EARTHQUAKE FATIGUE EFFECTS ON CANDU NUCLEAR POWER PLANT EQUIPMENT

C.G. Duff and A.C. Heidebrecht

SYNOPSIS

This paper presents the results of an investigation into the seismic fatigue effects on equipment located in CANDU nuclear power plants. The supporting structure and equipment are each modelled as single degree of freedom systems. The equipment responses are evaluated for realistic ranges of structural and equipment frequencies, subjecting the overall system to five different earthquake records. Using common material fatigue life curves, a method is devised to calculate the number of fatigue cycles equivalent to the total seismic response, with reference to some specific amplitude of response. This method is applied to the response results in order to determine maximum equivalent fatigue cycles for various conditions. The results are used to make recommendations for fatigue evaluation in the design of nuclear power plant equipment.

RESUME

Cette communication fait état d'une investigation sur l'effet des séismes par rapport à la fatigue des équipements situés dans un réacteur du type CANDU. La structure ainsi que l'équipement sont chacun idéalisés en un système à un degré de liberté. Pour différentes fréquences de l'équipement en question ainsi que pour différents tremblements de terre, une méthode est présentée afin d'évaluer la vie des composantes nucléaires tenant compte de l'aspect fatigue de l'équipement.

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INTRODUCTION

The safety philosophy for CANDU nuclear power plants (NPP) requires the primary heat transport system and certain other high-pressure systems to be designed to resist the Design Basis Earthquake (DBE) without failure, to ensure that a gross loss-of-coolant accident (LOCA) will not occur as a direct consequence of such an earthquake. This is assured first by limiting primary stresses (due to pressure, weight and earthquake inertia loads) to stress Level 'C' of the ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components. While Level 'C' permits direct primary stresses to reach the yield point, it is a far more conservative criterion than Level 'D' allowed in the U.S.A. for the Safe Shutdown Earthquake (SSE), which is similar in severity to the DBE.

Avoidance of a LOCA is further assured by performing a fatigue analysis, where necessary, to account for the cyclic stresses developed in such critical systems during the DBE, so that the total cyclic damage caused by the earthquake can be evaluated, along with the fatigue effects produced by normal NPP operation.

To avoid complex and costly time-history fatigue analyses of each critical pressure vessel and piping system, an investigation was made to establish, in general terms, the fatigue effects when such a secondary system responds to the seismic excitation of the reactor building (primary system) which supports it. From this investigation, convenient rules were established for estimating the fatigue usage factors to apply to the design of actual secondary systems.

SCOPE

Dynamic Model

For the purpose of this investigation, both the primary and secondary systems are idealized as single degree of freedom linear mass-spring systems. The primary system is excited by the seismic ground motion and the secondary system is excited, in an uncoupled manner, by the motion of the primary mass. Both systems are viscously damped, with a damping ratio of 0.035 for the primary system and 0.010 for the secondary system. Since this investigation is primarily concerned with fatigue, these levels of damping are chosen as realistic minima for both levels, and would therefore allow the maximum expected oscillation of both systems when subjected to a particular seismic excitation.

The dynamic response of each system was calculated using the linear acceleration numerical integration approach. The time interval used was the lower of 0.004 sec. or 0.02 times the lowest of the two natural periods.

Earthquakes

Five earthquake records were used in order to gain an appreciation of the variation of results which could be expected and therefore be able to make design recommendations which would have a broad range of validity. The five records, designated by letters A through E are described in Table 1. One spectrum-compatible artificial record was included, in addition to four strong-motion records obtained during actual earthquakes.

In each case, the strong ground motion is contained within the first 15 seconds of excitation and the computations were based on that duration. Because the lightly-damped secondary system would continue oscillating for a significant time following cessation of the excitations, response computations were continued until the peaks of the secondary level acceleration were less than 25 percent of the maximum-peak secondary acceleration. Even though there would still be some secondary motion after that time, the cumulative fatigue damage after that time would be negligible.

Parametric Variations

Three distinct studies are reported in this paper. First the case of secondary system in resonance with the primary system is considered, since such conditions will produce the maximum response and are likely to have the most severe fatigue effect. For CASE I, the resonant frequency is varied from 3 to 7Hz, a range which is considered to include the fundamental structural frequencies in most CANDU nuclear power plants. The response parameters of interest in this case are the maximum secondary acceleration and the ensemble of all secondary acceleration peaks, both positive and negative, during the entire response time-history.

CASE II studies the situation in which the secondary system is not in resonance with the primary system. It is considered that secondary system frequencies can be in the range 1 to 33Hz. By varying the primary frequency within the range given above for CASE I and then varying the secondary frequency away from the primary, it is possible to evaluate the fatigue effects produced in the non-resonant situation.

Certain equipment is mounted directly at ground level and it is also necessary to consider the possibility of fatigue damage in such cases. In CASE III the primary system damping is reduced to 0.010 and the maximum primary acceleration and the ensemble of primary acceleration peaks are used to evaluate fatigue effects.

FATIGUE EQUIVALENCE

General Rule

The objective of this investigation is to determine, for each time-history response, the number of cycles at some specified reference acceleration amplitude which will have the same fatigue effect as the ensemble of acceleration peaks of varying amplitude. The manner chosen to determine such equivalence is essentially that described by Fischer and Wolff (1), which was developed for a linear log S - log N fatigue-life relationship, in which S is the strain amplitude parameter and N is the number of cycles of fatigue life. Another way of expressing that same relationship is given by:

$$\frac{1}{N} = CS^{\beta} \tag{1}$$

in which C is a constant dependent upon the position of the curve (on the log S - log N diagram) and β is a constant related to the slope of the curve. For this type of fatigue-life relationship, the equivalence rule can be stated as:

> Given N_i cycles at an amplitude S_i, this
> is equivalent to N_i^* cycles at an amplitude
> S^*, where N_i^* is given by:

$$N_i^* = N_i \left\{\frac{S_i}{S^*}\right\}^{\beta} \tag{2}$$

The above equivalence rule is shown diagramatically in Fig. 1. It should be noted that the parameter β is inversely proportional to the slope of the fatigue-life curve and consequently, from Eq. 2, N_i^* will be largest for fatigue-life curves with the largest slope and therefore the lowest value of β. Also, the equivalence rule stated above is dependent upon the parameter β and not on the actual position of the fatigue-life curve.

Application to Seismic Response

First, it is necessary to consider the parameter which would be analagous to the strain-amplitude parameter S referred to in the previous paragraphs. Since this is a generalized study and since, for linear-elastic systems the acceleration amplitude is directly proportional to strain, it is assumed that acceleration 'A' is the analagous parameter.

Second, it is necessary to consider an appropriate value of the parameter β. Typical fatigue-life curves for materials used in CANDU nuclear power plants are given in Figs. 2 and 3 (2). These are expressed in terms of the alternating stress amplitude S_a which is proportional to the strain-amplitude parameter S, in terms of the modulus of elasticity of the material. Even though these curves are not linear over the total domain, close fitting straight-line approximations can be used over the domain of interest, i.e. N<1000 cycles. Examining such curves yielded values of β ranging from 3 to 5. Since the lowest value of β is most critical, this study was done using $\beta=3$.

If there are 'n' acceleration response peaks each designated by A_i, then the total number of equivalent cycles N_{EQ} referenced to the maximum response acceleration A_{max} of that same time-history is obtained by summing Eq. 2 applied to each peak, yielding;

$$N_{EQ} = \frac{1}{2} \sum_{i=1}^{n} (A_i/A_{max})^{\beta} \tag{3}$$

The factor $\frac{1}{2}$ is included because each acceleration peak really represents only one-half cycle of response.

The equivalence given by Eq. 3 is referenced specifically to the maximum response acceleration occurring within that same time-history. If it is desired to choose an independent reference level $\bar{A}$, then the results of Eq. 3 can be referenced to this new level by applying Eq. 2 again, yielding;

$$\bar{N}_{EQ} = (A_{max}/\bar{A})^{\beta}\, N_{EQ} \tag{4}$$

For purposes of normalization, response acceleration 'A' can be replaced by an 'amplification factor' which is defined as the ratio of the maximum acceleration of response to the peak ground-motion acceleration.

RESULTS

Case I Analysis

CASE I analysis was done for all five earthquakes given in Table 1. A summary of results is given in Table 2, together with a detailed explanation of each column of results. To illustrate the application of the previously developed fatigue equivalence equations, consider the results for the two systems in resonance at 4.5Hz, and excited by earthquake record B (defined in Table 1). This secondary response had an amplification factor of 25.7 and a direct application of Eq. 3 yielded $N_{EQ}=24.1$ cycles. This was in fact the largest N_{EQ} from all five earthquake responses at that frequency and consequently the value of 24.1 appears as the maximum N_{EQ} in column (3) of Table 2. However excitation, at the same frequency, by earthquake record E yielded an amplification factor of 53.5 but a value of $N_{EQ}=9.7$. It can be seen, therefore, that since the larger number of N_{EQ} produced from record B is referenced to a smaller amplitude (when considering the system to be subjected to the same level of ground acceleration) it is not directly comparable to the results from record E. In order to make a suitable comparison, Eq. 4 is applied to the results from record B, using the amplification factor of 53.5 as the new reference level, yielding;

$$\bar{N}_{EQ-B} = (25.7/53.3)^{3.0} \times 24.1 = 2.7 < 9.7 \qquad (5)$$

Eq. 5 shows that when referenced to the same amplitude, record B produces a much smaller number of equivalent fatigue cycles than record E. When considering the same type of comparison for other records, it was found that the 9.7 equivalent cycles produced by record E (which had the largest amplification factor) was the largest and therefore that number is entered as Max $\bar{N}_{EQ}$ in column (4) of Table 2.

Considering Table 2 as a whole, it can be seen that the largest value of N_{EQ} is 32.7. However, the example illustrated above leads one to question the validity of using N_{EQ} as a basis for establishing fatigue equivalence, since it does not allow for a consideration of the amplitude level which is being used as a reference.

If one assumes that the design of secondary level equipment would be based on broadened floor response spectra using amplification factors which would envelope those obtained from actual earthquake response studies, then a realistic reference level, at each frequency, would be the maximum acceleration amplification factor. Using these reference levels results in the maximum $\bar{N}_{EQ}$ values given in column (4) of Table 2. The largest value of $\bar{N}_{EQ}$ is 22.5.

Another useful way of specifying fatigue equivalence is in terms of the number of seconds of oscillation at the peak value. This data is given in column (5) of Table 2, which shows durations which are less than 5 seconds, except at a frequency of 3.3Hz., which has an equivalent duration of 6.7 seconds.

Case II Analysis

Several response studies in which the secondary frequency was varied over a very large range while the primary frequency was kept constant showed that N_{EQ} dropped off rapidly as the frequency ratio moved away from unity. More extensive response evaluations were then conducted in the near-resonance range, i.e. frequency ratios between 0.7 and 1.3. A typical set of results is given in Table 3. From these results it was seen that the maximum value of N_{EQ} (referenced to the maximum acceleration in each time-history) were always less than 33. It was also observed that the maximum amplification factors often occurred slightly away from the resonant condition.

As discussed for CASE I, a more realistic reference value is the maximum amplification factor (for responses to all five earthquakes at a given primary frequency). When values of $\bar{N}_{EQ}$ are computed on this basis, they are always less than 25, except for one particular instance in which a value of 28 is reached. Also, values of $\bar{N}_{EQ}$ are always less than 10 when the secondary frequency is more than ten percent different from the primary frequency.

Case III Analysis

The results for this analysis are presented in Table 4, using the same format as Table 2 for CASE I. It can be seen that the fatigue effect for equipment mounted on the ground is substantially less severe than for equipment mounted on the structure. The largest value of $\bar{N}_{EQ}$ is 14.3 and the equivalent durations are all less than 3 seconds, except at a frequency of 3.3Hz., which has an equivalent duration of 4.3 seconds.

DISCUSSION AND RECOMMENDATIONS

Discussion

The foregoing results clearly indicate that there are upper limits to the fatigue effect induced in secondary level equipment due to seismic response. It is useful to consider the implication of the study on fatigue evaluation in actual design situations. Since this study has used single-degree-of-freedom systems to represent both the structure and the equipment, it is necessary to discuss the practical situation in which both are multi-degree-of-freedom systems. From this study, the fatigue effect would be negligible for primary and secondary modes having frequencies differing by more than ten percent. This is so both because of the reduced secondary response amplitudes in such cases and because the secondary motion is less regular, thereby producing lower values of N_{EQ}. Consequently, the only situations in which several modes could contribute significantly to the fatigue effect would be when two closely-spaced modes of one system have frequencies nearly coninciding with one mode of the other system or if both systems should have several coincident frequencies, which is highly unlikely. It is only in the case of a light-weight, uncoupled tertiary system in resonance with the secondary system to which it is attached that longer-duration vibration and therefore greater fatigue damage might be possible. Where such systems are closely coupled to the secondary system and the unlikely coincidence of strong resonance between the primary-secondary system, as well as between the secondary-tertiary system is not evident, the fatigue effect in the tertiary system will be very similar to that of the multi-degree-of-freedom system described above.

Considering that the maximum amplitude of inertial response of a multi-degree-of-freedom system represents the combined effects of all modes of vibration of both primary and secondary systems, it is reasonable and convenient to assume that the total fatigue effect is based on this maximum amplitude.

Where frequency is a consideration, the frequency of the dominant mode of vibration of the secondary system can be used. Where anchor-point movements (e.g. two ends of a pipe) are the source of the fatigue effect under consideration, the frequency of the dominant mode of the anchor points (e.g. building floor) can be used. As the frequency of the dominant mode of response of the secondary system is frequently the same as or higher than that of the floor on which it is located, the combined alternating stress amplitude from both inertia and anchor-point movements of the secondary system can be used for assessing the overall fatigue effect, using the higher frequency.

As the total stress, based on the maximum amplitude of response is often in the plastic range (calculated elastically), it is customary to increase the stress concentration factor (e.g. at notches) to compensate for the plastic strain. This has the effect of reducing the number of allowable fatigue cycles, based on Fig. 2 or Fig. 3. Applying the principle of Eq. 4, it would be possible to use less than the maximum amplitude (e.g. average amplitude of response during the earthquake or average amplitude during the strong-motion phase of the earthquake -- say the first 10 seconds), and accept more cycles. This could be used to advantage to reduce the effective alternating stress amplitude below the plastic range, where the maximum stress goes plastic, resulting in a less severe cyclic fatigue criterion. Thus, it is claimed that application of the maximum combined seismic response for determining the fatigue effect is conservative.

There has been concern expressed that a number of smaller seismic events could produce more fatigue damage than one Design Basis Earthquake (DBE). In the U.S.A. this concern has been expressed by requiring a fatigue evaluation for five Operating Basis Earthquakes (OBE), each having one-half the peak acceleration of the DBE. It can be seen, from Eq. 4, that an amplitude reduction by one-half would yield, for $\beta=3$, one-eighth of the fatigue damage. Consequently, it would require at least eight OBE events to produce the fatigue of one DBE. Therefore, it is not considered necessary to require fatigue damage evaluation at the OBE level.

Recommendations

Based on the above investigation, the following recommendations or rules can be made for determining the earthquake fatigue effect on systems and components in nuclear power plants:

1. Cycles of Response

    a) For secondary systems, apply 25 cycles (minimum) at the maximum combined modal response level, without regard to frequency (Ref. Table 2, Column 4). Both inertial and anchor-point movement effects may be combined under these criteria.*
    b) For primary systems (i.e. resting directly on the ground), apply 15 cycles (minimum) at the maximum combined modal response level, without regard to frequency (Ref. Table 4, Column 4).

or 2. Duration of Earthquake

Apply the most severe 15 seconds of the Design Basis time-history to the base of the primary system and determine the integrated earthquake fatigue effect on the primary or secondary system in accordance with Equation 3.

or 3. Duration of Response

a) For secondary systems, apply at least 8 seconds at the frequency of the dominant mode (Ref. Table 2, Column 5), to determine the number of cycles, using the maximum combined modal response level.

These criteria may be applied separately to both inertial response modes and those due to earthquake-induced anchor-point movements. In the latter instance, the frequency used will be that of the dominant mode of the primary system at the level of the anchors. The inertial and anchor-point movement fatigue effects may be taken together by combining the maximum responses due to each effect and using the higher of the frequencies determined above (i.e. greater of secondary or primary dominant modal frequency) to find the number of cycles. *

b) For primary systems, apply at least 5 seconds at the frequency of the dominant mode (Ref. Table 4, Column 5), to determine the number of cycles, using the maximum combined modal response level.

4. Total Fatigue Effect

The fatigue 'usage factor' (i.e. ratio of fatigue cycles applied, to cycles permitted at a given alternating stress amplitude) for the Design Basis Earthquake (DBE) must be combined with the usage factors derived for all other design conditions involving alternating stresses. Normally, this combination should not exceed unity; however, since the design fatigue curves (e.g. Figs. 2 and 3) are based on a factor of safety of 2 on stress or a factor of safety of 20 on cycles, whichever is more conservative at each point (2), the sum of the usage factors can exceed unity by a considerable margin without failure. Thus, it is reasonable to justify a combined usage factor exceeding unity, when earthquake fatigue effects are included, provided that the sum of the usage factors does not exceed unity without the earthquake.

Currently, it is recommended that the combined fatigue usage factor should not exceed unity, including the cyclic fatigue effect of a single DBE and all other specified fatigue effects. The available margin discussed above will adequately cater for the fatigue effect of a forced plant shutdown following a DBE, if such should occur, although this is not a current design requirement for CANDU Nuclear Power Plants. It should also be possible to permit a combined fatigue usage factor exceeding unity under special circumstances, especially if suitable inspection is carried out at the first opportunity following a DBE to detect possible fatigue damage.

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*Combine the stresses by the square root of the sum of the squares when inertial and anchor-point movement responses are at different frequencies or are otherwise known to be out of phase.

As discussed under the Introduction, the ASME Code (2) Level 'C' stress limits are applied under DBE conditions. These limits are from 1.2 to 1.5 times those that are permitted under normal plant operating conditions. Applying the lower limit of 1.2 to A_{max} in Eq. 4 and 1.0 to $\bar{A}$ gives a ratio of $\bar{N}_{EQ}/N_{EQ} = 1.7$. This provides a measure of the increase in allowable fatigue cycles corresponding to a 20% change in allowable stress. The factor 1.7 could then be considered the maximum permissible combined fatigue usage factor under earthquake conditions.+ Thus, the total usage factor under normal operating conditions could be permitted to reach unity, allowing a further usage factor of 0.7 for the DBE.

Applying the 1.7 factor to Recommendations 1a) and 1b) above results in a decrease in the minimum required earthquake cycles from 25 to 15 and from 15 to 9, respectively; while retaining a maximum combined usage factor of unity.

Where justified, it is recommended that the number of earthquake fatigue cycles given under Recommendations 1a) and 1b) above be decreased to 15 and 9, respectively, based on the foregoing.

5. Avoidance of Earthquake Fatigue Evaluation

Where it is decided to avoid an earthquake fatigue evaluation or where the ASME Code (2) rules do not cater for low-cycle fatigue effects, a reduced limit for high-cycle fatigue could be used instead. This principle, when applied to Subsection NF of the ASME Code dealing with 'Component Supports', and utilizing Recommendation 1a) above, assuming the full Level 'C' stress limit applies to the earthquake loading alone, still caters for high-cycle fatigue under normal operating conditions up to about 60% of the allowable cycles.

For pressure-retaining systems, where the majority of the primary stress under operating conditions is due to pressure and dead weight, the stress increment available for earthquakes (inertial effects), using Level 'C' stress limits, is about 70%. Assuming an equal margin for additional secondary earthquake stresses (due to anchor-point movements)++, where there is no prescribed ASME Code limit for the DBE; assuming that inertial and anchor-point movement responses are out of phase (the usual case) and stresses are combined accordingly; assuming a stress-concentration factor of 3 and ASME-SA106 Gr B material (common for primary heat transport system of a CANDU-NPP, ref. Fig. 2 dashed); and assuming 25 cycles at maximum stress amplitude, the earthquake fatigue usage factor will be of the order of only 0.064. This leaves an ample total fatigue usage factor of 0.94 for normal operating stress cycles.

+This corresponds to a reduction in the factor of safety on cycles from 20 to 12, which is still considerable.

++This is considered conservative, as earthquake-induced stresses in NPP components, especially piping, are predominantly due to inertial effects.

Although the above serve only as examples, it is clear that a set of rules can be developed for each type of material and application to enable the designer to limit the total fatigue usage factor to something less than unity, in lieu of performing a formal earthquake fatigue analysis. This would only be permitted when Level 'C' primary stress limits have been met and secondary stresses due to anchor-point movements, caused by the earthquake, have been suitably limited as well. Further investigation of the above approach is recommended.

ACKNOWLEDGEMENTS

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REFERENCES

1. Fischer, E.C. and Wolff, F.H., 'Comparison of Fatigue Effects in Simulated and Actual Earthquakes', Experimental Mechanics, Vol.12, No. 12, December 1973, pp 531-538.

2. ASME Boiler and Pressure Vessel Code Section III, 'Nuclear Power Plant Components', Division 1, Subsections NB and NF and Appendices III and XIV, American Society of Mechanical Engineers, New York, July 1977.

TABLE 1

List of Earthquake Records Used in this Study

Record Designation	Description of Record	Max.Accel./g
A	AECL Spectrum-Compatible Artificial Record (1978)	0.211
B	El Centro 1940, N-S Component	0.348
C	El Centro 1940, E-W Component	0.214
D	San Fernando 1971, N-S Component at basement, Wiltshire Boulevard	0.136
E	Taft 1952, N21E Component	0.156

TABLE 2

Results for CASE I - Analysis of Secondary Level Response when Primary and Secondary Systems are in Resonance

(1) Frequency (Hz)	(2) Maximum Amplification Factor	(3) Max N_{EQ} (cycles)	(4) Max. $\bar{N}_{EQ}$ (cycles)	(5) Duration of Motion at Max $\bar{N}_{EQ}$ (sec)
3.0	48.8	20.5	7.6	2.5
3.3	46.9	22.2	22.2	6.7
3.7	47.6	18.1	17.4	4.7
4.0	41.4	23.7	15.4	3.9
4.5	53.5	24.1	9.7	2.2
5.0	48.6	31.5	22.5	4.5
5.5	73.4	23.2	18.3	3.3
6.0	45.5	32.7	20.3	3.4
6.5	63.5	20.2	17.1	2.6
7.0	62.7	25.3	18.2	2.6

Column (2) - maximum amplification factor of secondary acceleration relative to ground acceleration, from responses to five earthquake records

Column (3) - maximum N_{EQ} from responses to five earthquakes, referenced to maximum acceleration in each response time-history

Column (4) - maximum value of $\bar{N}_{EQ}$, in which each is referenced to the maximum amplification factor at the same frequency

NOTE: Primary damping factor = 0.035 and secondary damping factor = 0.010

TABLE 3

Typical CASE II Results - Secondary System not in Resonance with Primary System

(Earthquake Record D, Primary Frequency = 5.5 Hz.)

(1) Secondary Frequency (Hz)	(2) Secondary Amplification Factor	(3) N_{EQ} (Cycles)	(4) $\bar{N}_{EQ}$ (Cycles)
3.7	6.8	2.6	<1.0
4.4	14.7	5.6	<1.0
4.9	22.0	11.1	<1.0
5.2	40.0	7.5	1.2
5.4	66.3	16.2	11.9
5.5	73.4	18.3	18.3
5.6	58.0	18.9	9.3
5.8	50.0	11.3	3.6
6.1	27.4	9.0	<1.0
6.6	21.2	5.4	<1.0
7.3	12.9	4.5	<1.0

$\bar{N}_{EQ}$ is referenced to the maximum secondary amplification factor (73.4)

NOTE: Primary damping factor = 0.035 and
Secondary damping factor = 0.010

TABLE 4

Results for CASE III - Analysis of Primary Level (Primary Damping Factor = 0.010)

(1) Frequency (Hz)	(2) Maximum Amplification Factor	(3) Max N_{EQ} (cycles)	(4) Max $\bar{N}_{EQ}$ (cycles)	(5) Duration of Motion at Max $\bar{N}_{EQ}$ (sec)
3.0	5.2	9.3	5.0	1.7
3.3	4.2	14.3	14.3	4.3
3.7	4.5	13.9	9.7	2.6
4.0	3.8	11.9	10.5	2.6
4.5	5.2	11.9	6.1	1.4
5.0	4.7	18.0	11.7	2.3
5.5	6.2	13.4	13.4	2.4
6.0	5.5	21.4	5.2	0.9
6.5	6.4	13.8	8.5	1.3
7.0	6.2	14.3	9.3	1.3

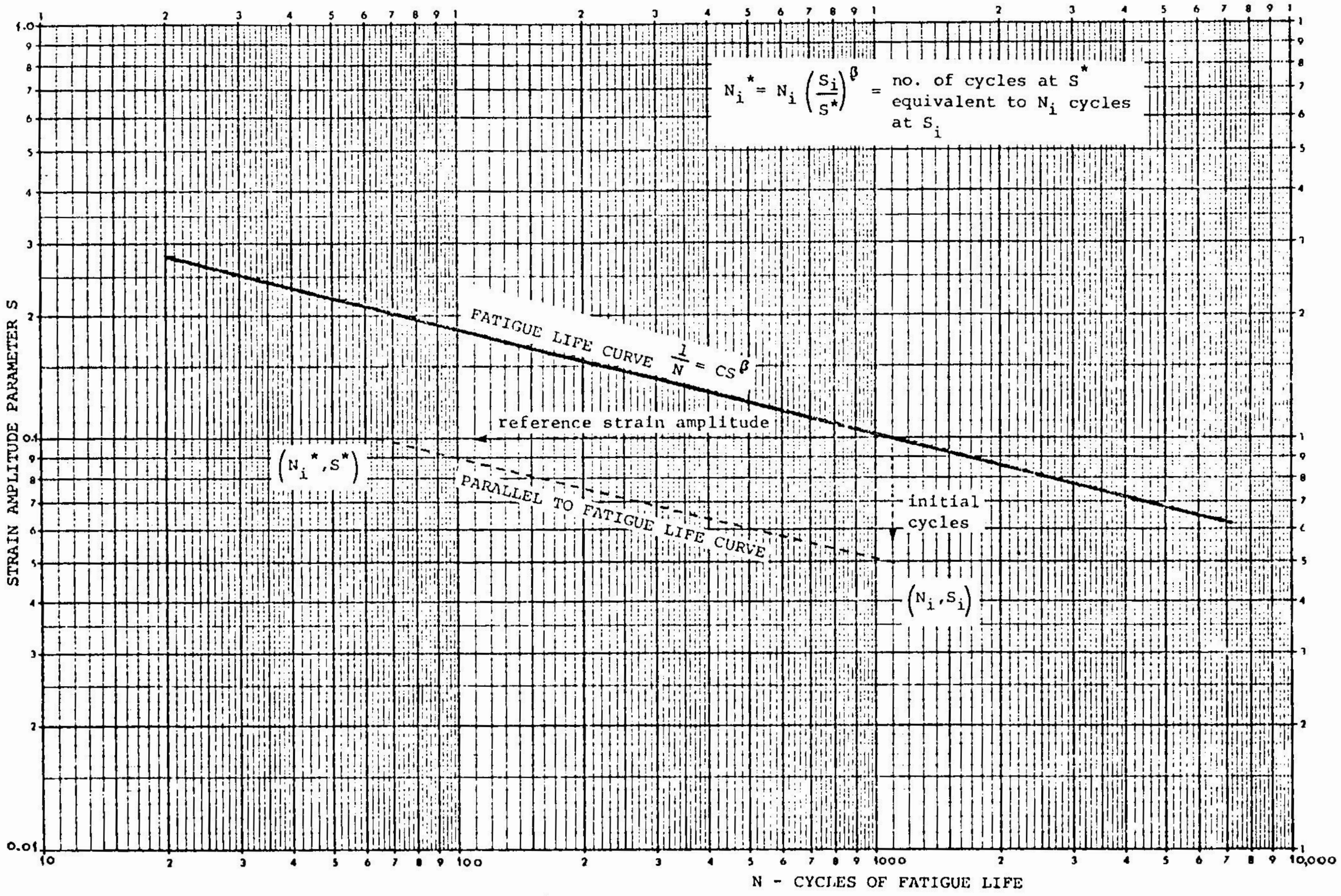
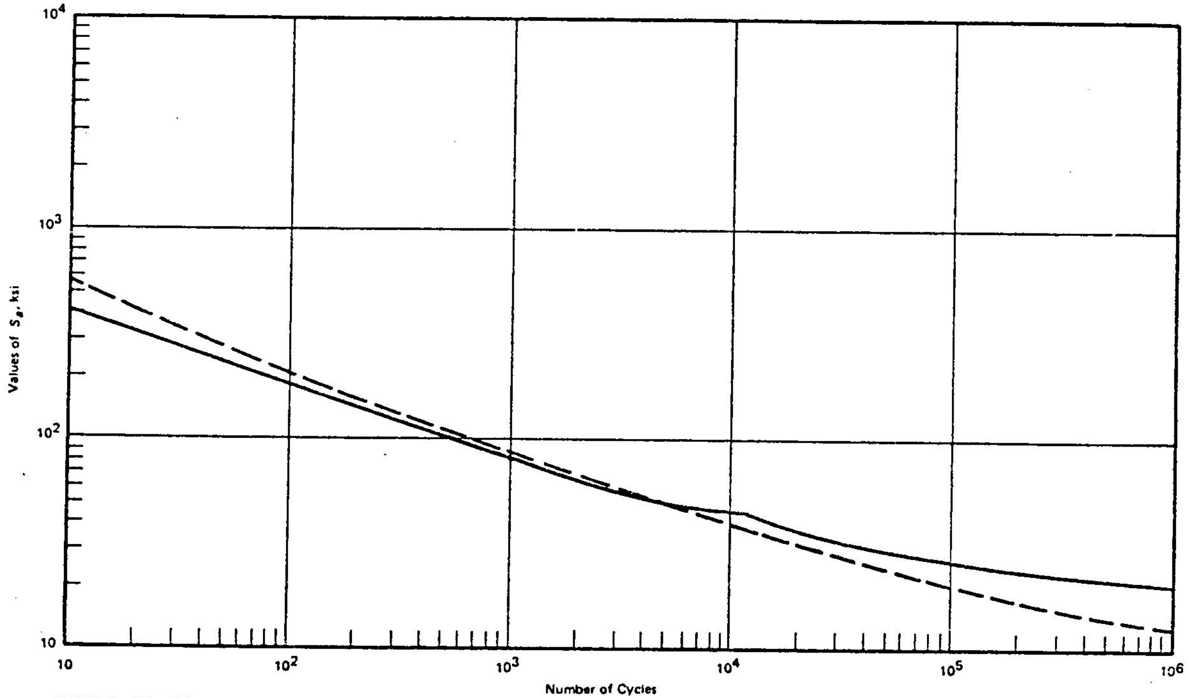


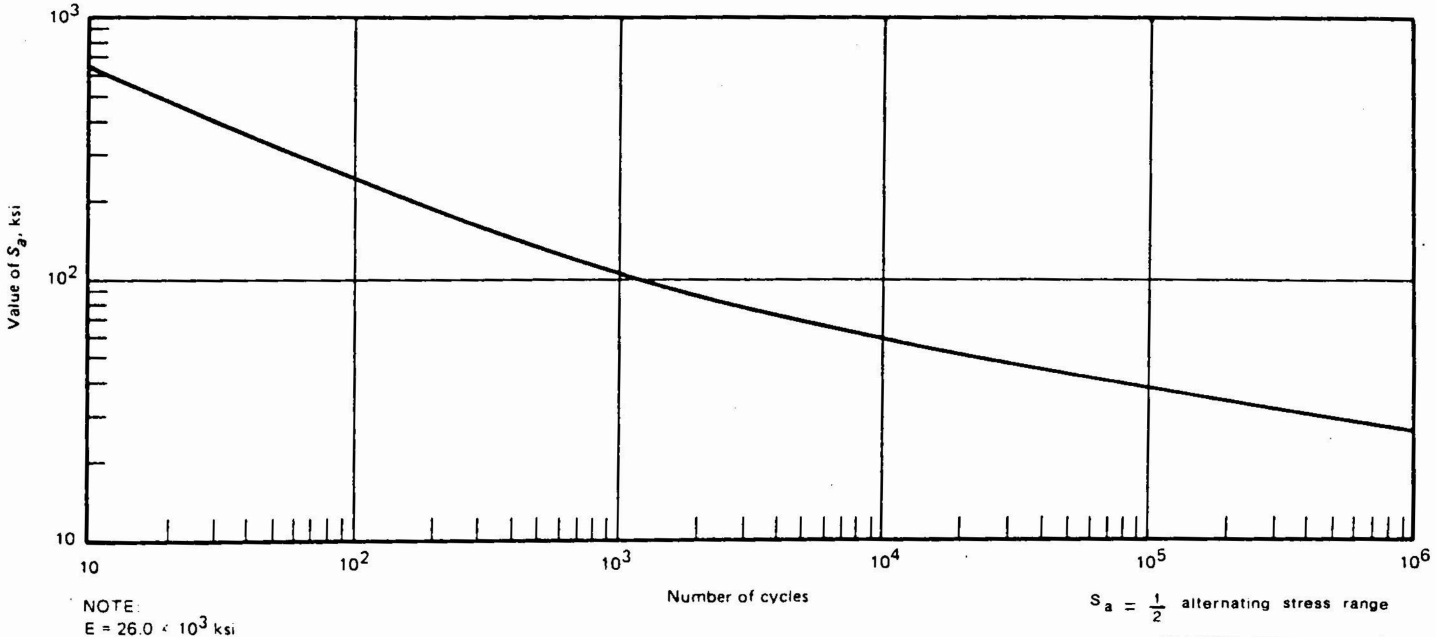
FIGURE 1 FATIGUE EQUIVALENCE RULE



NOTE: $E = 30 \times 10^3$ ksi
----- UTS < 80.0 ksi
—— UTS 115.0-130.0 ksi
Interpolate for UTS 80.0–115.0 ksi

$S_a = \frac{1}{2}$ alternating stress range
= alternating stress amplitude

FIGURE 2 DESIGN FATIGUE CURVES FOR CARBON, NON-ALLOY, SERIES 4XX, HIGH ALLOY STEELS AND HIGH TENSILE STEELS FOR TEMPERATURES NOT EXCEEDING 700F



NOTE:
$E = 26.0 \times 10^3$ ksi

$S_a = \frac{1}{2}$ alternating stress range

= alternating stress amplitude

FIGURE 3 DESIGN FATIGUE CURVE FOR SERIES 3XX HIGH ALLOY STEELS, NICKEL-CHROMIUM IRON ALLOY, NICKEL-IRON-CHROMIUM ALLOY, AND NICKEL-COPPER ALLOY FOR TEMPERATURES NOT EXCEEDING 800F