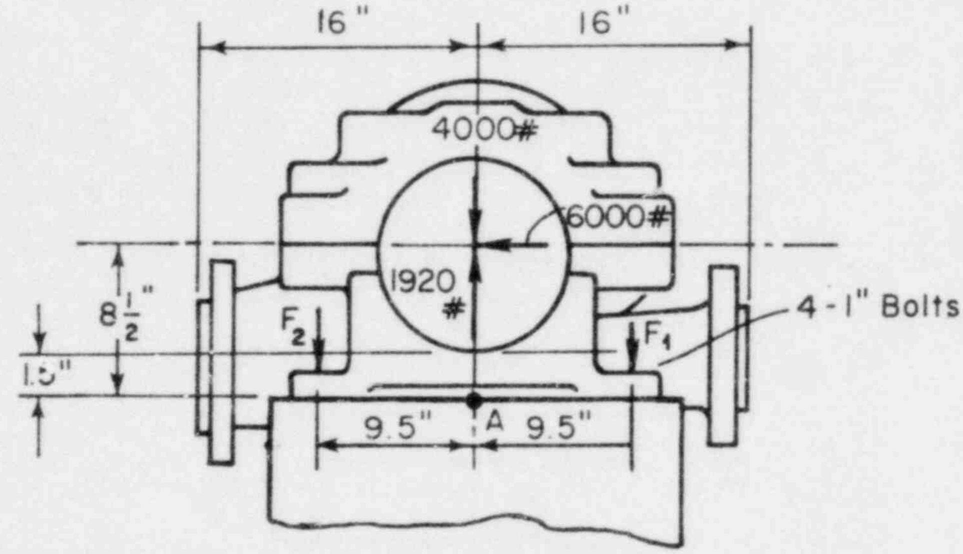


FIGURE 3. NORTH ANNA SITE CALCULATED RESPONSE SPECTRA FOR FLOOR OF AUXILIARY FEEDWATER PUMP ROOM



a. Model for Loads on Motor Feet Bolts



b. Model for Loads on Pump Feet Bolts

FIGURE 4. MODELS FOR MOTOR AND PUMP FEET BOLTS

In addition to the seismic inertial loads, all other loads which might act on the equipment during an earthquake should be evaluated because these pumps might be called on to operate during an earthquake. The 450-hp motor will exert a torque about the shaft center which must be resisted by the bolts and/or weight of the motor. At operating speed N = 60 rps, the motor torque is given by:

$$M_{xmt} = hp \times 550 \times 12/(2\pi N) = 7878 \text{ in.-lb}$$

The maximum torque probably will not exceed $2 \times M_{xmt}$, but, to be conservative, we assume that the maximum torque is $3 \times M_{xmt}$ = 23600 in.-lb. The total moment about A is:

$$M_x = F_z \times 14.5 + 3M_{xmt}$$

$$= 1.5 \times 3900 \times 14.5 + 23600 = 108425 \text{ in.-lb}$$

The tension bolt stress due to M_x is:

$$S_{mx} = \frac{108425}{4 \times 11.5 \times 0.419} = 5625 \text{ psi}$$

The downward (-y) force on the motor with the motor being accelerated downward by 0.48 g is 3900 (1-.48) = 2028 lb. This, divided by the total bolt area of 4 x 0.419 in.^{2}, gives a negative bolt stress of 1210 psi. Subtracting this from S_{mx} of 5625 gives the net tensile bolt stress of 4415 psi.

For combinations of shear and tensile stress, the maximum shear stress and maximum principal stress should be determined for comparison with allowable stresses. These are obtained by the equations:

$$\tau_{max} = [(S/2)^2 + \tau^2]^{1/2} \quad (10)$$

$$S_p = \tau_{max} + S/2 \quad (11)$$

For this example, S = 4415 psi, τ = 3490 psi, and, from Equations (10) and (11), τ_{max} = 4130 psi and S_p = 6337 psi. The AISC Manual [2] allowable stresses for A307 Grade B bolting are 20,000 psi tension and 10,000 psi shear. The Seismic Margin, Equation (1), is:

$$\text{Seismic Margin} = \frac{10000}{4130} = 2.42$$

The yield strength and ultimate tensile strength of A307 Grade B bolting are 33000 psi and 60000 psi, respectively. The Nominal Margins, Equations (2) and (3), are:

$$\text{Nominal Margin on Yielding} = \frac{33000}{6337} = 5.21$$

$$\text{Nominal Margin on Breaking} = \frac{60000}{6337} = 9.47$$

It may be useful to look at conservatisms in the seismic analysis. The g-loading, according to the floor response spectra, is approximately 0.18 g rather than 1.5 g horizontal and 0.12 g rather than 0.48 g vertical. With these floor response spectra g-loads:

$$\tau = \frac{0.18 \times 3900}{4 \times 0.419} = 419 \text{ psi}$$

$$S = \frac{M_x}{2 \times 23 \times 0.419} = \frac{0.18 \times 3900 \times 14.5 - (1 - .12) \times 3900 \times 11.5 + 23600}{19.274}$$

$$= -295 \text{ psi.}$$

The negative value of S means that the weight of the motor would prevent overturning under the combined seismic and motor torque. Further, if the bolts are tightened in installation (as is normally done) and the bolts stay tightened, the shear loads would be resisted by friction between the motor feet and pedestal rather than by shear stress in the bolts.

6.1.2 Pump Feet Bolting

The model for the pump feet bolting is shown in Figure 4(b). The pump is anchored to the pedestal by four 1-in. A307 Grade B bolts. As indicated in Figure 2, the bolt spacing parallel to the shaft is larger than that perpendicular to the shaft. As a result, the model evaluates the 1.5 g horizontal loading in the direction of the smallest bolt spacing. The evaluation is analogous to that described for the motor feet bolts, except that forces imposed by the attached piping must be included rather than motor torque.

In the early evaluation stage, before the results of piping system analysis are available, the pipe forces might be taken as the allowable forces permitted by the pump manufacturer. For this example, we will use the calculated pipe forces; these are shown in Table 3. It may be observed in Table 3 that forces due to the DBE are not necessarily larger than those due to the OBE. This is because larger damping is used in the analysis of DBE than for OBE. In this example, we use the larger of OBE or DBE forces. Also, "thermal" (restraint of free thermal expansion of the piping system) may or may not be present during an earthquake; the forces due to "thermal" are combined with the other forces so as to obtain the maximum combined forces, whether "thermal" is or is not present. Because the piping is analyzed by a response spectrum method, the signs of the forces must be taken as $\pm$ to obtain maximum combined loads.

The inertial shear force is $\pm$ 1.5 x 4000 = $\pm$ 6000 lb in the z-direction. From Table 3, the piping OBE/DBE resultant shear forces, $(F_x^2 + F_z^2)^{1/2}$, are $\pm [(40 + 28)^2 + (30 + 55)^2]^{1/2} = \pm 109$ lb. The thermal plus weight resultant shear forces are $[(1004 - 281 + 55)^2 + (-688 + 78 - 30)^2]^{1/2} =$ 1007 lb. Using the conservative assumption that the piping shear forces act in the same direction as the inertia shear forces, the total shear force is 6000 + 109 + 1007 = 7116 lb. The shear stress is simply the shear force divided by the cross sectional area of the four bolts. The cross sectional root area of 1-in.-NC bolts is 0.551 in.^{2}; hence the bolt shear stress, τ, is:

TABLE 3: PIPE LOADS ON AUXILIARY FEEDWATER PUMP (1-FW-P-3A)

Nozzle	Load	Forces, Lb			Moments, Ft-Lb		
		F_x	F_y	F_z	M_x	M_y	M_z
Discharge	Thermal	1004	0	-688	0	943	0
	Weight	0	-109	0	80	0	20
	± OBE	40	20	28	8	34	1
	± DBE	35	10	26	9	32	3
Suction	Thermal	-281	79	78	-246	628	-704
	Weight	55	-478	-30	-707	-74	42
	± OBE	27	77	38	153	69	45
	± DBE	30	103	55	207	90	48

$$\tau = \frac{7116}{4 \times .551} = 3229 \text{ psi}$$

The inertial moment about A [Fig. 4(b)] is $\pm$ 1.5 x 4000 x 8.5 = $\pm$ 51000 in.-lb. The corresponding piping OBE/DBE M_x is $\pm$ (9 + 207) x 12 = $\pm$ 2592 in.-lb. The absolute value of the thermal + weight M_x is |80 - 246 - 707| x 12 = 10476 in.-lb. The forces applied to the pump nozzles also produce a moment about A in Figure 4(b). These are calculated by:

$$M_{xA} = (F_{zd} + F_{zs}) \times 1.5 + (F_{ys} - F_{yd}) \times 16 \qquad (12)$$

where

F_{zd} = force in z-direction, piping on discharge nozzle

F_{zs} = force in z-direction, piping on suction nozzle

The moment arms of 1.5 in. and 16 in. are indicated in Figure 4(b). The magnitudes of the forces are included in Table 3. Equation (12) gives

M_{xAt} = (-688 + 78) x 1.5 + (79-0) x 16 = 349 in.-lb, thermal

M_{xAw} = (0-30) x 1.5 + (-478 + 109) x 16 = -5949 in.-lb, weight

$\pm M_{xAE}$ = (28 + 55) x 1.5 + (103 + 20) x 16 = $\pm$2093 in.-lb, OBE/DBE

The largest absolute sum of these moments is 7693 in.-lb. The total maximum magnitude of M_x is:

$$M_x = 51000 + 2592 + 10476 + 7693 = 71761 \text{ in.-lb}$$

The first term is the inertia effect on the pump body; the last three terms are moments imposed by the piping on the pump. The tension bolt stress due the moment M_x is:

$$S_{Mx} = \frac{71761}{4 \times 9.5 \times 0.551} = 3427 \text{ psi}$$

The downward (-y) force on the pump with the pump being accelerated downward by 0.48 g is 4000 (1-.48) = 2080 lb. This, divided by the total bolt area of 4 x 0.551 in.^{2}, gives a "negative" bolt stress of 944 psi. Subtracting this from S_{Mx} gives S = 2483 psi.

Using Equations (10) and (11) with τ = 3229 psi, S = 2483 psi gives:

τ_{max} = 3460 psi

S_p = 4701 psi

Seismic Margin = 10000/3460 = 2.89

Nominal Margin on yielding = 33000/4701 = 7.02

Nominal Margin on Breaking = 60000/4701 = 12.8

This example uses highly conservative inertial loads with piping loads that are reasonable estimates for this particular pump installation. By using inertial g loads of 0.18 horizontal (instead of 1.5) and 0.12 vertical (instead of 0.48) and retracing our steps, we obtain:

$$\tau = \frac{1836}{4 \times .551} = 833 \text{ psi}$$

M_x = 26881 in.-lb

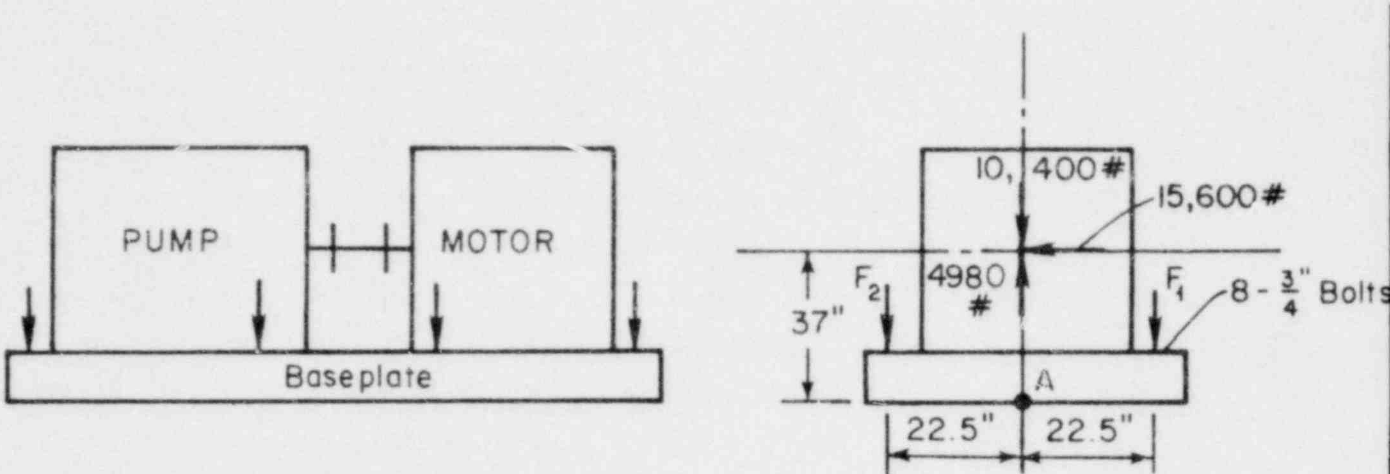
S_{Mx} = 1284 psi

S = 1284 - 1597 = -313 psi

The negative value of S means that the weight of the motor would prevent overturning under the combined seismic and motor torque. Further, if the bolts are tightened in installation as is normally done, and the bolts stay tightened, the shear loads would be resisted by friction between the motor feet and pedestal rather than by shear stress in the bolts.

6.1.3 Baseplate to Floor Bolting

The model for the baseplate is shown in Figure 5. The baseplate is anchored to the concrete floor with eight 3/4-in. A307 Grade B bolts. The bolts are



Motor Wt.	3900 #
Pump Wt.	4000 #
Baseplate Wt.	2500 #
Total	10,400 #

= pounds

Horizontal F	± 1.5	x	10,400	=	±15,600 #
Vertical F	±0.48	x	10,400	=	±4980 #
Bolt Area	0.302 in^2 each				

FIGURE 5. MODEL FOR LOADS ON PUMP BASEPLATE

placed before the concrete is poured; the embedment is sufficient to ensure that the full strength of the bolts can be developed without pulling out of the concrete.

The inertial shear force is $\pm$ 1.5 x 10,400 = $\pm$ 15600 lb. The piping shear forces are the same as in the previous example (that is, 109 + 1007 = 1116 lb). The cross-sectional root area of 3/4-in.- NC bolts is 0.302 in.^{2}; hence the bolt shear stress is:

$$\tau = \frac{15600 + 1116}{8 \times 0.302} = 6919 \text{ psi}$$

The inertial moment about A, as shown in Figure 5, is $\pm$ 1.5 x 10400 x 37 = $\pm$ 577200 in.-lb. The piping moments are calculated as for the pump feet bolting example except that in Equation (12) the lever arm for (F_{zd} + F_{zs}) is 30 in. instead of 1.5 in. The total moment, including the motor torque of 23600 in.-lb., is

$$M_x = 577200 + 2592 + 10476 + 28298 + 23600 = 642200 \text{ in.-lb}$$

The tension bolt stress due to the moment is:

$$S_{Mx} = \frac{642200}{8 \times 22.5 \times 0.302} = 11814 \text{ psi}$$

The downward force (-y) on the assembly, with downward acceleration of 0.48 g, is 10400 (1-.48) = 5408 lb. This, divided by the total bolt area of 8 x 0.302 in.^{2}, gives a "negative" bolt stress of 2238 psi. Subtracting this from S_{Mx} gives S = 9576 psi.

Using Equations (10) and (11) with τ_{max} = 6919 psi, S = 9576 psi gives:

τ_{max} = 8420 psi
S_p = 13200
Seismic Margin = 10000/8420 = 1.19
Nominal Margin on Yielding = 33000/13200 = 2.50
Nominal Margin on Breaking = 60000/13200 = 4.55

The Seismic Margin of 1.19 is an example of what might appear in a safety analysis report and might raise concern about whether sufficient margin exists for earthquakes larger than the DBE. The Nominal Margins should give some reassurance in this respect. However, the point we wish to make here is that Seismic Margins may contain gross conservatisms, in this example, by the use of 1.5 g horizontal and 0.48 g vertical inertial loads. To illustrate this aspect with this example, we retrace the proceding steps using the g-loadings indicated by the floor response spectra of 0.18 g horizontal, 0.12 g vertical

$$\tau = \frac{0.18 \times 10400 + 1116}{8 \times 0.302} = 1237 \text{ psi}$$

$$M_x = 0.18 \times 10400 \times 37 + 2592 + 10476 + 28298 + 23600 = 134200 \text{ in.-lb}$$

$$S_{Mx} = \frac{134200}{8 \times 22.5 \times 0.302} = 2469 \text{ psi}$$

Negative stress = 10400 x (1-.12)/(8 x .302) = -3788 psi

The negative stress means that the weight of the pump would prevent overturning. The Seismic Margin, with τ = 1237 psi, is 10000/1237 = 8.08. However, if the bolts were tightened in installation, this shear stress would not exist.

6.2 Valves

The example selected is the main steam isolation valve illustrated in Figures 6 and 7. It is a 600 Class valve with body made of A216 Grade WCB material (cast carbon steel). The present-day rating pressures (American National Standards Institute standard B16.34-1977) are 1480 psi at 100 F, 1145 psi at 550 F, and 1075 psi at 650 F. The valve weight is approximately 8500 lb.

The valve is welded to 33.75 in. outside diameter, 1-in. wall thickness pipes, and is supported by the attached pipes. During normal operation, the valve disc is held in the open position by two air-operated cylinders as indicated in Figure 7. Release or loss of air pressure permits the disc to swing to the closed position. The weight of the disc of 350 lb and the mechanical spring

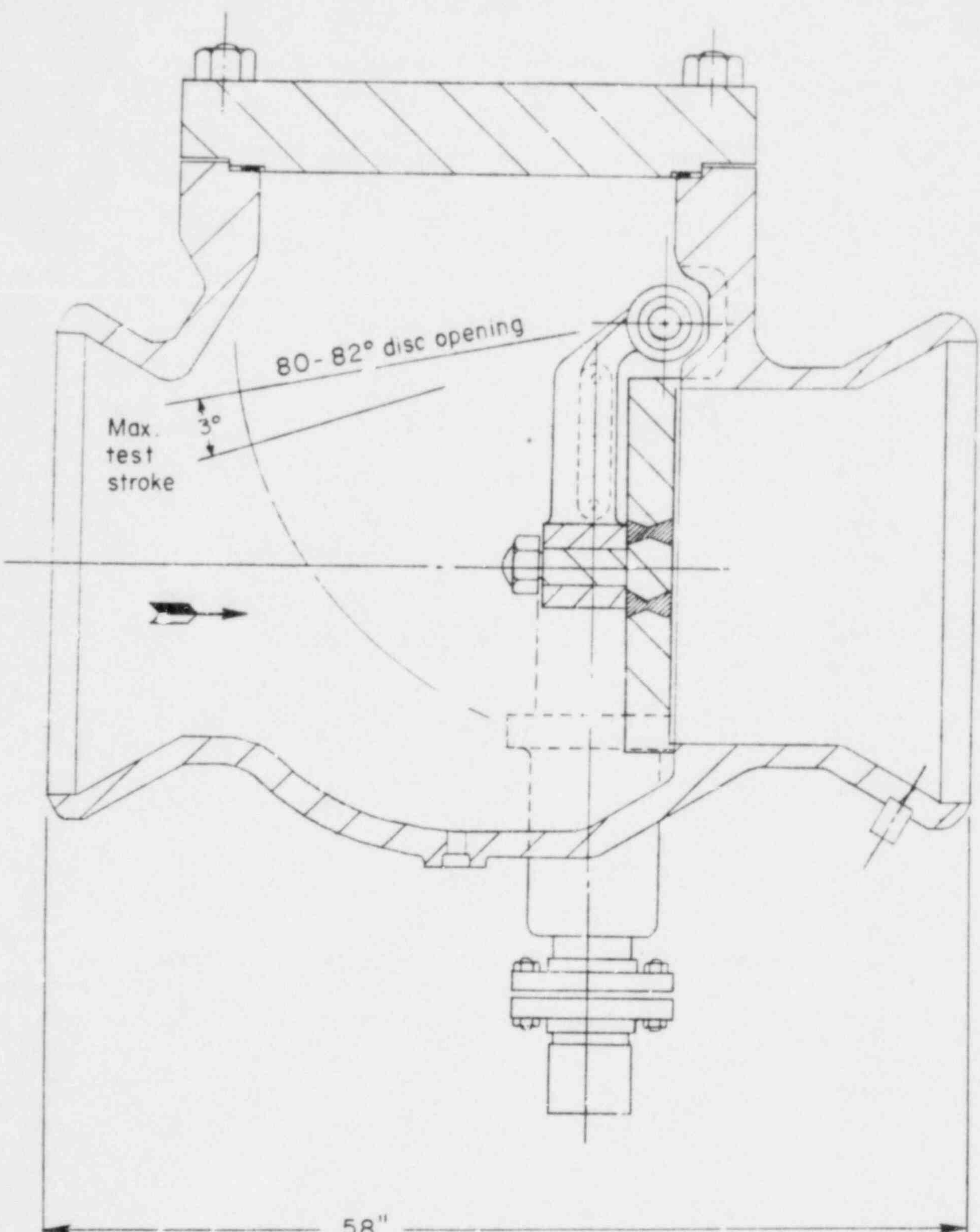


FIGURE 6. CROSS-SECTION THROUGH MAIN STEAM ISOLATION VALVE

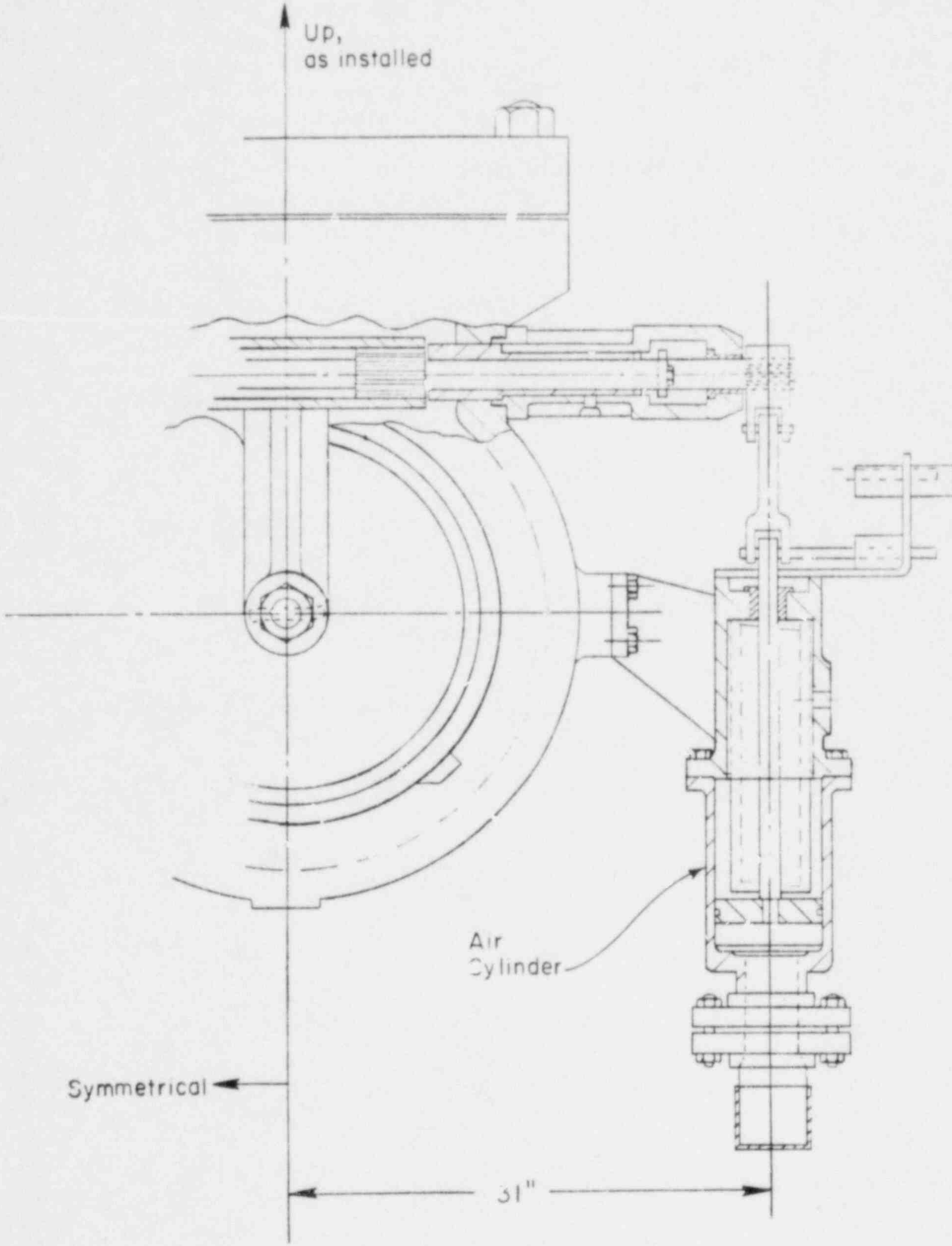


FIGURE 7. END VIEW OF MAIN STEAM ISOLATION VALVE

in the air cylinders initiate the closure action. If steam is flowing from the containment, that flow will assist the closure, acting as a normal check valve. Air bleed rates are controlled so that "slamming" does not occur; opening and closure times are estimated to be about 1 to 3 seconds.

The evaluation starts with approximate but conservative checks of first mode natural frequencies. The valve body is modeled as shown in Figure 8(a); the first mode frequency for that model is 838 Hz. Because the attached pipes do not completely "fix" the valve body ends, a model as shown in Figure 8(b) might have been used; the first mode frequency for that model is 370 Hz. A check was also made of the valve disc with its link to the shaft, considering the disc as a cantilevered concentrated mass, as indicated in Figure 8(c); this model gives a first mode frequency of 62 Hz. These checks sufficed to show that the valve and its internals would respond to earthquake frequencies (33 Hz or less) as a rigid body. The adequacy of the valve was evaluated using conservative estimates of 2.55 g horizontal and 1.6 g vertical seismic loadings. The analysis of the connected piping system, which is now available, shows that g-loads acting on the valve body are 0.65 horizontal and 0.52 vertical for the DBE; accordingly, the accelerations used in the evaluation of the valve body are conservative.

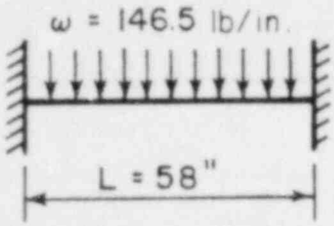
The maximum stress in the valve body, using the model shown in Figure 8(a) and the vector sum of vertical and horizontal accelerations is:

$$S_{max} = \frac{Mc}{I} = \frac{W(2.55^2 + 2.6^2)^{1/2}\ Lc}{8\ I} = \frac{8500 \times 3.64 \times 58 \times 25}{8 \times 8189}$$

$$= 685 \text{ psi}$$

Accordingly, stresses generated due to g-loadings on the valve body itself are of negligible magnitude.

The maximum stress in the tail link was calculated using the model shown in Figure 8(d); the calculated maximum stress is 4554 psi. The tail link is made



$$f_1 = \frac{22.4}{2\pi}\sqrt{\frac{EI}{(w/g)\ L^4}}$$, lowest natural frequency

Smallest cross section: 25" O.D. x 21.75" I.D.

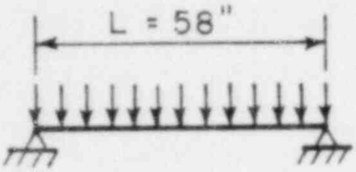
I = moment of inertia = 8190 in^4

E = modulus of elasticity = 2.9×10^7 psi

g = 386 in/sec^2

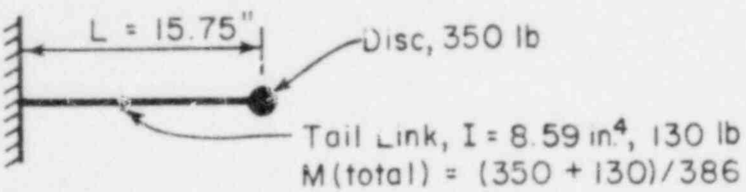
f_1 = 838 Hz

(a) Natural Frequency Model for Valve Body with Fixed Ends



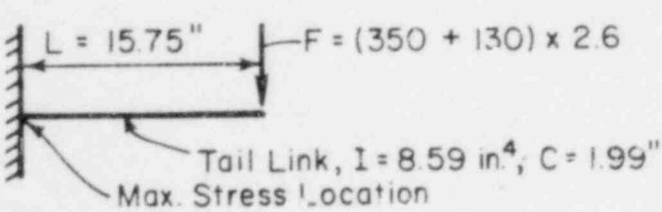
$$f_1 = \frac{9.85}{2\pi}\sqrt{\frac{EI}{(w/g)\ L^4}} = 369\ \text{Hz}$$

(b) Alternative Natural Frequency Model for Valve Body with Supported Ends



$$f_1 = \frac{1}{2\pi}\sqrt{\frac{3EI}{ML^3}} = 62.4\ \text{Hz}$$

(c) Natural Frequency Model for Valve Disc Assembly



$$S = \frac{FLC}{I} = 4554\ \text{psi}$$

(d) Maximum Stress Model for Tail Link

FIGURE 8. MODELS FOR MAIN STEAM ISOLATION VALVE NATURAL FREQUENCIES AND TAIL LINK STRESS.

of A216 Grade WCB material, which has an expected ultimate strength at 550 F of 70000 psi, yield strength of 27800 psi, allowable stress (ASME Class 2) of 17500 psi. Accordingly:

Seismic Margin = 17500/4554 = 3.84

Nominal Margin on yielding = 27800/4554 = 6.10

The valve air-operated cylinders are attached to the valve body as indicated in Figure 7. The adequacy of the bolts used to attach the cylinders to the valve body was checked using the model shown in Figure 9.

The highest bolt stresses occur when the valve body is accelerated to the left (-x direction), and is accelerated downward (+z direction*). Under these conditions, the shear stress of the bolts is

$$\tau = \frac{0.6 \times 478}{4 \times 0.302} + \frac{4764}{4 \times 0.302} = 4181 \text{ psi}$$

The first term contains the upward inertial load due to the downward acceleration at 1.6 g. The second term contains the upward force on the cylinder as it holds the disc in the open position. The maximum tensile stress in the bolts due to the moment about the y-axis is:

$$S_{My} = \frac{2.55 \times 478 \times 16.6 + 0.6 \times 478 \times 8.8 + 4764 \times 9.25}{2 \times 3.75 \times 0.302}$$

$$= 29503 \text{ psi}$$

The -x direction acceleration produces an additional tensile stress of 2.55 x 478 lb; dividing this by the total bolt area of 4 x 0.302 and adding to S_{My} gives:

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*To appreciate the complexity of this seemingly simple example, the reader may wish to check this statement, recognizing that there is an infinite number of possible horizontal-direction earthquakes, combined with $\pm$ vertical earthquake and the cylinder force.

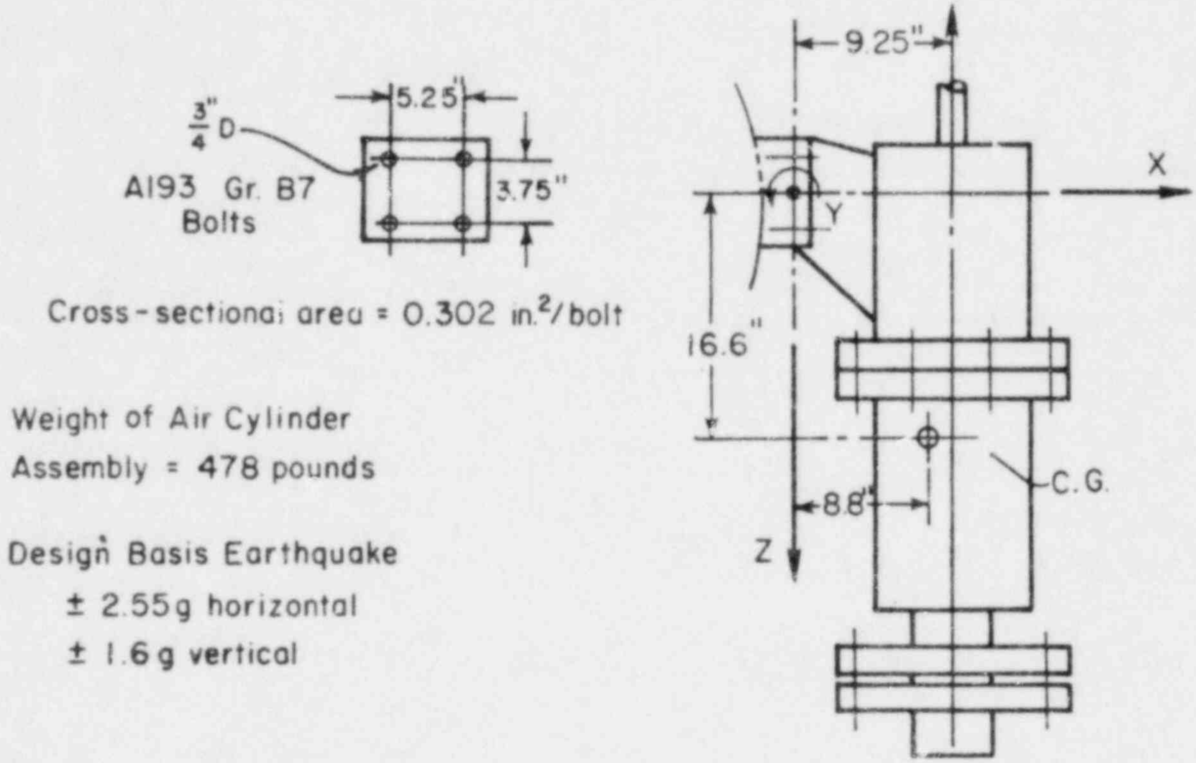


FIGURE 9. MODEL FOR EVALUATION OF BOLTING USED TO ANCHOR AIR CYLINDER TO MAIN STEAM ISOLATION VALVE

$$S = \frac{2.55 \times 478}{4 \times 0.302} + 29503 = 30512 \text{ psi}$$

Using Equations (10) and (11) with $\tau = 4181$ psi and $S = 30512$ psi gives:

$$\tau_{max} = 15819 \text{ psi}$$

$$S_p = 31075 \text{ psi}$$

The bolt material is A193 Grade B7; the allowable stress (ASME Class 2) for this material at 500 F is 25000 psi. The evaluation is for a design basis earthquake which is usually considered as a Level D service loading for which the allowable stress would be 50000 psi. The bolt material has a minimum expected yield strength at 500 F of 88,500 psi. Accordingly:

$$\text{Seismic Margin} = \frac{50000}{31075} = 1.61$$

$$\text{Nominal Margin on yielding} = \frac{88500}{31075} = 2.85$$

As remarked earlier, the valve body evaluations were based on conservative estimates of 2.55 g horizontal and 1.6 g vertical earthquake accelerations. The analysis of the piping system, now available, indicates that the valve body will be subjected to 0.65 g horizontal and 0.52 g vertical during a DBE. With these g-loads, the Seismic Margin (- x horizontal, + z vertical earthquake) is 2.33.

6.2.1 Piping Loads on Valves

For most valves, the valve body has a thicker wall and/or a greater diameter than the attached pipe so that a check of the attached piping is sufficient to assure that the valve body is strong enough to withstand the piping loads. However, as can be seen in Figure 6, this particular valve has a reduced-diameter section which should be checked for adequacy.

The moments imposed by the piping on the valve body were obtained from the piping system analysis; these moments are tabulated in Table 4. The maximum

TABLE 4. PIPING MOMENTS ON MAIN STEAM ISOLATION VALVE

Location	Load	Moments, ft-lb			
		M_x	M_y	M_z	M_r [(a)]
Upstream End	Thermal	-11996	173832	65128	---
	Weight	-135017	-20042	-627	---
	DBE	±358320	±82060	±154752	---
	Turbine Trip	±12386	±5667	±155234	
	Combined	-517719	241517	374487	683084
Downsteam End	Thermal	8985	150812	65128	---
	Weight	-23885	-16915	-627	---
	DBE	±153198	±63687	±154752	---
	Turbine Trip	±3936	±42661	±155407	---
	Combined	-172034	240245	374660	477162

(a) $M_r = (M_x^2 + M_y^2 + M_z^2)^{1/2}$

resultant* moment, M_r, is 683084 ft-lb. The minimum cross section of the valve body can be conservatively described as a cylindrical shell with 25 in. outside diameter and 21.75 in. inside diameter. The stress due to the resultant moment is

$$S = \frac{M_r}{Z} = \frac{683084 \times 12 \times 25}{(\pi/32)\,(25^4 - 21.75^4)} = 12511 \text{ psi}$$

The valve body material is SA-216 Grade WCB material, a cast carbon steel. The Code [1], for Class 2/3 components, gives an allowable stress at 550 F for this material of 17.5 ksi. The minimum expected yield strength at 550 F is 27850 psi. Accordingly, the margins are:

$$\text{Seismic Margin} = \frac{17500}{12511} = 1.40$$

$$\text{Nominal Margin on Yielding} = \frac{27850}{12511} = 2.23$$

6.3 Main Steam Piping Outside Containment

The evaluation of piping starts with a piping system analysis. The piping system in this example is shown in Figure 10. It consists of three separate steam lines extending from the containment to a header which is anchored on one end, guided on the other end.

The piping system is evaluated for:

(1) restraint of thermal expansion/thermal anchor movements

(2) dead weight of pipe, valves, insulation and contained fluid

---

*Resultant moment = $(M_x^2 + M_y^2 + M_z^2)^{1/2}$. The equation $S = M_r/Z$ then gives the maximum stress intensity (2 times maximum shear stress) for direct comparison with allowable tensile stresses.

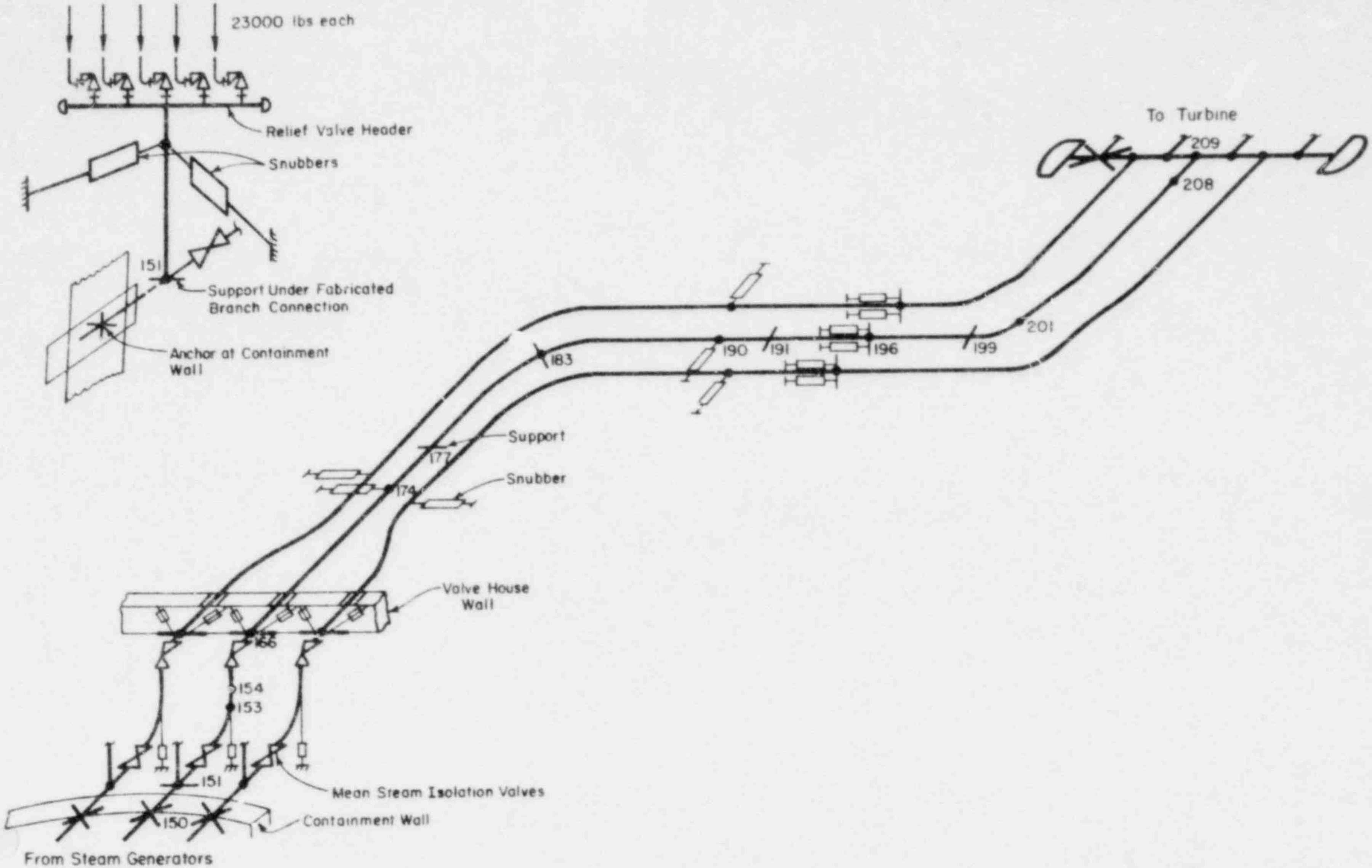


FIGURE 10. MAIN STEAM PIPING OUTSIDE CONTAINMENT

(3) earthquakes

(a) inertial effects in which the input motion is represented by a response spectra which envelopes the response spectra at the various support points.

(b) Earthquake-caused anchor movements (for example, movement of the containment at the point 150 in Figure 10)

(4) turbine trip (sudden close of steam inlet valve at turbine, causing a "steam hammer" effect (evaluated using a time-history dynamic analysis)

(5) relief valve operation, in which the opening of the relief valves causes a sudden and sustained thrust on the piping (evaluated using a time-history dynamic analysis)

The model used in the piping system analysis includes all of the anchors, supports, and snubbers indicated in Figure 10. For dynamic effects (earthquakes, turbine trip, early portion of relief valve operation) the snubbers are assumed to "lock-up".

The piping system analysis gives sets of moments acting at various locations in the piping system. These moments are converted into stresses using procedures given in ANSI B31.1 - 1967 [11]. This Code uses stress intensification factors (i) to indicate the relative strength of a component (for example, an elbow) to the strength of straight pipe. Stresses such as those due to an OBE and associated loads are usually limited to 1.2 S_h, where S_h is the allowable stress at the operating temperature. This corresponds to the present (1980) ASME Code [1] stress limit for Class 2/3 piping of 1.2 S_h for Level B limits.

The stress at various locations in the center of the three steam lines are summarized in Table 5. The headings of Table 5 are:

TABLE 5: STRESSES IN THE CENTER STEAM LINE, FIGURE 10

Point No.	i	S_p	S_w	S_{EQ}	S_{TT}	S_{RV}	Total Stress	$\frac{S_{EQ}}{Total}$
151	3.58	3781	5784	8661	5945	271	24442	0.35
153	2.63	7875	1591	8053	1445	383	19347	0.42
154	2.63	7875	2053	5891	1613	361	17793	0.33
166	1.00	7875	1329	5173	1104	71	15552	0.33
174	1.00	7875	319	1464	493	0	10151	0.14
177	1.00	7875	188	2891	1268	0	12222	0.24
183	1.18	7875	619	1361	211	0	10066	0.14
190	1.00	7875	776	2010	358	0	11019	0.18
191	1.00	7875	1421	1597	316	0	11209	0.14
196	1.00	7875	789	1232	288	0	10184	0.12
199	1.00	7875	740	717	331	0	9663	0.07
201	2.63	7875	1328	2285	284	0	11772	0.19
208	1.0	7875	2778	1528	482	0	12663	0.12
209	3.58	7875	4286	3915	4471	0	20547	0.19

(1) Point No.: the location identified in Figure 10

(2) i: stress intensification factor, as defined in ANSI B31.1 -1967 [11]

(3) S_p: axial stress due to design pressure of 1085 psi

(4) S_w: stress due to deadweight of pipe, valves, insulation, and contained fluid

(5) S_{EQ}: stress due to OBE, including both inertial and anchor movement effects

(6) S_{TT}: stress due to turbine trip

(7) S_{RV}: stress due to relief valve operation

(8) Total: sum of S_p, S_w, S_{EQ}, S_{TT}, and S_{RV}

(9) S_{EQ}/Total: fraction of stresses which are roughly proportional to the earthquake magnitude to the total of all stresses

Stresses due to restraint of thermal expansion are not included in Table 5 because restraint of thermal expansion is not a primary load. If stresses due to such loads are above the elastic capacity, the higher stressed portions of the piping yield slightly to accommodate the thermal expansion. This concept also applies to anchor displacements, including anchor displacements due to earthquake. The magnitudes of S_{EQ} include both inertial and anchor movement effects. This is a conservative approach, and in deriving a Nominal Margin, we will use only the inertial portion of the DBE.

Table 5 illustrates a typical aspect of piping systems in that only a few points are highly stressed. The highest stressed is point 151; we will discuss the margins at that point.

The material in the piping system is SA155 Grade CMS 75, which has an allowable stress of S_h at 550 F of 18750 psi; hence, $1.2S_h$ = 22500 psi. It can be seen in Table 5 that at point 151 (a fabricated branch connnection), the sum of the stresses of 24442 psi is greater than the limit of $1.2S_h$ = 22500 psi. However, the summation of stresses implies that the peaks of the stresses S_{EQ}, S_{TT}, and S_{RV} will occur at the same time; this is highly unlikely. If S_{EQ} and S_{TT} are combined by the square root of the sum of the squares and then added to the other stresses:

$$\text{Total Stress} = 3781 + 5784 + (8661^2 + 5945^2)^{1/2} + 271 = 20341 \text{ psi.}$$

The Seismic Margin might then be presented in a safety analysis report as:

$$\text{Seismic Margin} = \frac{22500}{20341} = 1.11$$

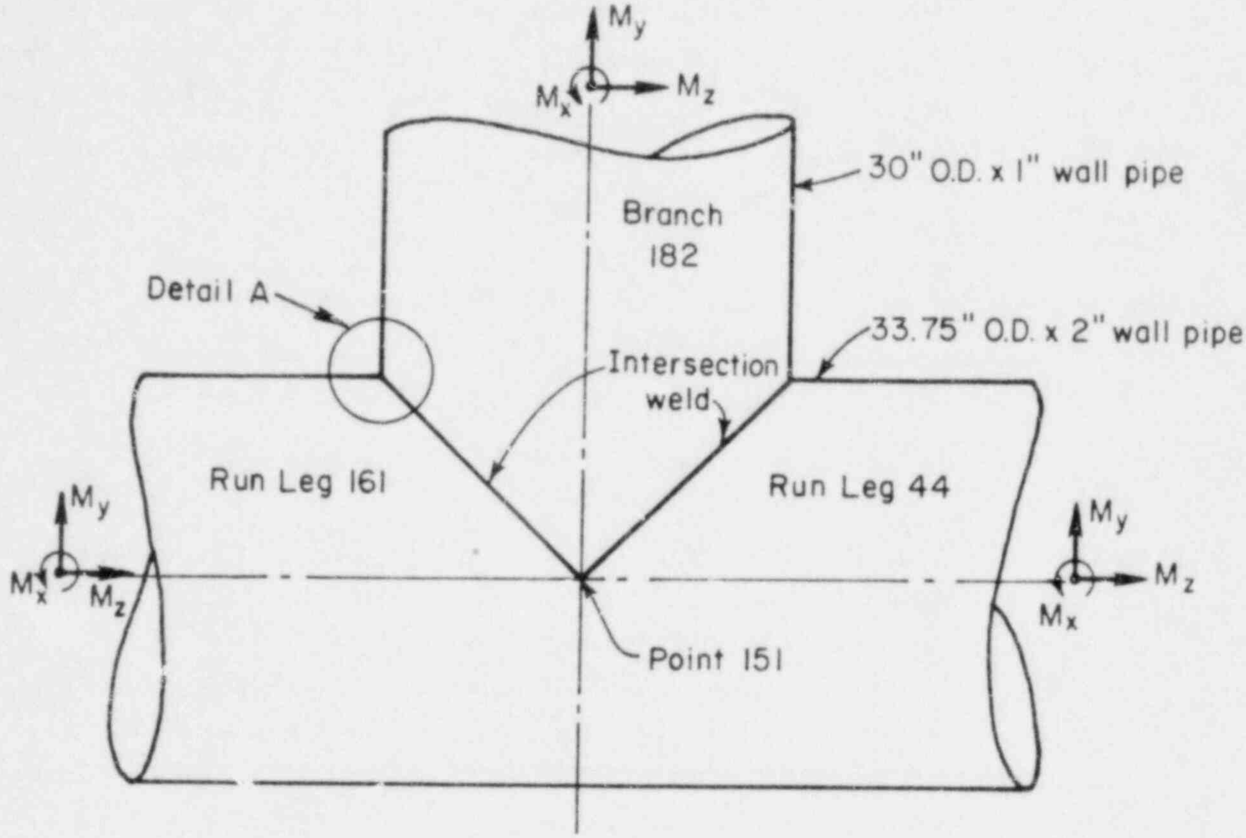
This is an example of the aspect discussed in the introduction to "specific applications"; a general criteria was established and, for point 151 of the piping system, was not satisfied. The conservatisms involved in the general criteria were then examined and one change was made. Other conservatisms could have been examined. For example, S_{EQ} is the stress due to both inertial effects and anchor movements. Considering only inertial effects (which produce primary stresses) and not anchor movements, the value of S_{EQ} is reduced by about 6000 psi and the total stress would be less than 22500 psi.

For the DBE, the value of S_{EQ} at point 151 is 15699 psi, giving a total stress of 31420 psi. Stresses such as those due to DBE and associated loads may be limited to $1.8S_h$, where S_h is the allowable stress at the operating temperature. This corresponds to the present (1980) ASME Code [1] stress limit for Class 2/3 piping of $1.8S_h$ for Level C limits. The Seismic Margin, on this basis, is:

$$\text{Seismic Margin} = \frac{1.8 \times 18750}{31420} = 1.07$$

An estimate of the Nominal Margin for this point is rather complex, mainly because point 151 represents a fabricated branch connection, a complex structure which is subjected to a complex set of nine moments plus internal pressure. This aspect is indicated in Figure 11.

The minimum expected yield strength of SA 155 Grade CMS 75 at 550 F is 31200 psi (from Reference 1). In previous examples, a Nominal Margin on yielding was obtained as a ratio of material yield strength to the maximum calculated stress. This is not appropriate in this example for two reasons. First, the i-factor is not a measure of maximum stress; rather, it is a measure of the



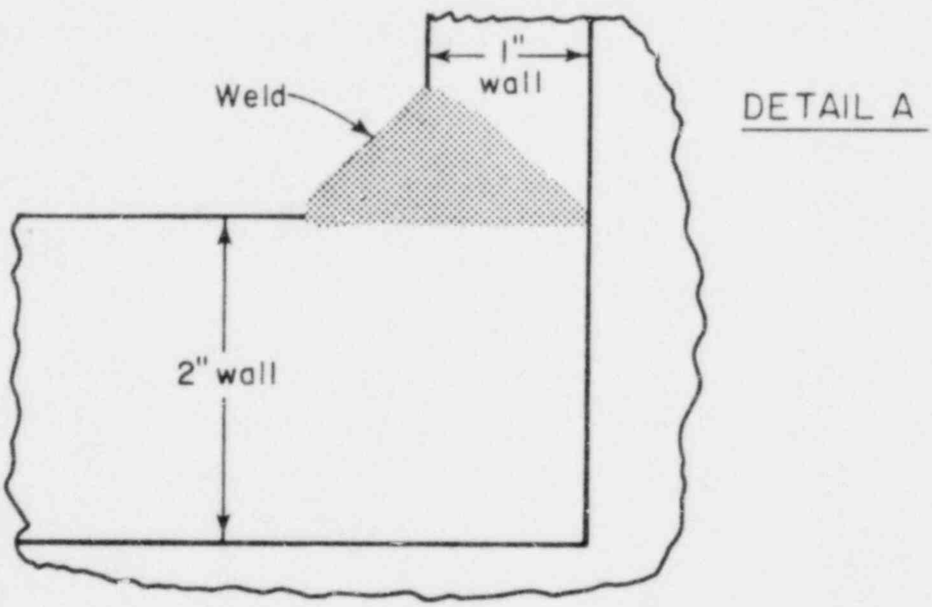


FIGURE 11. FAPRICATED BRANCH CONNECTION AT POINT 151 OF FIGURE 10.

fatigue strength of a fabricated branch connection relative to the fatigue strength of a typical girth butt weld in straight pipe. Second, the relevant failure mode is plastic deformation of the branch connection; this characteristic is described by test data and theory of "limit loads" (limit loads may be considered to be a set of loads at or below which the plastic deformation is small and tolerable in a piping system).

To estimate a Nominal Margin for the fabricated branch connection shown in Figure 11, it is appropriate to examine the primary moments tabulated in Table 6. Test data [12] indicate that pressure of the magnitude involved in this example does not significantly affect the limit moment capacity; accordingly, the relevant loads are the primary moments. These are the inertial portion of S_{EQ} for the DBE, the deadweight, turbine trip, and relief valve operation. The total of these involves the conservative assumption that peak moments from the dynamic loads do occur at the same time. The next step in the evaluation is to convert the individual moments into a resultant moment, $M_r = [M_x^2 + M_y^2 + M_z^2]^{1/2}$. Next, it is necessary to calculate the limit moment capacity of the branch pipe and the run pipe. The appropriate equations and results for all of these are shown in Table 6.

It can be seen that the resultant moments applied by the primary moments are about 10 percent of the limit moments of the branch pipe or the run pipe. However, the subject of the evaluation is the complex branch connection shown in Figure 11. From test data [12], the branch connection limit moment is about one-half of the branch pipe limit moment for moments applied to the branch. From simple limit load concepts, the branch connection limit is not less than one-quarter of the run pipe limit moment for moments applied to run legs of the branch connection. Assuming that the limit moment capacity under both branch and run moments is a linear combination, we arrive at the estimate that the applied primary loads are equal to 0.693 times the limit moment capacity. The Nominal Margin against excessive plastic deformation is the inverse of 0.693:

$$\text{Nominal Margin} = \frac{1}{0.693} = 1.4$$

TABLE 6: PRIMARY MOMENTS ACTING ON POINT 151 (FIGURE 10), FABRICATED BRANCH CONNECTION (FIGURE 11).

Load (a)	Moments, ft-lb.								
	Branch 182			Run Side 161			Run Side 44		
	M_x	M_y	M_z	M_x	M_y	M_z	M_x	M_y	M_z
DBEI	30058	26250	53418	20680	80013	48470	22974	65760	79547
WEIGHT	1021	0	0	243680	16528	2953	244699	16527	2954
T.T.	86386	2292	1876	120912	101	1931	206987	2501	3714
R.V.O.	16941	0	14	5451	110	68	11488	110	83
Combined	134406	28542	55308	390723	96752	53422	486148	84898	86298
M_r	148117			406053			500994		

(a) DBEI = inertial loads portion of Design Basis Earthquake, Weight = dead weight, T.T. = turbine trip, R.V.O. = relief valve (s) operation, $M_r = [M_x^2 + M_y^2 + M_z^2]^{1/2}$

Yield moments of straight pipe: Branch Pipe: $M_{Lb} = Z_b S_y = 639.3 \times 31200/12 = 1662000$ ft-lb.

Run Pipe: $M_{Lr} = Z_r S_y = 1496 \times 31200/12 = 3890000$ ft-lb.

Z_b = section modulus of branch pipe, Z_r = section modulus of run pipe, S_y = yield strength of pipe material

Estimated fabricated branch connection capacities: Branch moment only: $M_{Lb}/2$

Run moment only: $M_{Lr}/4$

Linear Combination of branch and run moment loads

$$\frac{148000}{0.5 \times 1662000} + \frac{501000}{0.25 \times 3890000} = 0.693; \quad \text{Nominal Margin} = \frac{1}{0.693} = 1.44$$

This means that at DBE plus associated loads (with peaks of dynamic loads assumed to occur at the same time), there is a significant available reserve strength margin. However, this cannot be expressed as a margin available for some earthquake with magnitude greater than the postulated DBE because of the amount of damping assumed to exist with various earthquake magnitudes. The calculation of OBE moments, in this example, used 0.5 percent of critical damping and for DBE, 1 percent of critical damping. As a result, the inertial moments due to the DBE are not two times those due to OBE (as would happen if the moments increased in proportion to the zero period ground acceleration). Rather, for this particular example, the inertial moments due to OBE are almost the same as those due to DBE. If we repeated the evaluation of the Nominal Margin = 1.4 using the OBE inertial moments rather than the DBE inertial moments, we would end up with the same Nominal Margins 1.4, but now for the OBE. This seeming anomaly reflects the state of the art of estimating loadings due to earthquakes.

6.4 Summary of Examples

Seismic Margins and Nominal Margins for the examples are summarized in the following table.

Item	Margin		
	Seismic	Nominal on Yield	Nominal on Break
Pump			
Motor Feet Bolts	2.42	5.21	9.47
Pump Feet Bolts	2.89	7.02	12.8
Baseplate Bolts	1.19	2.50	4.55
Valve			
Tail Link	3.84	6.10	-
Cylinder Bolts	1.61	2.85	-
Valve Body	1.40	2.23	-
Piping			
Point 151	1.07	1.4	-

Except for Piping, Point 151 (fabricated branch connection), the Margins are based on preliminary conservative estimates of seismic g-loadings. Using g-loadings indicated by the floor response spectra for the pump, or g-loadings obtained from the piping system for the valve, the Margins would increase substantially. For example, the Seismic Margin for the pump baseplate bolts would increase from 1.19 to 8.08.

7. SUMMARY

7.1 Allowable Stresses and Nominal Margins

The term "Seismic Margin" has been defined as:

$$\text{Seismic Margin} = \frac{\text{Allowable Stress}}{\text{Calculated Stress}} = \frac{S_A}{\sigma_c}$$

For an item to be acceptable, the Seismic Margin must not be less than 1.00. When the Seismic Margin is close to unity (e.g., 1.01) the question arises: If the loads are underestimated will failure of the item occur? This question is addressed in terms of "Nominal Margins" defined as:

$$\text{Nominal Margin on Yielding} = \frac{S_y}{S_A}$$

$$\text{Nominal Margin on Breaking} = \frac{S_u}{S_A}$$

Nominal Margins indicate the reserve strength that is available when the Seismic Margin is unity. Nominal Margins for tensile loadings are summarized in the following table.

Failure Criteria	Nominal Margins			
	ASME Code, for Pressure Boundary Integrity		AISC Manual, for Supports	
	OBE	SSE	Basic	Seismic
Break	3.0 to 10.4	1.43 to 5.2	2.6 to 3.1	2.0 to 2.3
Yield	1.1 to 4.8	0.55 to 2.4	1.67	1.25

The ASME Code and AISC Manual also contain rules for other loadings:

Shear Loads [(Figure 1(b)]

Compressive Loads [(Figure 1(c)]

Bending Loads [(Figure 1(d)]

Combinations of Loads

In general, the rules are such that Nominal Margins for these other loadings are about the same as for tensile loads.

In detail, the Nominal Margin corresponding to a Seismic Margin of 1.00 depends upon the following:

(1) material
(2) operating temperature
(3) type of loading
(4) failure criteria
(5) exact source of the allowable stress, S_A. For example, ASME Code, Level B allowable stress for pressure boundary integrity, or AISC Manual, basic allowable stress

In addition, to establish the margins on seismic loading only, that portion of the calculated stress due to seismic loading must be identified.

The Nominal Margins cited herein are related to minimum material properties (see Appendix A). An assumption is made that calculated stresses, σ_c, are accurate. Presently used methods for estimating seismic loadings are deemed to be such that σ_c is probably higher than will actually occur, leading to further increase in actual margins over the Nominal Margins.

7.2 Concrete Expansion Anchor Bolts

Design loads for concrete expansion anchor bolts are normally taken to be one-quarter of manufacturer's catalog-listed loads. The catalog-listed loads are average loads, hence the average Nominal Margin corresponding to a Seismic Margin of Unity is 4.0. Available test data (see Appendix B) indicates that, by using one-quarter of average strength as a design basis, the probability of failure at 2 times the design load is about 0.023, and, at the design load, is less than 0.001.

These estimates are based on the assumption that the anchor bolts are installed with the skill and care that is at least equivalent to that used in preparing the test installations.

7.3 Operability

Operability of pumps and valves may be evaluated, in part or whole, by checking such aspects as bearing loads, impeller clearance, shaft deflections, for pumps; and yoke and/or stem lateral displacements for valves. Because limits for such aspects are established by the manufacturers with their specialized knowledge of their equipment, we cannot generically quantify the capacity of their equipment to exceed their limits.

Seismic qualification of complex mechanisms such as valve operators may be achieved by testing of the type described by IEEE Std. 344 [10]. Most test results are from "proof" tests (that is, the item operated satisfactorily during and after the test). That item may have been able to pass a test of several times the g-load used in the test. Accordingly, a Seismic Margin of 1.00 based on proof tests may correspond to a Nominal Margin significantly greater than 1.00; but not necessarily.

7.4 Specific Applications

Examples of the development of Seismic Margins and Nominal Margins for pumps, valves and piping bring out the aspect that σ_c used in defining Seismic Margins and Nominal Margins is seldom accurately known. Rather, because of the large number of complex items that must be evaluated, simple but conservative models and criteria are established. In the early stages of evaluation, loads may not be accurately known. In their absence, conservative and sometimes very conservative estimates are made. The Seismic Margins given in final safety analysis reports may have substantial embedded conservatisms. In such cases, the Nominal Margins identified in 7.1 of this summary will only indicate lower bounds.

7.5 Aspects Not Included in Nominal Margins

Portions of this report may convey an unintended impression that pumps, valves, and piping in nuclear power plants always perform satisfactorily. Actually, of course, there is an extensive history of valve operators which do not always operate and piping which develops leaks. These have nothing to do with earthquakes, but the potential of "something wrong" at the time an earthquake occurs is a concern. The "not included aspects" are discussed briefly in Section 3.1.4 and include:

(a) presence of fabrication defects
(b) initiation and/or growth of defects in service due to, for example, corrosion or stress-corrosion cracking
(c) design errors
(d) fabrication errors (such as, an improperly installed concrete anchor expansion bolt or a missing or loose nut on a hold-down bolt)

The Nominal Margins in 7.1 of this summary are based on the assumption that quality control, preservice inspection, and inservice inspection are sufficient to minimize the importance of these not-included aspects.

REFERENCES

Documents marked with an asterisk may be ordered from the NRC/GPO Sales Program, Washington, DC 20555 and/or the National Technical Information Service, Springfield, VA 22161. All other documents may be obtained through public technical libraries or by contacting the publisher named in the citation.

(1) ASME Boiler and Pressure Vessel Code, Section III, Division 1, "Nuclear Power Plant Components", 1980 Edition. Published by ASME, 345 E. 47th St., New York, NY 10017.

(2) AISC "Manual of Steel Construction", Seventh Edition. Published by American Institute of Steel Construction, 400 North Michigan Avenue, Chicago, IL 60611.

(3) USNRC Regulatory Guide 1.48, "Design Limits and Loading Combinations for Seismic Category 1 Fluid System Components", May 1973. Published by USNRC, Washington, D.C. 20555.*

(4) USNRC Regulatory Guide 1.124, "Service Limits and Loading Combinations for Class 1 Linear-Type Component Supports", Rev. 1, Jan. 1978. Published by USNRC, Washington, D.C. 20555.*

(5) USNRC Regulatory Guide 1.130, "Service Limits and Loading Combinations for Class 1 Plate-and-Shell-Type Component Supports", Rev. 1, Oct. 1978. Published by USNRC, Washington, D.C. 20555.*

(6) USNRC, IE Bulletin 79-02, "Pipe Support Base Plate Design Using Concrete Expansion Anchor Bolts", March 1979. Available for inspection and copying for a fee in the NRC Public Document Room, 1717 H St., NW, Washington, D.C. 20555.

(7) Ciatto, R. D., and Boentgen, R. R., "Strength of Concrete Expansion Anchors for Pipe Supports", pp 247-262 in 'Effects of Piping Restraints on Piping Integrity,' PVP-40 (1980). Published by ASME, 345 E. 47th St., New York, NY 10017.

(8) Clark, G. L., "Installation of Concrete Expansion Anchors at the Fast Flux Test Facility", pp 263-272 in 'Effects of Piping Restraints on Piping Integrity,' PVP-40 (1980). Published by ASME, 345 E. 47th St., New York, NY 10017.

(9) Teledyne Engineering Service, Summary Report on "Generic Response to USNRC IE Bulletin Number 79-02, Base Plate/Concrete Expansion Anchor Bolts," August 30, 1979, 303 Bear Hill Road, Waltham, MA 02154.

(10) IEEE Standard 344-1975, "Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations." Published by Institute of Electrical and Electronic Engineers, 345 E. 47th St., New York, NY 10017.

(11) American National Standards Institute, ANSI B31.1-1967, "Power Piping, published by ASME, 345 E. 47th St., New York, NY 10017.

(12) Rodabaugh, E.C., "Interpretive Reprrt on Limit Analysis and Plastic Behavior of Piping Products." Welding Research Council Bulletin 254, November 1979.

APPENDIX A

STATISTICAL DATA ON ULTIMATE AND YIELD TENSILE PROPERTIES OF HOT FINISHED CARBON STEEL MATERIALS

APPENDIX A

STATISTICAL DATA ON ULTIMATE AND YIELD TENSILE PROPERTIES OF HOT FINISHED CARBON STEEL MATERIALS

Seismic Margin, based on stresses, is defined herein as S_A/σ_c, where S_A = allowable stress, and σ_c = calculated stress. Allowable Stress S_A is established as a fraction of S_y or S_u (See Table 1), where S_y and S_u are minimum or minimum expected yield strengths and ultimate tensile strengths, respectively. We have defined and tabulated Nominal Margins in terms of the minimums of S_y and S_u. However, it is informative to examine the distribution of tensile properties so as to estimate the average and probability of obtaining lower-than-average or lower-than-minimum tensile properties.

Statistical data on the type of steels ordinarily used for pumps, valves and piping and their supports are quite sparse. Data in available published documents (References [1] and [2]) were not sufficient for our purpose. We requested and obtained data from J. R. Farr of Babcock and Wilcox Co.* and we wish to express our appreciation for that data.

Data Base and Evaluation

Directly relevant data are those on materials purchased to either an SA-Specification or an A-Specification. The SA indicates an ASME Code material specification. The A indicates an ASTM material specification; these are usually identical to corresponding SA-Specifications. For our purpose, the specification must include specified minimum strengths so that comparisons of average strengths with minimum specified strengths can be made and estimates of the probability of having material with strengths less than the minimum specified can be made.

*Private communication with author, July 30, 1980.

Table A1 summarizes the available data. The column headed "No. of Samples" lists the number of tests, with each representing a different "heat" of the material. Reference [1] data are presented in the American Society for Metals handbook in the form of bar graphs. They are in both the 1961 Edition and the 1978 Edition. The 1978 Edition uses the present day designations for these materials, but the data were obtained prior to 1961. Farr's data were obtained from mill test reports accumulated over the past two years (1979 and 1980).

The data were evaluated by an elementary statistical analysis, the standard deviation, σ, was calculated by the equation:

$$\sigma = \left[\frac{\Sigma fS^2}{n} - S_a^2\right]^{1/2} \qquad \text{(A1)}$$

where f = frequency, S = sample stress, S_a = average stress, and n is the number of samples.

We note that the materials covered by Table A1 have minimum specified strengths and, for A516-70 and A299, maximum specified ultimate tensile strengths. The question arises: How do these limits influence the distribution of strengths? Figure A1 shows a bar graph for a hot finished carbon steel material which does <u>not</u> have strength limits. The normal distribution (arbitrarily at a frequency of 95 at the average strength) is also shown. It can be seen that the distribution is reasonably close to normal. This is representative of several groups of data given in References [1] and [2] for materials without strength limits. The distributions are all approximately "normal", where normal is defined by the equation:

$$f = C \cdot e^{-[(S_a - S)/(\sqrt{2}\,\sigma)]^2} \qquad \text{(A2)}$$

where f = frequency

S_a = average strength

S = strength

σ = standard deviation

TABLE A1. SUMMARY OF STATISTICAL DATA

Ref.	Material (a)	Strength (b)	S_s, ksi (c)	No. of Samples	S_a, ksi (c)	$\frac{S_a}{S_s}$	σ, ksi (c)
(1)	A285-A	Y.S.	24.0	21	32.62	1.36	1.463
↓	A285-B	↓	27.0	70	36.14	1.34	1.959
	A285-C		30.0	220	37.44	1.25	1.538
	A201-A		30.0	26	37.31	1.24	1.435
	A201-B		35.0	34	44.18	1.26	2.176
(*)	A106-B		35.0	102	45.68	1.31	4.248
(1)	A212-B		38.0	33	45.42	1.19	1.891
(*)	A516-70		38.0	52	48.62	1.28	3.525
(*)	A299		41.0	98	51.45	1.25	2.821
(*)	A106-B	U.T.S.	60.0	102	71.92	1.20	4.178
↓	A516-70	↓	70.0	52	77.04	1.10	3.474
	A299		75.0	98	81.38	1.09	3.130

(a) These are plate materials, except for A106-B, which is a seamless pipe material. The present designations of A201-A, A212-A and A212-B are A516-55, A516-65 and A516-70, respectively.

(b) Y.S. = yield strength, U.T.S. = ultimate tensile strength.

(c) S_s = specified minimum strength

S_a = average strength

σ = standard deviation

For A516-70 and A299, maximum U.T.S. of 90 ksi and 95 ksi, respectively are specified.

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*Data from Farr.

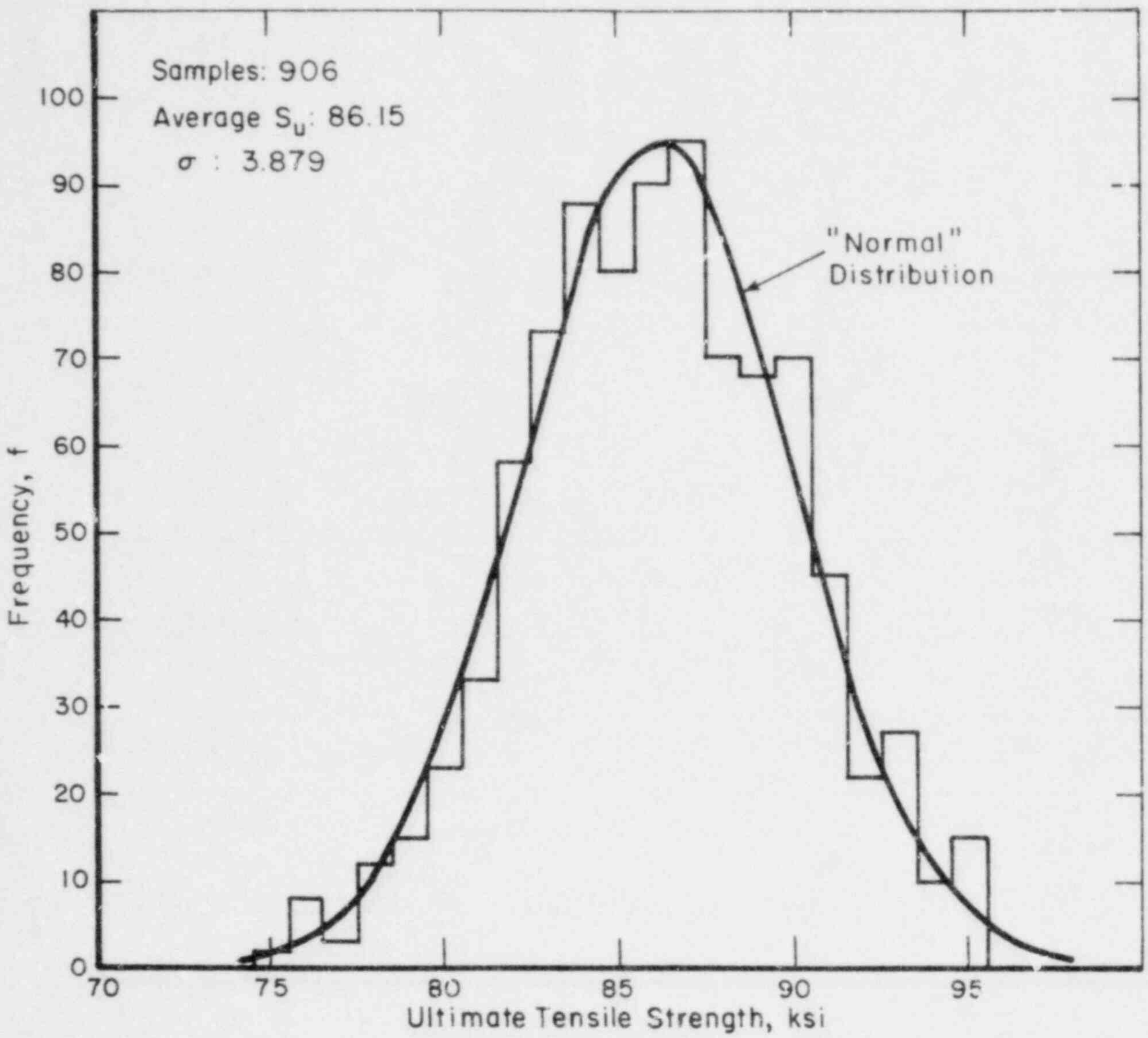


FIGURE A1. DISTRIBUTION OF ULTIMATE STRENGTH OF A HOT FINISHED CARBON STEEL MATERIAL WITH NO STRENGTH LIMITS [DATA ON 1035 BARS FROM REF. (1a)]

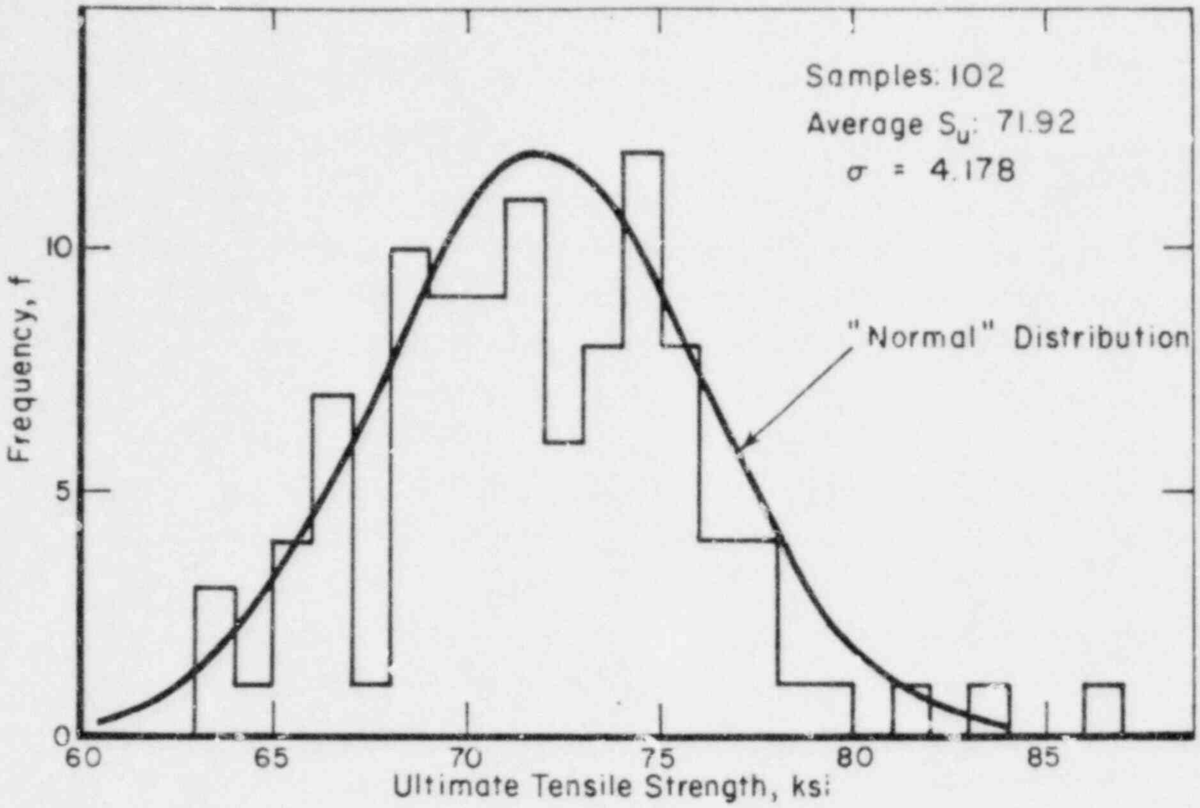
For comparison with bar graphs, C is selected to fit the data at about $S = S_a$. (If the graphs were normalized to unit area under the curve, then C would be $1/(\sigma\sqrt{2\pi})$.)

Figure A2 shows the distribution of strengths for A106-B material. Figure A3 shows the distribution of ultimate tensile strength of A299 material, as an example of the effect of both minimum and maximum limits. These distributions are quite erratic as compared to that shown in Figure A1; this is presumably due to the relatively small number of samples available for Figures A2 and A3 ($\sim$100) as contrasted to the approximately 900 samples for Figure A1. Further, there is some evidence of the effect of the limits; particularly for the minimum S_u for A299 material. Nevertheless, the distribution is reasonably close to "normal", and we assume that distribution in our evaluations.

We note that if "heat" strength properties are less than specified minimums, the material (by definition) is <u>not</u> the specified material. Such material is culled out by the manufacturer and used for some other purpose; e.g., material that does not meet A106-B may be sold as A106-A. However, even assuming this culling process is 100 percent effective, there still remains some possibility that a particular piece of material purchased to an SA- or A-Specification will have strengths less than specified minimums. The reason, of course, is that the "heat" sample represents a sample from what usually is a large amount of material in the form of plates, bars, forgings or pipe. The question arises: Given the "heat strengths, what can be expected if one now cuts samples from various portions of the products? Reference [2] addresses that question.

Reference [2] gives data on:

(1) "Official Tests", the equivalent of "heat" tests, and
(2) Differences between the "Official Tests" and tests on coupons cut from the product with that particular "Official Test".



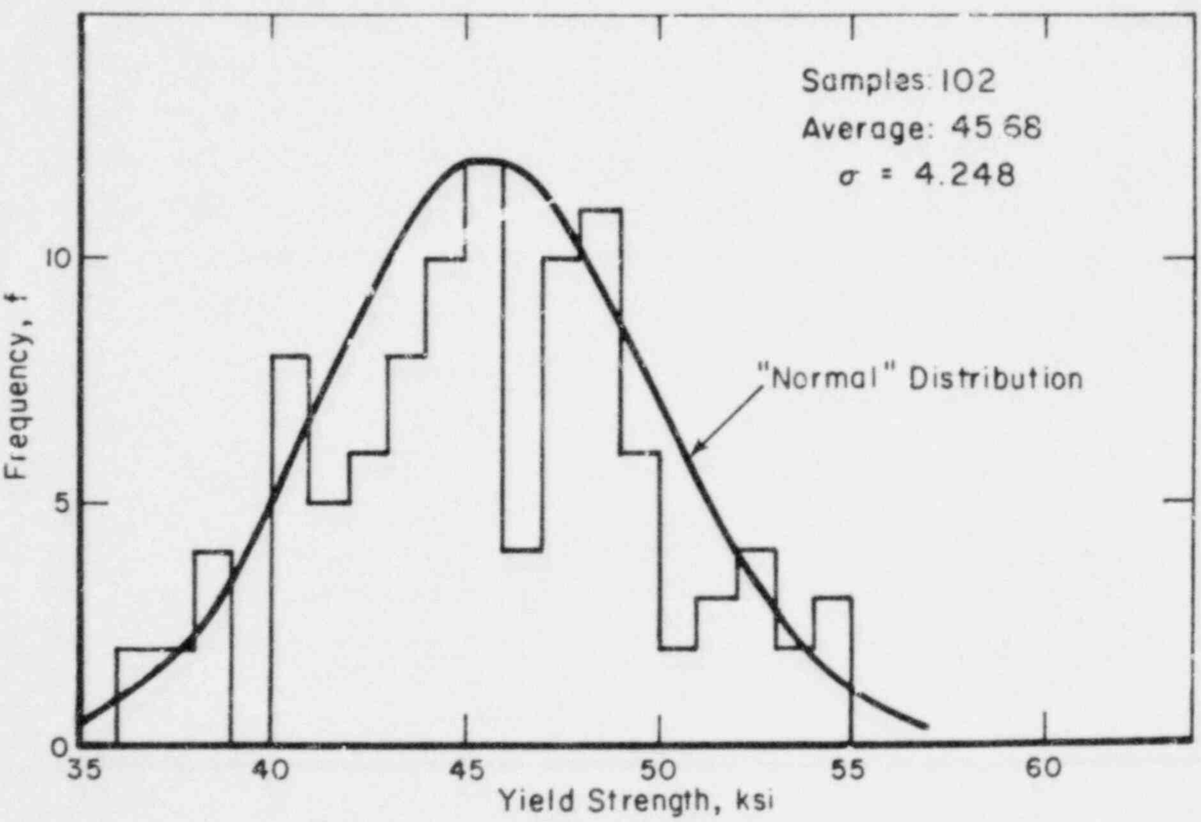


FIGURE A2. DISTRIBUTION OF ULTIMATE AND YIELD STRENGTH FOR A106-B MATERIAL *

*Data from Farr.

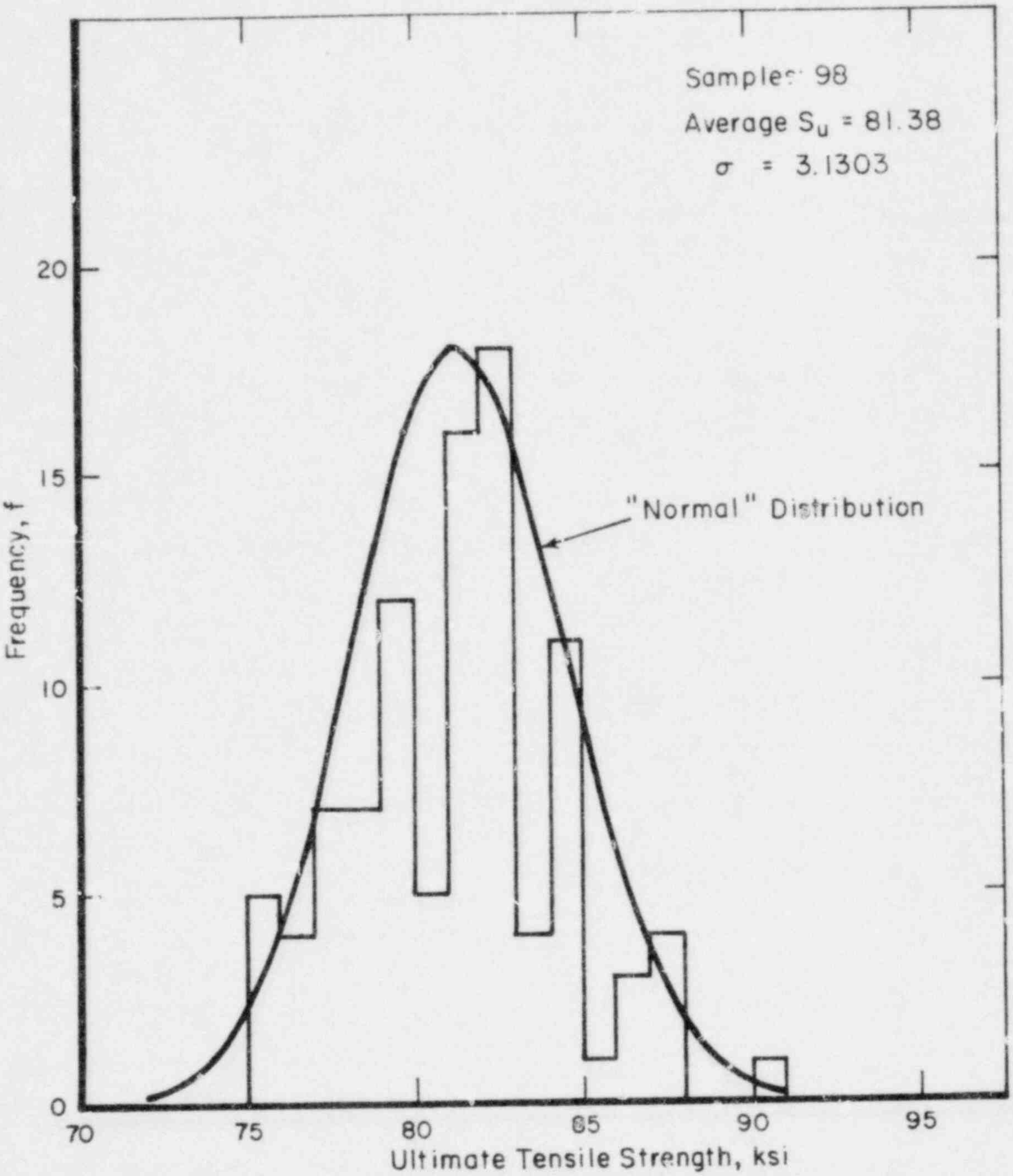


FIGURE A3. DISTRIBUTION OF ULTIMATE TENSILE STRENGTH FOR A299 MATERIAL*

*Data from Farr.

These tests were all run on materials which had no specified strength minimums or maximums. Accordingly, they are not directly applicable to materials to SA- or A-Specifications. However, they give the best available indication of the "below-specified-strength" aspect. The data pertinent to our evaluation are summarized in Table A2.

Three groups of tests were run:

(1) SU/18: Carbon Steel Plates
(2) SU/20: Variation Within As-Rolled Plates
(3) Carbon Steel and HSLA Wide Flange Sections

Reference [2] reports on trends such as variation with strength level, plate thickness, exact location in wide flange sections, and so forth. However, we are using this data as representative of the types of SA- and A-Specification steels listed in Table A1. Accordingly, we have shown results for the entire groups and have used the averages of the standard deviations to estimate probabilities of strengths at or below minimum specified.

Reference [2] implies that the differences were not "normally" distributed. However, by using the "normal" distribution assumptions, we obtain quite close agreement with their final results. Accordingly, the distribution must be fairly close to "normal" and we have assumed that distribution. The probability of strengths at or below a constant, k, times the minimum specified strength, S_s, was obtained by:

$$Pr(S < kS_s) = \int_{S_s}^{\infty} \left[\frac{1}{\sigma\sqrt{2\pi}} e^{-[(S_A - S)/(\sqrt{2}\sigma)]^2} dS \right] x \; Pr(S_h < S_p) \qquad (A3)$$

where S_s = minimum specified strength and $Pr(S_h < S_p)$ is the probability that the heat strength is less than the product strength. This value is given by:

TABLE A2. ABSTRACT OF TEST RESULTS FROM REF. (2), DIFFERENCES BETWEEN OFFICIAL (HEAT) TESTS AND SAMPLES FROM PRODUCT

Test Group	Strength[c]	No. of Samples		Official Average, ksi	Differences[a]	
		Official	Product		Avg., %	σ_p, ksi
SU/18	U.T.S.	481	2,305	68.30	+0.026	2.542
	Y.S.	480	2,302	39.94	-1.768	3.137
SU/20	U.T.S.	357	2.125	65.46	+0.237	1.890
	Y.S.	357	2,125	40.27	-0.291	2.219
SU/19	U.T.S.	361	1,433	67.84	-0.961	3.600
	Y.S.	361	1,433	43.95	-2.835	4.003
Average[b]	U.T.S.	---	-----	-----	-0.139	2.564
	Y.S.	---	-----	-----	-1.493	3.016

(a) Value of product test minus value of official test.

(b) Weighted by number of product samples.

(c) U.T.S. = Ultimate tensile strength

Y.S. = Yield Strength

$$Pr(S_h < S_p) = \int_{-\infty}^{S} \frac{1}{\sigma_p\sqrt{2\pi}} e^{-[(S_s - S)/(\sqrt{2}\sigma_p)]^2} dS \qquad (A4)$$

where σ_p is the average standard deviation shown in Table A3, with 2.564 ksi for U.T.S. and 3.016 ksi for Y.S.

Values of $Pr(S<kS_s)$ for k = 1.00, 0.95, and 0.90 are shown in Table A3.

TABLE A3. SUMMARY OF ESTIMATED PROBABILITIES THAT STRENGTHS WILL BE BELOW MINIMUM SPECIFIED STRENGTHS[(a)]

Material	Strength[(b)]	$Pr(S<kS_s)$[(c)] k = 1.00	k = 0.95	k = 0.90
A285-A	Y.S.	5.1E-3	1.7E-3	5.1E-4
A285-B	"	5.5E-3	1.8E-3	5.0E-4
A285-C	"	1.4E-2	4.1E-3	1.0E-3
A201-A	"	1.4E-2	4.2E-3	1.0E-3
A201-B	"	6.8E-3	1.6E-3	3.3E-4
A106-B	"	1.6E-2	5.6E-3	2.0E-3
A212-B	"	1.9E-2	4.4E-3	8.1E-4
A516-70	"	1.0E-2	3.0E-3	6.8E-4
A299	"	5.6E-3	1.2E-3	2.0E-4
A106-B	U.T.S.	6.1E-3	6.1E-4	2.6E-5
A516-70	"	3.7E-2	3.4E-3	5.6E-5
A299	"	4.4E-2	2.3E-3	4.8E-5

(a) S_s = minimum specified strength, see Table A1 for values.

(b) Y.S. = yield strength; U.T.S. = ultimate tensile strength.

(c) $Pr(S<kS_s)$ is the probability that the strength of a randomly selected sample of the material will be less than kS_s.

REFERENCES

(1) Metals Handbook, Vol 1, Properties and Selection: Iron and Steels, (a) Eighth Edition 1961, (b) Ninth Edition, 1978. Published by American Society for Metals, Metals Park, OH 44073.

(2) "The Variation of Product Analysis and Tensile Properties of Carbon Steel Plates and Wide Flange Shapes," September 1974. Published by American Iron and Steel Institute, 1000 16th St., N.W., Washington, D.C. 20036.

APPENDIX B

DATA ON LOAD CAPACITIES OF EXPANSION ANCHOR BOLTS

APPENDIX B

DATA ON LOAD CAPACITIES OF EXPANSION ANCHOR BOLTS

Securing of pumps, valves, and piping to the building structure is a major aspect of adequate design for seismic loadings. To attach to concrete floors, walls, or ceilings, anchor bolts can be installed prior to pouring the concrete, or, after the concrete is set, holes can be drilled in the concrete and expansion anchor bolts can be used.

In order to develop "rated" load capacities, expansion anchor bolts must be properly installed. Past experience in nuclear power plants indicated that this was not always done, leading to the issuance of NRC IE Bulletin 79-02 (1).

Teledyne Engineering Services (TES) has published the report "Generic Response to USNRC IE Bulletin Number 79-02, Base Plate/ Concrete Expansion Anchor Bolts" (2) (referred to as the TES report). The TES report gives the results of TES tests on anchor bolts made by different manufacturers. It also gives manufacturer's test data and manufacturer's catalog load capacities for anchor bolts.

The TES report gives data on 11 groups of manufacturer/types of expansion anchor bolts, identified as shown in Table B1. The bolt sizes tested are indicated by Table B2. In addition to tests with tension-only and shear-only, the TES report contains results of many tests with combined tension and shear.

In this Appendix, the following aspects of the TES report are reviewed:

TABLE B1. INDENTIFICATION OF GROUPS AND GENERIC TYPES

Group	Designation	Generic Type
A*	Phillips, Snap Off	Shell
B	Phillips, Wedge	Wedge
C	Phillips, Sleeve	Sleeve
D	Phillips, Stud Anchor	Shell
E	Hilti, Kwik Bolt	Wedge
F	USM, Parabolt	Wedge
G	Wej-It, Stud	Wedge
H*	Rawl, Snap Off	Shell
I	Star, Slug-In	Shell
J	Ramset, Wedge	Wedge
K	Ramset, Sleeve	Sleeve

* TES Report indicates these are indentical.

TABLE B2. COMPARISON OF CATALOG LOADS WITH TES AVERAGE TEST LOADS

Bolt Size	Type of Load	Ratio of Catalog Loads to TES Average Test Loads										
		A	B	C	D	E	F	G	H	I	J	K
1/4	Tension	----	----	----	----	1.2	----	1.1	----	----	----	----
	Shear	----	----	----	----	0.8	----	1.5	----	----	----	----
3/8	Tension	----	----	1.0	----	0.9	----	----	----	----	----	----
	Shear	0.9	----	0.9	----	1.1	----	0.8	----	----	----	----
1/2	Tension	1.2	1.1	1.0	----	1.3	0.7	----	1.2	2.9	0.7	0.9
	Shear	----	1.2	0.9	----	1.0	1.1	1.8	----	0.6	1.0	0.6
5/8	Tension	1.2	0.8	1.3	----	0.9	0.8	----	----	2.0	0.7	1.1
	Shear	1.0	0.9	0.8	----	0.8	1.1	1.8	----	0.6	0.9	1.2
3/4	Tension	1.3	1.2	0.9	1.5	1.0	1.2	1.6	1.3	3.7	1.4	0.9
	Shear	----	0.9	0.8	1.0	0.8	1.2	1.1	----	0.3	1.3	1.0
7/8	Tension	1.1	0.9	----	----	----	----	----	----	1.1	----	----
	Shear	1.6	1.3	----	----	----	----	1.0	----	0.4	----	----
1	Tension	----	0.7	----	----	0.8	----	1.2	----	1.6	0.8	----
	Shear	----	0.9	----	----	1.0	----	1.2	----	0.4	0.6	----
1-1/4	Tension	----	----	----	----	1.0	----	----	----	----	----	----
	Shear	----	1.1	----	----	1.1	----	1.0	----	----	----	----
Avg.	Tension	1.20	0.94	1.05	1.50	1.01	0.90	1.30	1.25	2.26	0.90	0.97
	Shear	1.17	1.05	0.85	1.00	0.94	1.13	1.27	----	0.46	0.95	0.93
	Both	1.19	1.00	0.95	1.25	0.98	1.02	1.28	1.25	1.36	0.92	0.95

(1) TES data versus manufacturer's catalog data
(2) statistical evaluation
(3) equivalent bolt stresses
(4) combined tension and shear
(5) cyclic loads
(6) other aspects--concrete strength, bolts installed near edges, or closely spaced bolts

TES Data Versus Manufacturer's Catalog Data

Users of anchor bolts look to the manufacturer's catalog for design information. The TES report gives catalog-loads as well as TES test data. Table B2 shows the ratios of catalog loads to TES average test loads. With the exception of Group I, tension loads, and considering the general scatter of the load data, the ratios are reasonably close to unity. Averages of the ratios are shown near the bottom of Table B2. For all data, except Group I, the average ratios are 1.05.

Group I data show that the catalog tension loads are up to 3.7 times the TES average tensile test load. This discrepancy also appears in a direct comparison between catalog tension loads in the various groups (for example, for 3/4-inch bolt size, the other groups give catalog tensile loads ranging from 7,000 to 14,000 pounds, averaging 11,000 pounds, whereas Group I catalog tension load is 20,000 pounds). However, for shear loads, Group I catalog data are significantly conservative with respect to TES test data.

With the exception of Group I, tension loads, the TES report results generally confirm the manufacturer's catalog data for the capacity of anchor bolts that are properly installed.

Statistical Evaluation

The test data indicate significant scatter about the average strength values. If the design load is taken as 1/4 of the average strengths, what is the probability of failure of the design loads, or at a load that is higher than the design load? To address that question, we have made a crude statistical analysis of the data for tension-only and shear-only data. The combined tension and shear data are discussed later.

The TES report contains both TES test data and manufacturer's data. The number of significant* tests are:

Type of Load	Test Points TES	Mfr	Total
Tension	94	58	152
Shear	58	55	113

The TES report shows the test loads as ratios to the TES average test load. We grouped these results into increments of 0.1; for example, those results which have ratios of 0.9 to 1.0 times the TES average test load are grouped together. Figures B1 and B2 show bar graphs for tension and shear loading, respectively. A "normal" distribution curve is also shown on these figures. The tension load distribution is reasonably close to "normal." The shear load distribution is biased to the high side, mainly because of manufacturer's data which are all points with ratios of 1.4 and higher. For the purpose of estimating probabilities of failure at low load we assume normal distribution for both tension and shear loads.

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* For a few individual Group/bolt sizes, only a single TES test result is given. Inclusion of these in our statistical evaluation is not appropriate because they contain no scatter indication for that particular Group/bolt size.

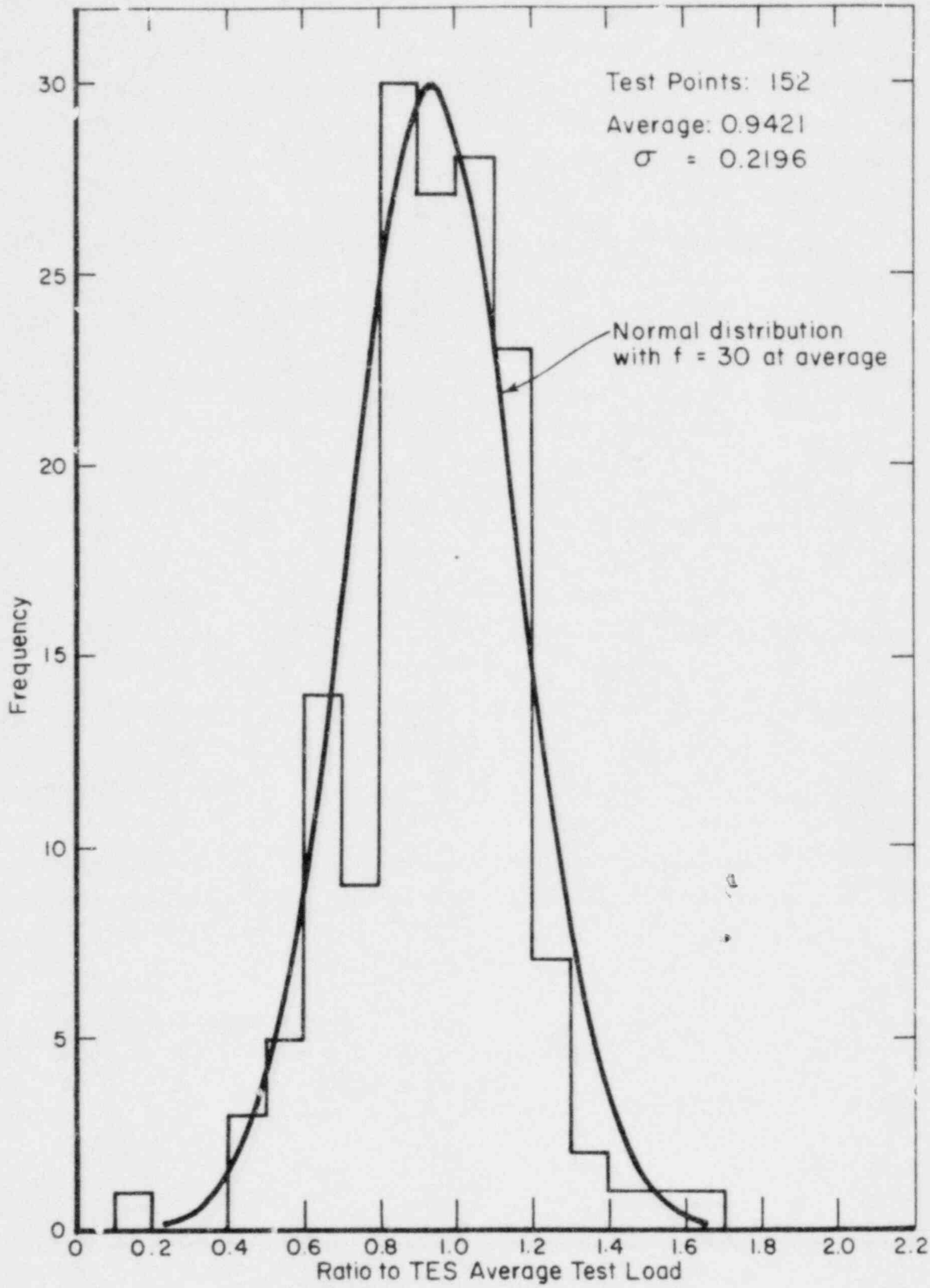

FIGURE B1: TENSION LOAD, TES AND MANUFACTURERS' DATA

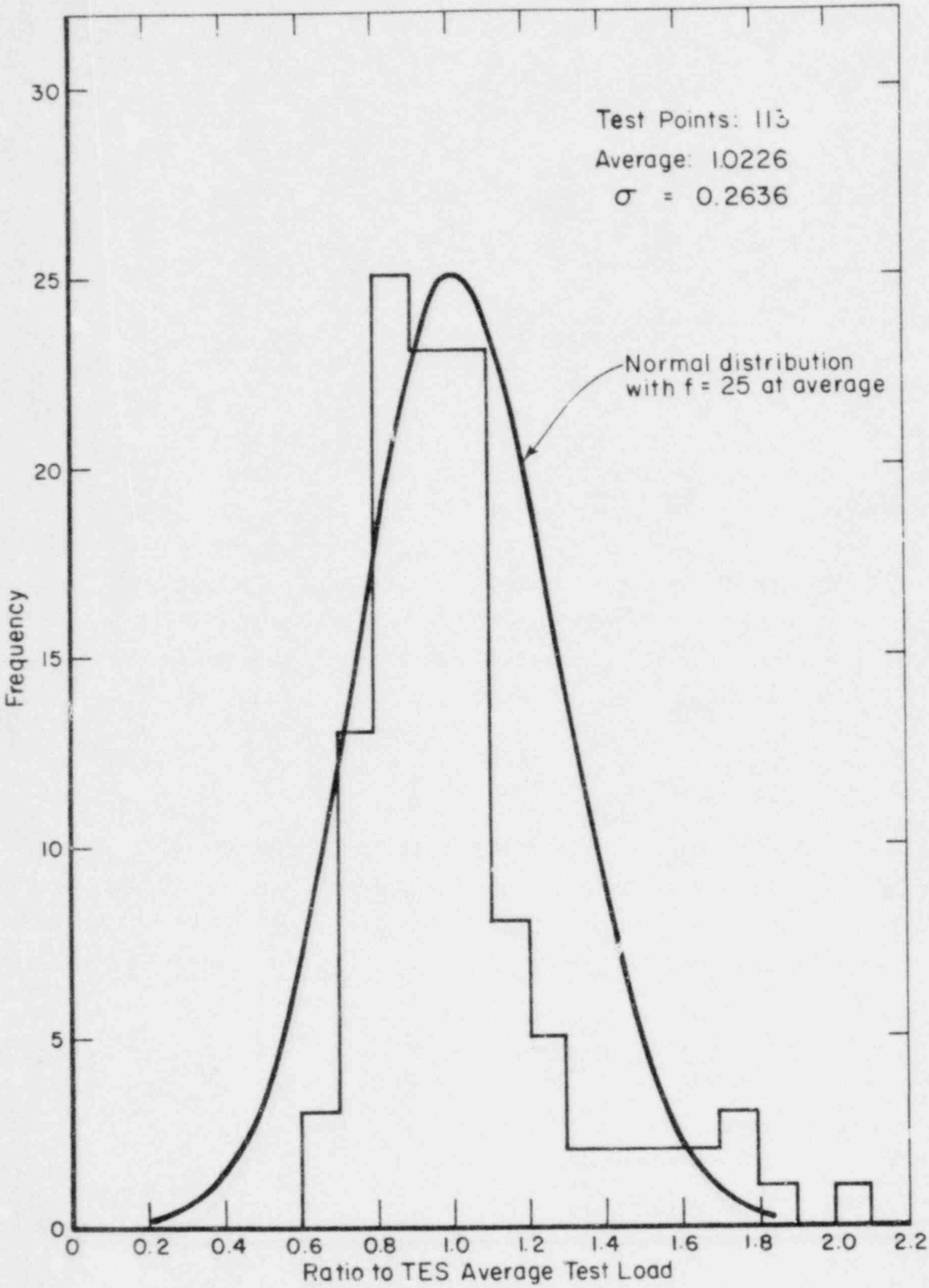

FIGURE B2: SHEAR LOAD, TES AND MANUFACTURERS' DATA

The results of our statistical evaluation are summarized in the following tabulation.

Type of Load	Data Base	Avg.	σ	Avg.-2
Tension	TES only	0.9904	0.1904	0.6096
	Mfr only	0.8638	0.2403	0.3832
	Both	0.9421	0.2196	0.5029
Shear	TES only	0.9672	0.1467	0.6738
	Mfr only	1.0809	0.3368	0.4072
	Both	1.0226	0.2657	0.4912

With the assumed normal distribution, the ratio of "Avg.-2 " corresponds to a probability of failure below that load ratio of 0.023. For design loads based on 1/4 of average loads, the probability of failure at the design load is less than 0.001. Of course, this depends upon skill and care in installation that is at least equivalent to that used by TES and the manufacturers in conducting their tests. As in most aspects of constructing a nuclear power plant, lack of skill and care could lead to higher failure probabilities.

Equivalent Bolt Stresses

To correlate allowable loads on anchor bolts with allowable stresses in the bolts, it is informative to express the allowable loads on the anchor bolts as stresses in the bolts. This is simply done by dividing the loads by the cross-sectional area of the bolts. The bolt stresses so derived are shown in Table B3.

Bolt stresses, at average failure loads, are:

Type of Load	Bolt Stress, ksi Max	Min	Avg
Tension	58.6	8.3	30.65
Shear	84.8	25.4	46.49

TABLE B3. TES AVERAGE LOADS EXPRESSED AS BOLT STRESSES

Nom. Size	A_b, in^2 (a)	Type of Load	Bolt Stress (ksi) at TES Average Load										
			A	B	C	D	E	F	G	H	I	J	K
1/4	.03182	Tension	----	----	----	----	32.2	----	39.3	----	----	----	----
		Shear	----	----	----	----	84.8	----	42.4	----	----	----	----
3/8	.07749	Tension	47.1	----	45.6	----	33.6	----	18.4	----	----	----	----
		Shear	51.6	----	41.0	----	[illegible]	----	40.7	----	----	----	----
1/2	.1419	Tension	----	37.0	28.7	----	26.8	38.2	8.3	41.2	19.5	49.9	41.7
		Shear	----	49.3	40.5	----	56.9	47.2	25.4	47.4	44.0	56.4	42.3
5/8	.2260	Tension	44.2	45.4	23.8	----	31.0	34.8	13.1	----	26.4	58.6	24.3
		Shear	50.9	58.6	44.2	----	60.2	50.9	26.8	----	36.4	54.2	33.2
3/4	.3345	Tension	----	28.4	30.3	22.7	28.2	27.2	29.1	31.4	16.2	26.2	22.7
		Shear	----	53.1	41.9	47.1	59.4	45.6	47.6	41.1	54.9	39.5	40.4
7/8	.4617	Tension	35.2	29.0	----	----	----	----	21.6	----	25.7	----	----
		Shear	[illegible]	42.2	----	----	----	----	44.0	----	52.0	----	----
1	.6057	Tension	----	39.3	----	----	30.4	----	31.4	----	20.9	36.9	----
		Shear	----	66.0	----	----	45.4	----	37.1	----	31.4	68.1	----
1-1/4	.9691	Tension	----	28.9	----	----	21.9	----	17.3	----	----	----	----
		Shear	----	46.4	----	----	33.6	----	39.7	----	----	----	----

(a) A_b = Tensile stress area, = $0.7854 [D-0.9743/n]^2$, D = nominal bolt size, n = threads per inch (UNC-series).

It can be seen that the anchor bolts developed tension loads about equal to the yield strength of SA-307 Grade B bolts. However, for shear loading, if we assume that shear failure occurs at about 0.6 times the tensile strength, the bolt stresses are greater than the capacity of SA-307 Grade B bolts for which $0.6S_u$ = 36 ksi.

The bolt materials used with the anchor bolts are not described in the TES Report. They were presumably materials with tensile properties like SA-193 Grade B7; 125,000 psi minimum ultimate tensile strength, 100,000 psi minimum yield strength. In shear, the maximum bolt stress is up to 84.8 ksi (1/4 inch Group E). Presumably, in this particular test the failure consisted of a shear failure of the bolt (unfortunately, the TES report does not describe the type of failures). If so, and if shear failures occur at 0.6 S_u, then the bolt material S_u was about 84.8/0.6 = 141 ksi. Of course, part of the resistance to shear may have been due to friction between the fixture and the concrete pad.

These aspects bring out the point that the bolt material itself can be a significant aspect of the strength of expansion anchor bolts. To obtain some of the high shear strengths given in manufacturer's catalog, the bolt material must itself be high strength. Care must be taken that a lower strength bolt material like SA-307 Grade B is not inadvertently used.

Combined Tension and Shear

For combination of Tension and Shear loads, the usual practice is to apply the limit:

$$\frac{P_t}{P_{td}} + \frac{P_s}{P_{sd}} \leq 1.00 \qquad \text{(B1)}$$

where

P_t = tensile load under service conditions

P_s = shear load under service conditions

P_{td} = design tensile load
P_{sd} = design shear load

} e.g., 1/4 of catalog loads

The TES report data indicate this is usually highly conservative and, indeed, some shear load usually increases the tension load capacity. A less conservative design limit such as:

$$\left(\frac{P_t}{P_{td}}\right)^2 + \left(\frac{P_s}{P_{sd}}\right)^2 \leq 1.00 \qquad \text{(B2)}$$

is representative of most TES data. However, some of the data (e.g., Group G, 3/4 inch bolt) follow Equation (B1) fairly well and to use Equation (B2) would not be conservative.

Cyclic Loads

The TES report contains results of tests in which cyclic loads were applied prior to static strength tests. After setting the expansion anchor, the nuts were backed off one-quarter turn in order to investigate cyclic load adequacy without preload. The anchor bolts were subjected to fractions of the average ultimate static strength, P_u, as indicated by the following tabulation.

Test Frequency	Number of Cycles	Maximum Load	Minimum Load
3 Hz	1000	$P_u/4$	$P_u/8$
80 Hz	10^6	$P_u/5$	$P_u/7.4$

The TES report states: "No anchor pullout failures occurred as a result of cyclic loading." The report also states: "The ultimate capacity of the anchor after cycling was comparable to that obtained in the shear-tension interaction test program."

Other Aspects

The TES tests were run with concrete that had a specified minimum compressive strength of 3000 psi at 28 days. No mention is made of the actual compressive strength, either at 28 days or any other time. An uncertainty thus exists in that, perhaps, the concrete used was actually much stronger than indicated by the specified minimum.

The static tests were run on a slab that was 3.5 ft x 7 ft x 1 ft thick. It appears that the anchor bolt was placed in the center of the slab, 1.75 ft and 3.5 ft from the edges. This size is sufficient so that no "edge effects" would be expected. In actual installations, an anchor bolt may be installed near an edge. In such installations, the capacity of the anchor bolt may be reduced. The American Concrete Institute (ACI) (Appendix B of ACI 349-76) provides guidance for such conditions and is presumably conservative.

In this respect, it is pertinent to note that the cyclic tests were run with a 14 in. x 14 in. x 14 in. cube of concrete; yet the static strengths after cycling averaged about the same as those obtained in the static tests with a 3.5 ft x 7 ft x 1 ft thick slab.

The tests are representative of "isolated" concrete anchor bolts. If such anchor bolts are spaced close together, the strength may be reduced. The ACI (and manufacturers) provide guidance for closely spaced anchor bolts, which presumably is conservative.

Summary

(1) The TES tests indicate that, for properly installed, isolated anchor bolts not near an edge, the manufacturer's Catalogs usually give a reasonable estimate of tension and shear load capacities.

(2) A crude statistical evaluation of the data indicates that, by using 1/4 of average strength as a design basis, the probability of failure at 2 times the design load is about 0.023 and, at the design load, less than 0.001.

(3) The bolt material used in anchor bolts must be of high strength (for example, 125,000 psi ultimate tensile strength) to obtain some of the Catalog shear loads.

(4) Use of linear combination [Equation (B1) herein] for combined tension and shear loads is generally conservative.

(5) Cyclic loading, in the range of loads less than $P_u/4$, did not have any significant effect on subsequent static load capacity.

(6) Anchor bolts installed near edges or installed close together may not have the strength indicated by the test data. Guidance is given by the ACI Std., 349-76, which is presumably conservative.

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Seismic design margins indicate the adequacy for earthquake resistance of pumps, valves, piping and their supports used in nuclear power plants. The margins that exist with the allowable stresses given in applicable codes and standards are reviewed in this report. Nuclear industry practice with respect to concrete expansion anchor bolts and operability of pumps and valves are also reviewed. Examples of specific applications are included to illustrate the significant seismic design margins which are present in the systems and equipment in nuclear power plants.

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