

GUIDE FOR THE

FATIGUE ASSESSMENT OF OFFSHORE STRUCTURES APRIL 2003

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COMMENTARY ON THE GUIDE FOR THE

FATIGUE ASSESSMENT OF OFFSHORE STRUCTURES (APRIL 2003)

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Foreword

This Commentary provides background, including source and additional technical details, for the ABS *Guide for the Fatigue Assessment of Offshore Structures*, April 2003, which is referred to herein as “the Guide”. The criteria contained in the Guide are necessarily brief in order to give clear descriptions of the fatigue assessment process. This Commentary allows the presentation of supplementary information to better explain the basis and intent of the criteria that are used in the fatigue assessment process.

It should be understood that the Commentary is applicable only to the indicated version of the Guide. The order of presentation of the material in this Commentary generally follows that of the Guide. The major topics of the Sections in both the Guide and Commentary are the same, but the detailed contents of the individual Subsections and Paragraphs will not typically correspond between the Guide and the Commentary.

In case of a conflict between anything presented herein and the ABS Rules or the Guide, precedence is given to the Rules or the Guide. This Commentary shall not be considered as being more authoritative than the Guide to which it refers.

ABS welcomes comments and suggestions for improvement of this Commentary. Comments or suggestions can be sent electronically to rsd@eagle.org.

COMMENTARY ON THE GUIDE FOR THE FATIGUE ASSESSMENT OF OFFSHORE STRUCTURES (APRIL 2003)

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SECTION 1 Introduction

1 General Comments

For over a half century, ABS has been involved in the development of fatigue technology, starting in 1946 with the formation of the Ship Structure Committee (SSC) for the specific goal of addressing avoidance of serious fracture in ships. The SSC, with strong financial support from ABS, has executed several fatigue research projects. Over the years, ABS has also provided support to numerous joint industry/agency fatigue projects in addition to independent investigators for their own in-house projects.

The current state of the art in fatigue technology represents worldwide contributions of a large numbers of investigators from government agencies, professional organizations, classification societies, universities and private industry, most notably petroleum companies. ABS has synthesized this body of knowledge to provide fatigue design criteria for marine structures. This document provides a review of the most relevant literature, describes how ABS criteria were established and compares ABS criteria with those of other organizations.

Because welded joints are subject to a variety of flaws, it is generally expected that fatigue cracks will start first at the joints. Therefore, the focus of this document will be on the joints, but the general principles and some of the fatigue strength data will apply to the base material.

2 Basic Terminology

N_T (or T)	=	Design life; the intended service life of the structure in cycles (or time)
N_f (or T_f)	=	Calculated fatigue life; the computed life in cycles (or time) of the structure using the design S-N curve
D	=	fatigue damage at the design life of the structure
Δ	=	maximum allowable fatigue damage at the design life of the structure
FDF	=	fatigue design factor; $FDF \geq 1.0$

The FDF accounts for:

- i) Uncertainty in the fatigue life estimation process
- ii) Consequences of failure (i.e., criticality)
- iii) Difficulty of inspection

3 The Deterministic Method and the Palmgren-Miner Rule to Define Fatigue Damage

Fatigue assessment in the Guide relies on the characteristic S-N curve to define fatigue strength under constant amplitude stress and a linear damage accumulation rule (Palmgren-Miner) to define fatigue strength under variable amplitude stress.

Fatigue stress is a random process. Stress ranges in the long-term process form a sequence of dependent random variables, S_i ; $i = 1, N_T$. For purposes of fatigue analysis and design, it is assumed that S_i are mutually independent. The set of S_i can be decomposed and discretized into J blocks of constant amplitude stress, as illustrated in Section 1, Table 1.

TABLE 1
Deterministic Stress Spectra

<i>Stress Range</i> S_i	<i>Number of Cycles</i> n_i
S_1	n_1
S_2	n_2
S_3	n_3
⋮	
S_{J-1}	n_{J-1}
S_J	n_J

Applying the Palmgren-Miner linear cumulative damage hypothesis to the block loading of Section 1, Table 1, cumulative fatigue damage, D , is defined as:

$$D = \sum_{i=1}^J \frac{n_i}{N_i} \quad \text{..... (1.1)}$$

where N_i is the number of cycles to failure at stress range S_i , as determined by the appropriate S-N curve. Failure is then said to occur if:

$$D > 1.0 \quad \text{..... (1.2)}$$

4 Application of the Palmgren-Miner (PM) Rule

The PM rule is a simple algorithm for predicting an extremely complex phenomenon (i.e., fatigue under random stress processes). Results of tests, however, have suggested that the PM rule is a reasonable engineering tool for predicting fatigue in welded joints subjected to random loading.

Statistical summaries of random fatigue tests have been reported by the UK Health and Safety Executive [HSE(1995)]. Let δ be a random variable denoting damage at failure and let δ_i denote damage at failure in a test of the i -th specimen in a sample of size, n . δ_i will depend on how the constant amplitude S-N curve is defined (e.g., as a median (best fit) curve through the center of the data or a design curve on the safe side (lower) of the data). The sample mean and standard deviation of δ can be computed from the random sample (δ_i ; $i = 1, n$). An empirical distribution can be fitted as well.

A limited number of tests on tubular joints is available. In HSE(1995), a lognormal distribution is assumed for δ . Statistics computed from the data presented are summarized in Section 1, Table 2. It is noted that the scatter is quite broad, and it is likely that the wide distribution is largely a result of the inherent scatter in fatigue data and not the suitability of the PM algorithm. For reference purposes, the probability of δ being less than the reference curve is also presented in Section 1, Table 2.

TABLE 2
Tubular Joints: Statistics on Damage at Failure,
(δ Lognormal Distribution Assumed)

	<i>Median, $\tilde{\delta}$</i>	<i>COV, C_δ</i>	<i>Percent less than S-N curve</i>
Best fit curve	1.41	0.98	34
Design curve	4.42	0.98	3.5

For plated joints*, there is a relatively large database. Again, a lognormal distribution for δ is assumed, and the statistics are presented in Section 1, Table 3.

TABLE 3
Plated Joints: Statistics on Damage at Failure,
(δ Lognormal Distribution Assumed)

	<i>Median, $\tilde{\delta}$</i>	<i>COV, C_δ</i>	<i>Percent less than S-N curve</i>
Best fit curve	1.38	0.70	33
Design curve	4.44	0.70	1.5

5 Safety Checking with Respect to Fatigue

The safety check expression can be based on damage or life. While the damage approach is featured in the Guide, either approach below can be used.

Damage

The design is considered to be safe if:

$$D \leq \Delta \dots\dots\dots (1.3)$$

where

$$\Delta = 1.0/FDF \dots\dots\dots (1.4)$$

Life

The design is considered to be safe if:

$$N_f \geq N_T \cdot FDF \dots\dots\dots (1.5)$$

* Note: In the Guide, to conform to practice, the two general categories of structural details are referred to as “tubular” (really meaning “tubular intersection”) details and “non-tubular” details. In the context of the HSE (1995), the “non-tubular” details are referred to as “plate” or “plate type” details. The “plate” terminology will be used in this Commentary.

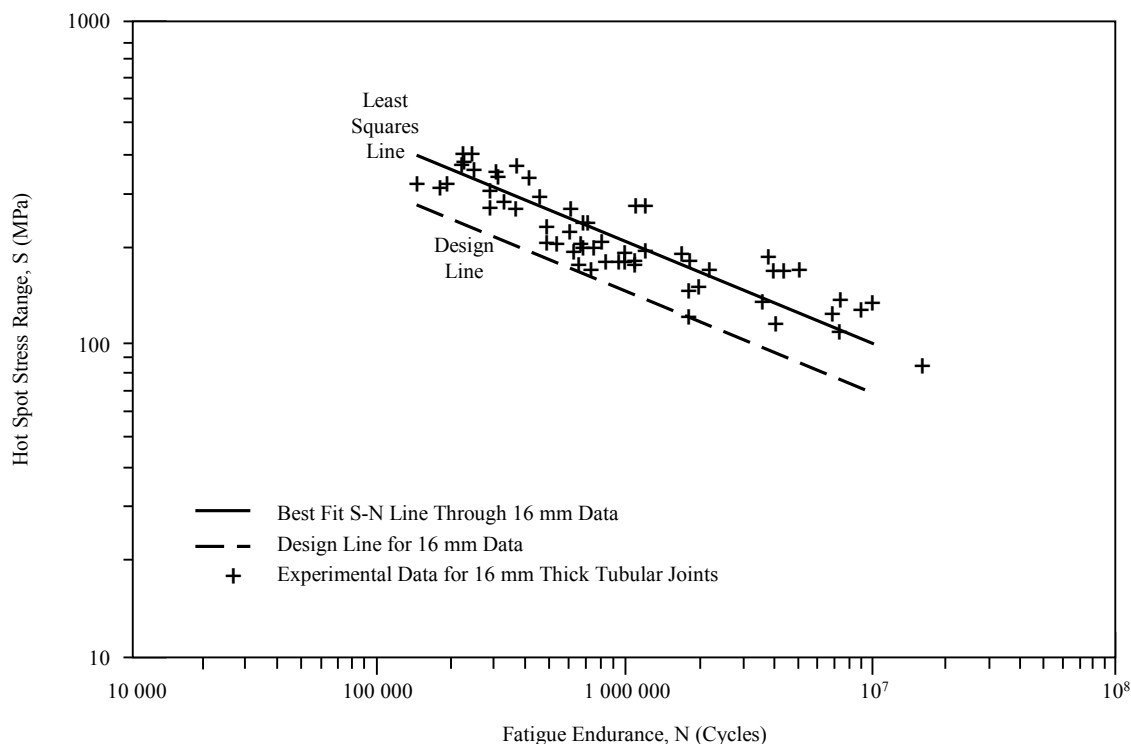
SECTION 2 Fatigue Strength Based on S-N Curves – General Concepts

1 Preliminary Comments

This Section introduces general concepts related to the S-N curve-based method of fatigue assessment. The next Section contains detailed information regarding S-N curves.

For the stress-based approach to fatigue, the S-N curve defines fatigue strength. An example of S-N data and a design curve are shown in Section 2, Figure 1. Each point represents the cycles to failure N of a specimen subjected to constant range stress S . $\log(N)$ is plotted versus $\log(S)$. Section 2, Figure 1 presents the results of fatigue tests on tubular joints where failure is defined as first through wall cracking.

FIGURE 1
An Example of S-N Fatigue Data Showing the Least Squares Line and the Design Line [HSE(1995)]



A design curve is defined on the safe (lower) side of the data. Note that an implicit fatigue design factor is thereby introduced. For purposes of safety checking, the design S-N curve defines fatigue strength, but one should keep in mind that there is a large statistical scatter in fatigue data (relative to other structural design factors) with cycles-to-failure data often spanning more than two orders of magnitude.

2 Statistical Analysis of S-N Data

The design curve is established as follows: First, it is noted that when S-N data are plotted in a log-log space, the data tend to plot as a straight line, as suggested in Section 2, Figure 1. A linear model can be employed, the form of which is:

$$\log(N) = \log(A) - m \log(S) \quad (2.1)$$

Base 10 logarithms are generally used. A and m are empirical constants to be determined from the data. A is called the *fatigue strength coefficient* and m is called the *fatigue strength exponent*. The parameter m is the negative reciprocal slope of the S-N curve, but for convenience, it is often referred to simply as the “slope”. Another component of the model is the standard deviation of N given S , denoted as $\sigma(N|S)$, or simply, σ . This parameter describes the scatter in life.

To estimate A , m and σ , the least squares method can be employed, thus providing parameters (A and m) to define the median S-N curve (i.e., a curve that passes through the center of the data). Note that S is the independent variable and N is the dependent variable. It is assumed that $\log(N)$ has a normal distribution, which means that N will have a lognormal distribution.

For many welded joint fatigue data, the parameter m is approximately equal to 3.0. Therefore, for convenience and consistency, a fixed value of $m = 3$ is assumed and least squares analysis is then employed to estimate A and σ . Let A' and σ' denote the estimates. For the sample data of Section 2, Figure 1:

$$m = 3$$

$$\log(A') = 12.942$$

$$\sigma' = 0.233$$

The coefficient of variation (standard deviation/mean) of cycle life N is required for a reliability analysis. The form for the COV is:

$$C_N = \sqrt{10^{(\sigma'^2 / 0.434)} - 1} \quad (2.2)$$

For the example:

$$C_N = 0.58, \text{ or } 58\%$$

3 The Design Curve

The design S-N curve is defined as the median curve minus two standard deviations on a log basis.

Thus, the basic S-N curves are of the form:

$$\log(N) = \log(A) - m \log(S)$$

where

$$\log(A) = \log(A_1) - 2\sigma$$

$$N = \text{predicted number of cycles to failure under stress range } S$$

$$A_1 = \text{constant relating to the mean S-N curve}$$

$$\sigma = \text{standard deviation of } \log N$$

$$m = \text{inverse slope of the S-N curve}$$

The relevant values of these terms are shown in the table below for the ABS “In-Air” S-N curves for plate-type (non-tubular) details.

The “in-air” S-N curves have a change of inverse slope from m to $m + 2$ at $N = 10^7$ cycles.

TABLE 1
Details of the Basic “In-Air” S-N Curves

Class	A_1	A_1		m	Standard Deviation		A
		$\log_{10}$	$\log_e$		$\log_{10}$	$\log_e$	
B	2.343×10^{15}	15.3697	35.3900	4.0	0.1821	0.4194	1.01×10^{15}
C	1.082×10^{14}	14.0342	32.3153	3.5	0.2041	0.4700	4.23×10^{13}
D	3.988×10^{12}	12.6007	29.0144	3.0	0.2095	0.4824	1.52×10^{12}
E	3.289×10^{12}	12.5169	28.8216	3.0	0.2509	0.5777	1.04×10^{12}
F	1.726×10^{12}	12.2370	28.1770	3.0	0.2183	0.5027	0.63×10^{12}
F₂	1.231×10^{12}	12.0900	27.8387	3.0	0.2279	0.5248	0.43×10^{12}
G	0.566×10^{12}	11.7525	27.0614	3.0	0.1793	0.4129	0.25×10^{12}
W	0.368×10^{12}	11.5662	26.6324	3.0	0.1846	0.4251	0.16×10^{12}

If cycles to failure were lognormally distributed, then a specimen selected at random would have a probability of 2.3% of falling below the design curve.

There may be confusion over this probability compared to those mentioned previously in Section 1, Tables 2 and 3. Different random variables are being referred to. In Section 1, Tables 2 and 3, the random variable is delta, the damage at failure. The statistics for delta are computed for both the best-fit curve and the design curve. Note that the fatigue test results are based on random stresses. The title of the column in the tables labeled, “Percent less than S-N curve” could have been alternatively labeled, “Percent of specimens that had lives below the S-N curve”.

The basic S-N curves are established from constant amplitude tests. Assuming a lognormal distribution for life, the design curve is that curve below which 2.3% of the specimens are expected to fall. So, random fatigue test results are being compared to constant amplitude test results. It would not necessarily be expected that the results would be the same, but it is gratifying to see that the results are so close.

4 The Endurance Range

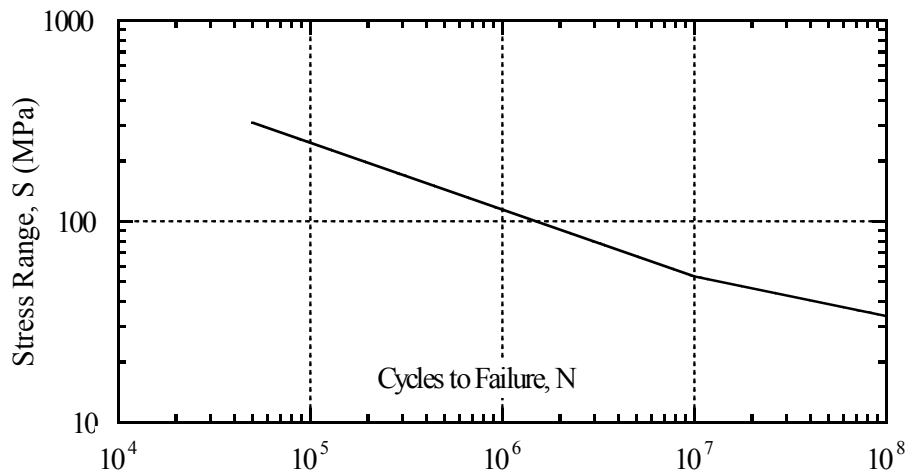
Test data are much more limited in the range beyond 10^7 cycles. It appears that there may be an endurance limit near this point (i.e., a stress below which fatigue life would be infinite). However, a more prudent extrapolation of the S-N curve into the high cycle range involves a change in slope. For in-air structure, the slope (actually the negative reciprocal slope) beyond 10^7 cycles is:

$$r = m + 2 \dots\dots\dots (2.3)$$

While defined by engineering judgment, this form seems to have performed well for an extended period of time. This algorithm is used by DEn(1990) and others, but ISO(2000) specifies the knee of the curve at 10^8 cycles.

As an example, consider the ABS-(A) class D curve.

FIGURE 2
The Design S-N Curve for the ABS-(A) Class D Joint



For plate joints that are cathodically protected, HSE(1995) specifies the knee at 10^6 cycles. For joints exposed to free corrosion, most organizations do not specify an endurance limit (i.e., the S-N curve is extrapolated into the high cycle range without a change in slope).

5 Stress Concentration Factors – Tubular Intersections

A major theme of the presentation in Section 2 of the Guide is that the fatigue assessment should employ applicable stress concentration factors (SCFs) and the appropriate S-N curve. For a tubular joint, the S-N curves recommended by DEn(1990)/HSE(1995) and API RP2A are meant to be used with SCFs obtained for the hot-spot locations at the weld toe.

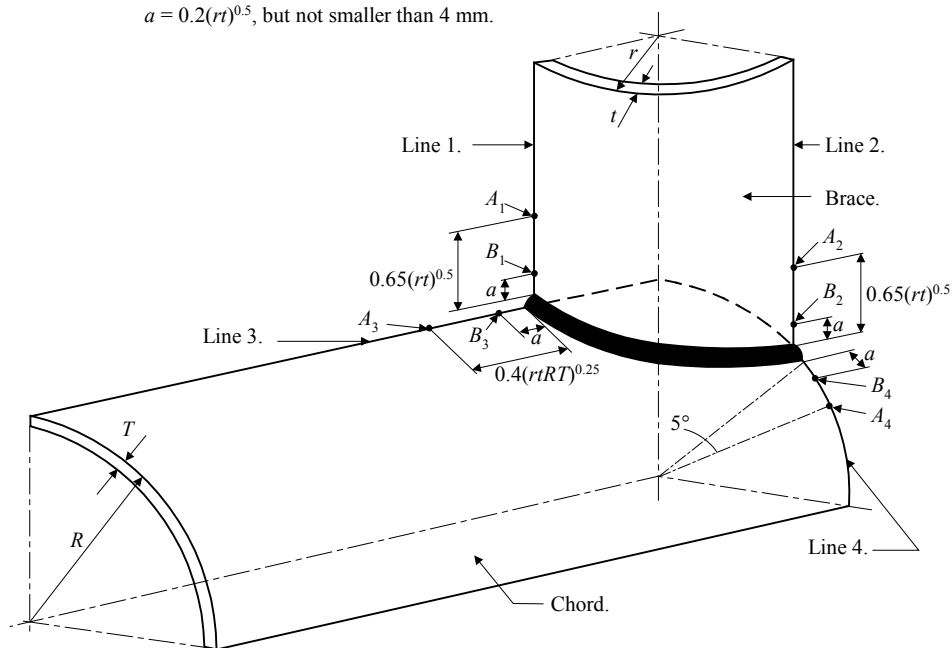
The SCF equations referenced in the Guide's Appendix 2 are meant to have precedence. However, allowance is made (Guide Paragraph 3/5.5) to also use, as appropriate, the parametric equations referenced in the API RP2A when it is permitted to use the API's tubular joint S-N curves (e.g., structure sited on the U.S. Outer Continental Shelf, subject to US Minerals Management Service Regulation).

Where conditions are such that the recommended parametric SCF equations cannot be applied confidently, then the SCFs can be obtained experimentally or numerically via finite element analysis. In either case, it is necessary to have a stress extrapolation procedure to weld toe locations that is compatible with the S-N curve. This is directly analogous to the extrapolation procedure for non-tubular details given in the Guide.

The DEn provided guidance, as shown in Section 2, Figure 3, on the specific locations where the stresses should be obtained for extrapolation to the hot-spot locations at the weld toe.

FIGURE 3
Weld Toe Extrapolation Points for a Tubular Joint

$$a = 0.2(rt)^{0.5}, \text{ but not smaller than 4 mm.}$$



SECTION 3 S-N Curves

1 Introduction

In the offshore industry, fatigue assessment and design are based primarily on S-N curves to define strength. These curves define the integrity of both plate-type details and tubular welded joints under oscillatory loading. ABS has performed a comprehensive review of fatigue test results and fatigue strength models employed for steel structural details for the purpose of defining the ABS requirements.

For the sources of design S-N curves, documents from three organizations, API (2000), AWS(2002), DEn (1990)/HSE(1995), are commonly cited by designers and analysts in the offshore industry. Agencies and organizations that provide structural design criteria for welded joints use these S-N curves and variations thereof. In order to gain a perspective on current practice, a digest of the S-N curves cited in various design criteria documents is provided in Subsection 3/2 below.

The approach used in the ABS Guide for the classification of details, the S-N curves and adjustments made to the curves, may be referred to as a “hybrid” of the DEn(1990) and HSE(1995) criteria. The ABS Guide criteria uses:

- The classification of details and basic S-N curves from the DEn(1990), which is almost identical to that found in HSE(1995) for plate-type details [a comparative description of DEn(1990) and HSE(1995) is given below in Subsection 3/2ii].
- For plate-type details, the thickness adjustment applies when $t > 22$ mm using $t_{ref} = 22$ mm and exponent of 0.25, and for tubular intersection details, the thickness adjustment applies when $t > 22$ mm using $t_{ref} = 32$ mm and exponent of 0.25.
- The HSE(1995) “Environmental Reduction Factors” (ERFs), which is akin to “Corrosiveness” in the ABS Guide are for plate type details: 2.5 where effective Cathodic Protection (CP) is provided and 3.0 for Free Corrosion (FC) conditions, and for tubular intersection details, the ERFs are 2.0 for CP and 3.0 for FC conditions.

2 A Digest of the S-N Curves Used for the Structural Details of Offshore Structures

- DEn (1990), Gurney (1979); A suite of eight curves for plated joints.* Change in slope at $1E7$ cycles, used successfully for many years by DEn and other criteria based on DEn
- HSE(1995).* Citations and comparisons to HSE and DEn criteria are difficult. The version of the fatigue criteria contained in the DEn “Guidance Notes” that was issued in 1990 was labeled the 4th Edition. It is referred to here as “DEn(1990).” Following DEn practice, changes to an edition were issued as “amendments” to that edition. Revision of the fatigue criteria in the 4th Edition was planned for publication in the 3rd amendment of the DEn “Guidance Notes” in 1995. At the same time, the DEn was undergoing organizational change, and the HSE became its successor organization. The document planned for release was relabeled, and is referred to here as “HSE(1995).” There were changes in the details of the criteria presentation between what had been planned as the 3rd amendment of the “Guidance Notes”, 4th Edition in 1995 and the superseding HSE(1995) document. However, immediately after the HSE(1995) fatigue criteria were issued, it was withdrawn along with all of the other DEn “Guidance Notes”.

For information, the essential features of the HSE(1995) fatigue criteria compared to DEn(1990) are as follows.

- The guidance provided on the classification of structural details and the assigned S-N curve to each class remained the same (see Appendix 1 of the Guide showing the classifications using the sketches of the various structural details and loading). Changes included in HSE(1995) were added guidance related to tubular member details and a change in the “W” S-N curve.
 - Also, in the detail classification guidance (for plate type details), it was planned to replace mention of the individual (8) S-N categories with one S-N curve, the “P” curve that was equivalent to the “D” curve in DEn(1990). Then, the detail classes would be related to the “P” curve by a ‘classification factor.’
 - The basic S-N curve for tubular intersection details was revised. In DEn(1990), the T curve is close to the “D”. The revised HSE(1995) T’ curve (in air) is higher than the 1990 T curve. However, the application of Environmental Reduction Factors (EFRs) and a revised thickness adjustment might produce significant reductions from the basic case.
 - In the DEn(1990), no reduction to an (in air) S-N curve is called for when effective Cathodic Protection is present. Based on additional testing, it was deemed necessary to include in HSE(1995) penalties for the Cathodic Protection (CP) case and to increase the penalties for the Free Corrosion case. For plate type details, the penalty factors are 2.5 and 3.0 for (CP) and (FC), respectively. For tubular intersection details, the respective penalty factors were 2.0 and 3.0. (The specific details of how these are applied are discussed in Subsection 3/7.)
 - Another planned, significant change between HSE(1995) and DEn(1990) concerns the adjustment to the S-N curves for thickness. The limiting thickness (above which adjustments are to be made), and the exponent and reference thickness in the adjustment equation were all affected.
- iii) *ABS (2001) Rules for Building and Classing Steel Vessels.* Since the original introduction in 1994, the criteria for fatigue strength in these Rules employ the DEn (1990) curves.
- iv) *Eurocode 3 (1992).* Uses a suite of 14 curves, with initial segments having slopes of 3.0. Beyond 5E6 cycles, the slopes are 5.0 for the curves up to 1E8 cycles, beyond which the curves are flat (endurance limit).
- v) *IIW (1996).* In general application, a suite of 14 S-N curves is presented. Each has an endurance limit at 5E6 cycles, after which the curve is flat. For marine application to be used together with Palmgren-Miner summation, another suite of 14 S-N curves that basically matches the Eurocode 3 curves is recommended: Beyond 5E6 cycles the curve has a slope of 5 and the curve has a cut-off limit at 1E8. The concept of a FAT class defines the joint detail.
- vi) *DNV (2000); RP-C203 for offshore structures.* Uses a suite of 14 curves [as in iv) and v)] that also incorporate the HSE(1995) curves. This reference also has S-N curves that reflect FC and CP conditions. It also has a curve for tubular joints, in-air and for CP and FC conditions in seawater.
- vii) *ISO/CD 19902 (2000).* The ISO draft standard appears to be based on DEn(1990), but the basic 2-segment S-N curves have a change of slope at 1E8 cycles, which is not the same as DEn(1990). S-N curves are also provided for tubular intersection details and cast steel tubular joints.
- viii) *API (2001 a & b).* RP2A (both WSD and LRFD) has S-N curves for tubular intersection joints. Defines X and X’ curves for joints with and without weld profile control, respectively. Cites ANSI/AWS D1.1- for plate joints.
- ix) *API RP2T(1997).* Cites RP2A for definition of S-N curves.

3 General Comparison

Section 3, Table 1 summarizes the characteristics of the S-N design curves of DEn(1990)/HSE(1995) and API/AWS relative to environment, cathodic protection, and weld improvement.

TABLE 1
Coverage of the Two Main Sources of S-N Curves
Used for Offshore Structures

<i>Detail Type</i>	<i>Corrosion Condition</i>	<i>API (2000) Notes 1&4</i>	<i>AWS D1.1</i>	<i>DEn(1990) HSE(1995) Notes 2&3</i>
Tubular Intersection	In-Air	√	-	√
	Cathodic Protection	√	-	√
	Free Corrosion in the Sea Water	√	-	√
Non-Tubular (Plate)	In-Air	-	√	√
	Cathodic Protection	-	-	√
	Free Corrosion in the Sea Water	-	Note 5	√

Notes:

- 1 & 2 Fatigue life enhancement via "Weld Improvement" techniques is explicitly permitted:
 - in API RP2A by weld profiling
 - in DEn/HSE by weld toe grinding
- 3 DEn/HSE is the basis of the ABS criteria
- 4 API RP 2A treats corrosion differently from the other codes. API RP 2A uses one curve with different endurance limits to represent the three corrosion cases (in-air, in seawater with free corrosion, and in seawater with cathodic protection). DEn/HSE use three curves to represent the three cases.
- 5 While AWS does not address modification of S-N curves for CP, API RP2A specifies an endurance limit at 2×10^8 cycles for plate type details.

4 Tubular Intersection Connections

4.1 Without Weld Profile Control

A summary of the API and HSE(1995) having no weld profile control is presented as follows.

API RP 2A(2000) uses the X' curve for the following three corrosion cases with various endurance limits:

- In the air, endurance limit = 2×10^7 cycles
- Cathodic protection, endurance limit = 2×10^8 cycles
- Free corrosion in sea water, no endurance limit

HSE(1995) defines a T' curve and its derivatives for the three corrosion cases:

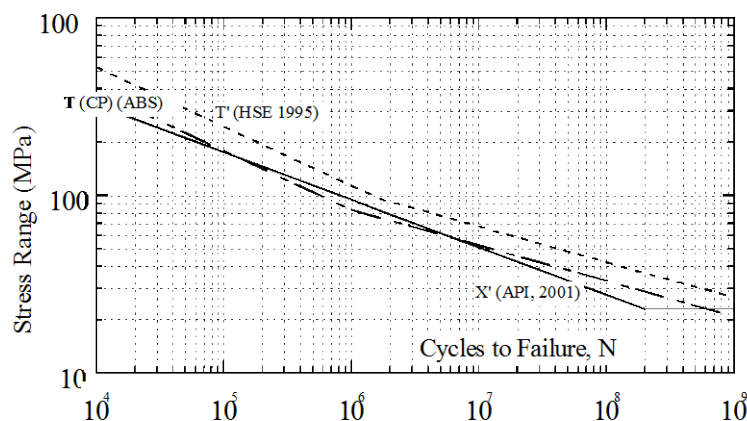
- In-air,
- Cathodic protection, (CP)
- Free corrosion in sea water, (FC)

The ABS Guide specifies a T curve and recognizes three corrosion cases:

- In-air, (A)
- Cathodic protection, (CP)
- Free corrosion in sea water, (FC)

Section 3, Figure 1 presents the S-N curves for the CP case for tubular joints for: HSE (1995) T' with CP, API RP2A the X' curve, and the ABS T (CP) curve, as provided in the ABS Guide. The latter is based on the use of the DEn(1990) T curve, which is adjusted as recommended in HSE (1995).

FIGURE 1
API, DEn, and ABS S-N design Curves for Tubular Joints;
Effective Cathodic Protection; No Profile Control Specified



4.2 With Weld Improvement (1 February 2013)

A summary of the API and HSE/DEN S-N curves for joints of tubular members having weld improvement is presented in the following.

API RP 2A(2000) uses the X curve for the following three corrosion cases with various endurance limits:

- In-air, endurance limit = 10^7 cycles
- Cathodic protection, endurance limit = 2×10^8 cycles
- Free corrosion in seawater, no endurance limit.

The crediting of weld profile control (i.e., concave weld profile) and other fatigue strength enhancements are not mentioned in the Guide for use with the ABS S-N curves. The main reason for this is to discourage (however, not ban) the use of such a credit in design. In this way, the credit will be available if needed in the future [say, if design changes occur after structural fabrication begins and even later in the structure's life should reconditioning or reuse be considered]. Out of necessity and in a limited, particular circumstance, the Guide (in its Appendix 3) allows the use of the API X curve, which requires weld profile control and NDE.

Grinding is preferably to be carried out by rotary burr and to extend below the plate surface in order to remove toe defects and the ground area is to have effective corrosion protection. The treatment is to produce a smooth concave profile at the weld toe with the depth of the depression penetrating into the plate surface to at least 0.5 mm below the bottom of any visible undercut. The depth of groove produced is to be kept to a minimum, and, in general, kept to a maximum of 1 mm. In no circumstances is the grinding depth to exceed 2 mm or 7% of the plate gross thickness, whichever is smaller. Grinding has to extend to areas well outside the highest stress region.

The finished shape of a weld surface treated by ultrasonic/hammer peening is to be smooth and all traces of the weld toe are to be removed. Peening depth below the original surface is to be maintained at least 0.2 mm. Maximum depth is generally not to exceed 0.5 mm.

Provided these recommendations are followed, when using the ABS S-N curves, a credit of 2 on fatigue life may be permitted when suitable toe grinding or ultrasonic/hammer peening are provided. Credit for an alternative life enhancement measure may be granted based on the submission of a well-documented, project-specific investigation that substantiates the claimed benefit of the technique to be used.

5 Plated Connections

For plated connections, API RP2A cites the ANSI/AWS D1.1-92 [AWS(1992)] S-N design curves. The S-N curves of the newer AWS(2002) document are essentially the same as AWS(1992). The AWS and DEn (1990) curves are compared below. Both references use sketches to help the designer in the selection of a detail's classification.

The comparison is not exact. Observations that contrast the two main reference sources are:

- i) DEn has eight classes or categories of joint types. AWS has six.
- ii) DEn is more discriminating in the number of joint types or details.
- iii) There are differences in the definition of the detail category.
- iv) DEn employs a thickness adjustment (see Subsection 3/6). There is no thickness adjustment in the AWS criteria.
- v) Except for free corrosion in seawater, AWS specifies a stress "endurance limit" in the high cycle range. DEn changes to a shallower slope.
- vi) Overall, there is no direct correspondence of categories, but there are a few that are similar. These are summarized in Section 3, Table 2.

TABLE 2
AWS-HSE/DEN Curves for Similar Detail Classes

<i>Detail Class</i>	<i>ANSI/AWS(1992)</i>	<i>DEn(1990)</i>
Base or parent material	A	B
Full penetration butt welds, groove welds	B	C
Parent material at the end of butt welded attachments	C ($L < 50$ mm) D ($50 < L < 100$) E ($L > 100$)	F ($L < 150$ mm) F2 ($L > 150$ mm)
Parent material of cruciform T-joints	C	F
Load carrying fillet welds transverse to the direction of stress (parent material)	E	F ($d > 10$ mm) G ($d < 10$)
Load carrying fillet welds transverse to the direction of stress (weld material)	F	W

For conditions of effective cathodic protection (CP):

- i) API specifies a stress endurance limit on the AWS curves at 2×10^8 cycles.
- ii) The DEn CP curves have a break at 10^6 cycles. The slope to the left is m ; to the right, it is $m + 2$. The DEn curves are lowered from the in-air curves by a factor of 2.5 on life, again maintaining the break point at 10^6 cycles.

For conditions of free corrosion, both curves have no endurance limit or slope change in the high cycle range (i.e., the low cycle curve with a slope of 3.0 is continued into the high cycle range). In addition, the DEn curves are lowered by a factor of 3.0 on life.

6 Discussion of the Thickness Effect

6.1 Introduction

The ABS-recommended thickness adjustment (size effect) is based on studies of fatigue test data as well as models used by others. A summary of this study is presented below.

The basic S-N design curve has the functional form:

$$\log_{10} N = \log_{10} A - m \log_{10} S \quad (3.1)$$

where N is cycles to failure, S is stress range, and A and m are respectively, the fatigue strength coefficient and exponent.

The size effect in fatigue in which larger sections tend to be weaker is manifest in welded joint fatigue by a thickness adjustment. In API, HSE/DEN and other codes, the effect of plate thickness is addressed by a similar adjustment formula:

$$S_f = S \left(\frac{t}{t_R} \right)^{-q} \quad t > t_0 \quad (3.2)$$

$$S_f = S \quad t \leq t_0 \quad (3.3)$$

where

- S_f = allowable stress range,
- S = allowable stress range from the nominal S-N design curve,
- q, t_R = parameters (t_R is the “reference” thickness),
- t_0 = thickness above which adjustments should be made,
- t = actual thickness.

A “thickness adjusted” S-N curve can be constructed when $t > t_0$.

$$\log_{10}(N) = \log_{10}(A) - m \log \left[S \left(\frac{t}{t_R} \right)^{-q} \right] \quad (3.4)$$

The parameters q and t_R are determined empirically. For plated joints, Section 3, Table 3 summarizes these parameter values from the references: DEN (1990), HSE (1995) and DNV (2000). (Size effect is not considered in ANSI/AWS D1.1.)

TABLE 3
Parameters of Plate Thickness Adjustment for Plated Joints

Parameters	DEN (1990)	HSE (1995)	DNV (2000)
q	0.25	0.30	0.0 – 0.25 depending on detail classification; 0.25 for F-curve
t_R	22 mm	16 mm	25 mm

These values do not depend upon the environment (i.e., they are the same for the in-air, cathodic protection and free corrosion curves).

The objective of this section is to compare the three parameter sets with the test data on plated joints that were used in reviewing the thickness effect by HSE (1995) and to recommend the algorithm to be used by ABS in the Guide.

For reference, the tubular joint parameters are also given in Section 3, Table 4.

TABLE 4
Parameters of Plate Thickness Adjustment for Tubular Joints

Parameters	API (2000, 1993)	HSE (1995)	DNV (2000)
q	0.25	0.30	0.25 for SCF < 10.0 0.30 for SCF > 10.0
t_R	25 mm	16 mm	32 mm

6.2 Fatigue Test Data on Plated Joints

An analysis was undertaken of data from tests on as-welded T-butt and cruciform joints that belong to the F classification [HSE(1995)]. The specimens varied in thickness from 16 mm to 200 mm. There are a total of 146 specimens in which 125 specimens have equal main plate and attachment thickness. Stress ranges in the tests varied from 56 MPa to 341 MPa and only four specimens had a fatigue life exceeding 10^7 cycles.

6.3 Design F-Curves with Thickness Adjustment

The parameters of the basic F-curves used in the three codes are shown in Section 3, Table 5. The F-curves in DEn (1990) and HSE (1995) are identical, but with different thickness adjustment formulae. The DNV (2000) F-curve is slightly less conservative than the other two.

TABLE 5
Parameters of F-curves

Codes	$N < 10^7$		$N > 10^7$	
	$\log_{10}(A)$	m	$\log_{10}(A)$	m
DEn (1990)	11.801	3	15.001	5
HSE (1995)	11.801	3	15.001	5
DNV (2000)	11.855	3	15.091	5

The design F-curves with thickness adjustment (Equation 3.4) are plotted in Section 3, Figures 2 through 19. In ascending order, each curve has a different thickness. The test data for each thickness are plotted. The HSE (1995) F-curve of 16 mm thickness (i.e., without thickness adjustment) is also plotted in figures where it is appropriate for reference. These series of figures demonstrate the general detrimental effect of increasing plate thickness. There exist relatively large safety margins between the test data and design curves, with the HSE (1995) curve having the largest gap.

6.4 Thickness Adjustments to Test Data and Their Regressed S-N Curves

For a different viewpoint, the adjustment of Equation 3.2 is applied to the data and then compared to the basic curves (without the thickness adjustment).

In this analysis, only data for specimens with equal main plate and attachment thicknesses were included because HSE used the same strategy in their study on thickness effect. Data with fatigue lives longer than 10^7 cycles were also excluded due to the small sample size (i.e., insufficient data to regress the curve segment for $N > 10^7$). With the adjusted data, “quasi-design” S-N curves were produced. These curves were constructed by taking the least squares line and shifting it two standard deviations (on a log basis) to the left. The adjusted data, (the quasi-design S-N curves,) and the basic F-curves, without thickness adjustments, are plotted together for comparison. The results for DEn (1990), HSE (1995) and DNV (2000) are shown in Section 3, Figures 20 through 22, respectively. The comparison across the codes is demonstrated in Section 3, Figure 23. The conclusion stated previously is justified. There are relatively large safety margins between the regressed S-N curves and design curves, with HSE (1995) curve having the largest margin.

6.5 Discussion

In reviewing the commentary document [HSE (1992)] that supports the HSE Fatigue Criteria [HSE (1995)], it is found that with the thickness adjustment of HSE (1995), all test data locate above the P-curve [i.e., D-curve in DEn (1990)], while the test specimens were as-welded T-butt and cruciform joints that belong to F-curve of joint classification. This gap indicates that HSE (1995) thickness adjustment formula is too conservative. Perhaps, in recognition of the possible excessive conservatism for particular details, a clause is included in HSE (1995) so that alternative adjustments may be used if they are supported by results from experiments or from fracture mechanics analyses.

A statement that the basic 16 mm P-curve is equivalent to the 22 mm D-curve in DEn (1990) is found in a commentary paper on the HSE (1995) [Stacey and Sharp (1995)]. Therefore, one may ask why it is necessary to make a thickness adjustment to joints with a 22 mm thickness.

In a commentary paper of DNV RP-C203 [Lotsberg and Larsen (2001)], a similar study was conducted and a conclusion is that use of the F-curve for this detail with reference thickness 16 mm is conservative.

6.6 Postscript

Due to the discrepancy between the thickness adjustment formulae, there is a question as to how the thickness adjustment formula of HSE (1995) was derived. It is speculated by the authors of this Commentary that the algorithm was obtained by borrowing the form for tubular joints, or by using a curve other than the F-curve as the target curve for regression analysis, or perhaps using some other procedure. The origin of the algorithm is not documented in HSE (1992). Thus, the procedure used to derive the thickness adjustment formula of HSE (1995), particularly the choice of 16 mm as basic thickness, is not clear.

FIGURE 2
F-Curves with Thickness Adjustment and Test Data; 16 mm Plate

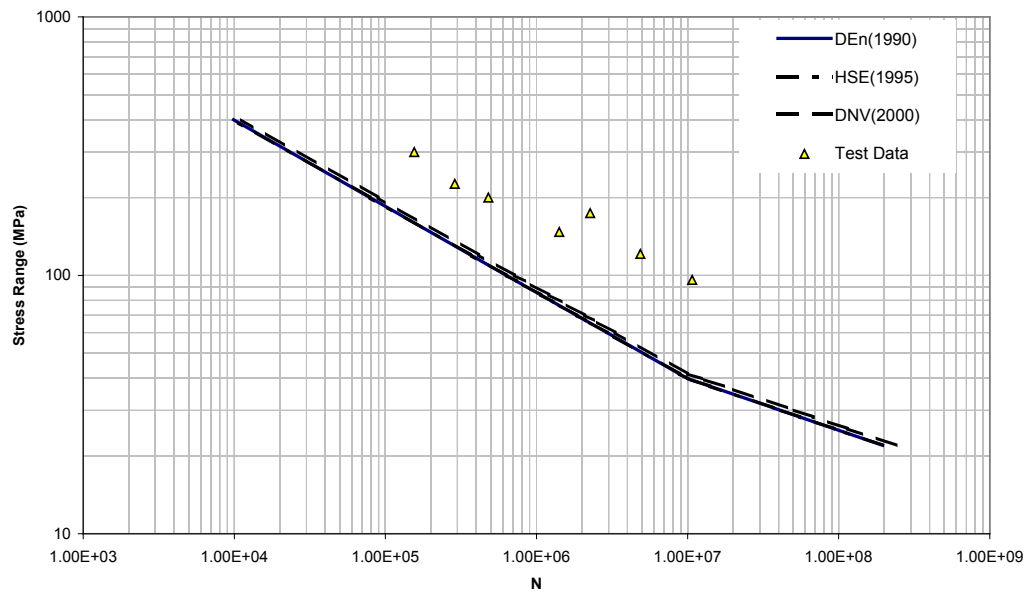


FIGURE 3
F-Curves with Thickness Adjustment and Test Data; 20 mm Plate

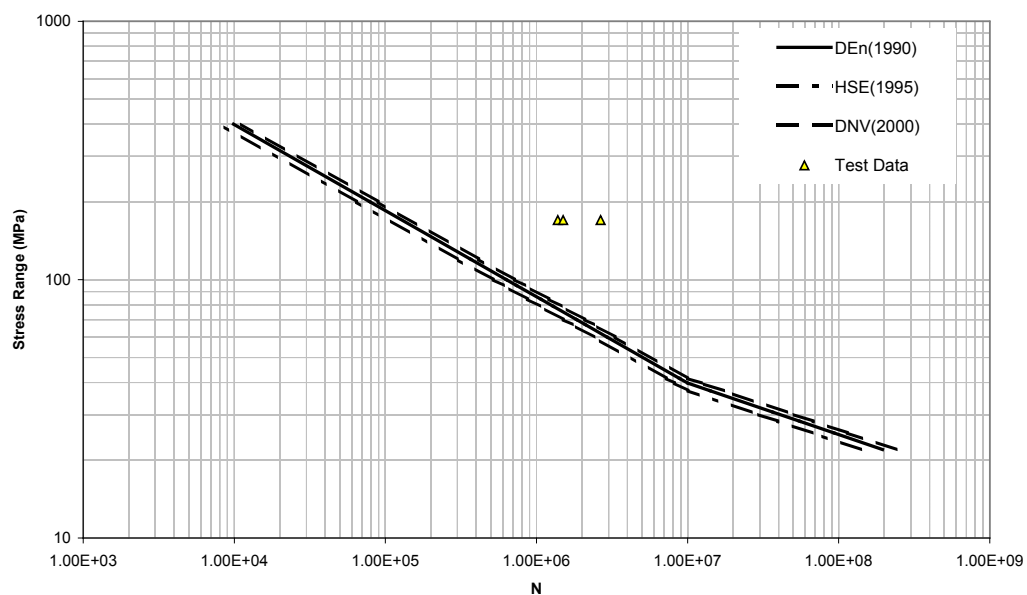


FIGURE 4
F-Curves with Thickness Adjustment and Test Data; 22 mm Plate

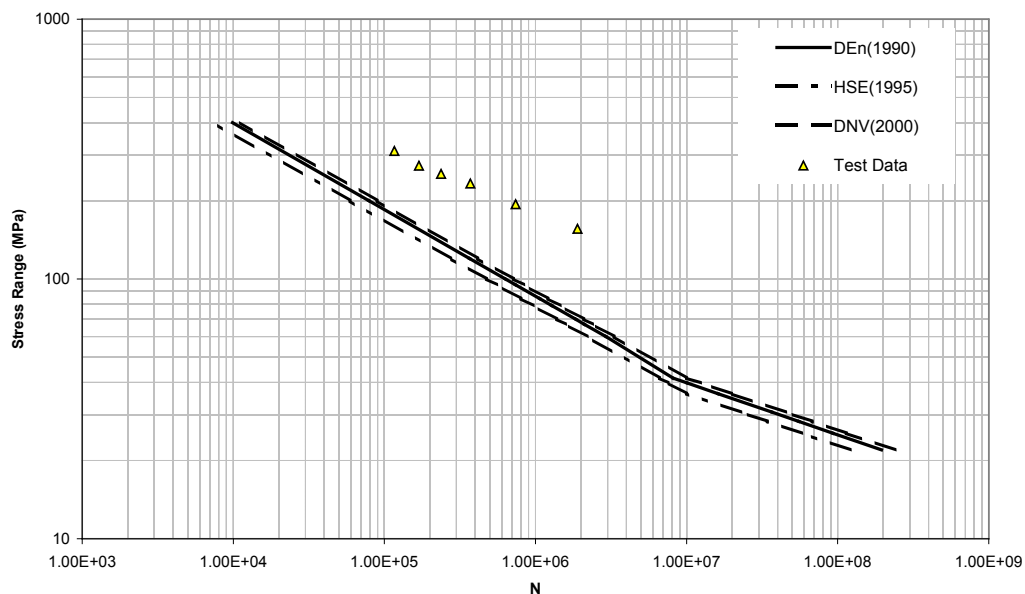


FIGURE 5
F-Curves with Thickness Adjustment and Test Data; 25 mm Plate

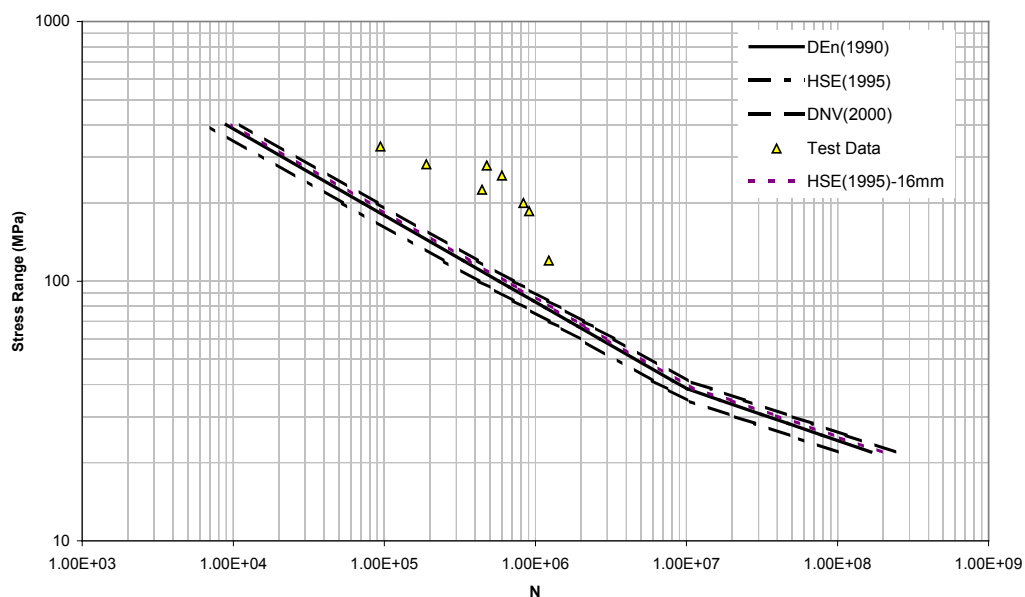


FIGURE 6
F-Curves with Thickness Adjustment and Test Data; 26 mm Plate

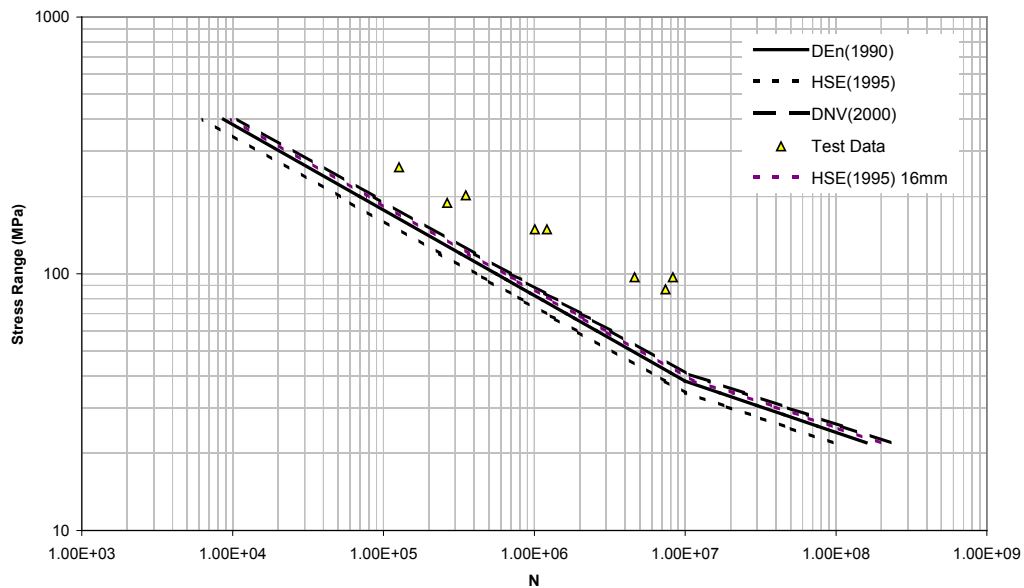


FIGURE 7
F-Curves with Thickness Adjustment and Test Data; 38 mm Plate

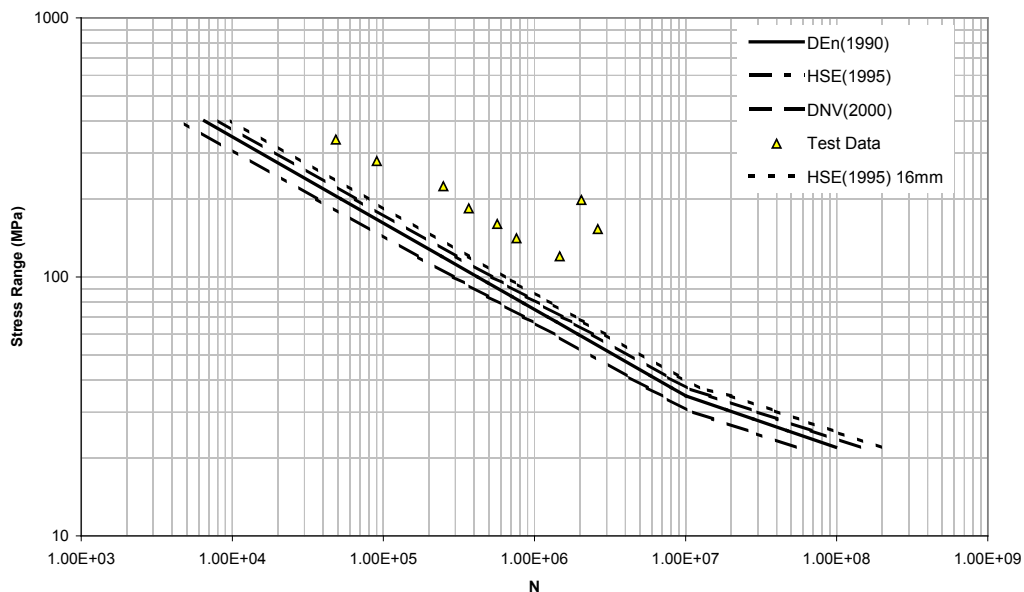


FIGURE 8
F-Curves with Thickness Adjustment and Test Data; 40 mm Plate

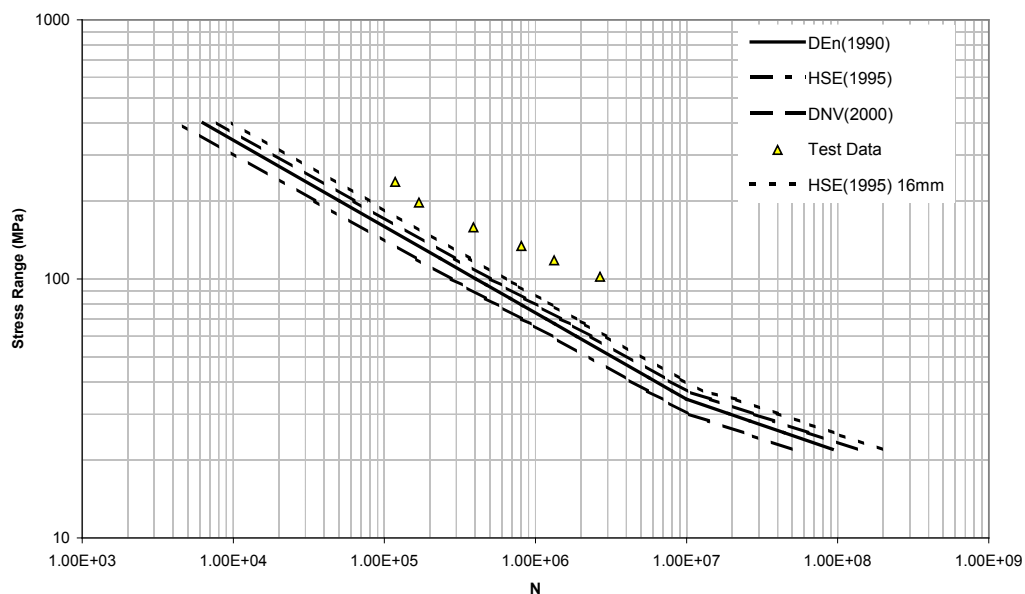


FIGURE 9
F-Curves with Thickness Adjustment and Test Data; 50 mm Plate

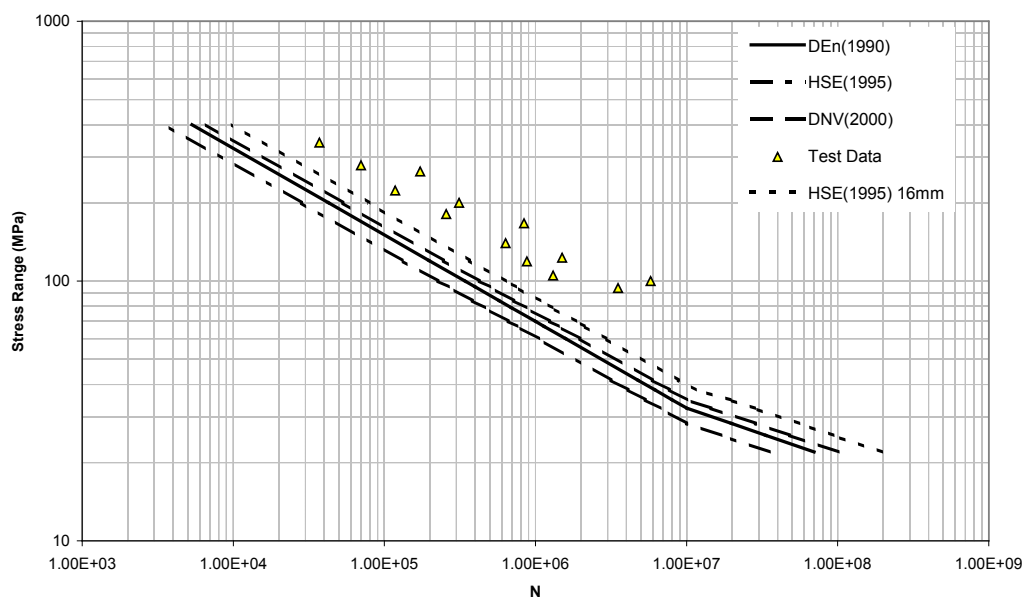


FIGURE 10
F-Curves with Thickness Adjustment and Test Data; 52 mm Plate

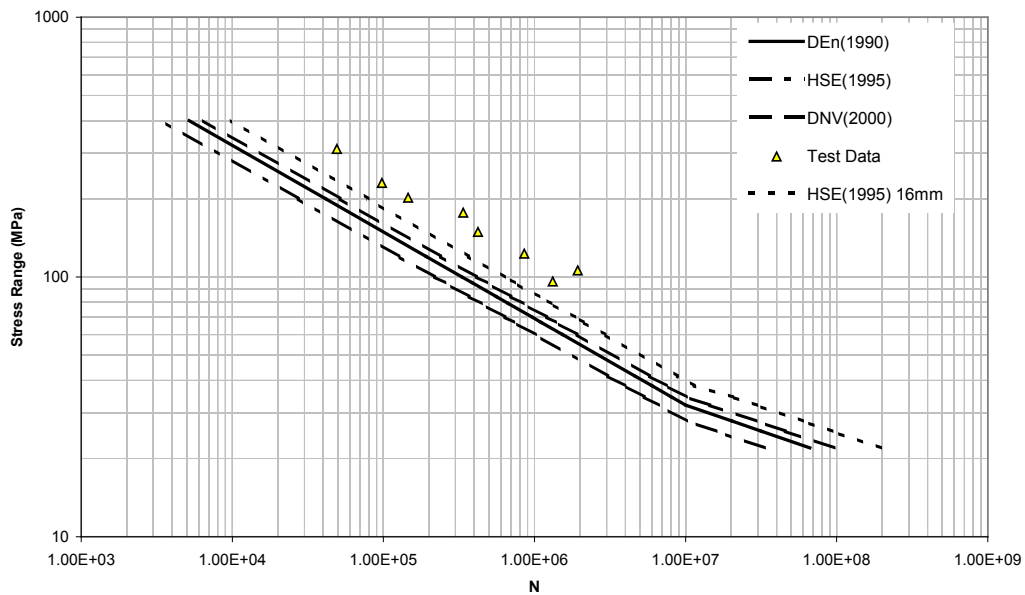


FIGURE 11
F-Curves with Thickness Adjustment and Test Data; 70 mm Plate

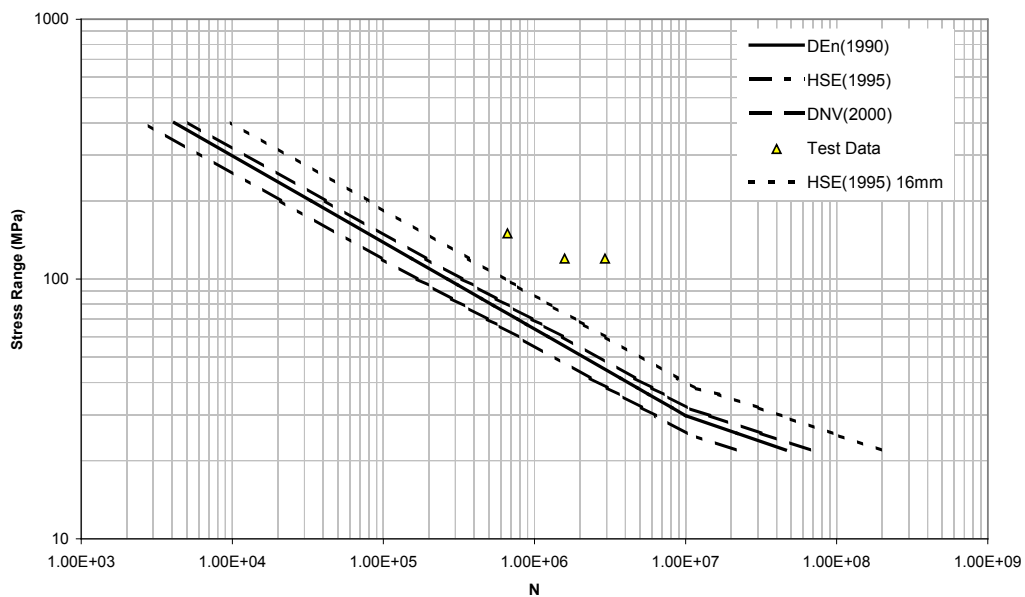


FIGURE 12
F-Curves with Thickness Adjustment and Test Data; 75 mm Plate

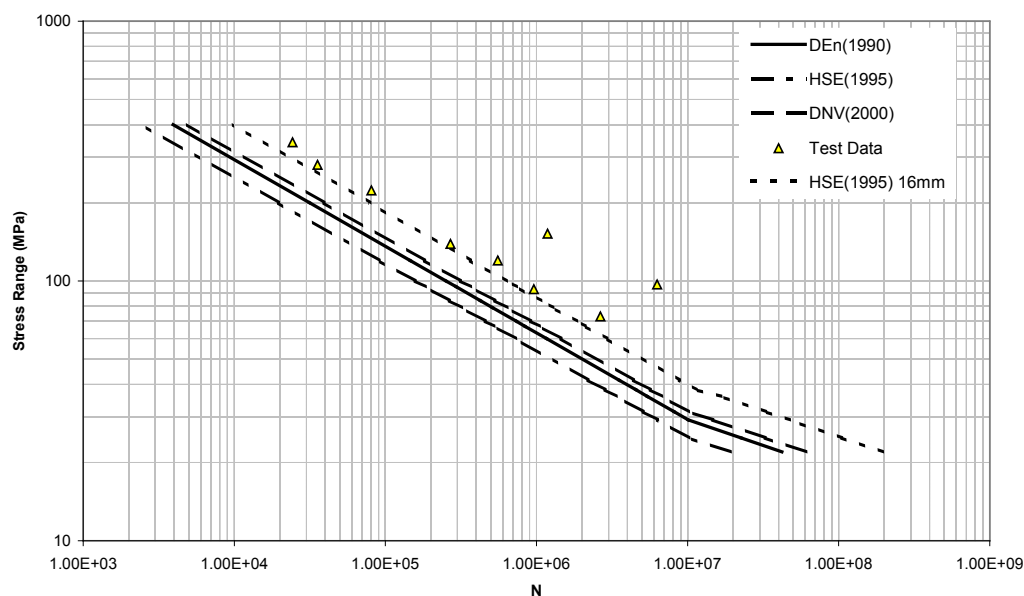


FIGURE 13
F-Curves with Thickness Adjustment and Test Data; 78 mm Plate

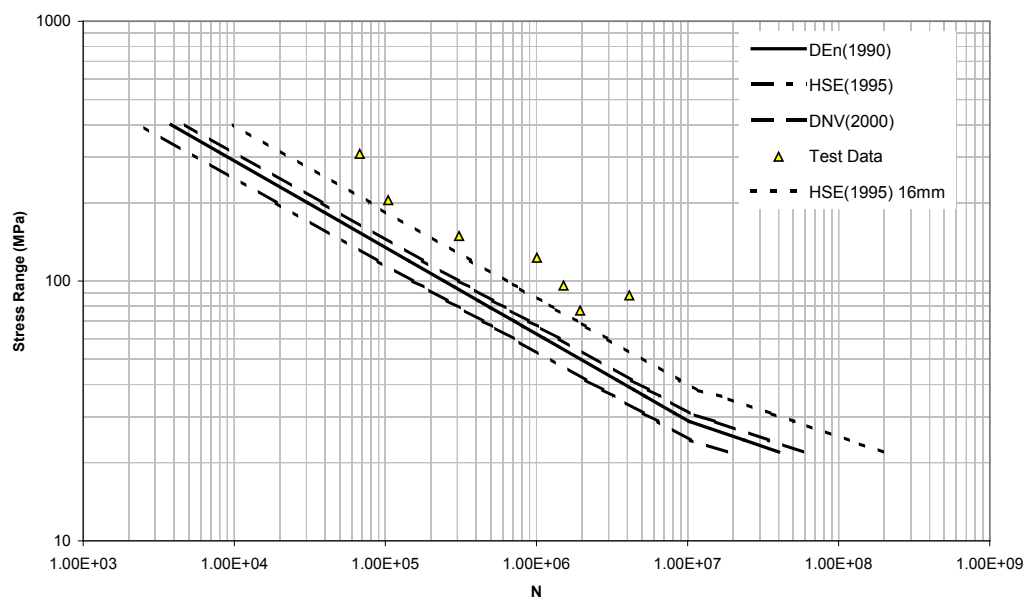


FIGURE 14
F-Curves with Thickness Adjustment and Test Data; 80 mm Plate

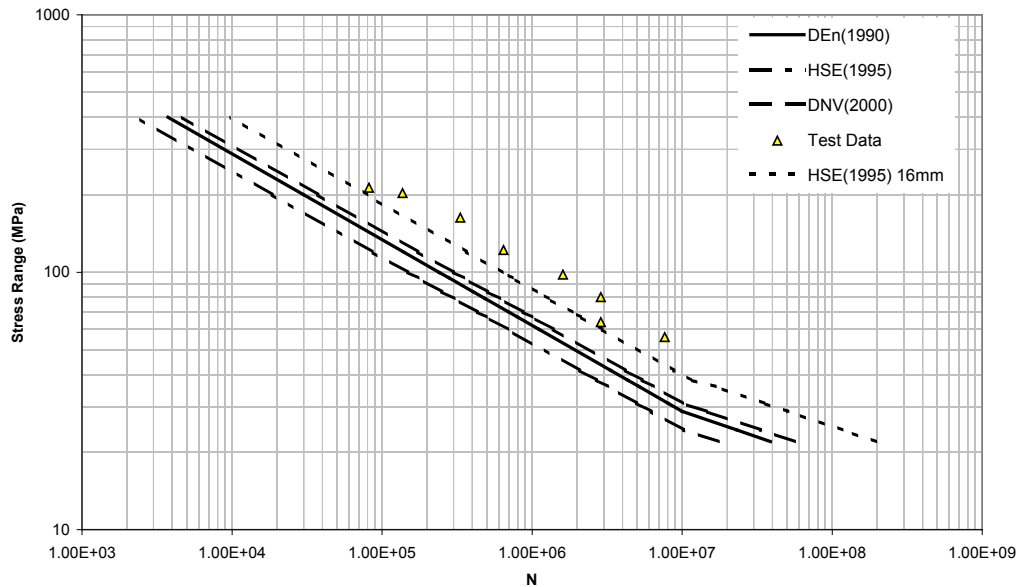


FIGURE 15
F-Curves with Thickness Adjustment and Test Data; 100 mm Plate

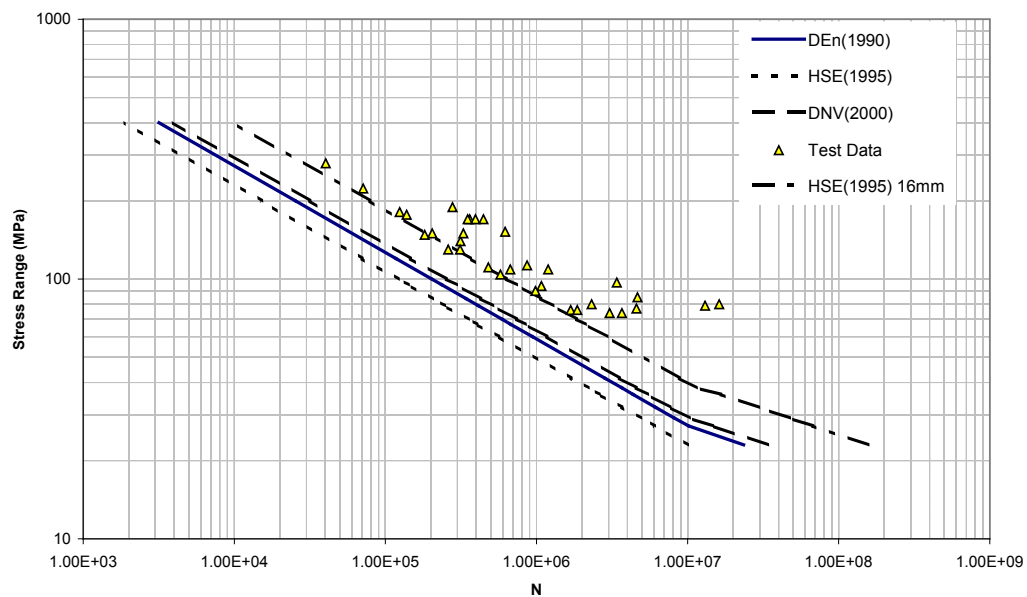


FIGURE 16
F-Curves with Thickness Adjustment and Test Data; 103 mm Plate

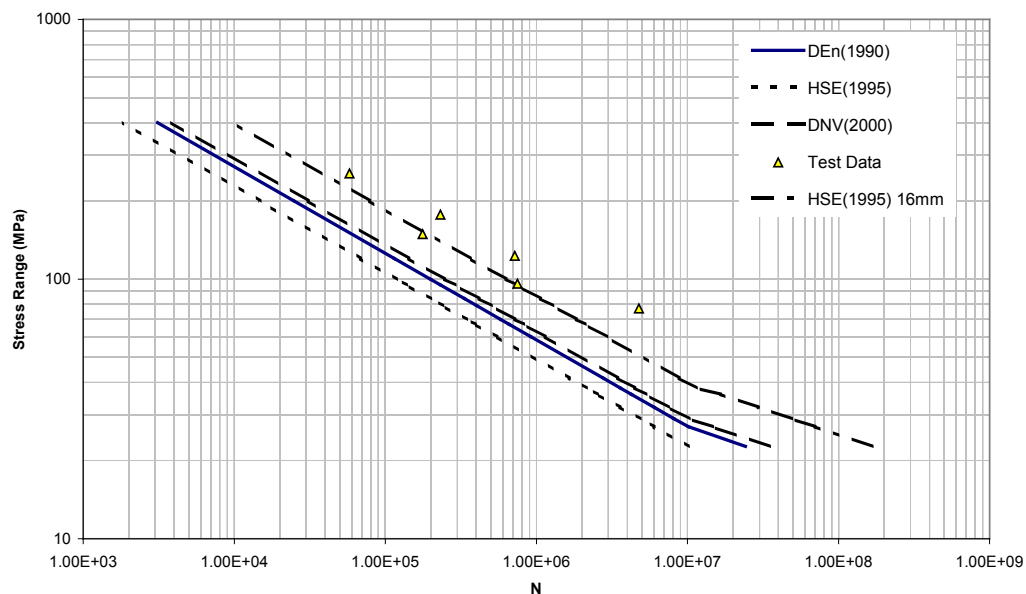


FIGURE 17
F-Curves with Thickness Adjustment and Test Data; 150 mm Plate

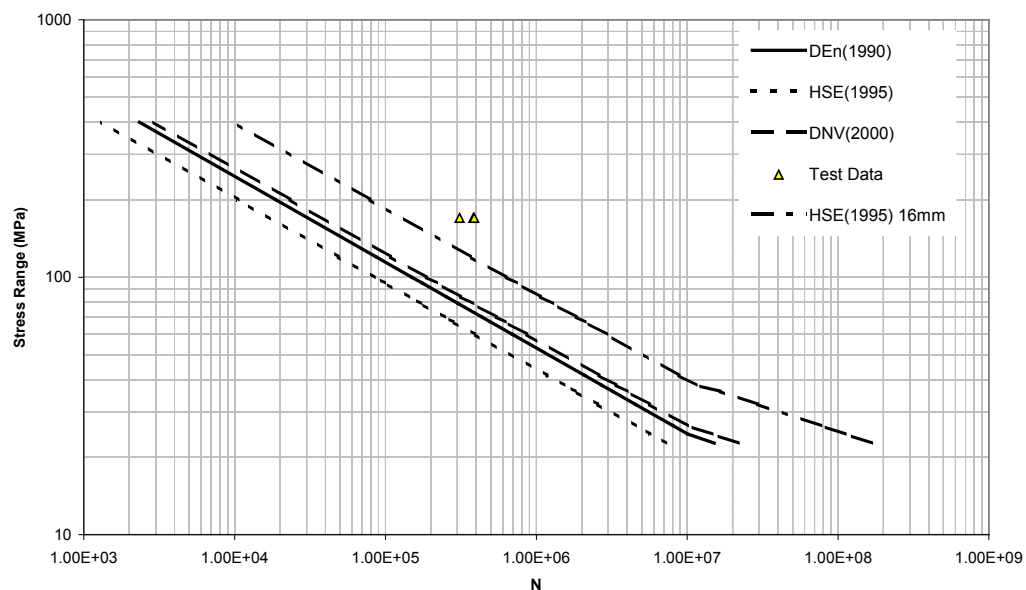


FIGURE 18
F-Curves with Thickness Adjustment and Test Data; 160 mm Plate

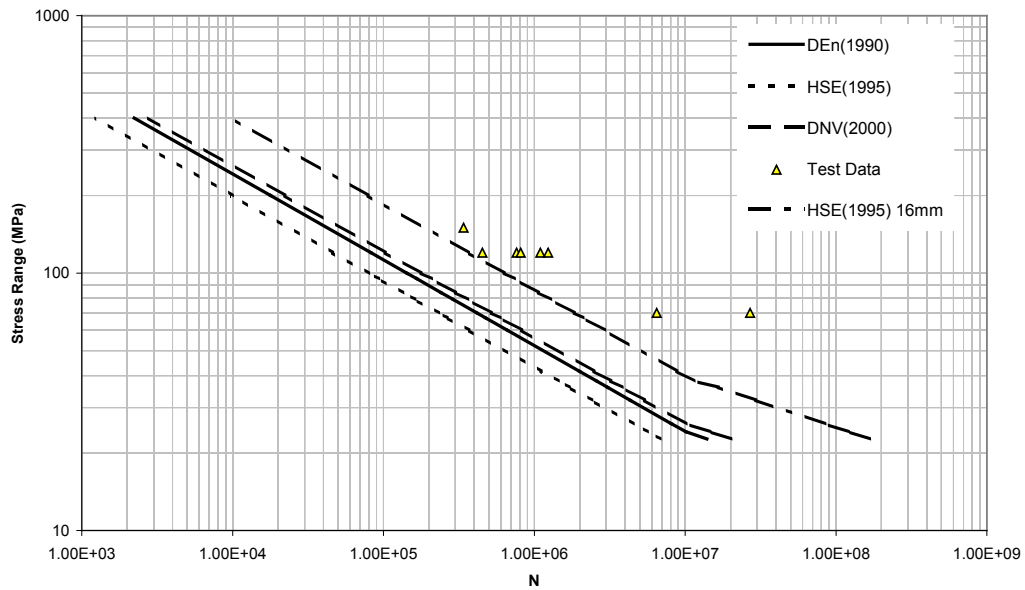


FIGURE 19
F-Curves with Thickness Adjustment and Test Data; 200 mm Plate

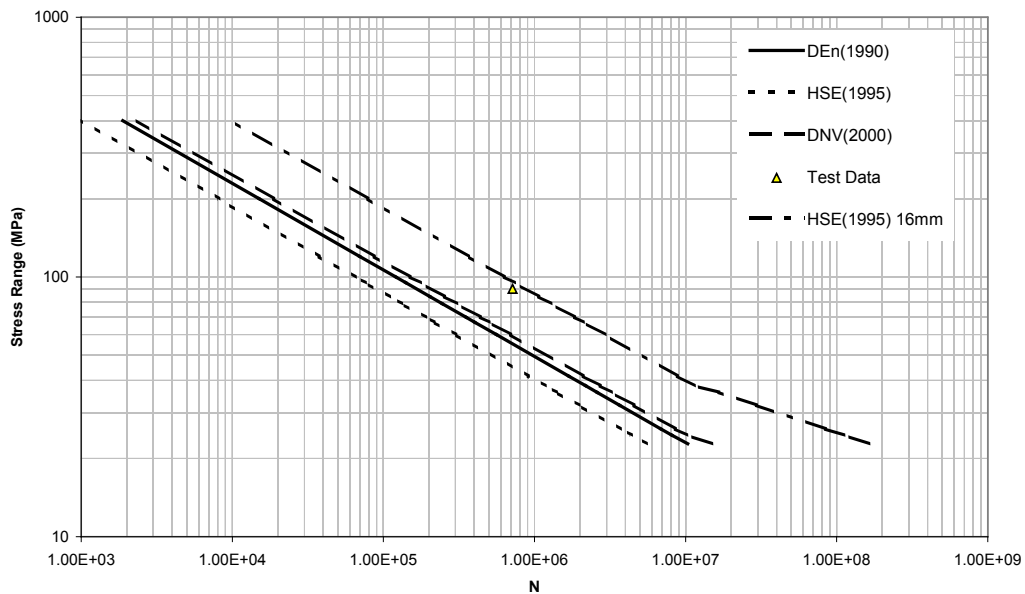


FIGURE 20
Test data with DEn(1990) Thickness Adjustment
and their Regressed S-N Curves (All Thicknesses)

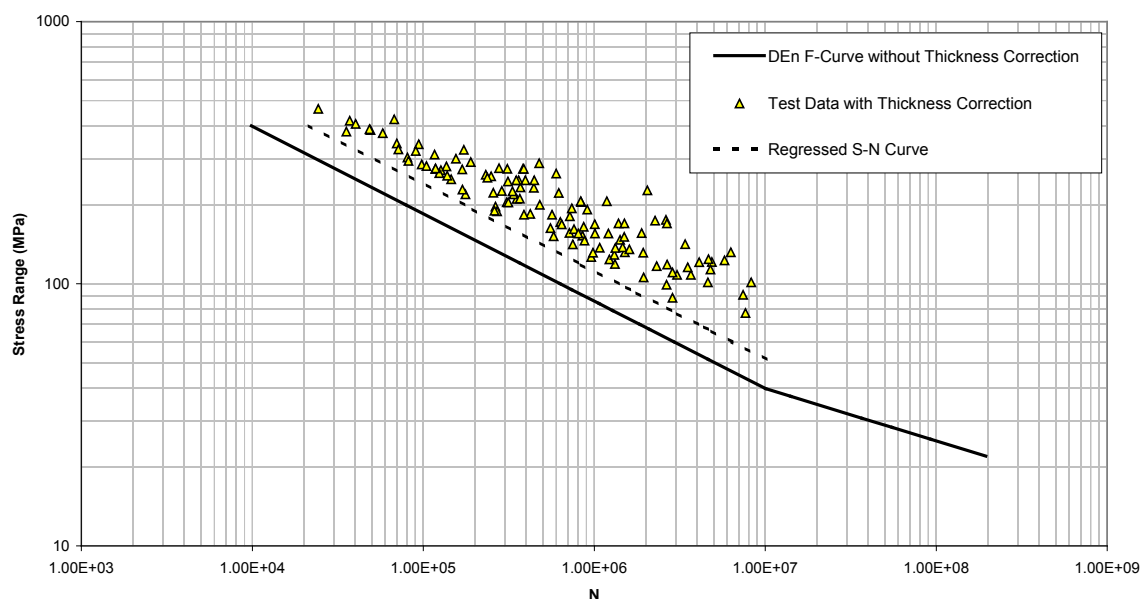


FIGURE 21
Test Data with HSE(1995) Thickness Adjustment
and their Regressed S-N Curves (All Thicknesses)

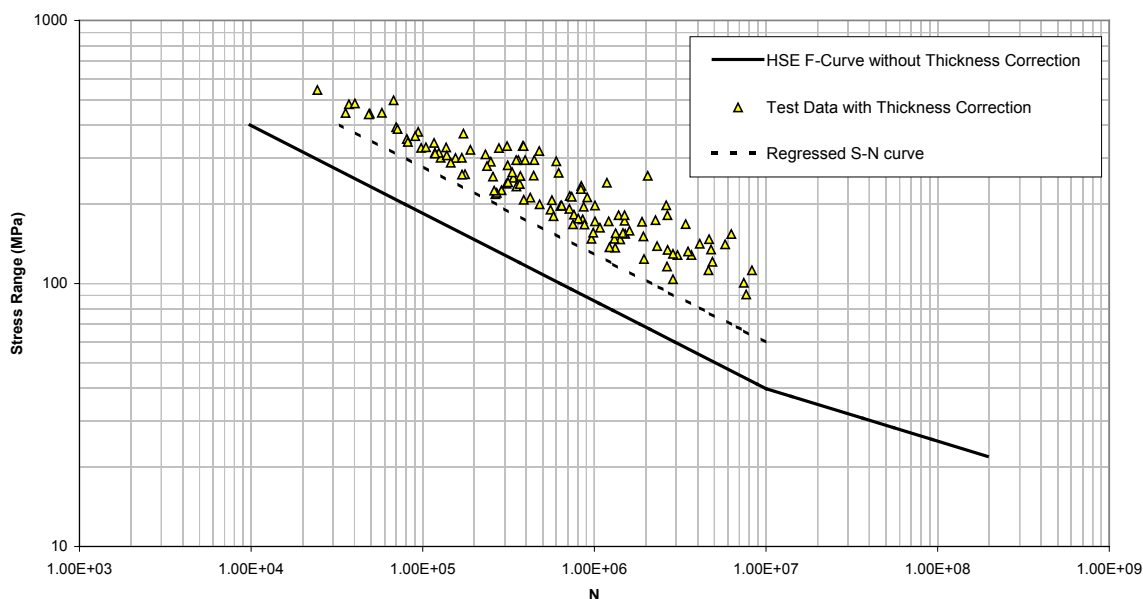


FIGURE 22
Test Data with DNV(2000) Thickness Adjustment
and their Regressed S-N Curves (All Thicknesses)

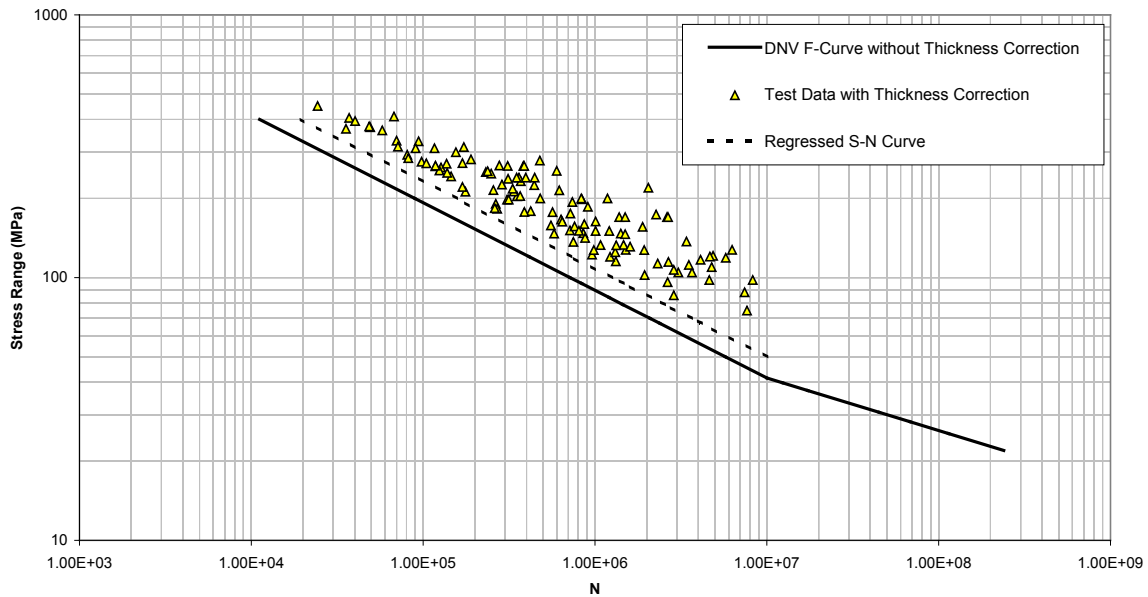
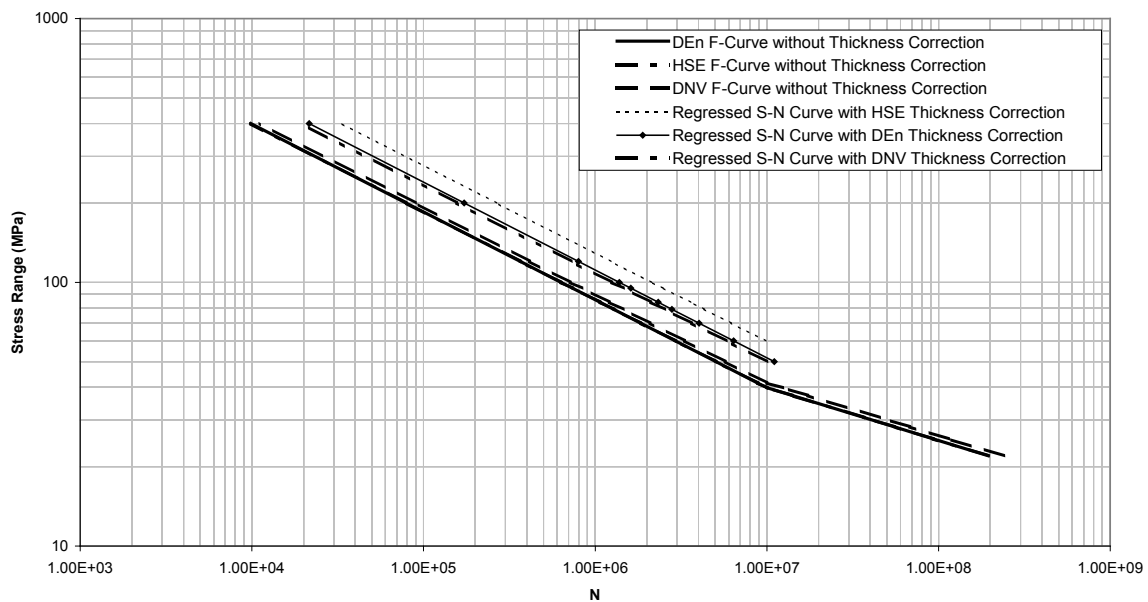


FIGURE 23
Regressed S-N Curves and Design F-curves



7 Effects of Corrosion on Fatigue Strength

7.1 Preliminary Remarks

ABS recommendations for considering the effects of corrosion on fatigue strength are based on a review of corrosion effects published in specifications, guidance and recommended practice documents relating to marine structures. A digest of the corrosion requirements relative to fatigue is presented for each of several documents in 3/7.3, below. There is no particular significance to the ordering of the documents presented.

7.2 A Summary of the Results

A review of the requirements suggests only that fatigue strength is reduced in the presence of free corrosion. One approach is providing separate S-N curves for in-air and free corrosion conditions. Another is to specify a reduction factor on in-air life when operating in a corrosive environment.

It is generally thought that effective cathodic protection restores fatigue strength to in-air values. However, both HSE and DNV specify a reduction of the in-air curves for CP joints exposed to seawater. Moreover, for DNV ship requirements, factors are provided for reduction of in-air S-N curves for those cases where cathodic protection has become ineffective later in life.

Some documents provide no adjustments for corrosive environments.

ABS archives contain results of corrosion studies on marine structures. These results suggest: (1) it is very difficult to characterize corrosion in a general, useful engineering context, and (2) there is enormous statistical variability in corrosion rates.

7.3 The Summaries

API RP2T [API(1997)]

No specific reference to corrosion requirements.

API RP2A [API(2000, 1993)]

- i) For all non-tubular members, refer to ANSI/AWS D1.1-92 (Table 10.2, Figure 10.6). No endurance limit should be considered for those members exposed to corrosion. For submerged members where cathodic protection is present, the endurance limit is set at 2×10^8 cycles.
- ii) The S-N curves are the X and X' curves. These curves assume effective cathodic protection. For splash zone, free corrosion or excessive corrosion conditions, no endurance limit should be considered.

Fatigue Design of Welded Joints and Components [IIW (1996)]

The basic fatigue requirements presented assume corrosion protection. If there is unprotected exposure, the fatigue class should be reduced. The fatigue limit may also be reduced considerably.

Offshore Installations: Guide on Design, Construction, and Certification, [HSE (1995)]

This document defines basic design curves for plates (P curve) and for tubular joints (T' curve). A classification factor is applied to the P curve to account for different joint types. There are three sets of the basic curves: (1) in-air, (2) seawater with corrosion protection, and (3) free corrosion. (3) is lower than (2) and (2) is lower than (1).

The S-N curves are defined in Section 3, Table 6.

TABLE 6
Details of Basic Design S-N Curves HSE(1995)

<i>Class</i>	<i>Environment</i>	<i>Log₁₀A</i>	<i>m</i>	<i>S₀ (N/mm²)</i>	<i>N₀ (cycles)</i>
P	Air	12.182	3	53	10 ⁷
P		15.637*	5**		
P	Seawater (CP)	11.784	3	84	1.026 × 10 ⁶
P	Seawater (CP)	15.637*	5**		
P	Seawater (FC)	11.705	3		
T'	Air	12.476	3	67	10 ⁷
T'		16.127*	5**		
T'	Seawater (CP)	12.175	3	95	1.745 × 10 ⁶
T'	Seawater (CP)	16.127*	5**		
T'	Seawater (FC)	12.000	3		

* Fatigue strength coefficient (*C*; see Section 5, Figure 4) beyond *N₀*

** Fatigue strength exponent (*r*; see Section 5, Figure 4) beyond *N₀*

The parameters of Section 3, Table 6 can be translated into reduction factors to be applied to life in the lower life segment of the in-air S-N curves. These factors are defined in Section 3, Table 7.

TABLE 7
Life Reduction Factors to be Applied to the Lower Cycle Segment of the Design S-N HSE Curves

	<i>Tubular Joints</i>	<i>Plated Joints</i>
Cathodic Protected	2.0	2.5
Free Corrosion	3.0	3.0

ISO CD 19902, International Standards Organization [ISO/CD 19902 (2000)]

This is a draft document.

Basic in-air S-N curves are defined for tubular joints, cast joints and other joints.

Joints with cathodic protection. The basic in-air curves apply for *N* greater than 10⁶ cycles. If significant damage may occur with *N* less than 10⁶ cycles, a factor of 2 reduction on life is recommended.

Free corrosion. A reduction factor of 3 on life is required. There is to be no slope change at 10⁸ cycles.

Note: The editing panel found these statements confusing, so they have requested a re-write.

RP-C203, Fatigue Strength Analysis of Offshore Structures, Det norske Veritas [DNV (2000)]

There are 14 S-N curves, each representing a joint classification. These S-N curves are specified separately for: (1) in-air, (2) seawater with cathodic protection, and (3) seawater with free corrosion.

In-air. The S-N curves have a break at 10⁷ cycles with a slope of *m* = 3 in the low cycle range and *m* = 5 in the high cycle range.

Cathodic protection. The S-N curves in the low cycle range are reduced by the factor of 2.5 on life for both tubular and plated joints. The curves have a break at 10⁶ cycles.

Free Corrosion. The S-N curves in the low cycle range are reduced by the factor of 3.0 on life for both tubular and plated joints (see Section 3, Table 8). There is no break in the curves (i.e., *m* = 3) for all values of *S*.

TABLE 8
Life Reduction Factors to be Applied to the Lower Segment
of the Design S-N DNV Curves

	<i>Tubular Joints</i>	<i>Plated Joints</i>
Cathodic Protected	2.5	2.5
Free Corrosion	3.0	3.0

Eurocode 3 Design of Steel Structures, BSI Standards, 1992 [Eurocode 3, (1992)]

No specific reference to corrosion.

Fatigue Assessment of Ship Structures, Classification Notes No. 30.7, Det norske Veritas, [DNV (1998)]

A factor is specified for reduction of in-air curves for those cases where cathodic protection is effective for only a fraction of the life.

BS 7608 Fatigue Design and Assessment of Steel Structures, British Standards Institute [BS 7608 (1993)]

For unprotected joints exposed to seawater, a factor of safety on life of 2 is required. For steels having a yield strength in excess of 400 MPa, this penalty may not be adequate.

ABS Design Curves; Guide on the Fatigue Assessment of Offshore Structures

The ABS in-air curves for both plated and tubular members are those given in DEn(1990). The basis for this choice is: (1) the history of successful practice, (2) worldwide acceptance, and (3) relatively conservative performance in the high cycle range.

The API (2000) curves are permitted as an alternative for application in the Gulf of Mexico based on the history of successful practice and their mandated use by U.S. Regulatory Bodies.

Adjustment for thickness (see Equations 3.2 and 3.3)

For plated details: $q = 0.25$; $t_R = 22$ mm

For tubular details: $q = 0.25$; $t_R = 32$ mm; This applies for thicknesses greater than 22 mm.

The following adjustments to the in-air curves for corrosion were subsequently recommended by the HSE(1995), these were adopted by ABS.

Tubular Details

- *With CP.* A penalty factor of 2.0 on life applied to the low cycle segment of the in-air S-N curve and no penalty on life applied to the high cycle segment of the in-air S-N curve.
- *Free corrosion.* A penalty factor of 3.0 on life applied to the low cycle segment of the in-air S-N curve and continuation of the obtained curve to the high cycle range.

Plated Details

- *With CP.* A penalty factor of 2.5 on life applied to the low cycle segment of the in-air S-N curve and no penalty on life applied to the high cycle segment of the in-air S-N curve.
- *Free corrosion.* A penalty factor of 3.0 on life applied to the low cycle segment of the in-air S-N curve and extrapolation of the obtained curve to the high cycle range.

The following adjustments to the in-air curves for corrosion are recommended for the API X and X' curves.

Tubular joints

- CP; endurance limit at 2×10^8 cycles.
- FC; no endurance limit.

SECTION 4 Fatigue Design Factors

1 Preliminary Remarks

The purpose of a fatigue design factor is to account for uncertainties in the fatigue assessment and design process. The process includes operations of estimating dynamic response and stresses under environmental conditions. The uncertainties include the following:

- Statistical models used to describe the sea states
- Prediction of the wave-induced loads from sea state data
- Computation of nominal element loads given the wave-induced loads
- Computation of fatigue stresses at the hot spot from nominal member forces
- Application of Miner's rule
- Fatigue strength as seen in the scatter in test data, where a typical coefficient of variation on life is approximately 50-60%.
- Environmental effects on fatigue strength (e.g., corrosion)
- Size effects on fatigue strength
- Manufacturing, assembly and installation operations

In addition to uncertainties, the fatigue design factor should also account for:

- Ease of in-service inspection of a detail
- Consequences of failure (criticality) of a detail

While reliability methods promise the most rational way of managing uncertainty, the concept of a factor of safety on life [referred herein as a *fatigue design factor* (FDF)], maintains universal acceptance.

2 The Safety Check Expression

The safety check expression can be based on damage or life. While the damage approach is featured in the Guide, either approach below can be used and are exactly equivalent.

Refer to Subsection 1/2 for terminology. Subsection 1/5 is repeated here for reference.

Damage.

The design is considered to be safe if:

$$D \leq \Delta \quad \text{..... (1.3)}$$

where

$$\Delta = \frac{1.0}{FDF} \quad \text{..... (1.4)}$$

Life.

The design is considered to be safe if:

$$N_f \geq (FDF) (N_T) \quad \text{..... (1.5)}$$

Fatigue design factors specified in relevant documents are summarized in this Section.