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CERTIFICATION TESTING METHODOLOGY FOR COMPOSITE STRUCTURE

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Volume I—Data Analysis

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This research developed a certification testing methodology for composite structures. The existing composite static strength and fatigue life data are analyzed statistically to determine the influence of test parameters on the scatter of composite data. Guidelines to use the composite data scatter in structural certification are recommended.

Various approaches to composite structures certification are analytically evaluated. The approaches evaluated are: scatter factor approach, load enhancement factor approach, ultimate strength approach and change in spectrum approach. The capability, advantages and disadvantages of each approach to determine the minimum life and/or strength are fully discussed.

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19. Abstract

A methodology for certification testing of composite structures is developed and a detailed description of the methodology is presented. Test data interpretation methodology is also developed. The methodology is demonstrated on existing composite structures.

Based on the results of this investigation, composite structure certification testing procedure and requirements are recommended.

Volume I of this report discusses the scatter analysis methods and results of static strength and fatigue life data analysis. Details of the certification approach evaluation, methodology development and demonstrations are given in Volume II. Volume II also contains the recommended certification testing procedure.

PREFACE

This report was prepared by the Northrop Corporation, Aircraft Division, Hawthorne, California, covering work performed under U.S. Navy Contract N62269-C-0243 between March 1984 and December 1985. The contract was administerd by the Naval Air Development Center, Warminster, Pennsylvania. Mr. Ed Kautz was the Navy Project Engineer. Partial finding of this effort was provided by the Federal Aviation Administration Technical Center, Atlantic City International Airport, NJ. Mr. L. M. Neri acted as the FAA Technical Manager.

The work was performed in the Northrop's Strength and Life Assurance Research Department under the overall supervision of Dr. R. S. Whitehead. The following Northrop personnel were the major contributors to the program.

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	C. Gatewood
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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES

SECTION 1

INTRODUCTION AND BACKGROUND

The application of composite materials to primary aircraft structures requires proven certification procedures to demonstrate their structural integrity. The crux of certification methodology is to demonstrate adequate static and fatigue strength by analysis and test. Application of the metallic certification data base to composite structures is limited by the inherent differences between composites and metals. Composites have a more linear load-strain response, a greater sensitivity to stress concentrations and environments, higher data scatter and a multiplicity of potential failure modes.

Current practice is to carry out an extensive design development test effort to:

1. Establish environmental and scatter knockdown for strength critical failure modes, and
2. Validate critical design features.

These tests are conducted at the coupon, element and subcomponent levels. Following these tests, certification culminates in room temperature ambient full-scale static and fatigue tests. Usually, only one article is available for each test.

In order to have confidence in the certification compliance of full scale tests, it is imperative to be able to quantitatively interpret the test data generated. This is achieved by using the design development data not only in their traditional role in design development but also in the interpretation of full-scale test data.

Current certification practices do not provide an overall testing methodology for the planning and quantitative interpretation of design development and full-scale test data.

The objective of this program is to develop a certification testing methodology for composite aircraft structures.

Specifically, the methodology will account for the effects on strength, life, and the scatter in strength and life of variation in structural configuration and complexity, stress or strain level, mixed composite-metal structure and fatigue spectrum shape. Test requirements and procedures for interpreting test results will be defined for the certification of future composite aircraft structure.

The program is composed of four tasks:

- TASK I - SCATTER ANALYSIS
- TASK II - CERTIFICATION APPROACH DEVELOPMENT/EVALUATION
- TASK III - METHODOLOGY DEVELOPMENT
- TASK IV - METHODOLOGY DEMONSTRATION

During Task I, existing composite static strength and fatigue life data are analyzed statistically to determine the influence of different test parameters on the scatter of composite data. The test variables included are: laminate lay-up, specimen type, loading mode, failure mode and test environment for both the static and fatigue data; in addition, stress level, stress ratio, spectrum variation and spectrum shape are investigated for fatigue data. The effects of each variable on static strength and fatigue life data scatter are established by performing statistical tests of significance. As a result of this task, guidelines to use the composite data scatter in structural certification are recommended and these guidelines are applied in the subsequent tasks of the program.

In Task II, various approaches to composite structure certification are analytically evaluated. The approaches evaluated are:

1. Scatter factor approach
2. Load enhancement factor approach
3. Ultimate strength approach
4. Change in spectrum approach

The capability, advantages, disadvantages of each approach to determine minimum (B-Basis) and mean life and/or strength are fully evaluated. Effects of these approaches on the certification procedure of composite-metal mixed structure are also investigated. The conclusions of this evaluation are then used in the methodology development.

A methodology for certification testing of composite structures is developed in Task III. The methodology is based on the results of the evaluation in Task II and the scatter analysis in Task I. The number and types of tests required at each level (coupon, element, subcomponent, component, and full-scale) of testing are defined. Test data interpretation methodology is also developed. As part of this task, a detailed description of the developed methodology is presented. This description includes detailed instructions for application and utilization of the methodology within the overall developmental process to satisfy design service life requirements for aircraft utilizing composite structures. The description also includes application of the methodology in an aircraft design/development program and determine the effects on service life resulting from usage change of an aircraft after its introduction into the fleet.

In Task IV, the methodology is demonstrated on an existing composite structure. The full-scale wing and fuselage components from the Composite Wing/Fuselage Program (Reference 1) are selected for this demonstration purpose. The results of the tests that have been performed on these demonstration articles are reevaluated using the methodology developed in Task III.

The scatter analysis methods and results of static strength and fatigue life data analysis are discussed in Volume I. Details of Task II - Certification Approach Development/Evaluation, Task III - Methodology Development and Task IV - Methodology Demonstration are given in Volume II. Recommendations and certification testing requirements are also documented in Volume II. Computer programs to evaluate structure reliability are appended to Volume II.

SECTION 2

SCATTER ANALYSIS METHODS

During the last two decades, the Navy and Air Force have generated a large amount of static and fatigue data on composites. These data have indicated that composites exhibit higher data scatter than their metallic counterparts in both static strength and fatigue life. In order to interpret this composite test data base in a meaningful manner and fully exploit its implications for future aircraft structure design and certification, it is necessary to use statistical methods of analysis. The analysis methods are discussed in the following paragraphs. The results of static strength data analysis are given in Section 3 and the results of fatigue life data analysis are presented in Section 4.

2.1 Two-Parameter Weibull Distribution

Several probabilistic distributions have been used in the past to describe the distribution of static strength, fatigue life and residual strength data of composites. Among these distributions, the three most commonly used have been:

1. The normal,
2. The log-normal distributions, and
3. The two- or three-parameter Weibull.

The two-parameter Weibull distribution is selected for data interpretation in this program for the following reasons:

1. The distribution is expressed in a simple functional form and easy to apply.
2. The distribution describes composite static and fatigue test data well and has been widely accepted for composite statistical data analysis.
3. Standard tables and computing routines are available.

4. Data can be interpreted on a sound physical basis, so that A-Basis and B-Basis allowables determined for static strength are more reliable.

5. Censoring techniques and pooling techniques are fully developed and verified.

6. Hypothesis testing methods for statistical significance are available and verified.

The two-parameter Weibull distribution is given by the probability density function:

$$D(x;\, \alpha, \beta) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha - 1} e^{-(x/\beta)^{\alpha}} \qquad (1)$$

or by the cumulative survival probability function

$$p(X \leqslant x) = e^{-(x/\beta)^{\alpha}} \qquad (2)$$

where

x is the random variable,

α is the shape parameter,

β is the scale parameter.

The mean and standard deviation of a Weibull population can be expressed in terms of α and β as

$$\mu = \beta\ \Gamma\left(\frac{\alpha+1}{\alpha}\right) \qquad (3)$$

and

$$\sigma = \beta \sqrt{\Gamma\left(\frac{\alpha+2}{\alpha}\right) - \Gamma^2\left(\frac{\alpha+1}{\alpha}\right)} \qquad (4)$$

where

μ is the population mean,

σ is the population standard deviation

Γ is the Gamma function.

For a given set of data, the shape and scale parameters of the Weibull distribution must be estimated. Some of the techniques used for determining these estimators are:

1. The maximum likelihood method,
2. Moments method, and
3. Least squares method.

The maximum likelihood method (MLE) was selected to estimate the parameters, because it is derived directly from the maximum likelihood functions and does not require any biased data fitting and, therefore, unique values of α and β can be obtained. The MLE method involves the solution of two algebraic equations given by

$$\frac{1}{\hat{\alpha}} = \frac{\sum_{i=1}^{n} x_i^{\hat{\alpha}} \ln x_i}{\sum_{i=1}^{n} x_i^{\hat{\alpha}}} - \frac{\sum_{i=1}^{n_f} \ln x_i}{n_f} \tag{5}$$

and

$$\hat{\beta} = \left(\frac{1}{n_f} \sum_{i=1}^{n} x_i^{\hat{\alpha}} \right)^{1/\hat{\alpha}} \tag{6}$$

where x_i is the data value

n is the total number of data points

n_f is the total number of failures

and $\hat{\alpha}$ and $\hat{\beta}$ are the estimators.

Equations (5) and (6) are applicable to both complete ($n_f = n$) and censored ($n_f < n$) samples. The value of $\hat{\alpha}$ is determined by solving Equation (5) using an iteration scheme and $\hat{\beta}$ is obtained from Equation (6).

In order to determine the allowable statistics, an interval estimate of the parameters must be first carried out. For a Weibull distribution with known shape parameter, it has been shown (Reference 2) that the scale parameters of random samples form a chi-square (χ^2) distribution. The γ level of confidence for the scale parameter ($\check{\beta}$) is then given by

$$\check{\beta}_\gamma = \frac{\hat{\beta}}{\left[\chi^2_{1-\gamma}(2n)/(2n)\right]^{1/\hat{\alpha}}} \tag{7}$$

where $\chi^2_{1-\gamma}(2n)$ is the value of chi-square function with 2n degree-of-freedom at $1-\gamma$ probability. The allowable statistics (N) can now be determined as

$$\check{N} = \check{\beta}\,(-\ln p)^{1/\hat{\alpha}} \tag{8}$$

or

$$\check{N} = \hat{\beta}\left[\frac{-\ln p}{\chi^2_{1-\gamma}(2n)/2n}\right]^{1/\hat{\alpha}} \tag{9}$$

where

p is the desired probability of survival,

$p = 0.90$ and $\gamma = 0.95$ for B-basis and

$p = 0.99$ and $\gamma = 0.95$ for A-basis.

A typical probability plot of the Weibull distribution of static composite strength is shown in Figure 1, which also shows the 0.95 confidence interval of β and the B-basis allowable.

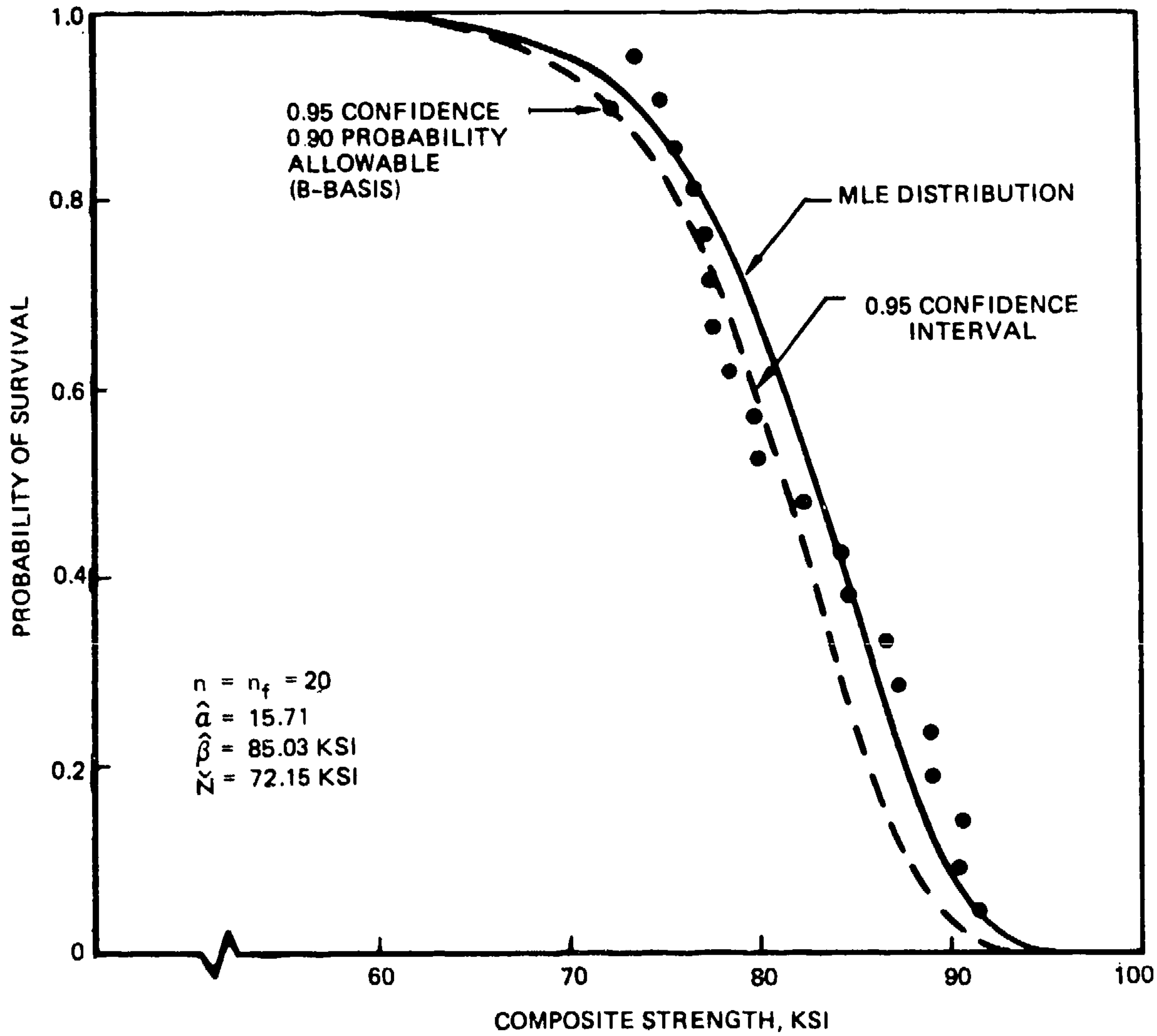

FIGURE 1. TYPICAL WEIBULL DISTRIBUTION OF COMPOSITE STRENGTH.

In addition to the above statistics, a scatter factor is defined as the ratio of the mean and allowable ($\mu/\check{N}$). Such a factor signifies the relation between the central tendency of a data set (the mean) and the extreme statistics (the allowable). The value of this factor depends upon the shape parameter (α) and the sample size (n). A typical plot of $\mu/\check{N}$ as a function of α for a sample size of five is shown in Figure 2.

A computer program has been written to compute the scale and shape parameters and the B-Basis allowables. The program listing as well as the input and output descriptions are given in the Appendix of Volume II.

2.2 Data Pooling Techniques

The two-parameter Weibull distributions, discussed in the previous subsection, is selected as the basic analytical tool for scatter analysis. The application of Weibull distribution to determine the allowable statistics with adequate confidence requires a sufficiently large number of test data point for each individual test condition. However, in most of the published composite research and development programs, fatigue data were generated at three or four stress levels with approximately three specimens tested at each stress level. These type of data are not adequate to determine the fatigue lifetime scatter at each stress level using the individual Weibull analysis. Therefore, in addition to the basic two-parameter Weibull analysis, two pooling techniques were selected for fatigue data scatter analysis in order to include this type of data in the scatter analysis data base. The objective of both techniques is to analyze the fatigue data obtained at all stress levels as one data set. This provides an adequate number of data points for an accurate statistical analysis.

The two pooling techniques selected were the Joint Weibull analysis and the Sendeckyj equivalent strength model (Reference 3).

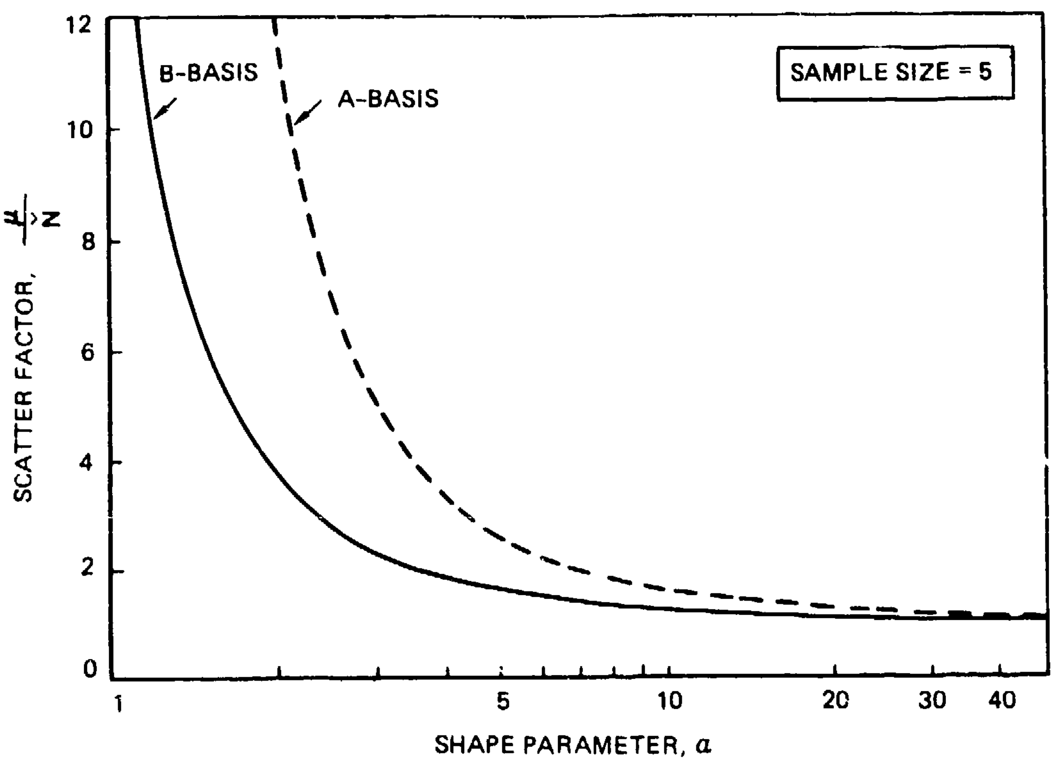

FIGURE 2. RELATIONSHIP BETWEEN SHAPE PARAMETER AND SCATTER FACTOR.

2.2.1 Joint Weibull Analysis

In the Joint Weibull analysis, M groups of data having a common shape parameter (α) but different scale parameters (β) are pooled. Application of this pooling technique to composite fatigue life data analysis makes the assumption that the individual α value is independent of the fatigue stress level. This assumption has been justified by the results of the individual Weibull analysis of fatigue data in Reference 4. A typical result is shown in Figure 3, which indicates that no definite relation exists between the Weibull shape parameter (α) and the normalized fatigue stress level, P_F/P_S.

The shape (α) and scale (β) parameters of the Joint Weibull distribution are obtained by the joint maximum likelihood estimate method. This analysis is similar to that used for the basic two-parameter Weibull analysis which was discussed in Section 2.1. However, the joint maximum likelihood estimate is applied to M groups of data (e.g., fatigue stress levels) by assuming their shape parameters are not significantly different. The estimators are obtained by solving the equations:

$$\sum_{i=1}^{M} \left[\frac{\sum_{j=1}^{n_i} x_{ij}^{\hat{\alpha}} \ln x_{ij}}{\sum_{j=1}^{n_i} x_{ij}^{\hat{\alpha}}} \right] - \frac{M}{\hat{\alpha}} - \left[\sum_{i=1}^{M} \frac{\sum_{j=1}^{n_{fi}} \ln x_{ij}}{n_{fi}} \right] = 0 \tag{10}$$

and

$$\hat{\beta}_i = \left[\frac{1}{n_{fi}} \sum_{j=1}^{n_i} x_{ij}^{\hat{\alpha}} \right]^{1/\hat{\alpha}} \tag{11}$$

where

n_i (i=1,2...,M) is the number of data points in the i^{th} group of data,

n_{fi}(i=1,2...,M) is the number of failures in the i^{th} group of data.

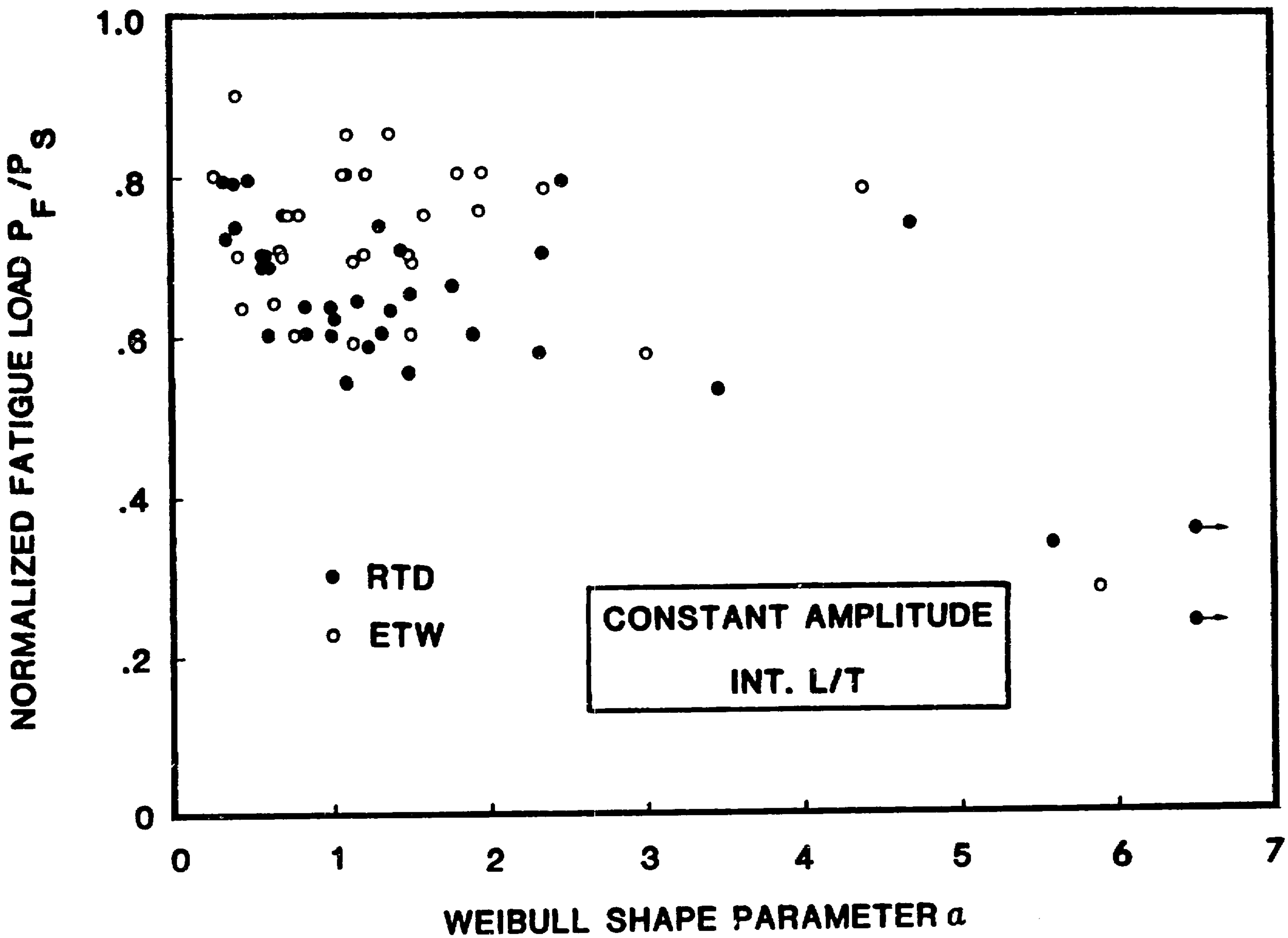

FIGURE 3. EFFECT OF NORMALIZED FATIGUE LOAD LEVEL ON CONSTANT AMPLITUDE FATIGUE LIFE WEIBULL SHAPE PARAMETER (NAVY DATA).

The pooled shape parameter (α_p) is determined from Equation (10) by iteration. The scale parameter (β) for each group (at each stress level) is then directly computed from Equation (11). The mean and the B- and A-Basis allowables are determined for each individual group by using Equations (3) and (9). The standard deviation and scatter factor are constant for all groups. The standard deviation is computed by using Equation (4).

2.2.2 Sendeckyj Equivalent Strength Model

The second pooling technique selected was the Sendeckyj equivalent strength model, which is presented in detail in References 3, 5 and 6. The basic Sendeckyj model (Reference 3) uses two fitting parameters to analyze pooled static strength, fatigue life and residual static strength data. All three types of data are converted to equivalent static strengths (α_e) through a wear-out equation and a fatigue power law. The equivalent static strength is then fitted to the two-parameter Weibull distribution.

Recently, Sendeckyj (References 5 and 6) has extended the two parameter model to include the R-ratio effect in fatigue data scatter analysis. Essentially, through the addition of a third parameter in the wear-out equation, fatigue data obtained from several R-ratios can be collapsed onto one stress-life plot. Thus, an overall scatter parameter can be obtained which includes the R-ratio effect. However, the application of the three parameter model is limited to analyze fatigue data with positive R-ratio. Therefore, only the basic two-parameter model is used in the present program.

The wear-out equations used in the basic Sendeckyj model is given by

$$\sigma_e = \sigma_a \left[(\sigma_r/\sigma_a)^{1/S} + (N - 1)\ C \right]^S \tag{12}$$

where

α_e is the equivalent static strength,

σ_a is the maximum applied cyclic stress,

σ_r is the residual strength

N is the number of fatigue cycles

S and C are fitting parameters

The fatigue power law is obtained from the wear-out equation by setting $\sigma_a = \sigma_r$, thus

$$\sigma_a (1 - C + CN)^S = \sigma_u \tag{13}$$

where σ_u is the static strength.

The basic Sendeckyj analysis calculates the scatter in equivalent static strength (not fatigue life). Through proper transformation of the probability function, it can be shown (Reference 3) that at each individual stress level, the fatigue life distribution (α_L) is also a Weibull distribution with a shape parameter

$$\alpha_L \approx S\alpha_e \tag{14}$$

where α_e is the Weibull shape parameter of the equivalent strength population and α_L is the shape parameter of the fatigue life distribution.

Figure 4 shows an example comparing the B-basis life determined from the individual Weibull analysis, pooled Weibull analysis and Sendeckyj analysis. For the individual Weibull analysis, the ratio of B-basis life to mean Weibull life is different for each stress level. The Joint Weibull analysis produces a constant ratio of B-basis life to mean Weibull life for all stress levels. The Sendeckyj analysis calculates the ratio of B-basis equivalent static strength to mean Weibull equivalent static strength, which then translates into a constant ratio of the B-basis stress life curve to the mean Weibull stress

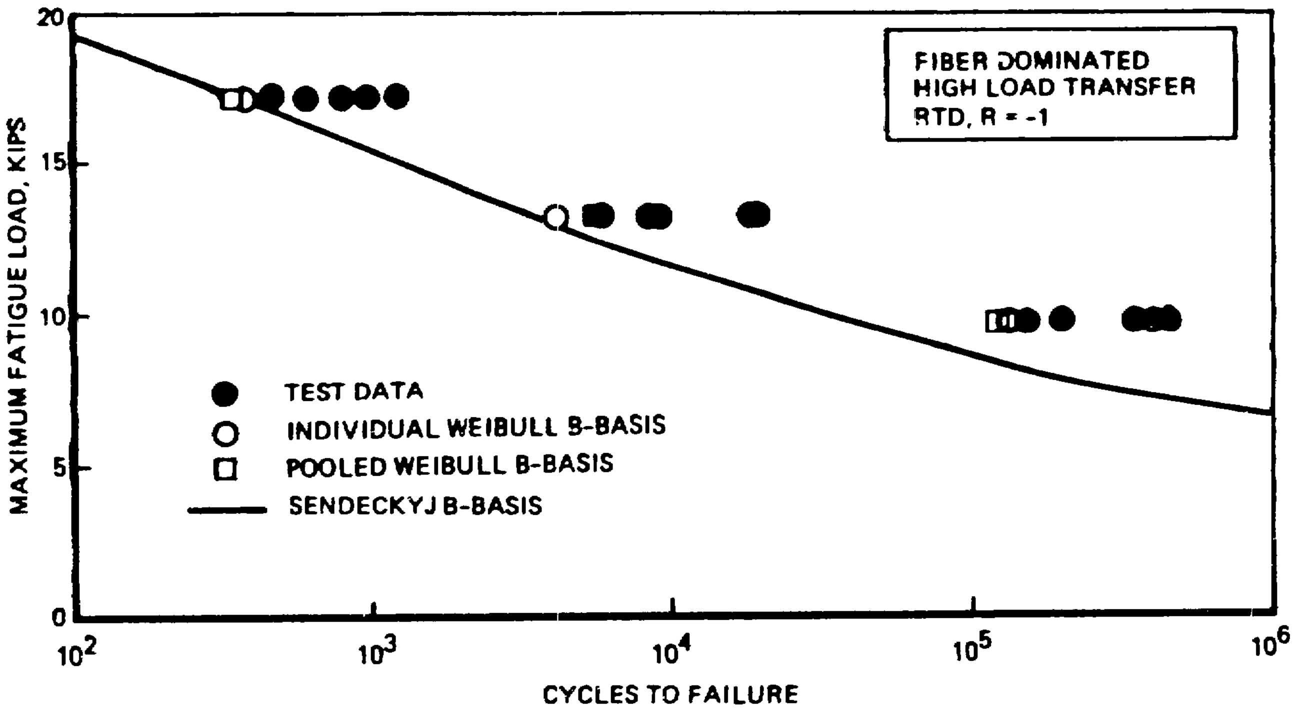

FIGURE 4. COMPARISON OF FATIGUE DATA SCATTER ANALYSIS METHODS.

life curve. Specific advantage of the Sendeckyj analysis is that, through its assumption of the mathematical form of the wear-out equation, it provides a mathematical function for the B-basis stress life curve. The data analysis example in Figure 4 shows B-basis life calculations. It should be noted that any statistical quantity (e.g., A-basis) can be calculated by the three analysis methods.

2.3 Statistical Significance Tests

The procedures for comparing two Weibull distributions have been discussed in Reference 7 through 11. Standard tables for statistical hypothesis testing of significance were generated in these references. In this program, the Weibull parameters determined for each test condition was statistically tested for their significance. In this manner, the significance of the effects of each test parameter on data scatter was defined and an allowable factor will be established for each test condition. The factors obtained can then be used with confidence for test data interpretation.

The equality of both the shape parameter and scale parameter for two Weibull distributions was tested. For the shape parameter, the null hypothesis to be tested is

$$H_o : \alpha_1 = \alpha_2 \tag{14}$$

against the alternative hypothesis

$$H_a : \alpha_1 \neq \alpha_2 \tag{15}$$

where α_1 and α_2 are the shape parameters of the two Weibull populations being compared.

At a level of significance γ, the null hypothesis H_o is rejected (i.e., the difference in a is significant) if

$$w = \frac{\hat{\alpha}_{max}}{\hat{\alpha}_{min}} \geqslant \ell_\gamma \tag{16}$$

where ℓ_γ depends on the significance level γ and the sample size. Values of ℓ_γ are given in Reference 8 in tabulated form. These values are used in the program for the test of equality of the Weibull shape parameters.

The test of equality of Weibull scale parameters is similar to that of the shape parameters. The null hypothesis

$$H_o : \beta_1 = \beta_2 \tag{17}$$

is tested against the alternative hypothesis

$$H_a : \beta_1 \neq \beta_2 \tag{18}$$

The null hypothesis H_o is rejected at a level of significance, , if

$$u = \frac{\hat{\beta}_{max}}{\hat{\beta}_{min}} > g\ (t_\gamma) \tag{19}$$

where t_γ depends on the significance level, γ , and the sample size. Values of t_γ are also available in Reference 8. The function $g(t_\gamma)$ is a function of the average shape parameter $\bar{a}$ and t_γ and is given by

$$g\ (t_\gamma) = \exp\ (t_\gamma / \bar{a}\ ) \tag{20}$$

where

$$\bar{a} = (\hat{a}_1 + \hat{a}_2)/2.0$$

The hypothesis testing procedures described above is applied to compare the scatters of static and fatigue data. A significance level of $\gamma = 0.95$ has been selected for these tests.

SECTION 3

STATIC DATA ANALYSIS

An extensive composite static strength data base exists in the literature. From this data base, the data in References 4 and 12 through 15 have been selected to determine static strength data scatter. Data source selection was based on two criteria: first, a minimum number of six data points per data set is required to permit accurate statistical analysis. Second, that the data cover a wide range of test variables such as loading mode, load transfer, laminate layup, specimen type and test environment. The data from References 4 and 12 through 15 yielded 71 separate data sets, which contained approximately 1500 data point.

The analysis is conducted in three phases. First, the static test data from Reference 4 ("Navy" data) are analyzed in detail. Second, the extensive static test data in References 12 through 15 ("Baseline" data) are analyzed. Third, the Navy and Baseline data sets are pooled to form a "Combined" data set for overall statistical analysis. The results of these analyses are presented in the following paragraphs.

3.1 Navy Data

The Navy static test data in Reference 4 represent a large variety of test variables, which are summarized in Table 1. For increased accuracy in the statistical analysis, only data sets containing six or more data points were used. This excluded the complex test specimen data from the overall analysis, because it was based on three replications. Table 2 and Figures 5 through 8 present the results of the statistical analysis in terms of four variables: loading mode, test environment, specimen geometry and laminate lay-up.

Figure 5 shows that, for all test data, tension loading tests data have a higher Weibull shape parameter, α , (less scatter) than compression test data. However, Figure 5 also shows

TABLE 1. SUMMARY OF TEST VARIABLES FOR NAVY DATA IN REFERENCE 4.

SPECIMEN CONFIGURATION	LAY-UP	LOADING MODE	ENVIRONMENT
NO LOAD TRANSFER	(16/80/4)	TENSION	RTD
INTERMEDIATE LOAD TRANSFER	(25/67/8)	COMPRESSION	ETW
HIGH LOAD TRANSFER	(48/48/4)		
COMPLEX			

TABLE 2. SUMMARY OF STATISTICAL ANALYSIS OF NAVY STATIC TEST DATA

LOADING MODE	ENVIRONMENT	SPECIMEN TYPE	LAY-UP	NUMBER OF DATA SETS	MEAN SHAPE PARAMETER α	VARIABILITY OF α C.V. %
TENSION	RTD	ALL	ALL	7	36.3	50.4
TENSION	ETW	ALL	ALL	6	22.2	48.5
TENSION	ALL	ALL	ALL	13	29.9	64.9
COMPRESSION	RTD	ALL	ALL	8	23.7	32.9
COMPRESSION	ETW	ALL	ALL	8	22.2	46.9
COMPRESSION	ALL	ALL	ALL	16	22.9	40.0
ALL	RTD	ALL	ALL	15	29.5	50.3
ALL	ETW	ALL	ALL	14	22.1	47.6
ALL	ALL	NO L/T	ALL	9	28.5	62.1
ALL	ALL	INT. L/T	ALL	10	23.3	54.2
ALL	ALL	HIGH L/T	ALL	10	26.3	29.5
ALL	ALL	ALL	(48/48/4)	12	21.3	50.1
ALL	ALL	ALL	(25/67/4)	5	30.7	21.8
ALL	ALL	ALL	(16/80/4)	12	28.9	55.4
AL	ALL	ALL	ALL	29	26.1	51.7

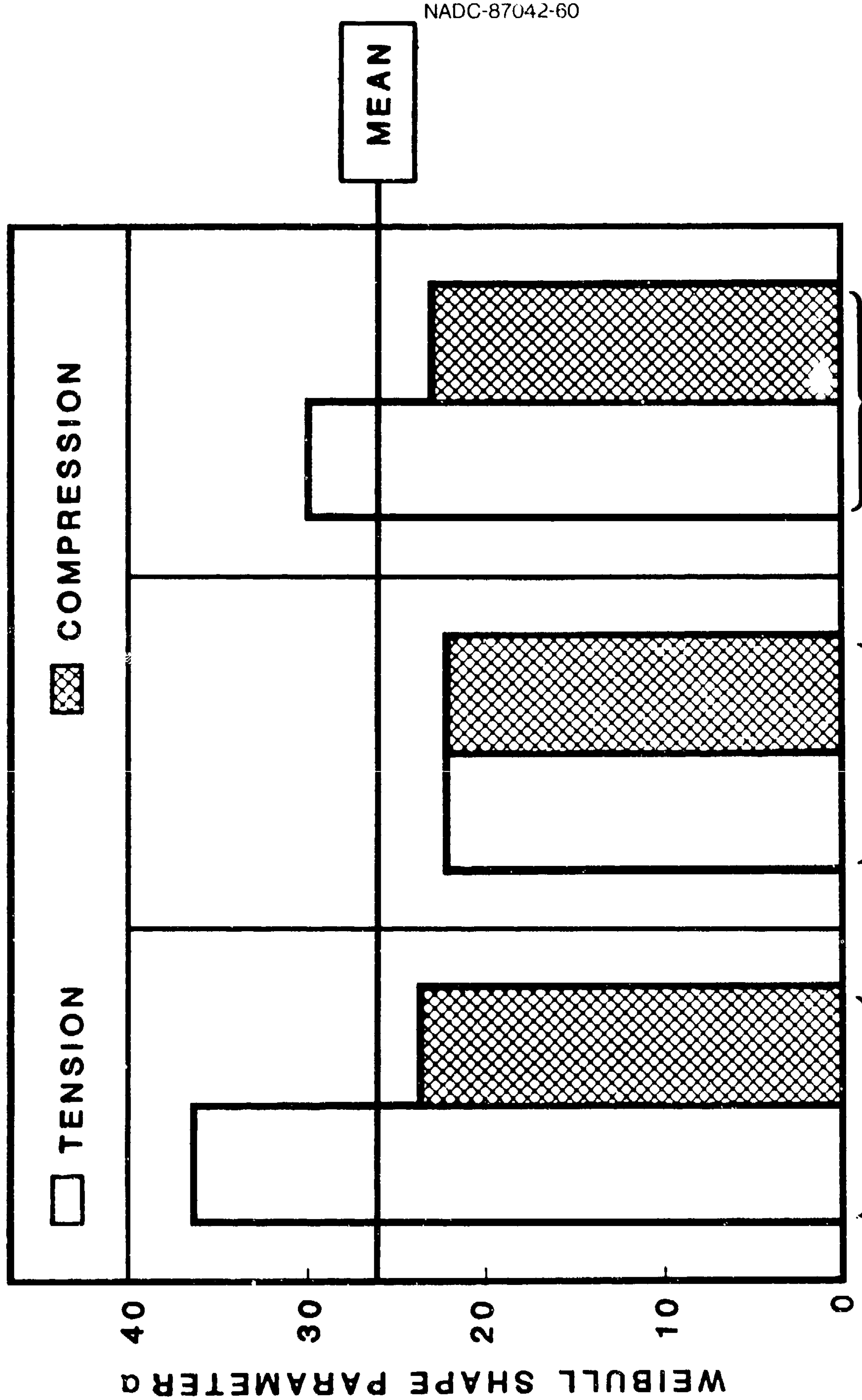

FIGURE 5. INFLUENCE OF LOADING MODE ON STATIC STRENGTH VARIABILITY OF NAVY TEST DATA.

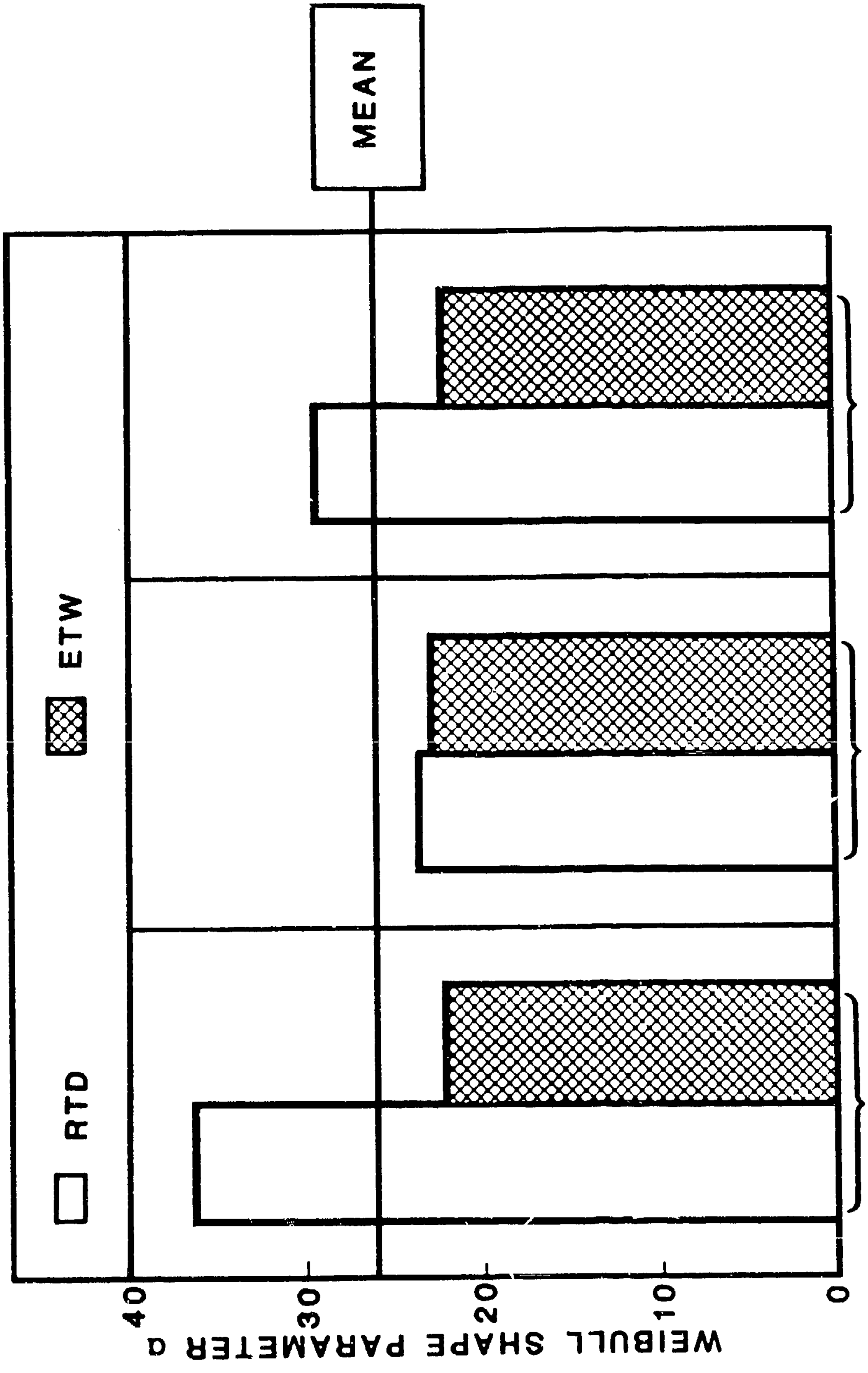

FIGURE 6. INFLUENCE OF ENVIRONMENT ON STATIC STRENGTH VARIABILITY OF NAVY TEST DATA.

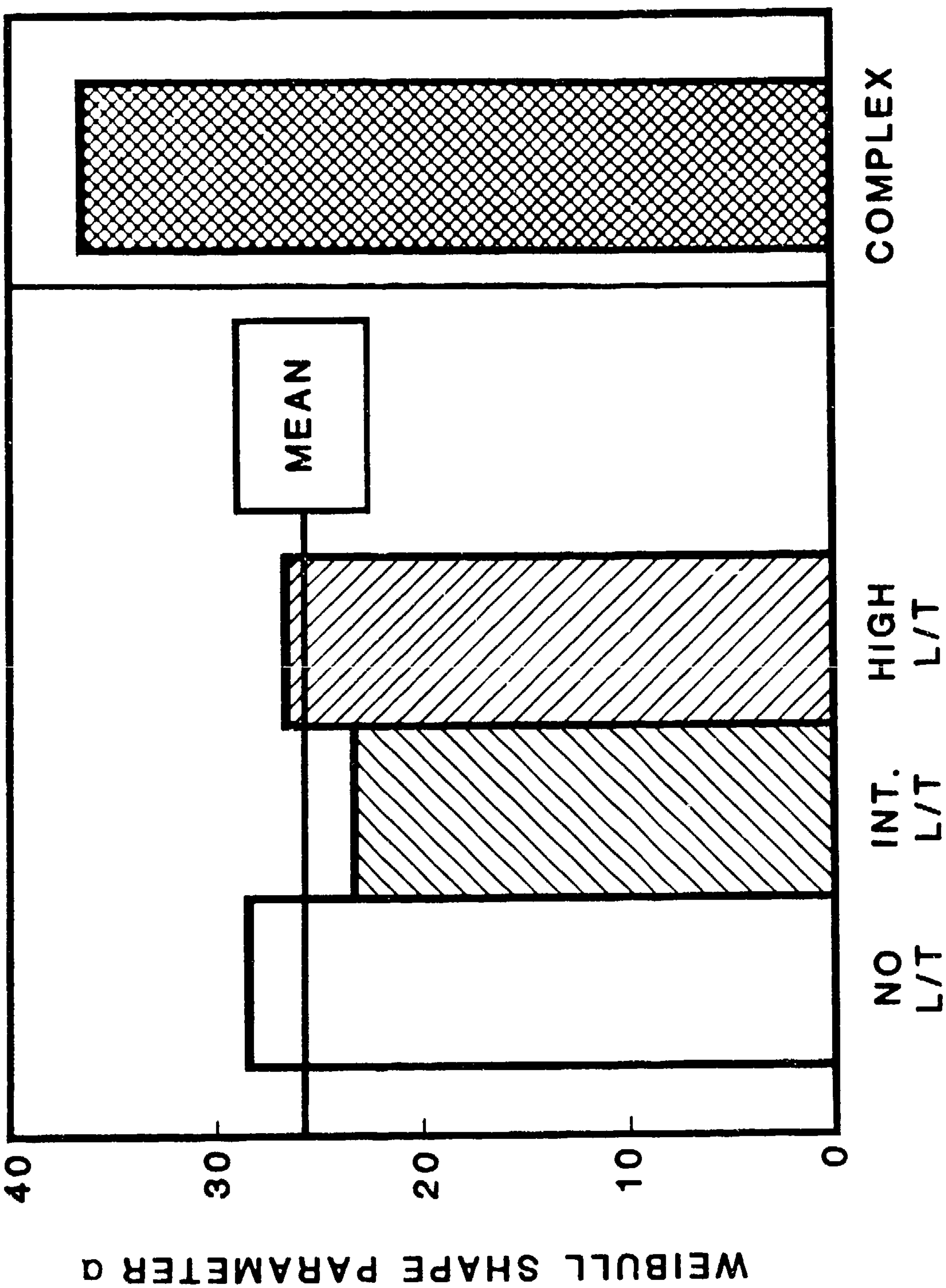

FIGURE 7. INFLUENCE OF SPECIMEN GEOMETRY ON STATIC STRENGTH VARIABILITY OF NAVY TEST DATA.

that this effect is most pronounced under RTD test conditions. Figure 6 shows that, for all test data, the RTD data have a higher α (lower scatter) than the ETW data. However, Figure 6 also shows that this effect is again most pronounced under tension loading. Figure 7 shows that the no-load transfer, intermediate load transfer and high load transfer specimens exhibit similar scatter. Although the complex specimen test data were not included in the overall analysis, data are shown in Figure 7 for comparative purposes. It can be seen that the complex specimen exhibits the lowest scatter of the four specimen configurations. Figure 8 shows that the (48/48/4) lay-up test data have a lower α (higher scatter) than the other two lay-ups.

Statistical significance checks are conducted to determine if the trends in α observed in Figure 5 through 8 were significant at the 95-percent significance level. Statistical significance tests were conducted on both the Weibull shape parameter, α, and the scatter in α (as measured by coefficient of variation) for each data set. The results of these significance checks are presented in Tables 3 through 6.

The significance tests on α show that no significant difference exists between the α values for any of the test variables. Thus, the trends in Figures 5 through 8 discussed above cannot be substantiated statistically. The reasons for this are twofold. First, the number of data points in most of the data sets is relatively small and, second, large variability in values (C.V.'s = 21% to 62%) is observed in each data set. Since no significant difference exists between the α values, the data base can be treated as one data set. The overall distribution of the Weibull shape parameters for all 29 Navy static data sets is shown in Figure 9. A Weibull analysis is performed on these α's. The following values of α are determined:

Mean	$\alpha =$	26.1
Modal	$\alpha =$	18.0
B-Basis	$\alpha =$	8.4

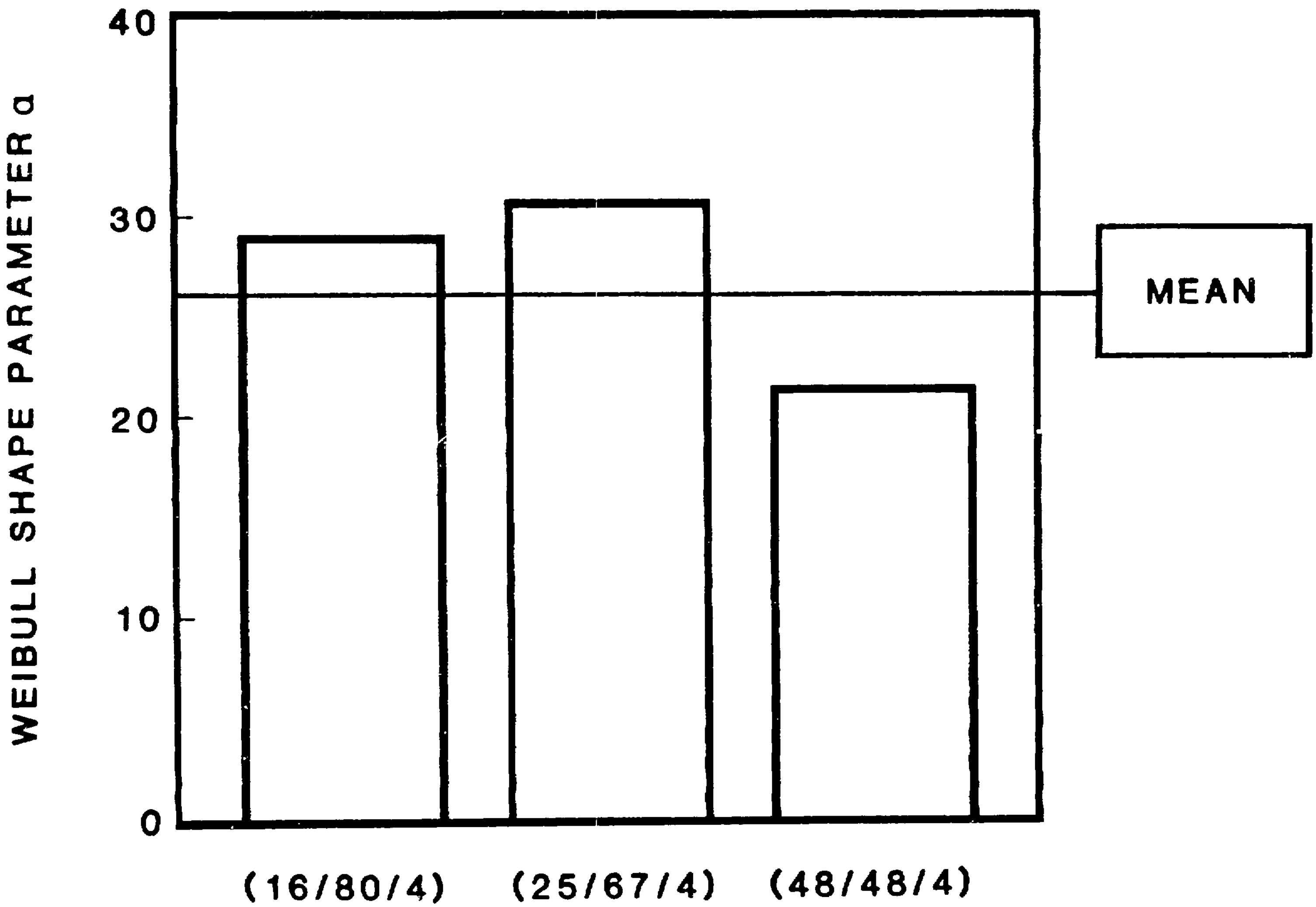

FIGURE 8. INFLUENCE OF LAY-UP ON STATIC STRENGTH VARIABILITY OF NAVY TEST DATA.

TABLE 3. SUMMARY OF SIGNIFICANCE TESTS FOR NAVY STATIC TEST DATA BY LOADING MODE.

SAMPLE A	SAMPLE B	0.95 SIGNIFICANCE	
		SHAPE PARAMETER α	VARIABILITY C.V. %
RTD TENSION	ETW TENSION	NO	NO
RTD TENSION	ALL TENSION	NO	NO
ETW TENSION	ALL TENSION	NO	NO
RTD TENSION	ALL STATIC	NO	NO
ETW TENSION	ALL STATIC	NO	NO
RTD TENSION	RTD COMPRESSION	NO	NO
ETW TENSION	ETW COMPRESSION	NO	NO
ALL TENSION	ALL COMPRESSION	NO	NO
RTD COMPRESSION	ETW COMPRESSION	NO	NO
RTD COMPRESSION	ALL COMPRESSION	NO	NO
ETW COMPRESSION	ALL COMPRESSION	NO	NO
RTD COMPRESSION	ALL STATIC	NO	NO
ETW COMPRESSION	ALL STATIC	NO	NO
ALL TENSION	ALL STATIC	NO	NO
ALL COMPRESSION	ALL STATIC	NO	NO

TABLE 4. SUMMARY OF SIGNIFICANCE TESTS FOR NAVY STATIC TEST DATA BY TEST ENVIRONMENT.

SAMPLE A	SAMPLE B	0.95 SIGNIFICANCE	
		SHAPE PARAMETER α	VARIABILITY C.V. %
RTD	ETW	NO	NO
RTD	ALL	NO	NO
ETW	ALL	NO	NO

TABLE 5. SUMMARY OF SIGNIFICANCE TESTS FOR NAVY STATIC TEST DATA BY SPECIMEN TYPE.

SAMPLE A	SAMPLE B	0.95 SIGNIFICANCE	
		SHAPE PARAMETER α	VARIABILITY C.V. %
NO L/T	INT. L/T	NO	NO
NO L/T	HIGH L/T	NO	YES
INT. L/T	HIGH L/T	NO	YES
NO L/T	ALL	NO	NO
INT. L/T	ALL	NO	NO
HIGH L/T	ALL	NO	NO

TABLE 6. SUMMARY OF SIGNIFICANCE TESTS FOR NAVY STATIC TEST DATA BY LAY-UP

SAMPLE A	SAMPLE B	0.95 SIGNIFICANCE	
		SHAPE PARAMETER α	VARIABILITY C.V. %
(48/48/4)	(25/67/8)	NO	NO
(48/48/4)	(16/80/4)	NO	NO
(25/67/8)	(16/80/4)	NO	YES
(48/48/4)	ALL	NO	NO
(25/67/8)	ALL	NO	NO
(16/80/4)	ALL	NO	NO

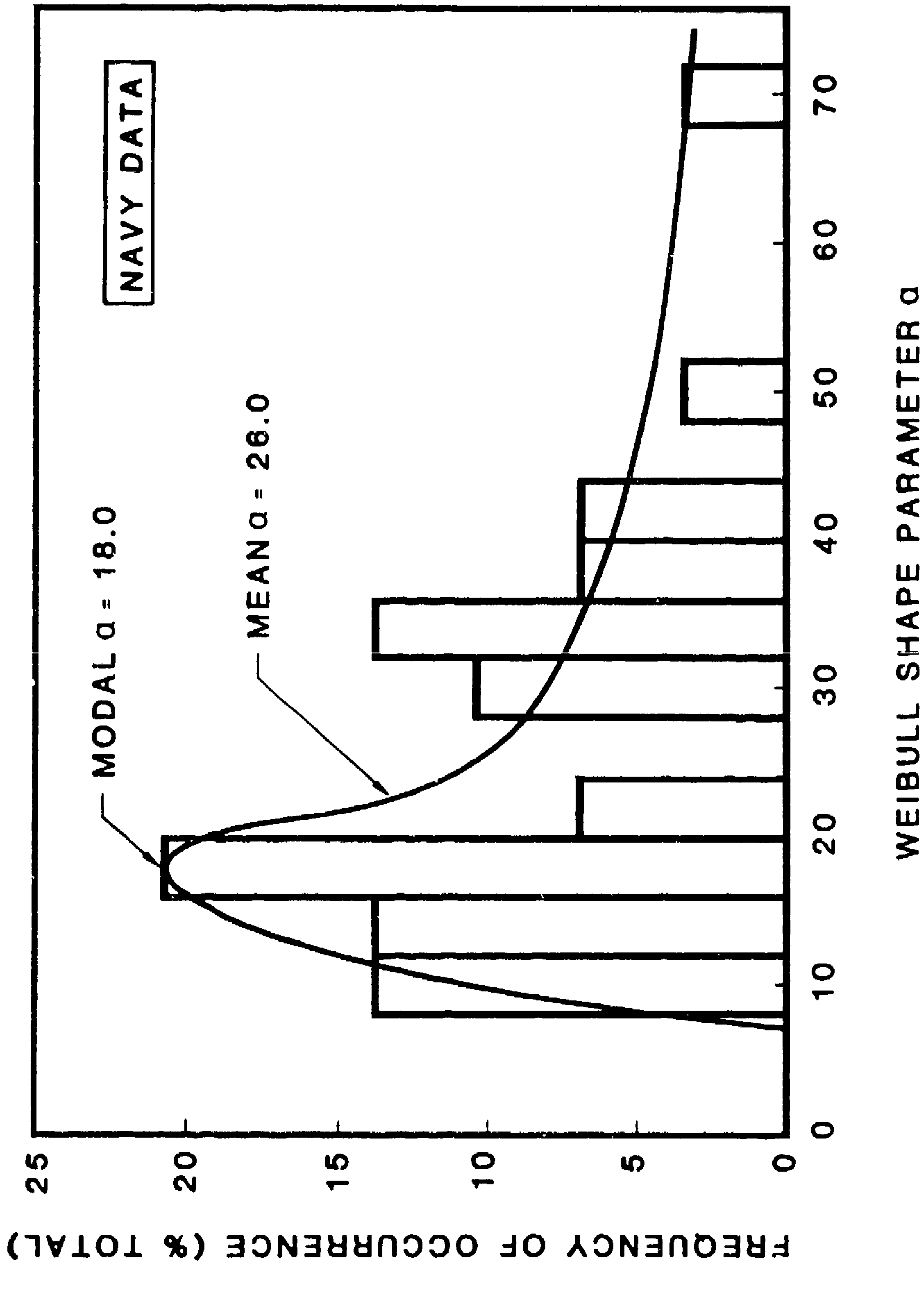

FIGURE 9. OVERALL DISTIBUTION OF SCATTER IN NAVY STATIC STRENGTH DATA.

The significance tests on the variability in α values also showed that, in general, the variability in α is not significantly different at the 95-percent significance level. However, the results in Table 5 show that the variability in α for the high load transfer specimen data is significantly lower than the no-load transfer and intermediate load transfer specimen test data. In addition, Table 6 shows that the variability in α values for the (25/67/8) lay-up is significantly lower than the (16/80/4) lay-up α values.

3.2 Baseline Data

The second phase of the static test data analysis was to determine the scatter in the extensive data in References 12 through 15. This is termed the Baseline data set. In Reference 12 the specimen used was 1.0-inch wide and 1.0-inch long in the test area with 3/16-inch hole at the specimen center. The hole was filled with an unloaded bolt. Hercules AS/3501-5A graphite/epoxy laminates with four different lay-ups were tested; the lay-ups were:

1. 8-ply $(0/\pm45/90)_s$
2. 8-ply $(0/\pm45/0)_s$
3. 16-ply $[(0/\pm45/90)_s]_2$, and
4. 16-ply $[(0/\pm45/0)_s]_2$.

Test data were obtained for both static tension and compression strength under RTD, ETD, RTW and ETW environments. Fifteen specimens were tested at each test condition. In References 13 and 15 two T300/934 graphite/epoxy laminates were tested. The laminate lay-ups were 16-ply $(0/45/90/-45_2/90/45/0)_s$ and 24-ply, $(0/45/0_2/-45/0_2/45/0_2/-45/0)_s$. The specimens tested were 0.875-inch wide and 5.5 inches long in the test area, with or without a 0.25-inch diameter central open hole. Both tension and compression static strength data were obtained under RTD, ETW environments. At least 15 specimens were tested at each test condition. Test data from Reference 14 were obtained on high load transfer bolted joint specimens. The laminate at the joining area was 48-ply or 74-ply AS/3501-5 graphite/epoxy. The test environments were RTD, RTW, and ETW. Ten to twenty specimens were tested at each test condition.

The results of the scatter analysis for Baseline test data are presented in Table 7 and Figure 10, which show the influence of loading mode and environment on the Weibull shape parameter, α. The trend is similar to that observed in the Navy static test data. That is, tension loading and RTD/RTW test conditions again show higher α values and lower data scatter. These trends are also tested for significance at the 95-percent significance level and the results are summarized in Table 8. The significance checks on α show that significant differences exist between the scatter in tension and compression data for both the RTD and ETW test environments. In addition, significant differences also exist between tension data scatter for the RTD and ETW environments. The significance checks on variability in α show that the ETW tension data have significantly lower scatter than the other static test data.

The overall distribution of the Weibull shape parameters for the Baseline data sets is shown in Figure 11. A Weibull analysis is performed on these α's. The following values are determined:

Mean	α = 21.2
Modal	α = 22.0
B-Basis	α = 9.2

Figure 12 shows a comparison of the overall distribution of the Weibull shape parameters for the Navy and Baseline data sets. The Navy α values show a more dispersed distribution compared to the Baseline values.

3.3 Combined Data

The third phase of the analysis is to analyze the data scatter in the pooled Navy and Baseline data sets. This is termed the Combined data set. The results of this analysis are

TABLE 7. SUMMARY OF STATISTICAL ANALYSIS OF BASELINE STATIC TEST DATA.

LOADING MODE	ENVIRONMENT	NUMBER OF DATA SETS	NUMBER OF DATA POINTS	MEAN SHAPE PARAMETER α	VARIABILITY C.V. %
TENSION	RTD/RTW	13	230	27.6	38.2
TENSION	ETW	10	170	20.6	20.1
TENSION	ALL	23	400	24.5	38.5
COMPRESSION	RTD/RTW	9	170	18.7	28.1
COMPRESSION	ETW	9	150	15.5	29.2
COMPRESSION	ALL	18	320	17.1	30.7
ALL	ALL	31	720	21.2	41.6

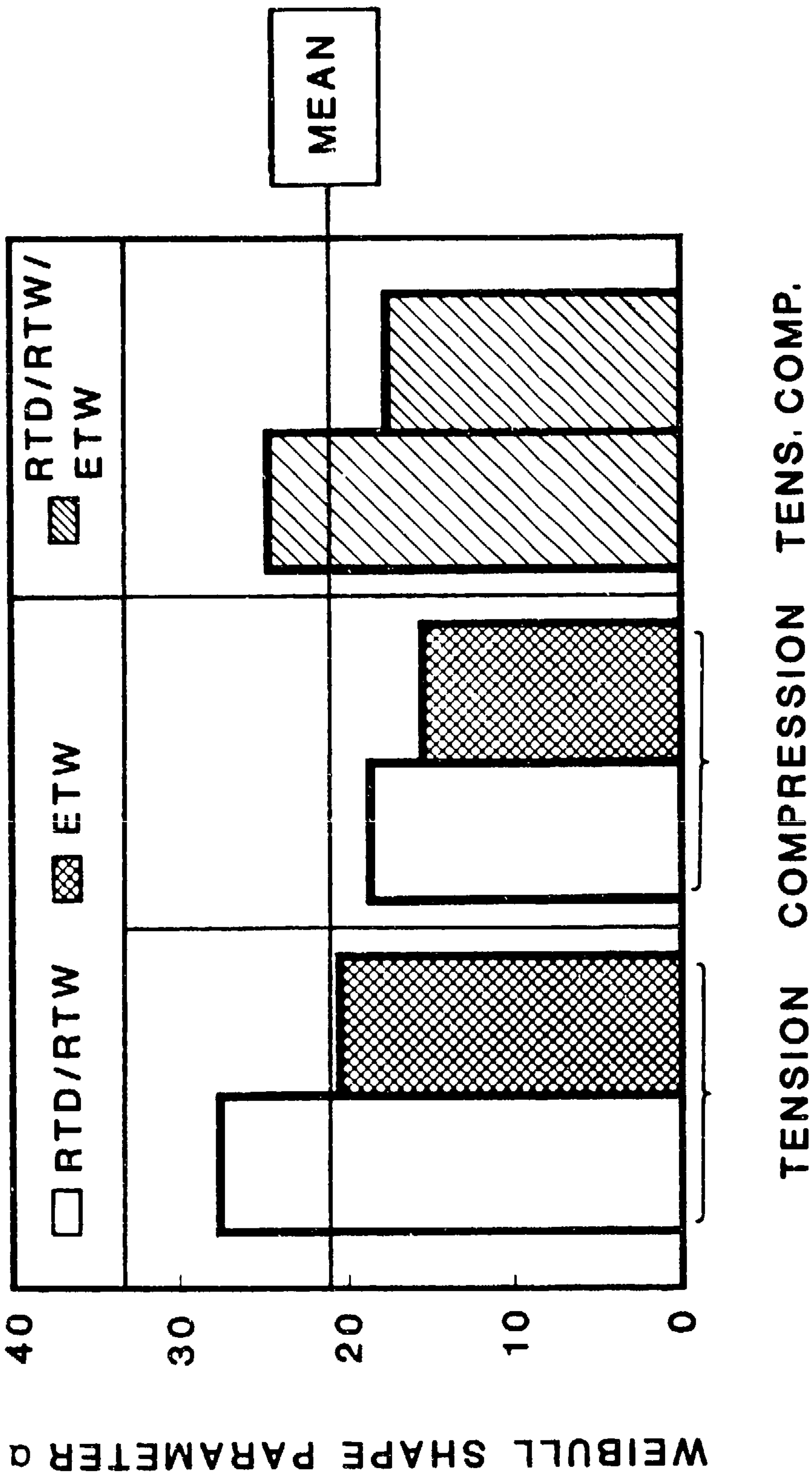

FIGURE 10. INFLUENCE OF LOADING MODE AND ENVIRONMENT ON STATIC STRENGTH VARIABILITY OF BASELINE TEST DATA.

TABLE 8. SUMMARY OF SIGNIFICANCE TESTS FOR BASELINE STATIC TEST DATA BY LOADING MODE AND ENVIRONMENT.

SAMPLE A	SAMPLE B	0.95 SIGNIFICANCE	
		SHAPE PARAMETER α	VARIABILITY C.V. %
RTD/RTW TENSION	ETW TENSION	YES	YES
RTD/RTW TENSION	ALL TENSION	NO	NO
ETW TENSION	ALL TENSION	YES	YES
RTD/RTW TENSION	ALL STATIC	NO	NO
ETW TENSION	ALL STATIC	NO	YES
RTD/RTW TENSION	RTD/RTW COMPRESSION	YES	NO
ETW TENSION	ETW COMPRESSION	YES	NO
ALL TENSION	ALL COMPRESSION	YES	NO
RTD/RTW COMPRESSION	ETW COMPRESSION	NO	NO
RTD/RTW COMPRESSION	ALL COMPRESSION	NO	NO
ETW COMPRESSION	ALL COMPRESSION	NO	NO
RTD/RTW COMPRESSION	ALL STATIC	NO	NO
ETW COMPRESSION	ALL STATIC	YES	NO
ALL TENSION	ALL STATIC	NO	NO
ALL COMPRESSION	ALL STATIC	YES	NO

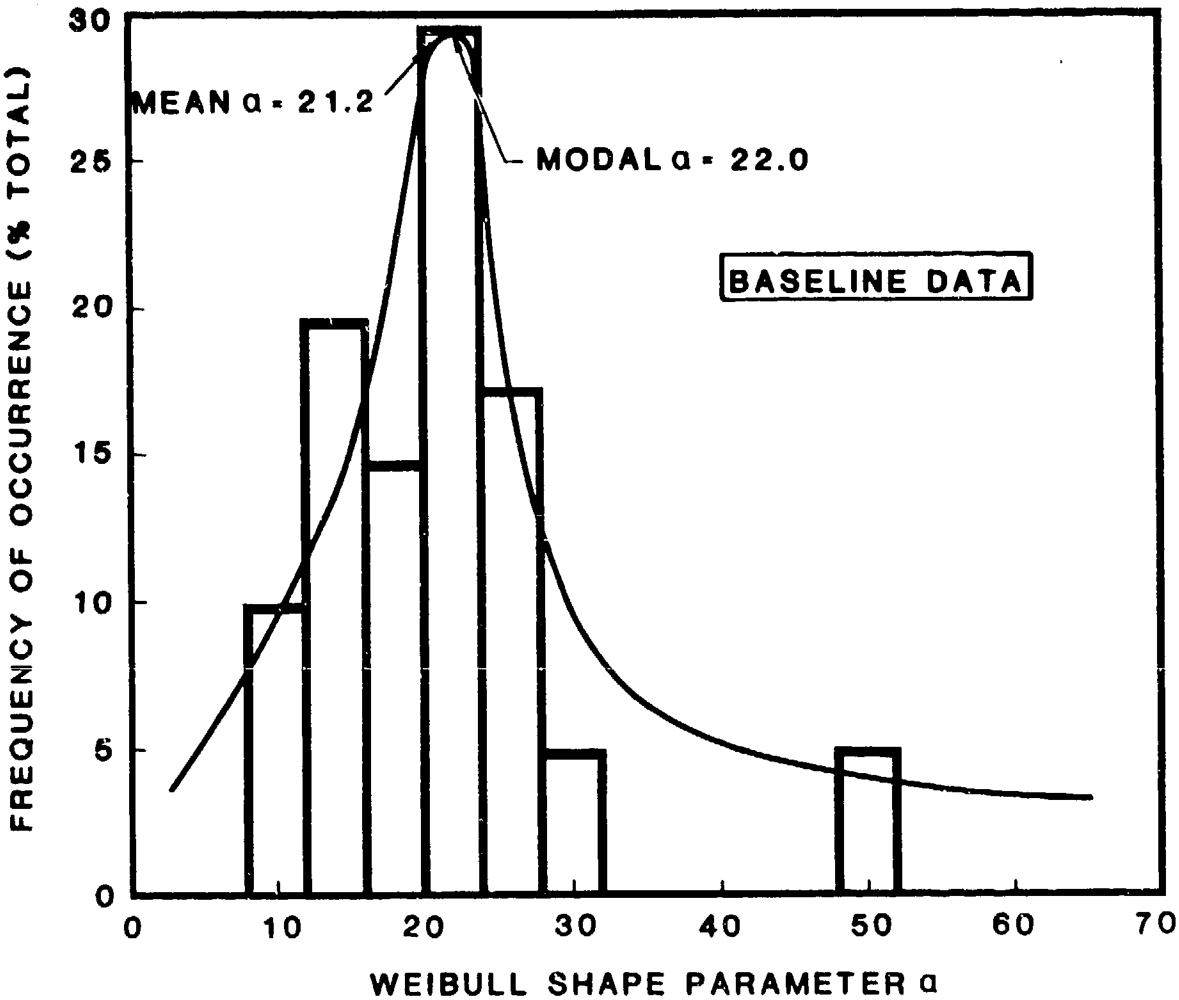

FIGURE 11. OVERALL DISTRIBUTION OF SCATTER IN BASELINE STATIC STRENGTH DATA.

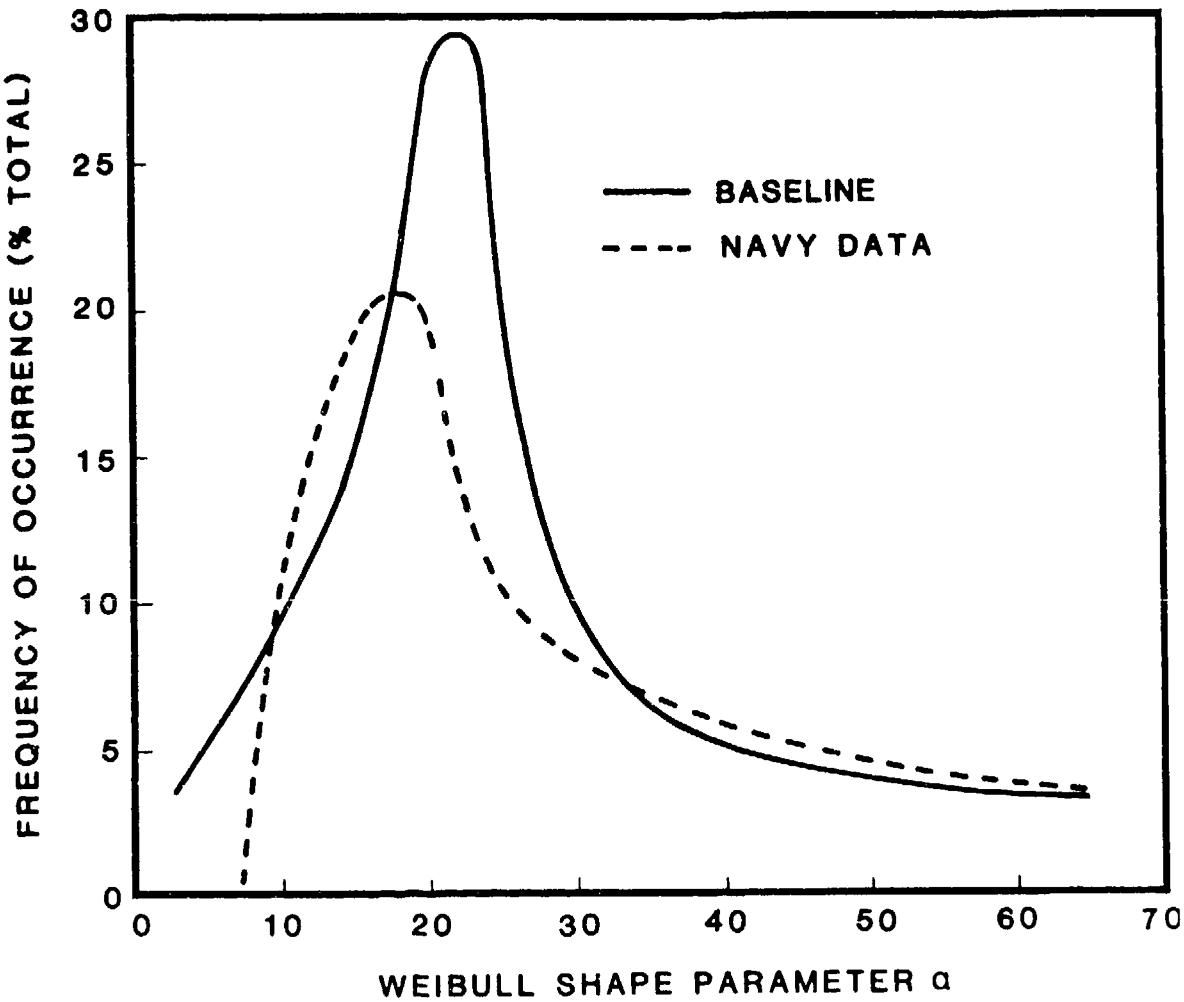

FIGURE 12. COMPARISON OF OVERALL DISTRIBUTION OF SCATTER IN NAVY AND BASELINE STATIC STRENGTH DATA.

presented in Table 9 and Figure 13. The results again show that tension loading and the RTD/RTW environment exhibit higher values and, therefore, lower scatter. The trends observed in Figure 13 are also tested for statistical significance to the 95-percent significance level. The results are presented in Table 10 which show that the trends observed in Figure 13 for tension loading and the RTD/RTW environment are statistically significant at the 95-percent significance level.

Additional significance tests are conducted between the Navy and combined static test data sets. The results are presented in Table 11 and indicate no significant differences between the two data sets. The overall distribution of the Weibull shape parameters for the combined data set is presented in Figure 14. A Weibull analysis is performed on these α's. The following values of α are obtained:

Mean	$\alpha =$	23.2
Modal	$\alpha =$	20.0
B-Basis	$\alpha =$	8.8

A comparison of the Mean, Modal and B-Basis values for the Navy, Baseline, and combined data sets is given in Table 12. These values indicate that the distribution of the Weibull shape parameter (α) for the three data sets are similar.

TABLE 9. SUMMARY OF STATISTICAL ANALYSIS OF COMBINED STATIC TEST DATA.

LOADING MODE	ENVIRONMENT	NUMBER OF DATA SETS	NUMBER OF DATA POINTS	MEAN SHAPE PARAMETER α	VARIABILITY C.V. %
TENSION	RTD/RTW	21	278	30.5	45.4
TENSION	ETW	16	221	21.1	37.1
TENSION	ALL	37	499	26.4	47.1
COMPRESSION	RTD/ETW	17	218	21.0	34.0
COMPRESSION	ETW	17	178	18.6	46.5
COMPRESSION	ALL	34	396	19.8	40.5
ALL	ALL	71	895	23.3	47.6

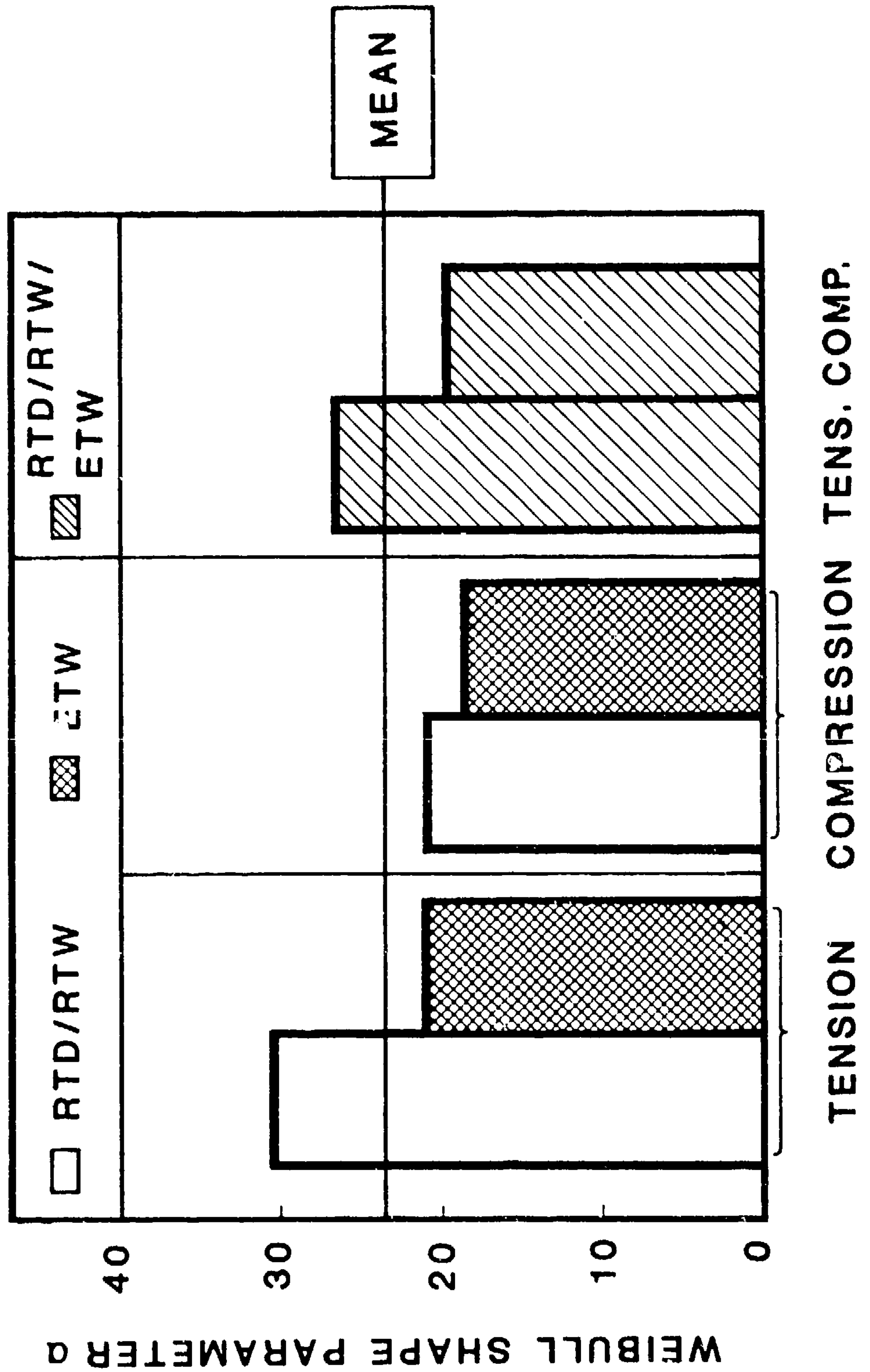

FIGURE 13. INFLUENCE OF LOADING MODE AND ENVIRONMENT ON STATIC STRENGTH VARIABILITY IN COMBINED TEST DATA.

TABLE 10. SUMMARY OF SIGNIFICANCE TESTS FOR COMBINED STATIC TEST DATA

SAMPLE A	SAMPLE B	0.95 SIGNIFICANCE	
		SHAPE PARAMETER α	VARIABILITY C.V. %
RTD/RTW TENSION	ETW TENSION	YES	NO
RTD/RTW COMPRESSION	ETW COMPRESSION	NO	NO
RTD/RTW TENSION	RTD/RTW COMPRESSION	YES	NO
ETW TENSION	ETW COMPRESSION	NO	NO
RTD/RTW TENSION	ALL STATIC	YES	NO
ETW TENSION	ALL STATIC	NO	NO
RTD/RTW COMPRESSION	ALL STATIC	NO	NO
ETW COMPRESSION	ALL STATIC	NO	NO
ALL TENSION	ALL COMPRESSION	YES	NO
ALL TENSION	ALL STATIC	NO	NO
ALL COMPRESSION	ALL STATIC	NO	NO

TABLE 11. SUMMARY OF SIGNIFICANCE TESTS BETWEEN NAVY AND COMBINED STATIC TEST DATA.

COMBINED DATA	NAVY DATA	0.95 SIGNIFICANCE	
		SHAPE PARAMETER α	VARIABILITY C.V. %
RTD/RTW TENSION	RTD TENSION	NO	NO
ETW TENSION	ETW TENSION	NO	NO
RTD/RTW COMPRESSION	RTD COMPRESSION	NO	NO
ETW COMPRESSION	ETW COMPRESSION	NO	NO
ALL TENSION	ALL TENSION	NO	NO
ALL COMPRESSION	ALL COMPRESSION	NO	NO
ALL STATIC	ALL STATIC	NO	NO

TABLE 12. SUMMARY OF WEIBULL ANALYSIS FOR STATIC TEST DATA SETS.

DATA SET	WEIBULL SHAPE PARAMETER α		
	MEAN	MODAL	B-BASIS
NAVY	26.1	18.0	8.4
BASELINE	21.2	22.0	9.2
COMBINED	23.2	20.0	8.8

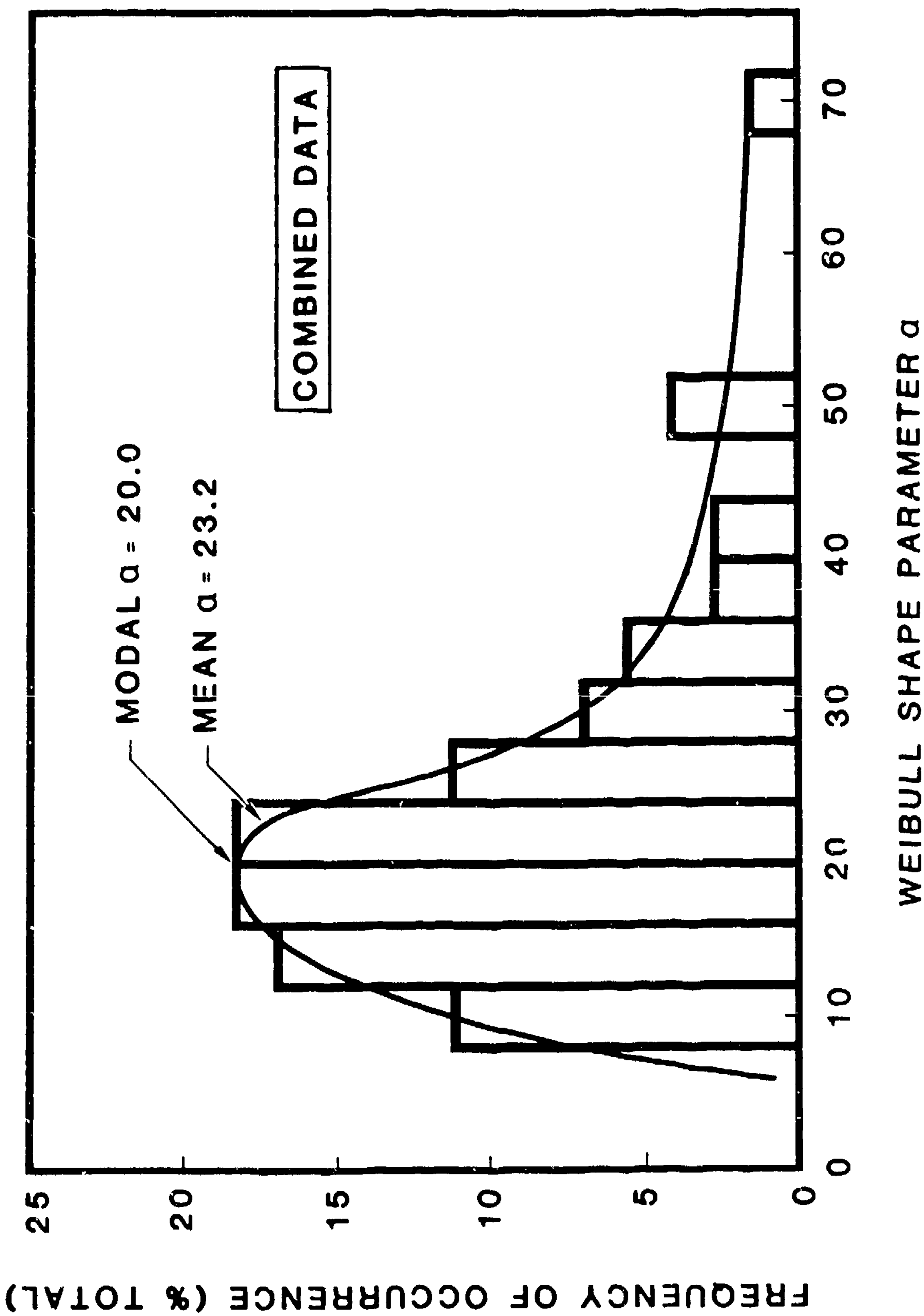

FIGURE 14. OVERALL DISTRIBUTION OF SCATTER IN COMBINED STATIC STRENGTH DATA

SECTION 4

FATIGUE DATA ANALYSIS

The fatigue data scatter analysis has been conducted in the same three phases as the static data analysis. First, the fatigue data from Reference 4 ("Navy" data) are analyzed in detail. Second, the extensive fatigue data scatter analysis conducted in Reference 16 is reviewed; this is termed the Baseline data set. Third, the Navy and Baseline data sets are pooled to form a combined data set for analysis purposes.

Wherever possible all test data sets are analyzed using the three selected analysis methods; that is, Individual Weibull, Joint Weibull and the Sendeckyj analyses. For increased analysis accuracy, only data sets containing five or more data points are used for the Individual Weibull analysis. Data sets for the pooled analysis methods generally contain a minimum of fifteen data points.

Following determination of fatigue life scatter using the three methods described above, the significance of the effects of each test parameter on fatigue life data scatter are determined. Significance checks are conducted using the methodology described in Section 2.3.

4.1 Navy Data

The Navy fatigue test data in Reference 4 represent a large variety of test variables, which are summarized in Table 1.

Tables 13 through 22 summarize the results of the statistical analyses in terms of five variables: R-ratio, loading mode, laminate lay-up, specimen geometry and test environment.

The influence of these five variables on the individual Weibull fatigue life shape parameter (α_I) is presented in Figures 15 through 20. Test variables which have a significant influence (95% significance) on α_I are denoted by an asterisk in these figures.

TABLE 13. SUMMARY OF WEIBULL SHAPE PARAMETERS FOR R = −1 CONSTANT AMPLITUDE TEST DATA.

SPECIMEN TYPE	WEIBULL SHAPE PARAMETER		
	INDIVIDUAL α_I	POOLED α_P	SENDECKYJ α_S
NO L/T	–	3.75	1.20
INT. L/T	2.4[illegible]	1.45	1.01
HIGH L/T	2.92	2.23	1.58
COMPLEX	2.69	2.17	1.13
ALL	2.71	2.40	1.23

TABLE 14. SUMMARY OF WEIBULL SHAPE PARAMETERS FOR R = −2 CONSTANT AMPLITUDE TEST DATA.

SPECIMEN TYPE	WEIBULL SHAPE PARAMETER		
	INDIVIDUAL α_I	POOLED α_P	SENDECKYJ α_S
NO L/T	–	4.79	1.13
INT. L/T	1.45	1.18	0.78
HIGH L/T	2.79	2.10	1.43
COMPLEX	4.45	3.60	1.03
ALL	2.48	2.92	1.09

TABLE 15. SUMMARY OF WEIBULL SHAPE PARAMETERS FOR $R = -\infty$ CONSTANT AMPLITUDE TEST DATA.

SPECIMEN TYPE	WEIBULL SHAPE PARAMETER		
	INDIVIDUAL α_I	POOLED α_P	SENDECKYJ α_S
NO L/T	-	2.67	0.60
INT. L/T	1.08	0.80	0.52
HIGH L/T	1.80	1.14	0.91
COMPLEX	2.33	1.62	0.57
ALL	1.58	1.56	0.65

TABLE 16. SUMMARY OF WEIBULL SHAPE PARAMETERS FOR ALL CONSTANT AMPLITUDE TEST DATA.

SPECIMEN TYPE	WEIBULL SHAPE PARAMETER		
	INDIVIDUAL α_I	POOLED α_P	SENDECKYJ α_S
NO L/T	-	3.75	1.08
INT. L/T	1.68	1.15	0.79
HIGH L/T	2.68	2.07	1.46
COMPLEX	3.07	2.46	0.91
ALL	2.34	2.36	1.06

TABLE 17. SUMMARY OF WEIBULL SHAPE PARAMETERS FOR ALL SPECTRUM TEST DATA.

SPECIMEN TYPE	WEIBULL SHAPE PARAMETER		
	INDIVIDUAL α_I	POOLED α_P	SENDECKYJ α_S
NO L/T	–	–	–
INT. L/T	1.72	1.15	0.94
HIGH L/T	2.60	2.20	1.69
COMPLEX	2.14	1.90	1.47
ALL	2.09	1.75	1.37

TABLE 18. SUMMARY OF WEIBULL SHAPE PARAMETERS FOR ALL (16/80/4) FATIGUE TEST DATA.

SPECIMEN TYPE	WEIBULL SHAPE PARAMETER		
	INDIVIDUAL α_I	POOLED α_P	SENDECKYJ α_S
NO L/T	–	2.98	1.17
INT. L/T	2.10	1.17	0.96
HIGH L/T	2.67	2.22	1.49
COMPLEX	1.75	1.52	0.86
ALL	2.17	1.97	1.12

TABLE 19. SUMMARY OF WEIBULL SHAPE PARAMETERS FOR ALL (48/48/4) FATIGUE TEST DATA.

SPECIMEN TYPE	WEIBULL SHAPE PARAMETER		
	INDIVIDUAL α_I	POOLED α_P	SENDECKYJ α_S
NO L/T	–	4.69	0.99
INT. L/T	1.08	0.92	0.65
HIGH L/T	2.60	2.01	1.49
COMPLEX	2.35	1.55	0.90
ALL	2.01	2.29	1.01

TABLE 20. SUMMARY OF FATIGUE LIFE WEIBULL SHAPE PARAMETERS FOR SPECIMEN GEOMETRY TEST DATA.

SPECIMEN TYPE	WEIBULL SHAPE PARAMETER		
	INDIVIDUAL α_I	POOLED α_P	SENDECKYJ α_S
NO L/T	–	3.75	1.08
INT. L/T	1.70	1.15	0.84
HIGH L/T	2.67	2.06	1.48
COMPLEX	2.74	2.23	1.05
ALL	2.29	2.29	1.11

TABLE 21. SUMMARY OF FATIGUE LIFE WEIBULL SHAPE PARAMETERS FOR ALL RTD TEST DATA.

SPECIMEN TYPE	WEIBULL SHAPE PARAMETER		
	INDIVIDUAL α_I	POOLED α_P	SENDECKYJ α_S
NO L/T	-	3.81	1.19
INT. L/T	2.03	1.28	0.97
HIGH L/T	3.10	2.01	1.51
COMPLEX	3.22	2.98	1.26
ALL	2.65	2.52	1.23

TABLE 22. SUMMARY OF FATIGUE LIFE WEIBULL SHAPE PARAMETERS FOR ETW TEST DATA.

SPECIMEN TYPE	WEIBULL SHAPE PARAMETER		
	INDIVIDUAL α_I	POOLED α_P	SENDECKYJ α_S
NO L/T	-	3.75	0.98
INT. L/T	1.36	1.03	0.70
HIGH L/T	2.30	2.21	1.57
COMPLEX	2.39	1.71	0.89
ALL	1.97	2.18	1.04

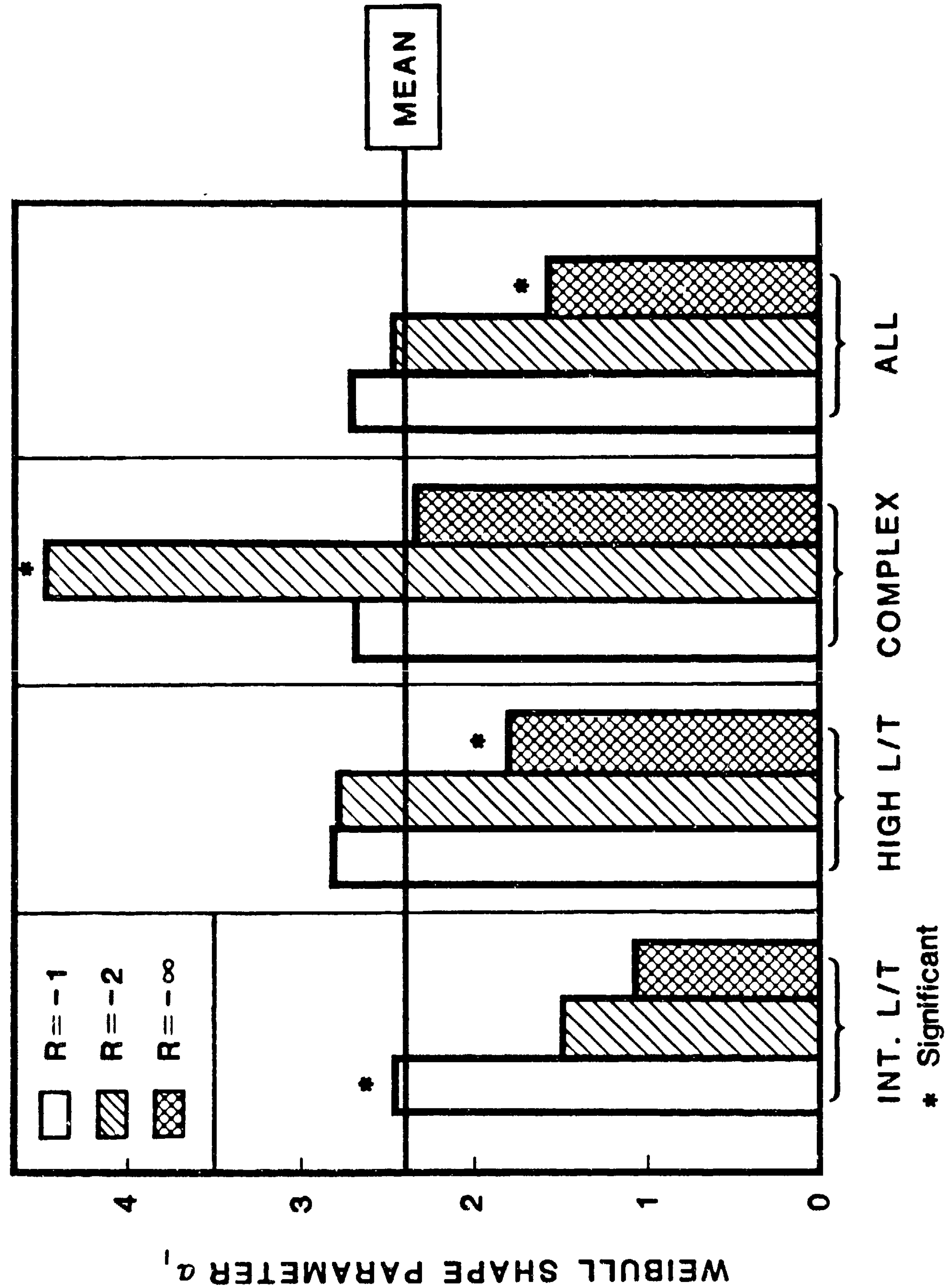

FIGURE 15. INFLUENCE OF R-RATIO ON INDIVIDUAL WEIBULL FATIGUE LIFE SHAPE PARAMETER (NAVY DATA).

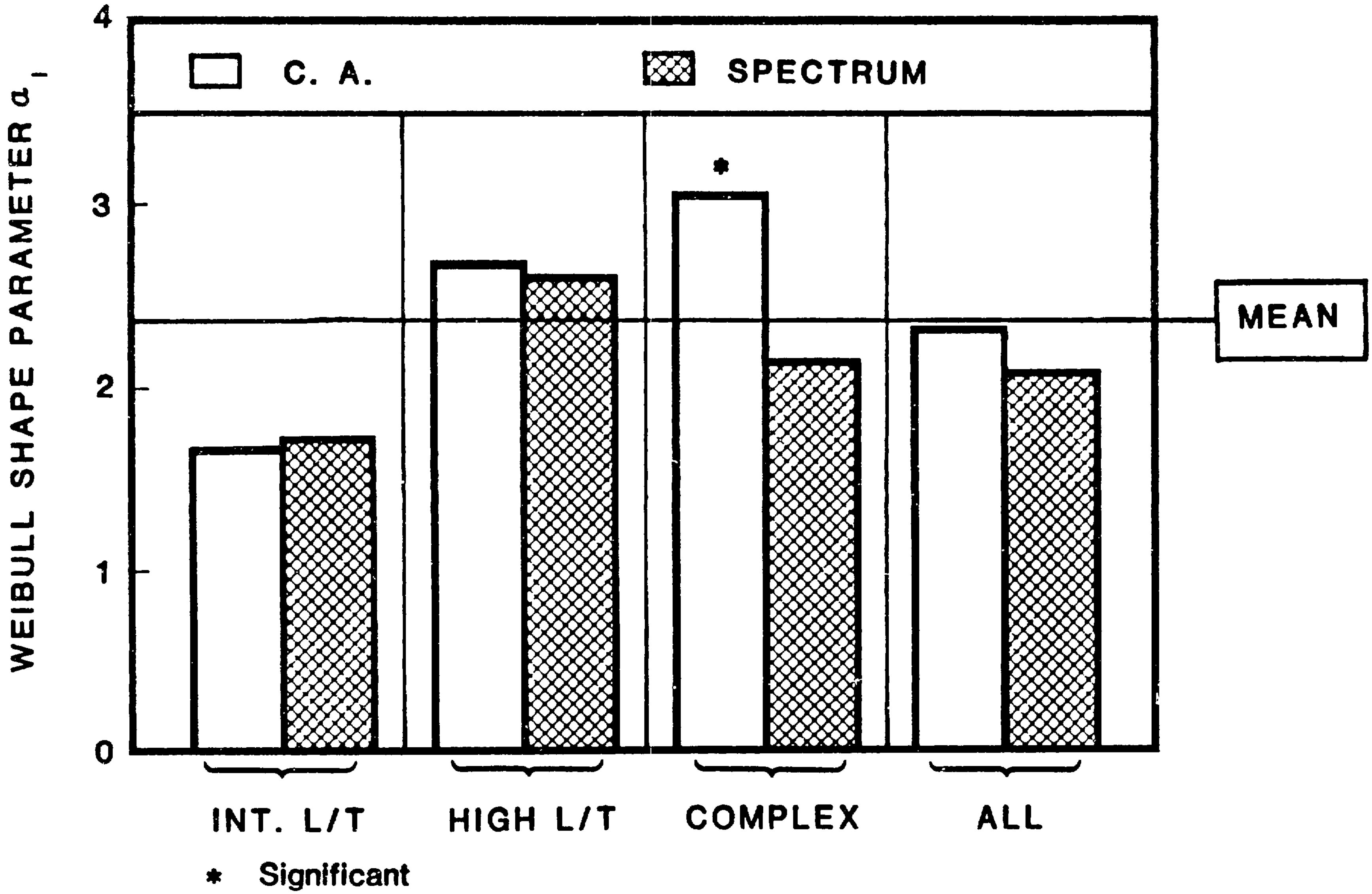

FIGURE 16. INFLUENCE OF LOADING MODE ON INDIVIDUAL WEIBULL FATIGUE LIFE SHAPE PARAMETER (NAVY DATA).

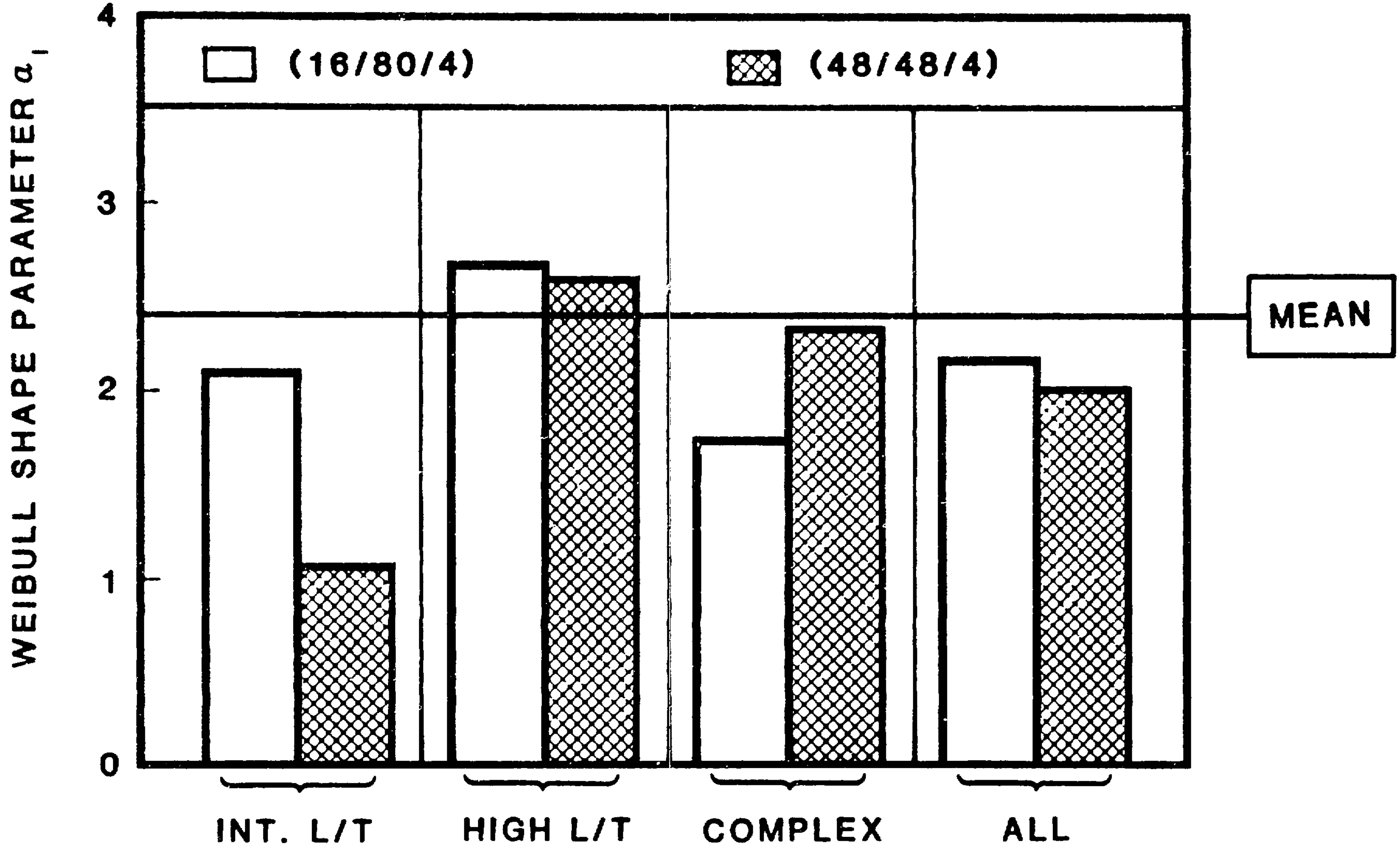

FIGURE 17. INFLUENCE OF LAMINATE LAY-UP ON INDIVIDUAL WEIBULL FATIGUE LIFE SHAPE PARAMETER (NAVY DATA).

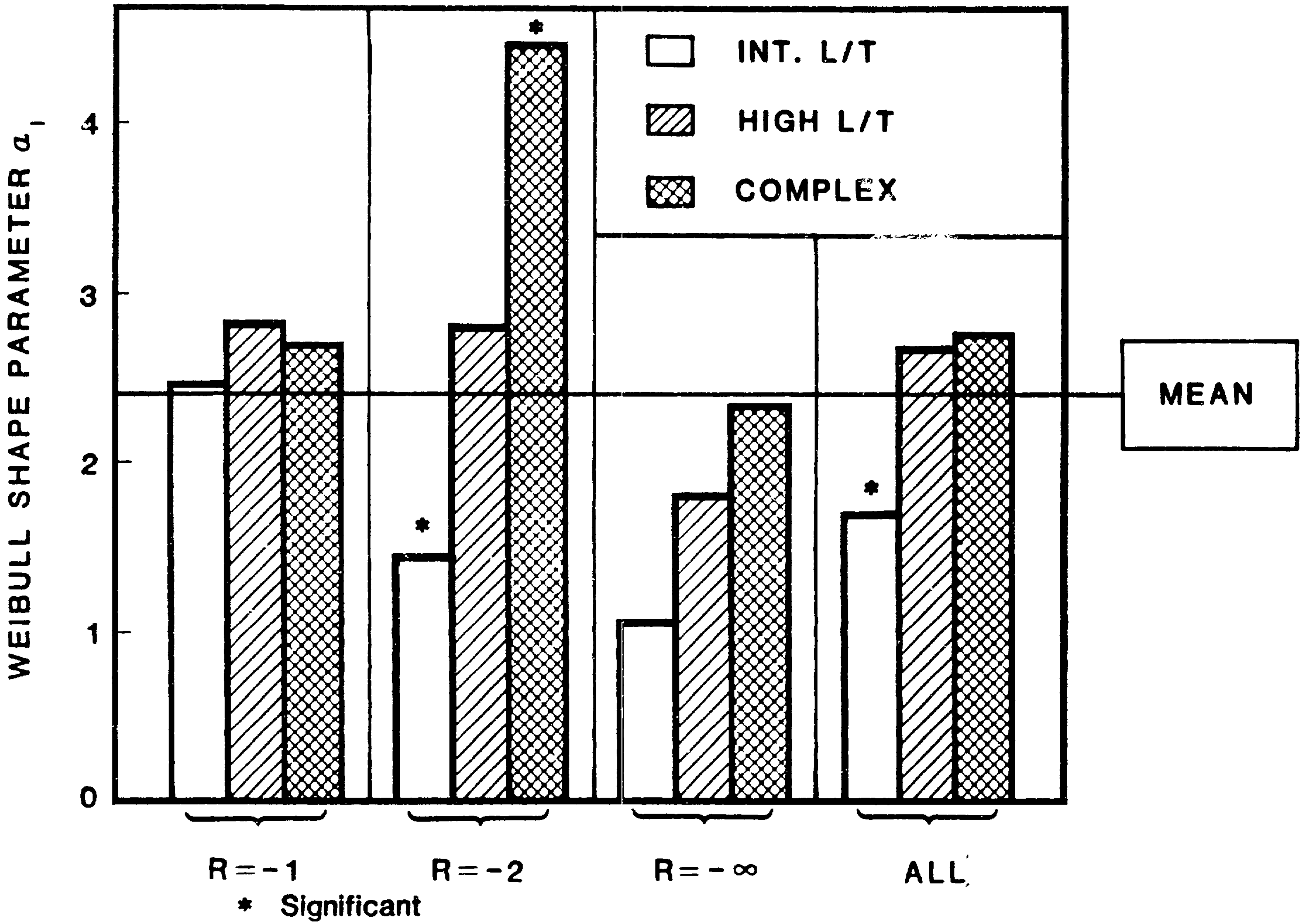

FIGURE 18. INFLUENCE OF SPECIMEN GEOMETRY ON INDIVIDUAL WEIBULL FATIGUE LIFE SHAPE PARAMETER (NAVY DATA).

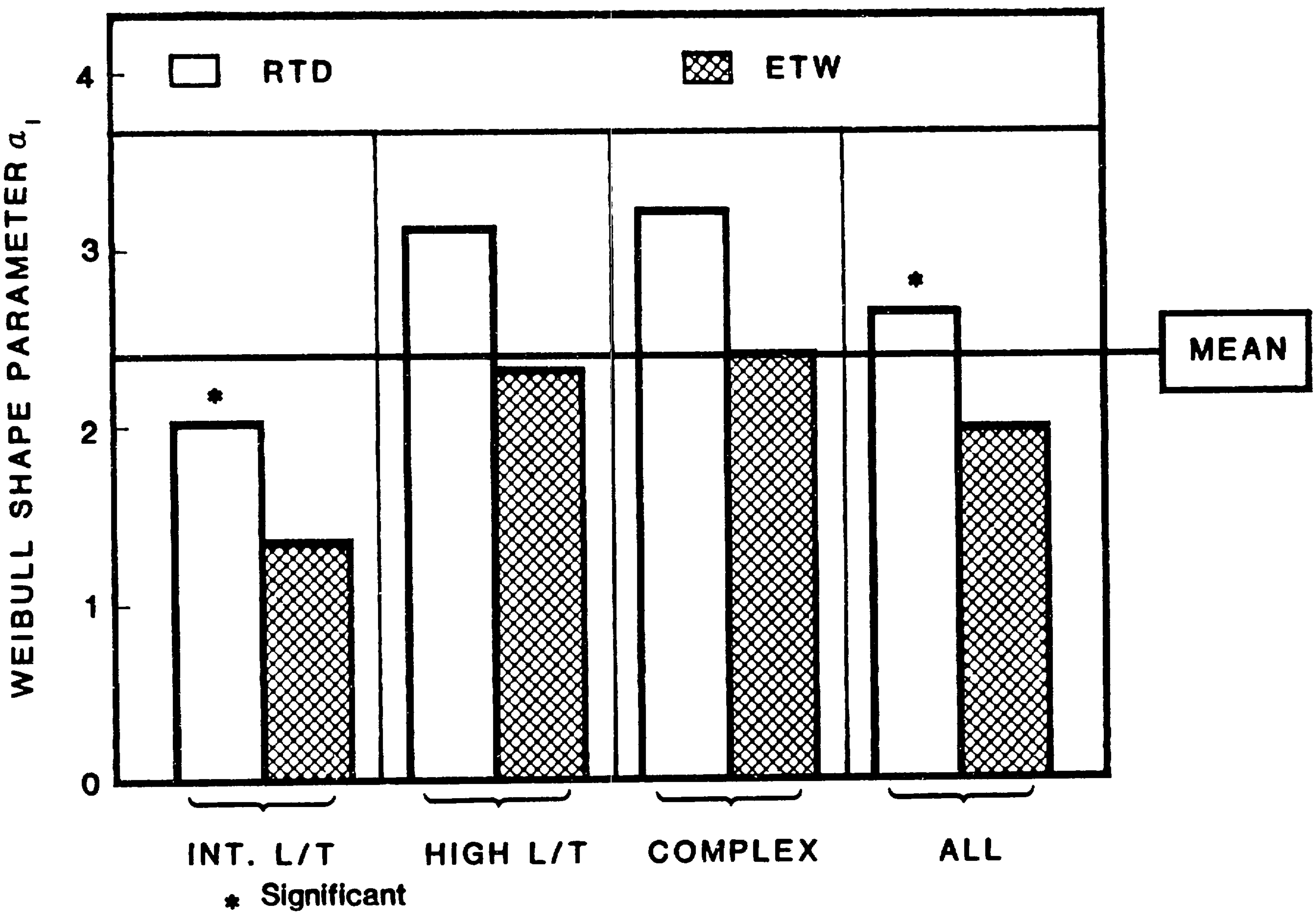

FIGURE 19. INFLUENCE OF TEST ENVIRONMENT ON INDIVIDUAL WEIBULL FATIGUE LIFE SHAPE PARAMETER (NAVY DATA).

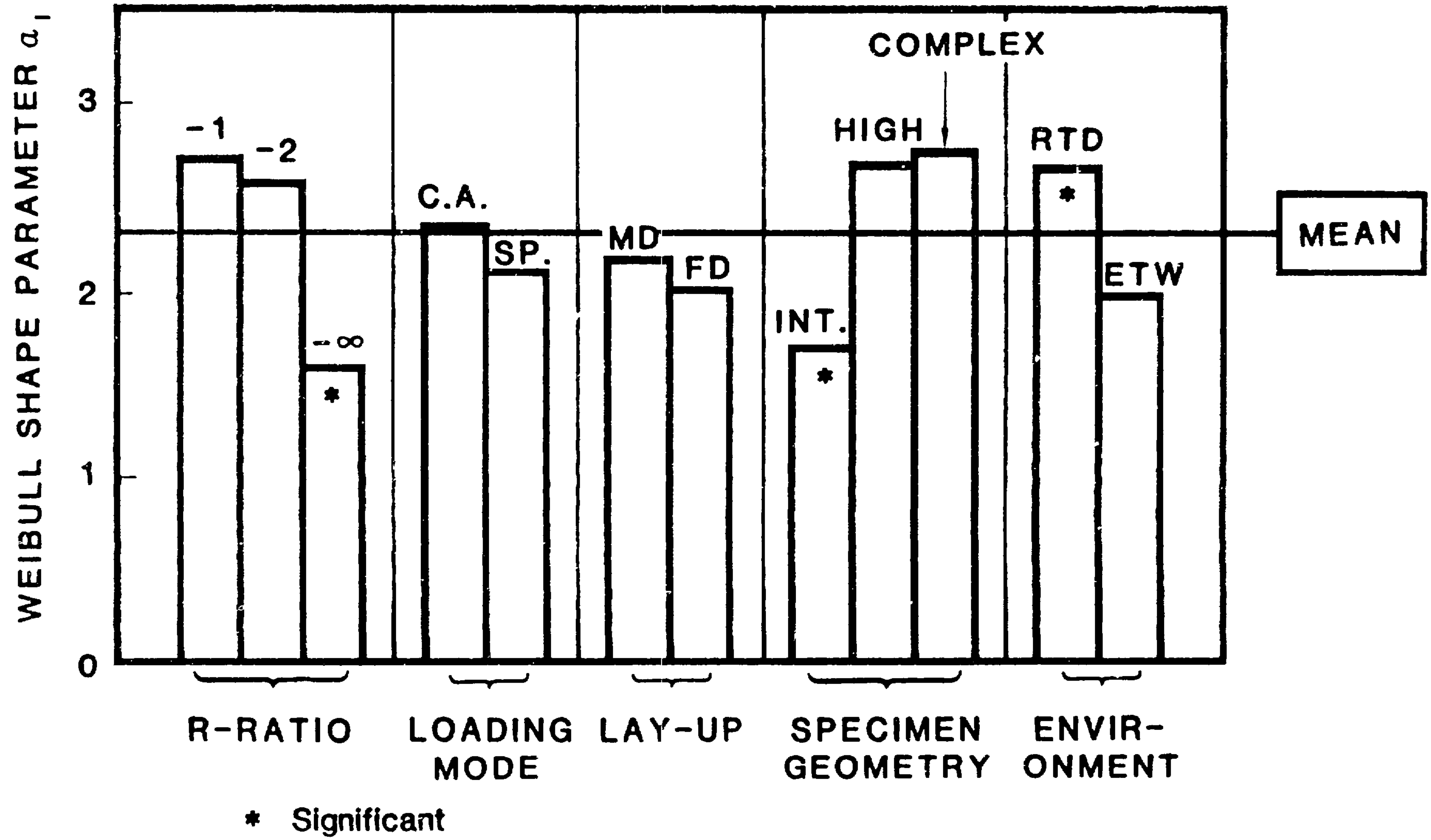

FIGURE 20. SUMMARY OF THE INFLUENCE OF ALL TEST VARIABLES ON INDIVIDUAL WEIBULL FATIGUE LIFE SHAPE PARAMETER (NAVY DATA).

Figure 15 shows the influence of R-ratio on α_I for each specimen type and the total (all) data set. The results for the total data set show that R = $-\infty$ loading produces a significantly lower α_I and higher life scatter than both the R = -2 and -1 loading modes. This observation is also significant for the intermediate and high load transfer specimen data sets. However, the complex specimen data set shows a different trend, in that the R = -2 loading mode has a significantly higher α_I and lower scatter than the other loading modes.

Figure 16 presents the influence of fatigue loading mode on fatigue life scatter. For the total (all) data set, there is no significant difference between the α_I values for constant amplitude and upper wing spectrum loading modes. This conclusion also holds for the intermediate and high load transfer specimen data sets. In contrast, for the complex specimen, constant amplitude data have a significantly higher α_I and lower life scatter than the spectrum fatigue data.

Figure 17 presents the influence of laminate lay-up on fatigue life scatter. For both the total (all) data set and the individual data sets α_I is not significantly influenced by laminate lay-up.

Figure 18 presents the influence of specimen geometry on fatigue life scatter. For the total (all) data set, the intermediate load transfer joint shows a significantly lower α_I and higher fatigue life scatter than the high load transfer and complex specimens. This trend is also observed for the individual R = -1, -2 and $-\infty$ data sets; however, it is only determined to be statistically significant for the R = -2 data.

Figure 19 shows the influence of test environment on fatigue life scatter. The total (all) data show that RTD test data have a significantly higher α_I and lower fatigue life scatter than the ETW test data. This trend is also observed for all three specimen geometries. However, it is only statistically significant for the intermediate load transfer specimen.

Figure 20 summarizes the influence of all five test variables on fatigue life scatter (α_I) for the total Navy data set. The following conclusions can be made from the data in this figure.

- Compression-compression (R = $-\infty$) fatigue loading produces a significantly higher fatigue life scatter than compression-tension (R = -1 and -2) fatigue loading.
- There is no significant difference between fatigue life scatter for constant amplitude and spectrum loading.
- Laminate lay-up does not significantly influence fatigue life scatter.
- Intermediate load transfer specimen fatigue life scatter is significantly higher than high load transfer and complex specimen fatigue life scatter.
- The RTD test environment produces significantly lower fatigue life scatter than the ETW test environment.

Detailed analysis of all the Individual Weibull shape parameters, α_I, showed that neither fatigue load level nor fatigue life has any significant influence on α_I. Typical data analyses supporting this conclusion are shown in Figures 3, 21 and 22, respectively.

The fatigue life shape parameters determined by the Joint Weibull and Sendeckyj analyses (which are presented in Table 13 through 22) also show similar trends to those presented for the Individual Weibull analyses in Figures 15 through 20. However, the methods pr .uced different absolute values of the fatigue life shape parameter. Comparisons of the three methods are shown in Figures 23 through 29 and Table 23. Figure 28 s ıows a comparison of the mean α values determined for each analysis method. It should be noted that the data base used for this comparison excluded the no-load transfer open hole specimen data because these data were inadequate for individual Weibull analysis. The comparison in Figure 28 shows that the Individual Weibull analysis gave the highest α values and the Sendeckyj analysis the lowest α value. Significance checks determined that the Sendeckyj mean α value was significantly lower than both the

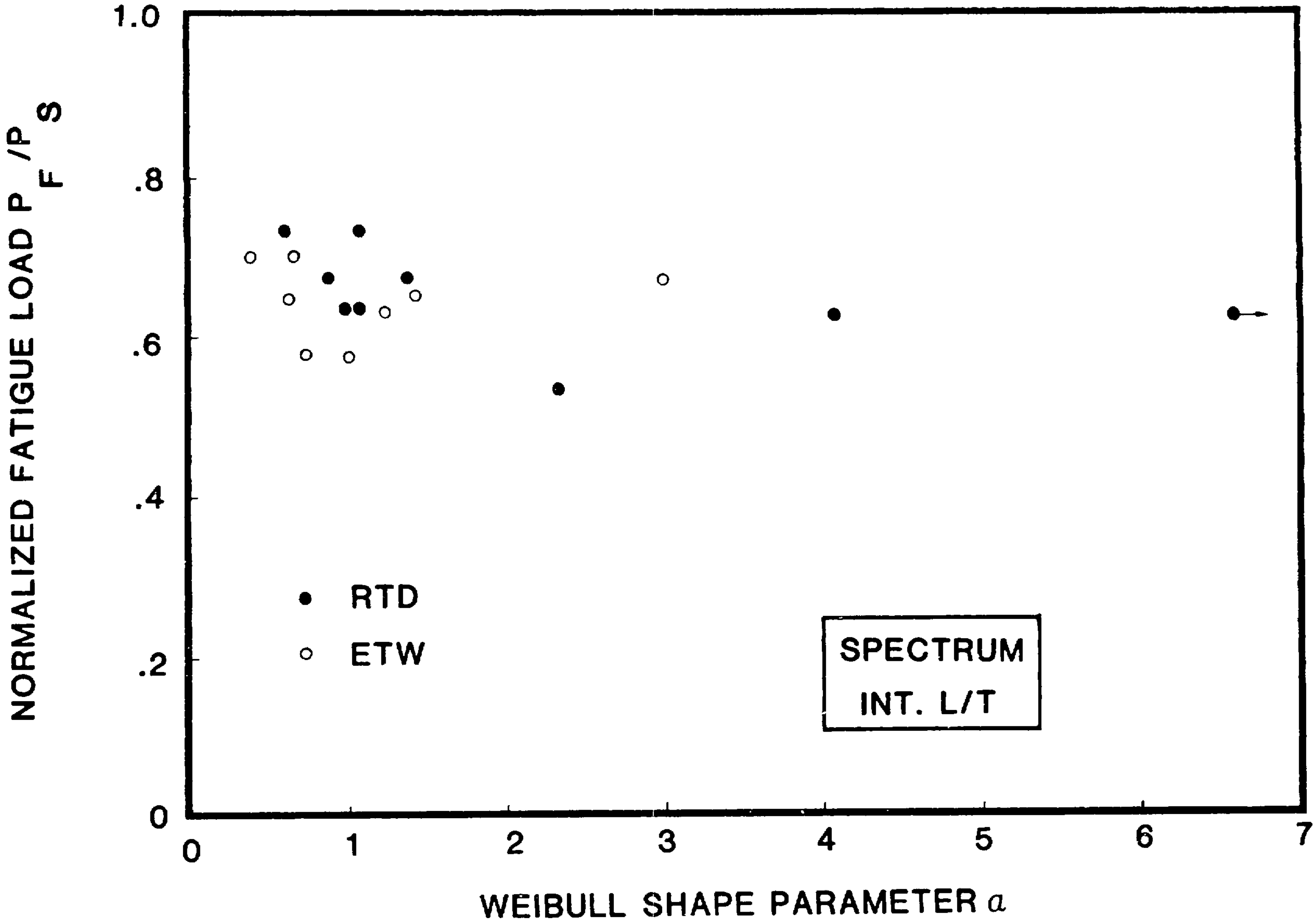

FIGURE 21. EFFECTS OF NORMALIZED FATIGUE LOAD LEVEL ON SPECTRUM FATIGUE LIFE WEIBULL SHAPE PARAMETER (NAVY DATA).

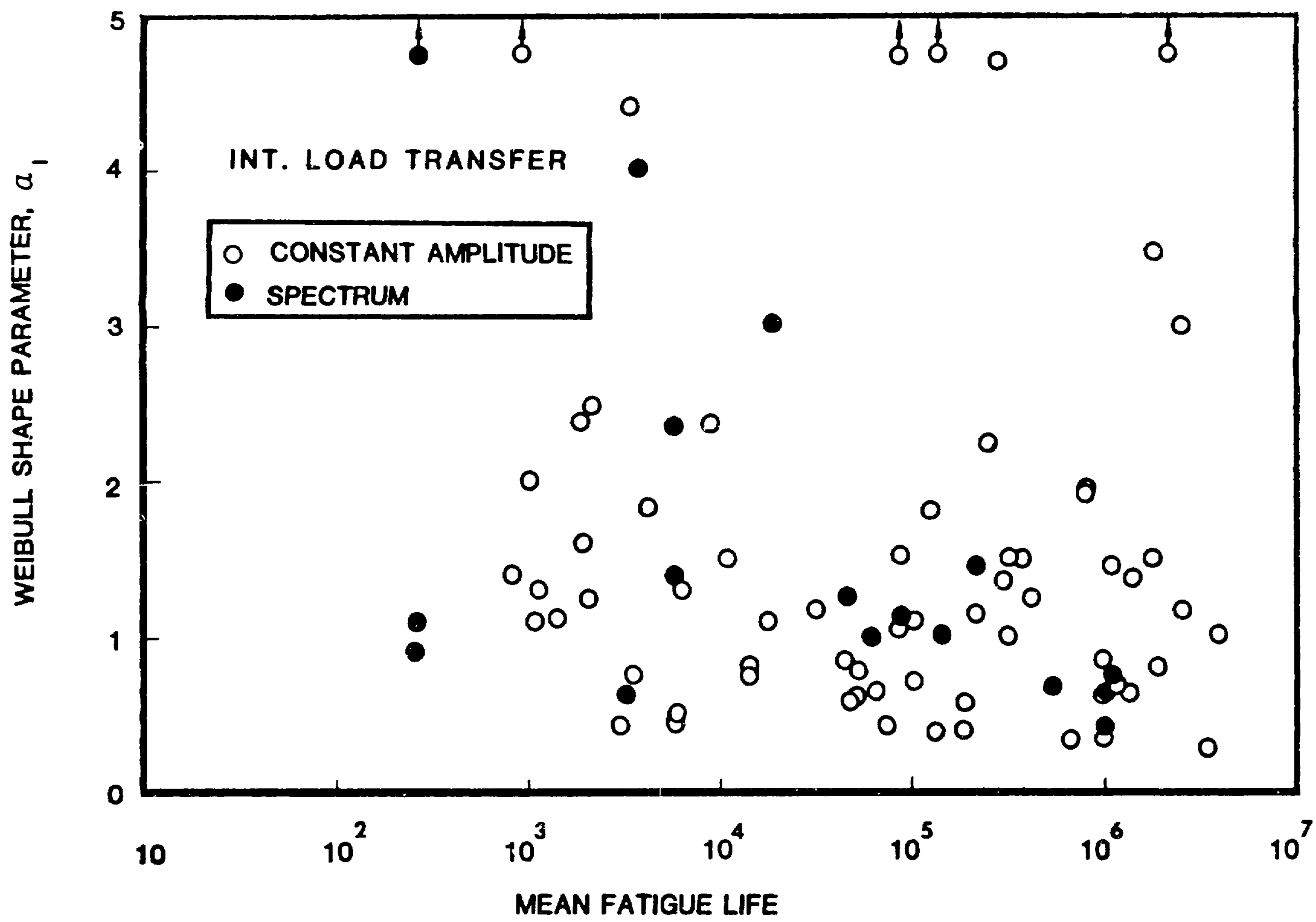

FIGURE 22. EFFECT OF MEAN FATIGUE LIFE ON INDIVIDUAL WEIBULL FATIGUE LIFE SHAPE PARAMETER (NAVY DATA).

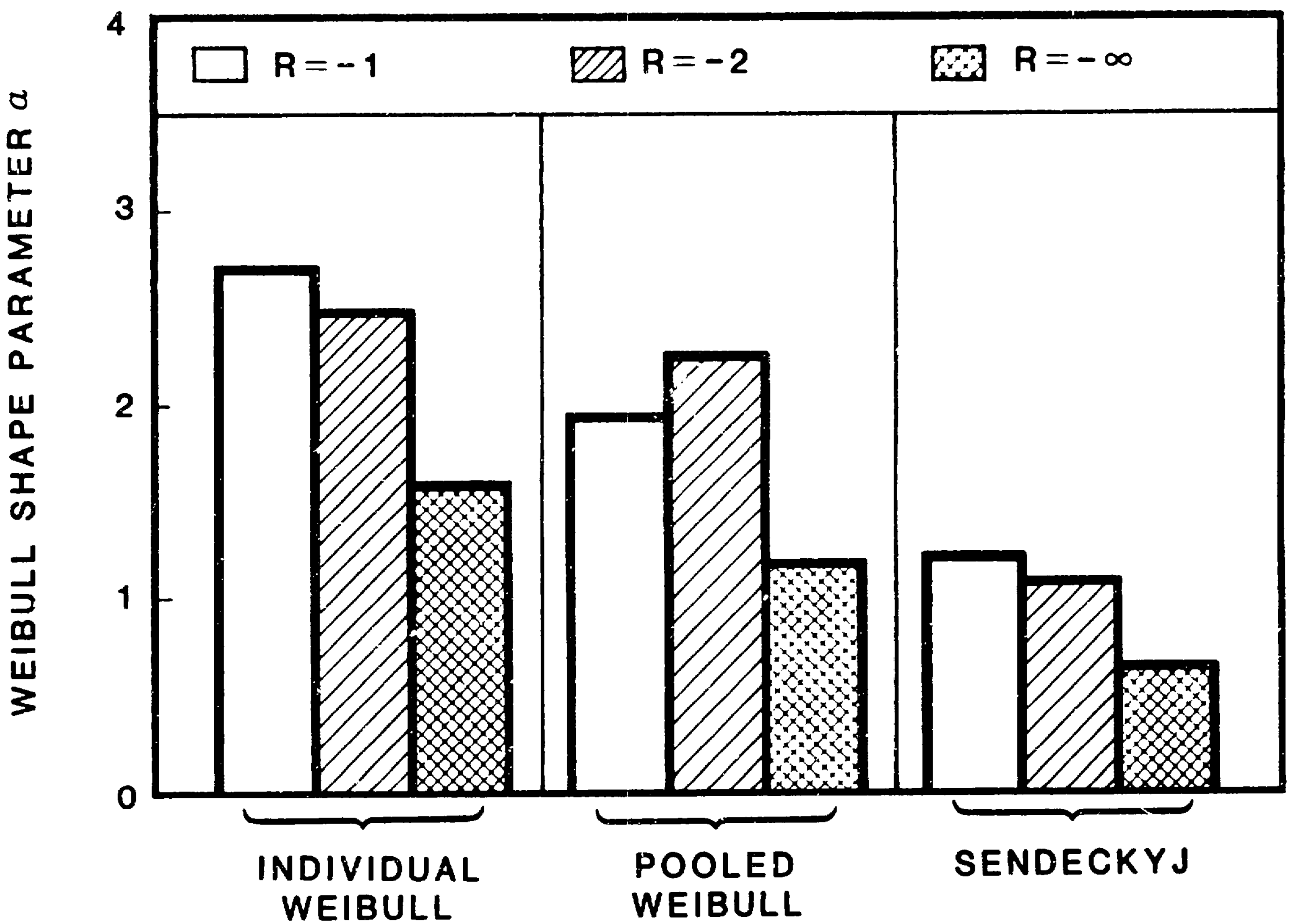

FIGURE 23. INFLUENCE OF FATIGUE LIFE SCATTER ANALYSIS METHOD ON WEIBULL SHAPE PARAMETER - R-RATIO EFFECTS (NAVY DATA).

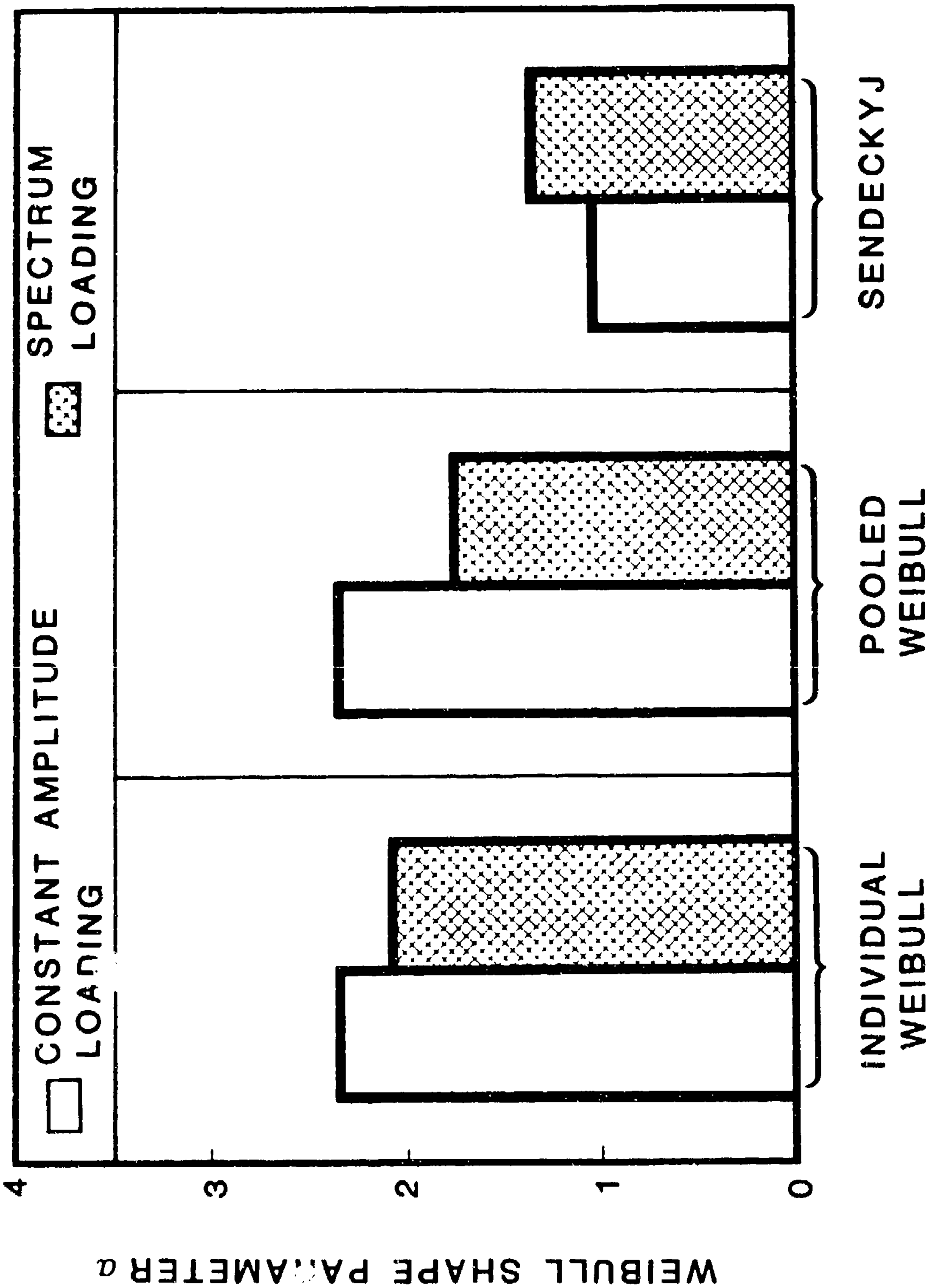

FIGURE 24. INFLUENCE OF FATIGUE LIFE SCATTER ANALYSIS METHOD ON WEIBULL SHAPE PARAMETERS – LOADING MODE EFFECTS (NAVY DATA).

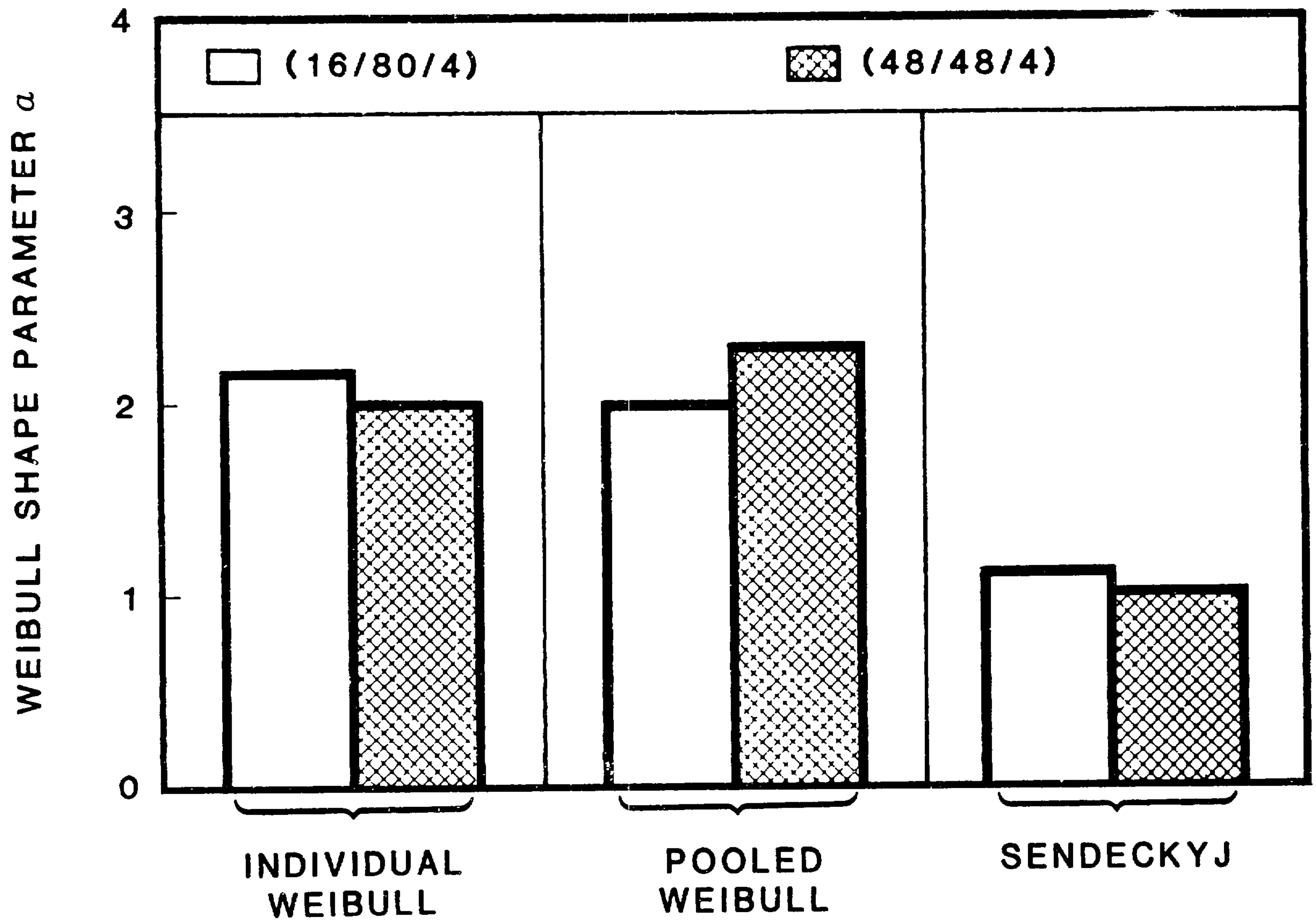

FIGURE 25. INFLUENCE OF FATIGUE LIFE SCATTER ANALYSIS METHODS ON WEIBULL SHAPE PARAMETERS - LAY-UP EFFECTS (NAVY DATA).

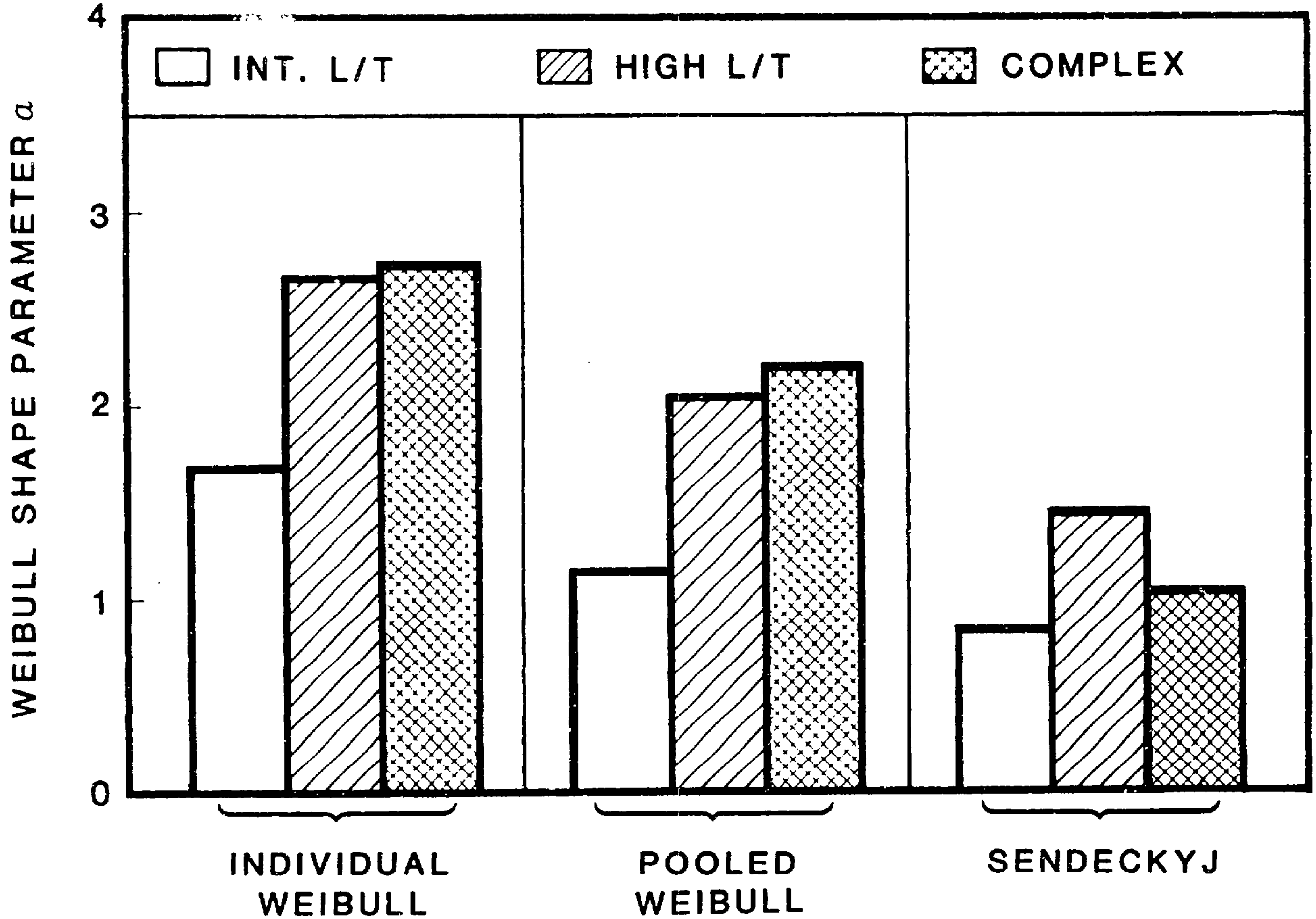

FIGURE 26. INFLUENCE OF FATIGUE LIFE SCATTER ANALYSIS METHODS ON WEIBULL SHAPE PARAMETER – SPECIMEN GEOMETRY EFFECTS (NAVY DATA).

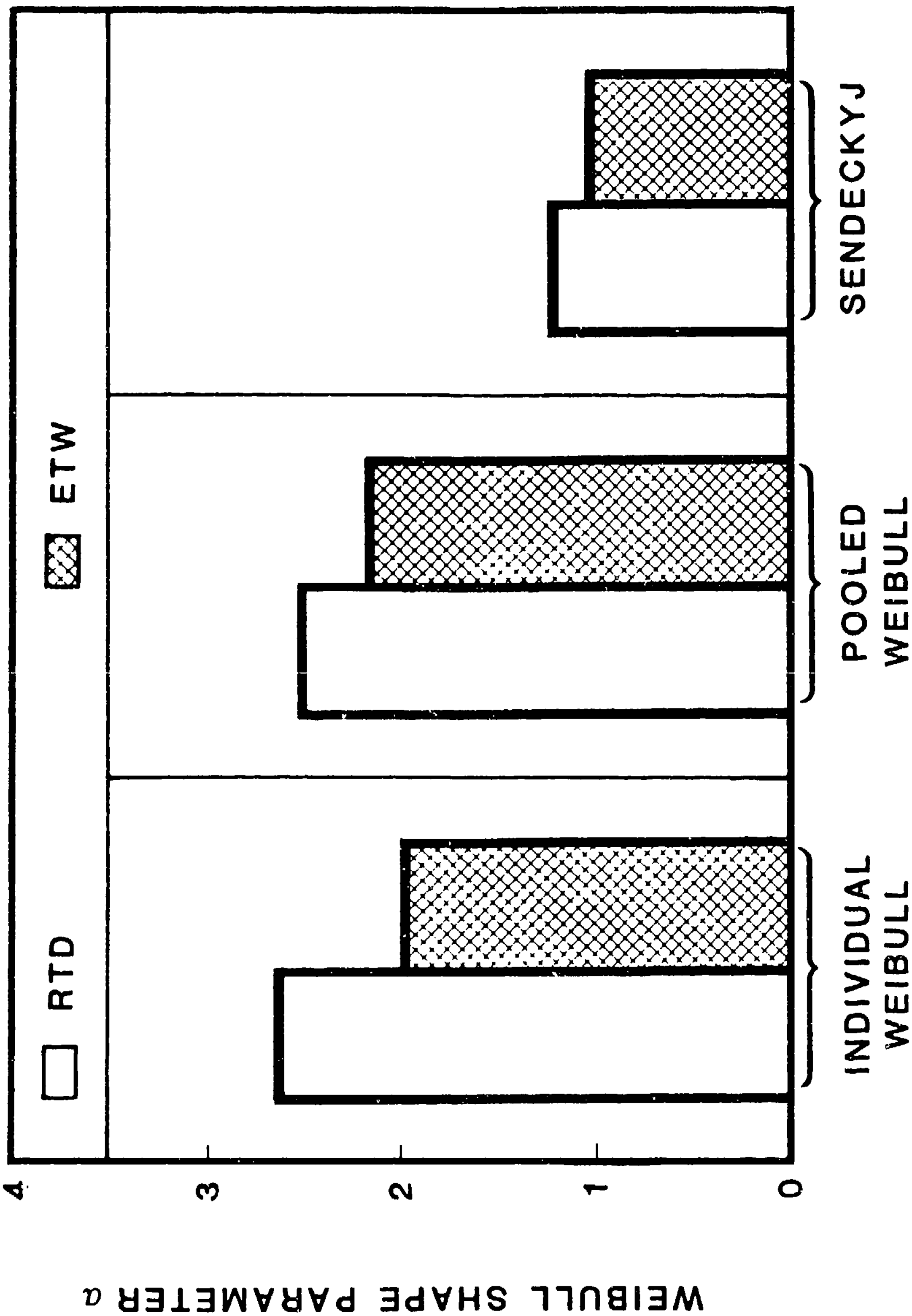

FIGURE 27. INFLUENCE OF FATIGUE LIFE SCATTER ANALYSIS METHOD ON WEIBULL SHAPE PARAMETER - ENVIRONMENT EFFECTS (NAVY DATA).

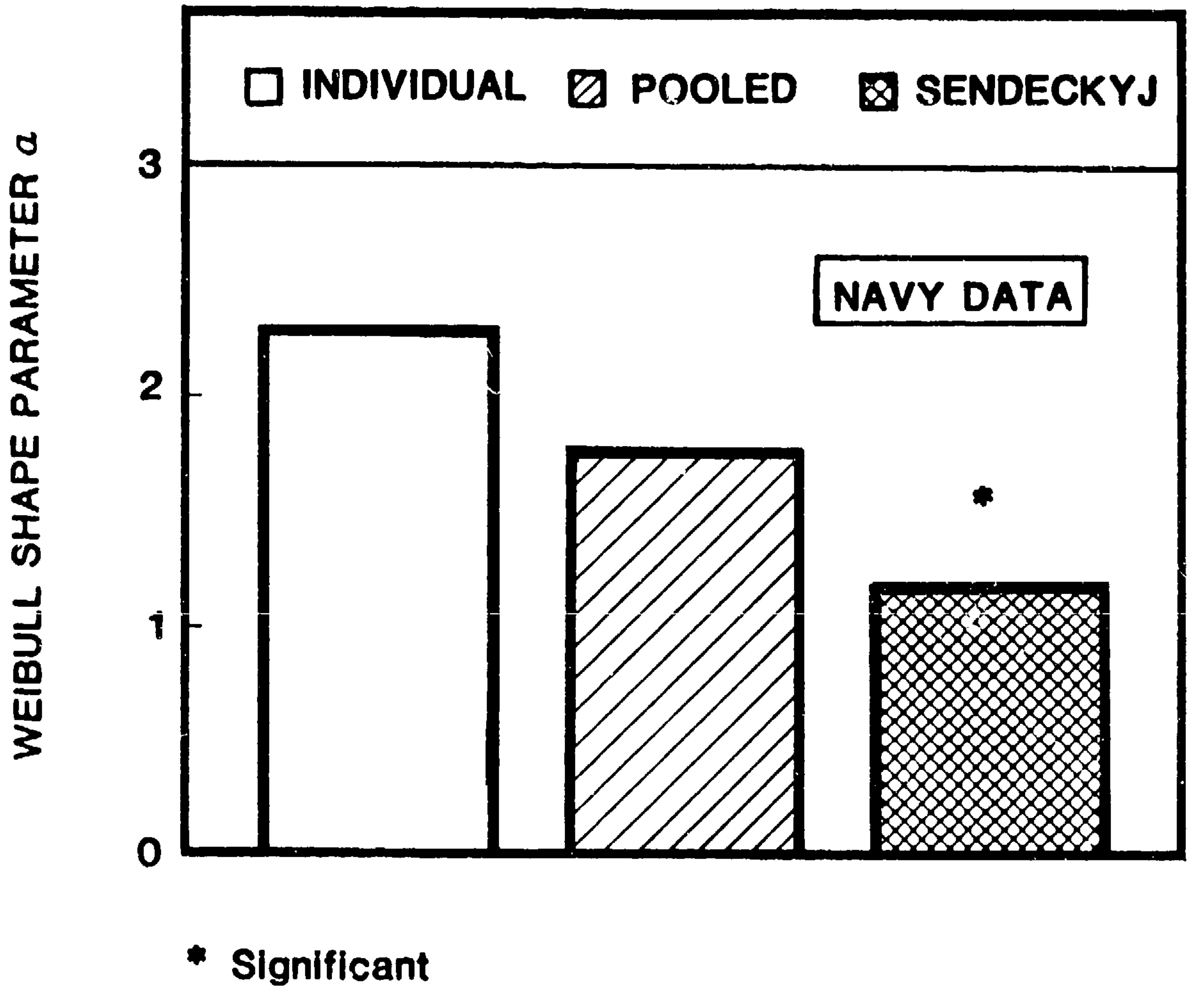

FIGURE 28. INFLUENCE OF FATIGUE LIFE SCATTER ANALYSIS METHOD ON WEIBULL SHAPE PARAMETER – ALL NAVY DATA.

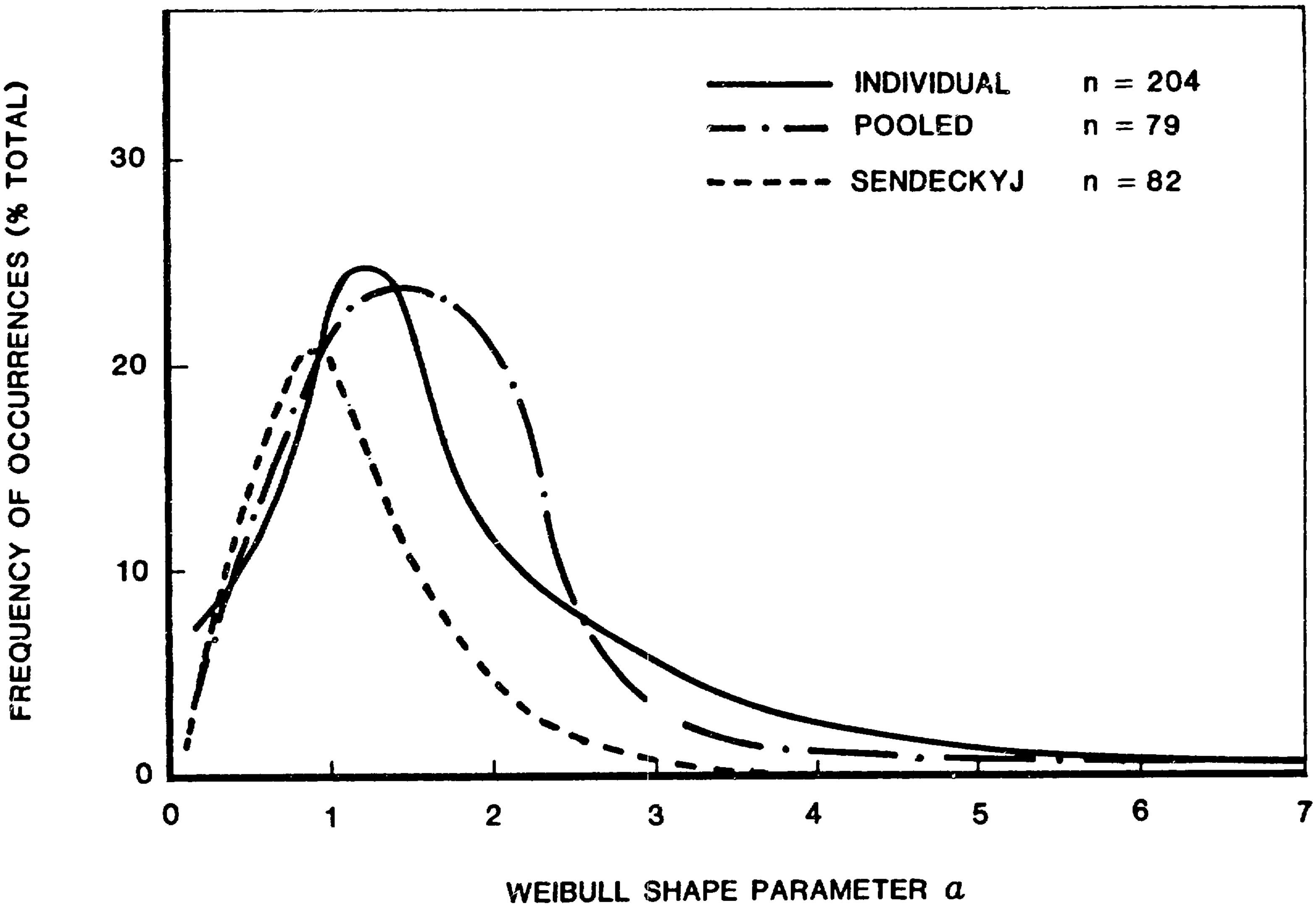

FIGURE 29. INFLUENCE OF SCATTER ANALYSIS METHOD ON FATIGUE LIFE SCATTER DISTRIBUTIONS (NAVY DATA).

TABLE 23. INFLUENCE OF ANALYSIS METHOD ON FATIGUE LIFE WEIBULL SHAPE PARAMETER (NAVY DATA).

ANALYSIS METHOD	NUMBER OF DATA SETS ANALIZED	WEIBULL SHAPE PARAMETER		
		MEAN α	MODAL α	B-BASIS α
INDIVIDUAL WEIBULL (α_I)	204	2.29	1.25	0.17
JOINT WEIBULL (α_P)	79	1.72	1.55	0.27
SENDECKYJ (α_S)	82	1.14	1.00	0.40

Individual and Joint (pooled) Weibull analysis α values. This indicates that the Sendeckyj analysis gives a higher scatter in fatigue life. The trend observed in Figure 28 is anticipated since the two pooling techniques are unbiased compared to the arithmetically averaged Individual Weibull α values. Figure 29 compares the fatigue life scatter distributions determined by each analysis method and Table 23 summarizes the mean, modal and B-Basis α values determined from each of these distributions.

The influence of fatigue failure mode on fatigue life scatter was investigated for the high load transfer specimen fatigue failure data. In these tests, two failure modes were consistently observed. They were: laminate rupture and hole wear-out. The test data are analyzed in two ways. First as a total data base and second, the laminate rupture failures are censored from the data base. Figure 30 presents a comparison of the fatigue life scatter values for the two data bases. The data show that the fatigue life scatter is the same for both data sets. Thus, it can be concluded that the mixed failure modes did not increase fatigue life scatter for the high load transfer specimen.

4.2 Baseline Data

The baseline data analysis was conducted in Reference 16 on a wide range of graphite/epoxy fatigue data. A summary of the data analyzed in the reference is shown in Table 24. A total of 120 sets of graphite/epoxy fatigue data with 2925 data points were used in the Sendeckyj analysis. Among the data 59 data sets with 830 data points were found adequate for individual Weibull analysis. The results of the individual Weibull analysis are shown in Figure 31. These results are compared with that of the Navy data. Figure 32 shows a comparison of the distribution of the individual Weibull shape parameter values for the Navy and baseline data. The distributions are very similar, except that Navy data show a slightly higher dispersion.

TABLE 24. SUMMARY OF COMPOSITE FATIGUE TEST DATA ANALYZED IN REFERENCE 16.

ANALYSIS METHOD	MATERIAL	NO. OF DATA SETS	NO. OF DATA POINTS	AVERAGE SAMPLE SIZE
SENDECKYJ	GRAPHITE/EPOXY	120	2925	24
INDIVIDUAL WEIBULL	GRAPHITE/EPOXY	59	830	14
	E-GLASS/EPOXY	26	450	17
	STEP-LAP BONDED JOINT	23	419	18

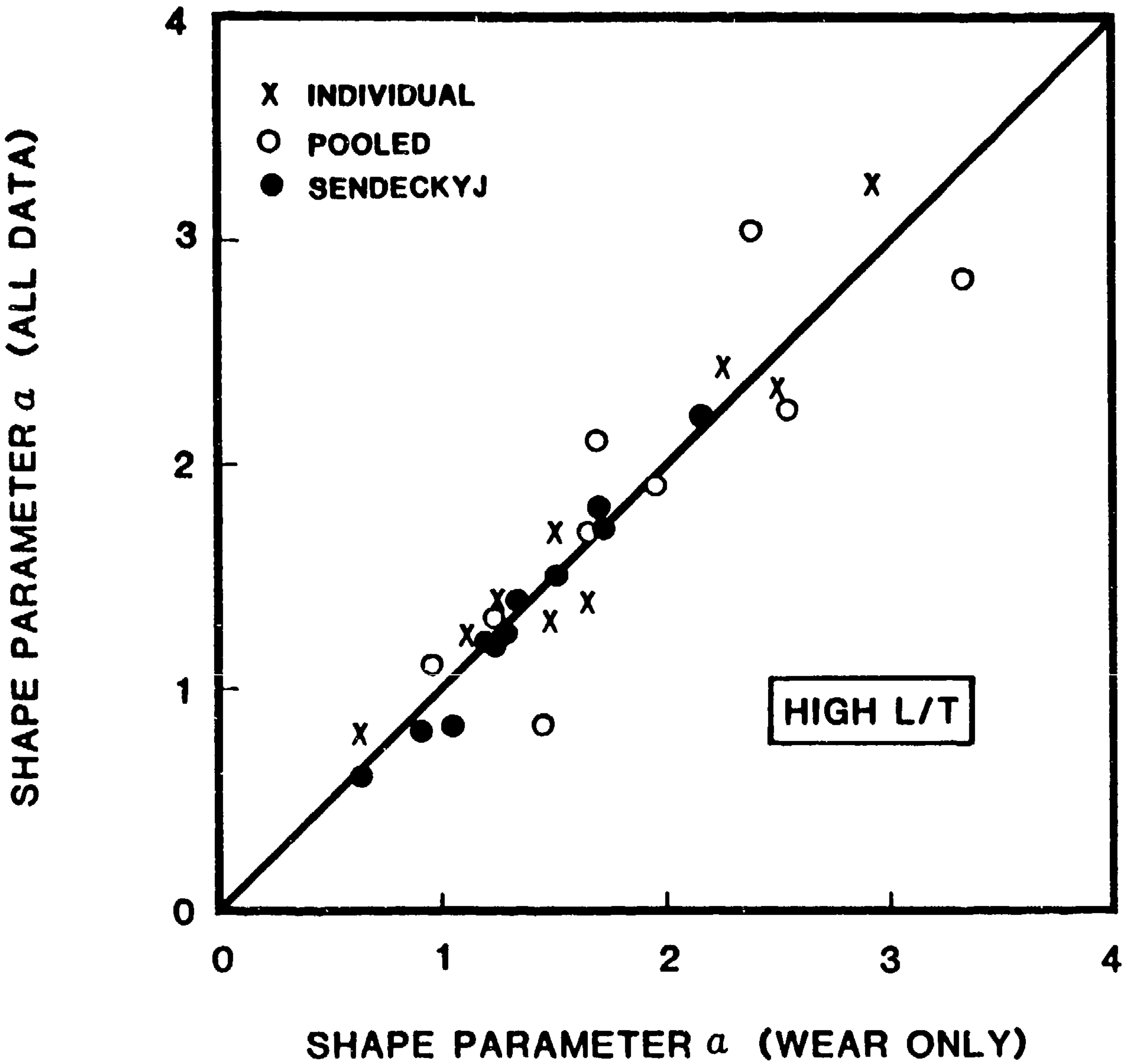

FIGURE 30. INFLUENCE OF MIXED FAILURE MODES ON FATIGUE LIFE SCATTER (NAVY HIGH LOAD TRANSFER DATA).

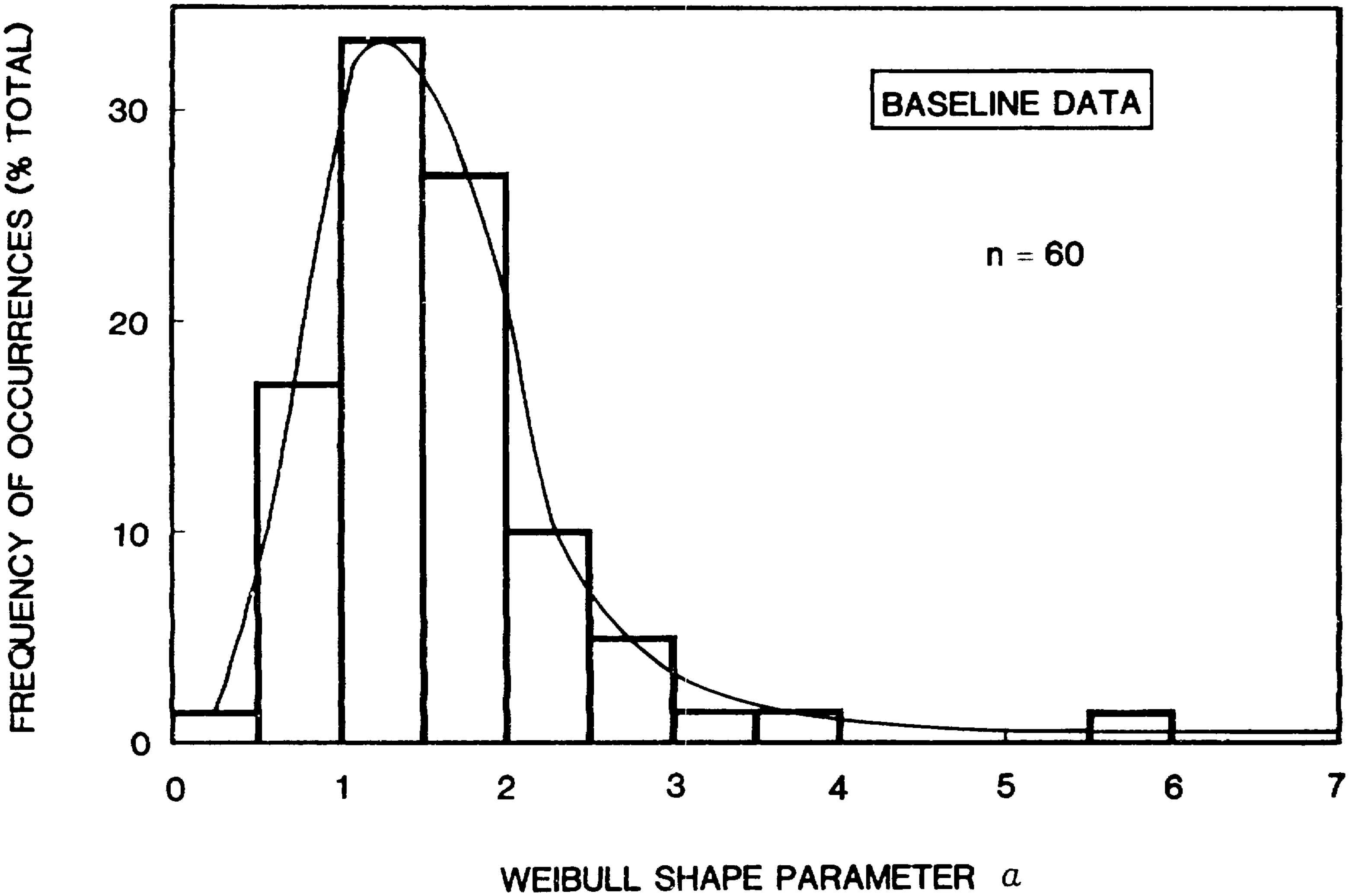

FIGURE 31. FATIGUE LIFE SCATTER DISTRIBUTION (BASELINE DATA).

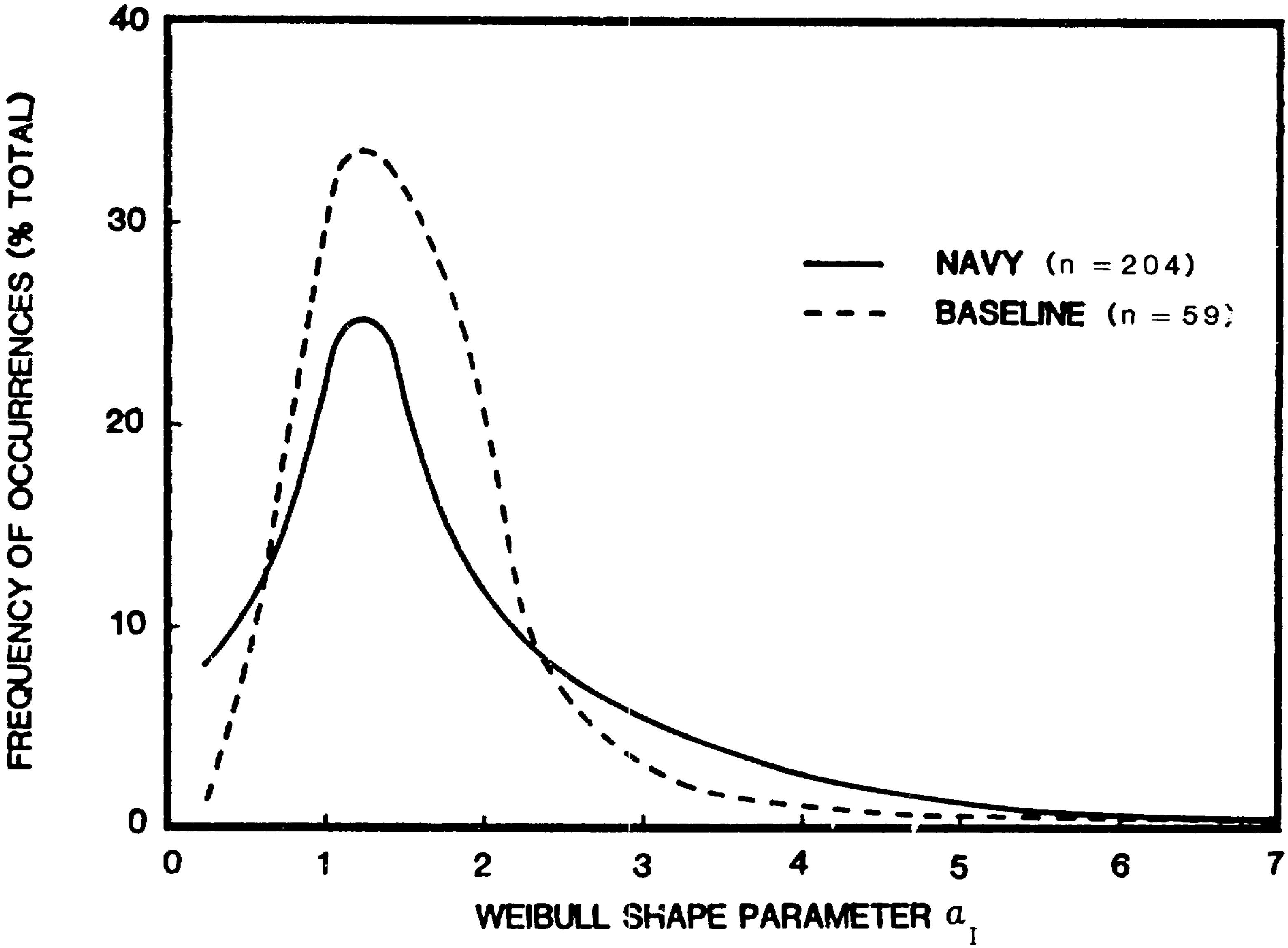

FIGURE 32. COMPARISON OF THE FATIGUE LIFE SCATTER DISTRIBUTIONS FOR NAVY AND BASELINE DATA.

4.3 Combined Data

The Navy and baseline data sets are pooled to form a combined data set. The distribution of α values for the combined data set is shown in Figure 33. Table 25 presents a comparison of the mean, modal and B-Basis α lues for the Navy, Baseline and combined data sets. All three data sets have the same modal α value. The Navy data have a higher mean α and a lower B-Basis α value than the Baseline data. This implies less fatigue life scatter in the Navy data, but more dispersion in the distribution of the α values. However, statistical significance checks showed that the differences in Mean and B-Basis α between the Navy and Baseline data sets is not significant.

Based on detailed comparisons of the Navy fatigue data with the extensive Baseline fatigue data base, it can be concluded that the Navy data fits well within the overall composite fatigue data base.

4.4 Comparison of Static Strength and Fatigue Life Scatter Distributions

Figure 34 shows a comparison of static strength and fatigue life scatter as determined by the Individual Weibull analysis. It can be seen that the fatigue life and static strength scatter distributions have similar shapes. However, fatigue life exhibits significantly more scatter than static strength.

4.5 Comparison of Composite and Aluminum Fatigue Life Scatter

An extensive investigation of fatigue life scatter in 2000 and 7000 series aluminum alloys was conducted in Reference 17. The fatigue life scatter data in this reference are used to generate the scatter distributions shown in Figure 35. It should be noted that the fatigue life scatter data in Reference 17 are carefully censored, such that only data sets containing five or more data points are included for the analysis in Figure 35. Figure 35 shows that for these aluminum alloys, the fatigue life scatter distributions are significantly affected by loading mode. Spectrum fatigue loading exhibits significantly less fatigue life

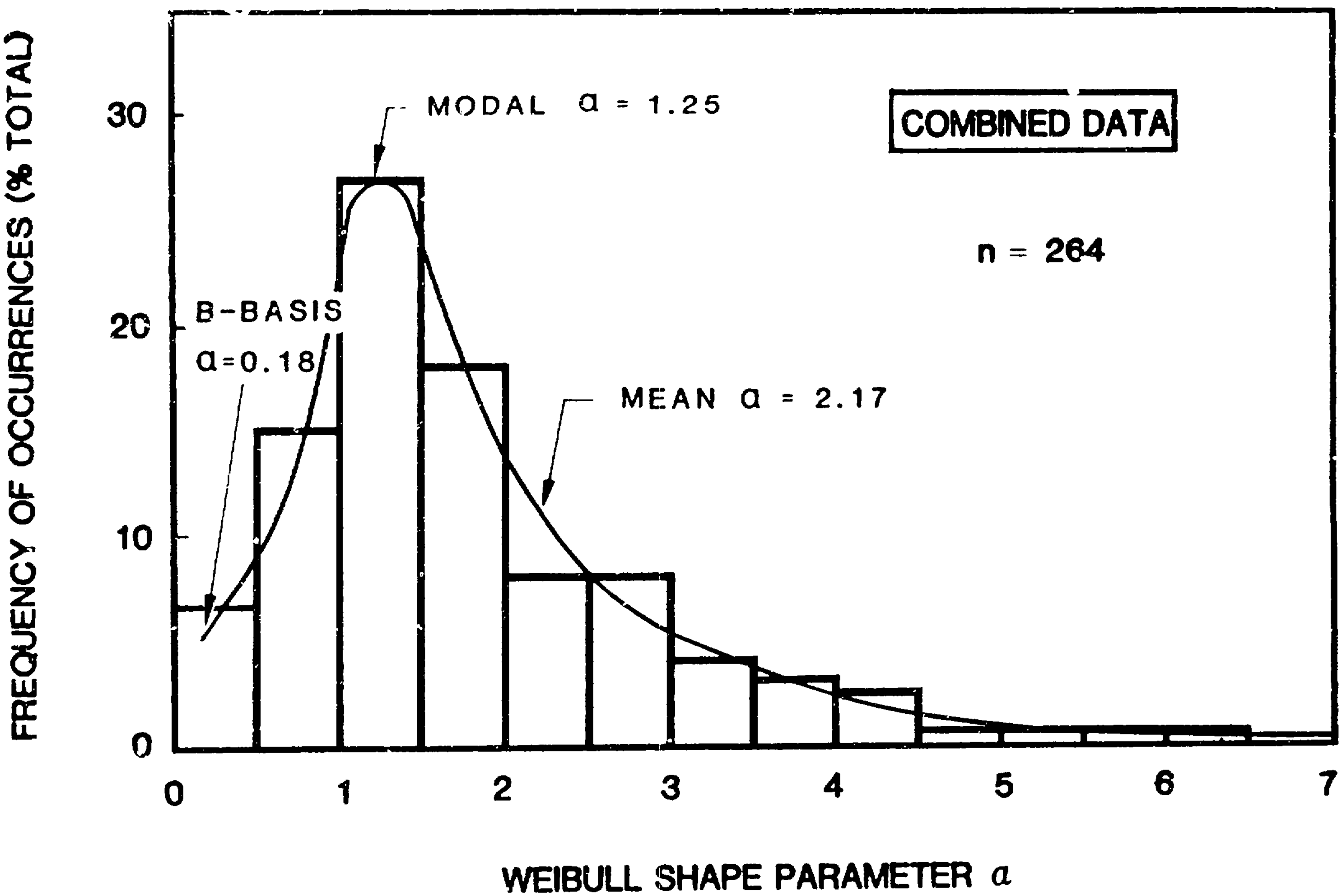

FIGURE 33. FATIGUE LIFE SCATTER DISTRIBUTION FOR COMBINED DATA SET.

TABLE 25. COMPARISON OF FATIGUE LIFE SHAPE PARAMETERS FOR NAVY, BASELINE AND COMBINED DATA SETS.

DATA	MEAN α	MODAL α	B-BASIS α
NAVY	2.29	1.25	0.17
BASELINE	1.68	1.25	0.26
COMBINED	2.17	1.25	0.18

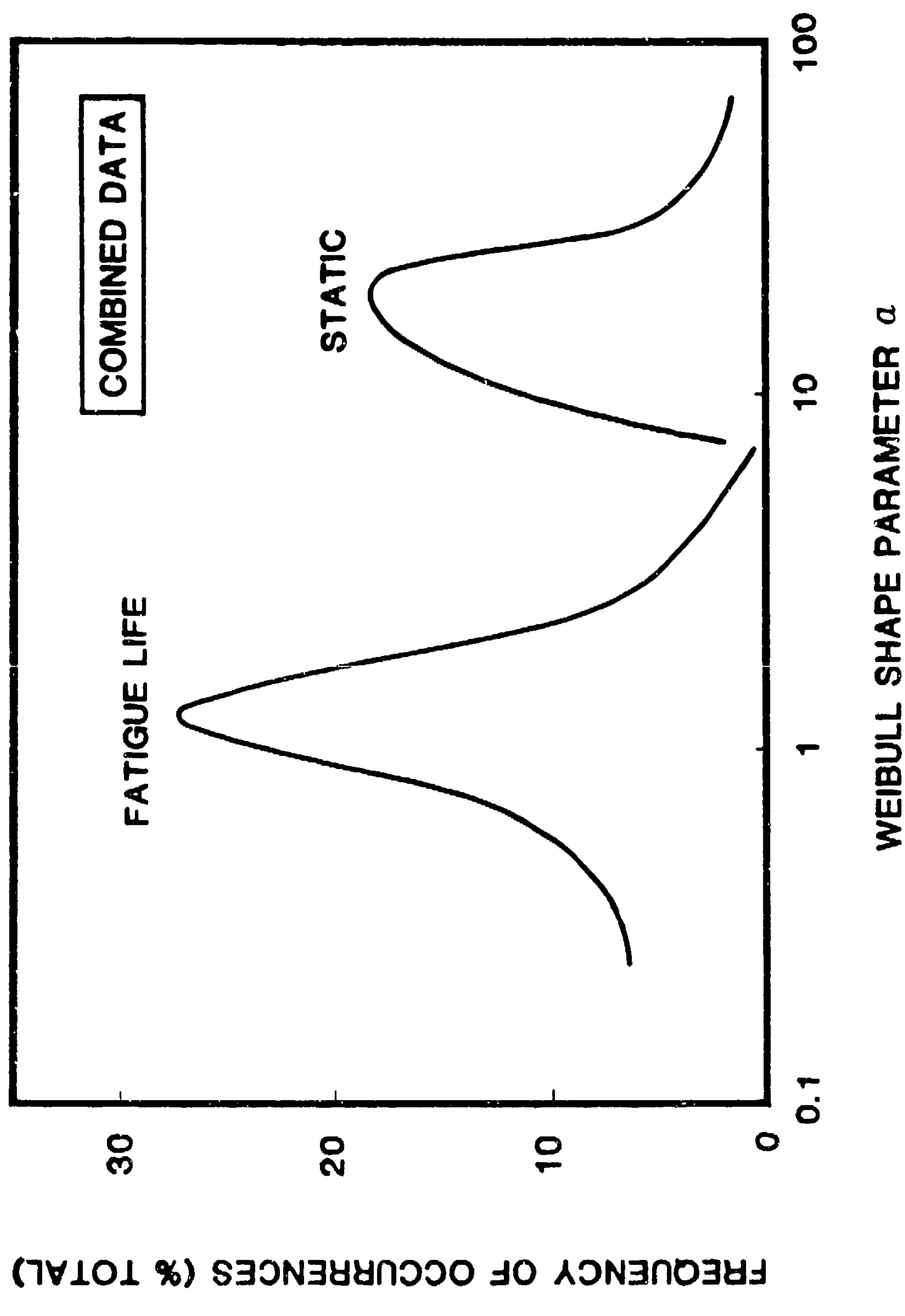

FIGURE 34. COMPARISON OF STATIC STRENGTH AND FATIGUE LIFE SCATTER DISTRIBUTIONS.

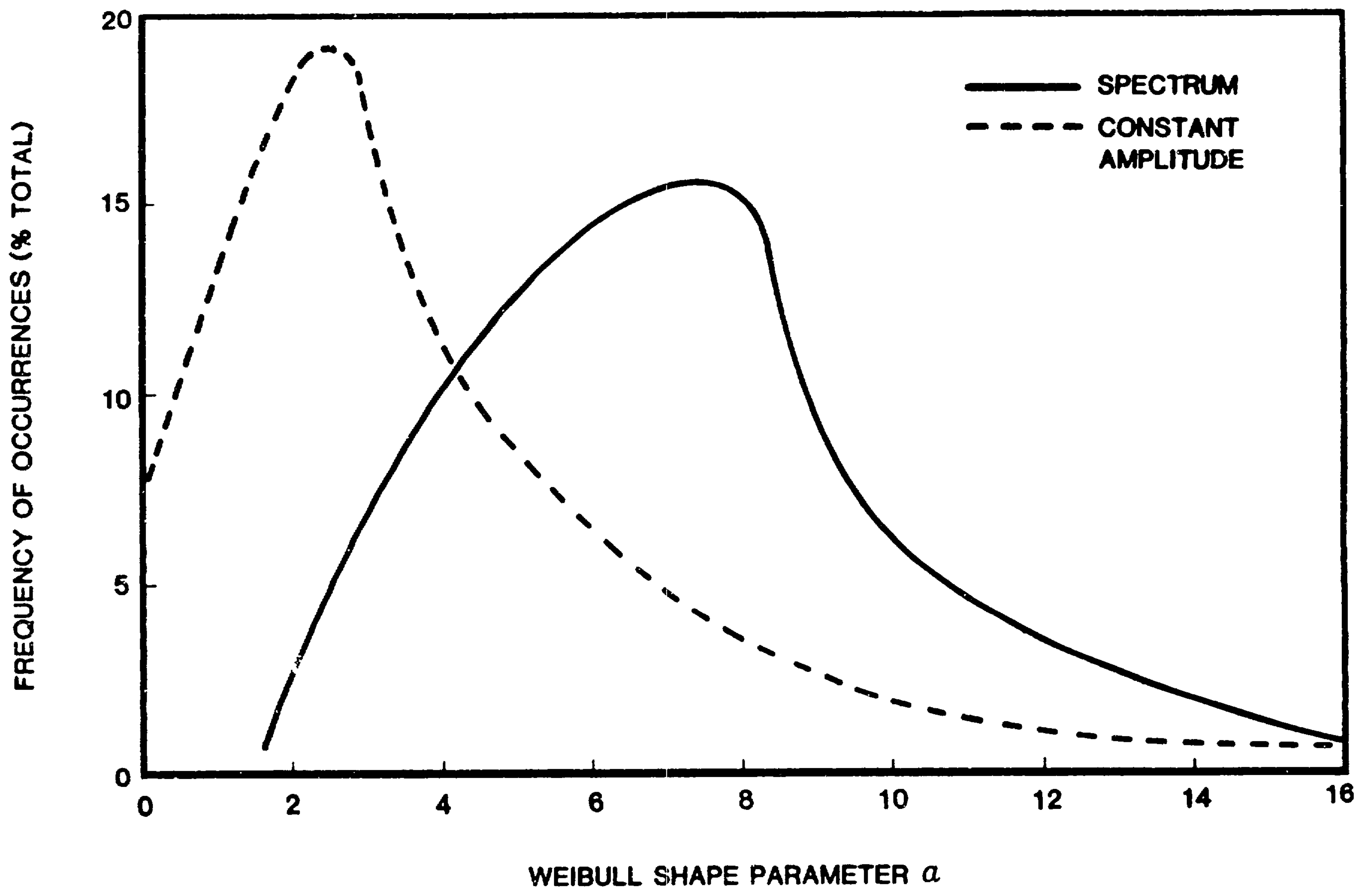

FIGURE 35. FATIGUE LIFE SCATTER DISTRIBUTIONS FOR 2000 AND 7000 SERIES ALUMINUM ALLOYS.

scatter. This is different from that observed for graphite/epoxy composites, where Figure 36 show that constant amplitude and spectrum loading exhibits very similar life scatter. The reason for this difference is related to the relative slopes of composite and aluminum stress-life curves. Composite S-N curves are relatively flat and have approximately a constant slope. This leads to composite life scatter being independent of fatigue load level and fatigue life as shown in Figure 3, 21 and 22. In contrast, aluminum alloys have S-N curves which vary considerably in slope. The slope decreases as fatigue life increases. This causes fatigue life scatter in aluminum alloys to increase as fatigue life increases (Reference 17). In spectrum fatigue tests of aluminum alloys, the major part of the total damage is caused by the higher load levels. Thus, spectrum tests are effectively low-cycle, low-life fatigue tests (even though the total number of spectrum cycles is large) and will, therefore, exhibit lower life scatter.

Figure 37 shows a comparison of the fatigue life scatter distributions for graphite/epoxy composite and aluminum. The aluminum spectrum loading life scatter is used in this comparison since certification testing is invariably conducted under spectrum loading. Figure 37 shows that graphite/epoxy laminates exhibit considerably more life scatter than aluminum alloys.

Table 26 presents a summary of fatigue life shape parameters for graphite/epoxy, E-glass/epoxy and aluminum. The data show that both graphite/epoxy and E-glass/epoxy exhibit similar life scatter, which is significantly higher than that exhibited by aluminum alloys.

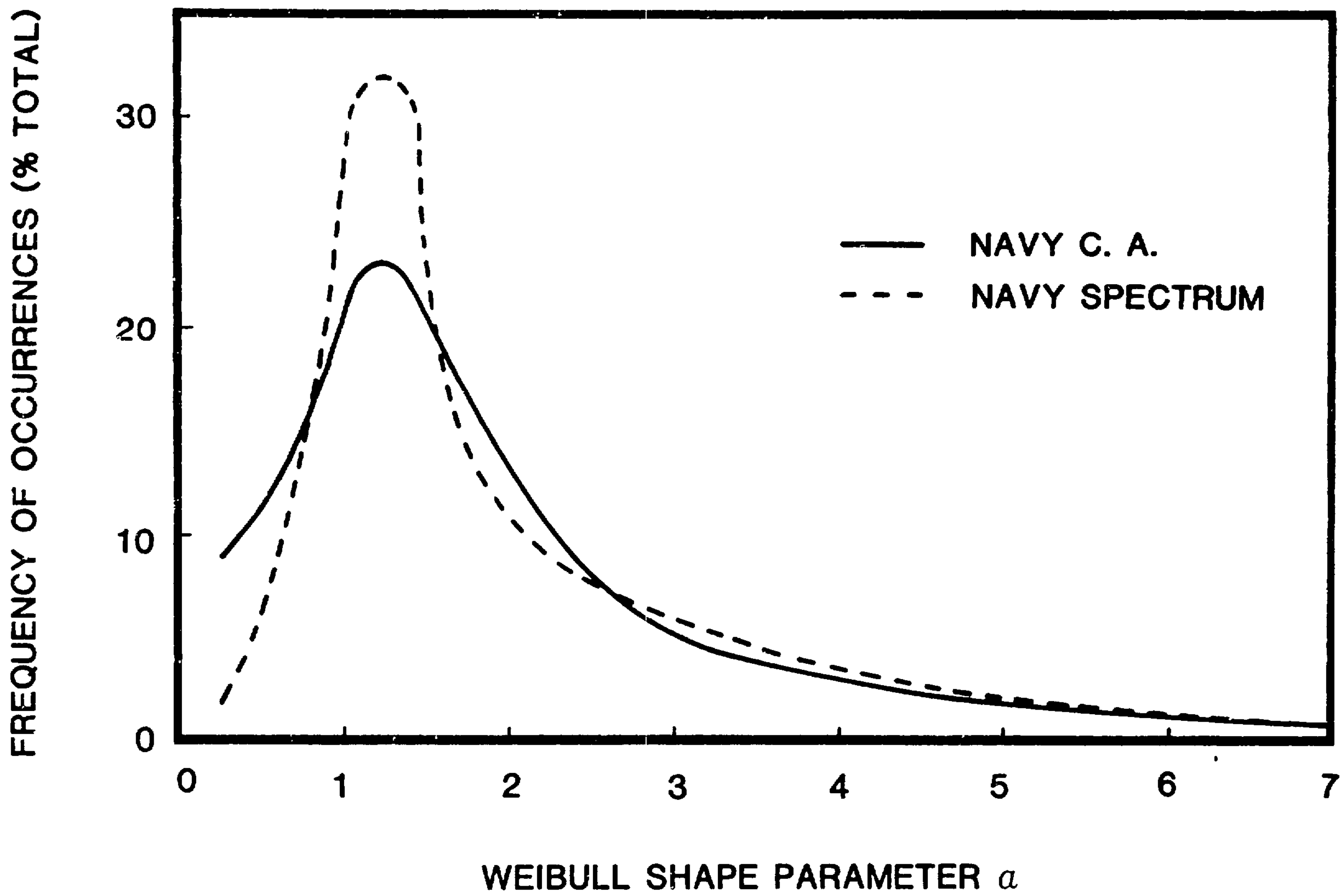

FIGURE 36. INFLUENCE OF FATIGUE LOADING MODE ON COMPOSITE LIFE SCATTER (NAVY DATA).

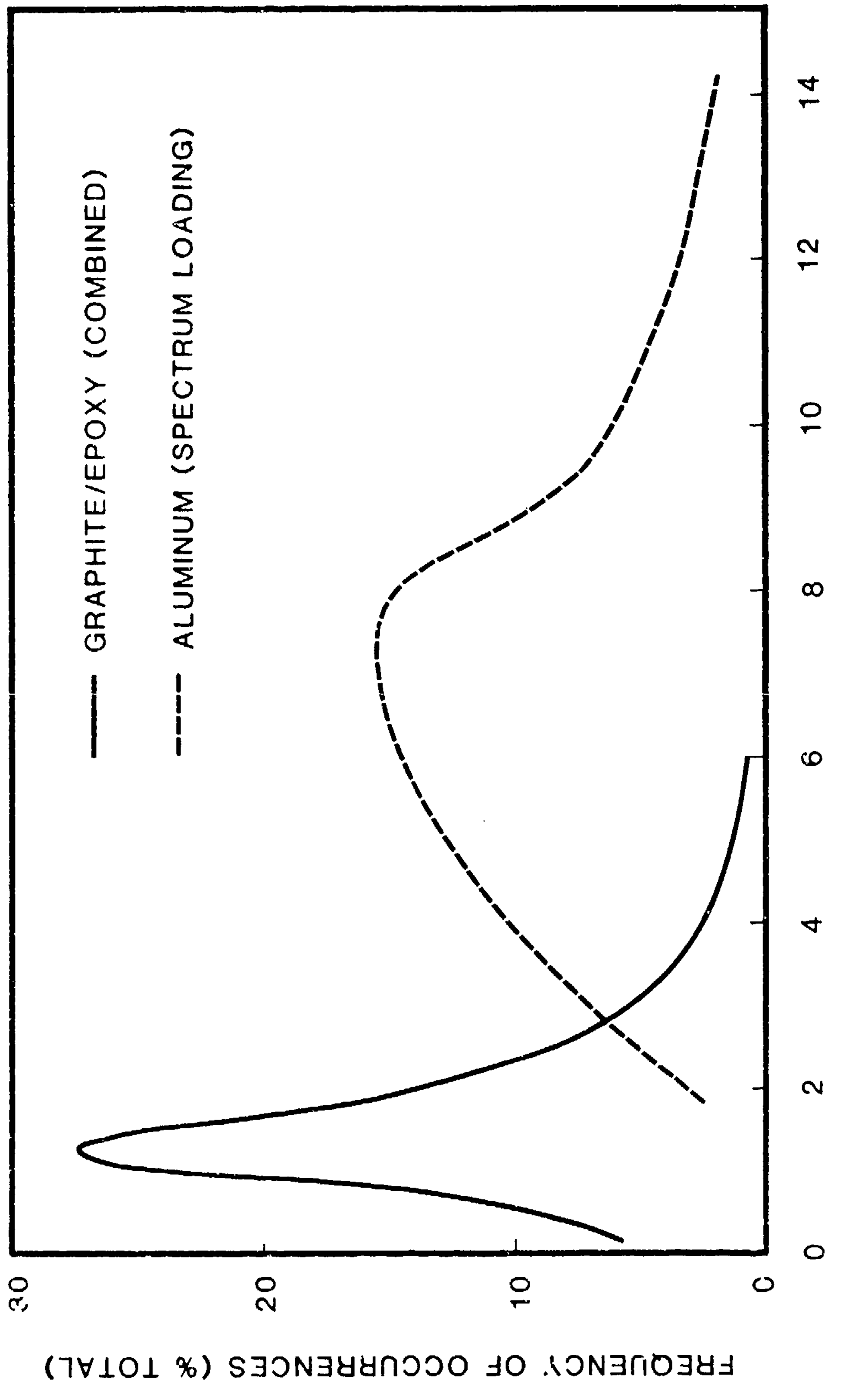

FIGURE 37. COMPARISON OF GRAPHITE/EPOXY AND ALUMINUM FATIGUE LIFE SCATTER DISTRIBUTIONS.

TABLE 26. SUMMARY OF FATIGUE LIFE SHAPE PARAMETERS.

MATERIAL	LOADING MODE	WEIBULL SHAPE PARAMETER, α		
		MEAN	MODAL	B-BASIS
GRAPHITE/EPOXY	ALL	2.17	1.25	0.18
E-GLASS-EPOXY	ALL	2.10	2.15	1.20
ALUMINUM	CONSTANT AMPLITUDE	4.30	2.50	0.80
	SPECTRUM	7.70	7.50	2.60

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the results of Task I data analysis, the following conclusions can be made:

1. Navy data (Reference 4), both static strength and fatigue life, fits well within the overall composite data base published in the literature.
2. Composite fatigue life exhibits significantly higher scatter than static strength (more than one order of magnitude in Weibull shape parameter).
3. Composite fatigue life scatter is significantly higher than that exhibited by aluminum alloys.
4. Composite static strength scatter is not significantly influenced by test variables such as loading mode, specimen geometry, test environment and laminate lay-up.
5. Composite fatigue life scatter is not significantly influenced by load level, loading mode, laminated lay-up, fatigue life, and failure mode. This justifies the use of pooling techniques in fatigue data analysis.
6. Composite fatigue life scatter may be influenced by R-ratio, specimen geometry and environment.

5.2 Recommendations

This section contains recommendations for statistical analysis techniques for the determination of composite data scatter and static strength and fatigue life scatter values.

1. The two-parameter Weibull distribution is recommended for static strength and fatigue life test data scatter analysis for the reasons stated in Section 2.

2. The use of a Weibull analysis for fatigue life scatter determination requires a large number of test replications at each stress level. Where these types of data are not available or it is uneconomic to obtain such data, a pooled analysis method is recommended. The recommended pooling analyses are the Joint Weibull analysis and the Sendeckyj analysis.

3. It is recommended that the modal values of α calculated from the combined data base for static strength and fatigue life be used to determine graphite/epoxy scatter factors. The values are:

Static Strength	α_S	= 20.0
Fatigue Life	α_L	= 1.25

Although both the static strength and fatigue life Weibull shape parameters were shown to be significantly influenced by some test parameters, single values are recommended for the following reasons:

(1) Simplicity

(2) Modal α values are lower than mean α values and, therefore, represent conservative values.

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