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ESTABLISHMENT OF A UNIFORM FORMAT FOR DATA REPORTING OF STRUCTURAL MATERIAL PROPERTIES FOR RELIABILITY ANALYSIS

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1993

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ESTABLISHMENT OF A UNIFORM FORMAT FOR DATA REPORTING OF STRUCTURAL MATERIAL PROPERTIES FOR RELIABILITY ANALYSIS

In recent years the SSC has instituted several studies in developing reliability based design methods for marine structures. Inherent in the process is the need to define the uncertainties of the design parameters. This report proposes a material property reporting format that is based on the earlier report SSC-352 and adds to it the necessary statistical data processing elements. A hierarchy for the data fields is developed to facilitate estimation of values where an insufficient quantity of data exists for a specific property. Recommendations are presented for future development of a working database of material properties.

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16. Abstract

A material property gathering format is proposed with the objective that the database so developed be suitable for deriving statistical measures (mean values, standard deviations, types of distributions) of the property required by reliability and design Engineers. Emphasis is placed on strength and toughness properties of marine steels and their welds.

The format developed and reported in the SSC report 352 was modified by incorporating the findings from a review of the material property representation formats reported in literature and an assessment of statistical data processing requirements. Finally, the concept of hierarchy of the data fields is proposed to facilitate estimation of statistical measures in cases where insufficient data for a specific property is available. The hierarchy approach enlarges the database by ignoring the lowest ranked fields which perceived to have the least influence on the property under consideration. Recommendations are made regarding the next steps that ought to be undertaken to have available a working database/software package.

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METRIC CONVERSION FACTORS

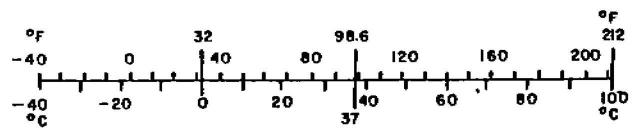
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Nomenclature

Cov(x,y)	covariance of random variables x and y
D(x)	standard deviation of random variable x
E(x)	expected value of random variable x
$F_r()$	cumulative probability distribution function (CDF)
$f_r()$	probability density function (PDF)
G_k, O_k, W_k	limit states design (LSD) or load and resistance factored design (LRFD) dead, live and wind load effect characteristic values
k	standard normal deviate identifying design load and/or resistance values
n	number of observations in a sample
P_f	probability of failure
P_s	probability of survival or reliability
r, R	resistance value, resistance distribution
s, S	load value, load distribution
V	coefficient of variation (σ/μ)
α	fractile identifying a characteristic value
β	reliability index
Θ	central safety factor (μ_r/μ_s)
μ_x	mean of random variable x
ρ_{ij}	correlation coefficient of the ith and jth random variables
σ_x	standard deviation of random variable x
Φ, Φ^{-1}	standard and inverse standard normal cumulative probability distribution functions

1.0 INTRODUCTION

1.1 Background

In recent years, there has been a great increase in the size and complexity of marine steel structures. Economic and safe deployment of such structures has fostered significant advances in structural analysis techniques as well as the use of a wide variety of steels in terms of their mechanical properties and ease of fabrication. Concurrently, the structural design practices have also been developing, and one of the notable trends has been towards reliability based design procedures as opposed to the deterministic design based on minimum specified properties.

Implementation of reliability based design procedures requires, amongst other things, material properties based on statistical or probabilistic considerations. For this reason and in order to better understand material property variability, several organizations have gathered appropriate data to form material property databases. However, in order to ensure that such databases are useful to the design community, one must be cognizant of the quality of the data therein. Secondly, the lack of complete uniformity in testing and reporting procedures, and incomplete testing or reporting for new materials requires that the databases be both adaptable and general enough to collect and interpret the data.

1.2 Objective

In the present project, the focus has been the tensile and toughness properties of ship structural steels and their weldments. From the ship design point of view, the potential for fatigue crack initiation and propagation is another important consideration. However the fatigue crack initiation life depends primarily on the geometry of the welded structural detail and less so on the material or weld zone properties. Due to these considerations, the material properties related to fatigue life (i.e. C & m from Paris law) are not included in the scope of this project.

A previous Ship Structure Committee (SSC) project[1], "Marine Structural Toughness Data Bank" (SSC 352), developed a format (FORMAT.TXT) for storing strength and toughness data of parent plate materials and their welds. The present project can be considered as an extension of the previous one and having the following two objectives:

i) to review the existing database to ensure that its format incorporates all of the data required in current and potential design practice;
ii) to ensure that the format is suitable for use in reliability-based design.

Figure 1.1 illustrates the relationship of the two objectives of this project. The first objective is to develop a material property database format which efficiently and effectively stores individual test information and results, while the second objective is to specify the requirements of a program which will act as a user interface in the retrieval, manipulation and quality assurance of the collected data.

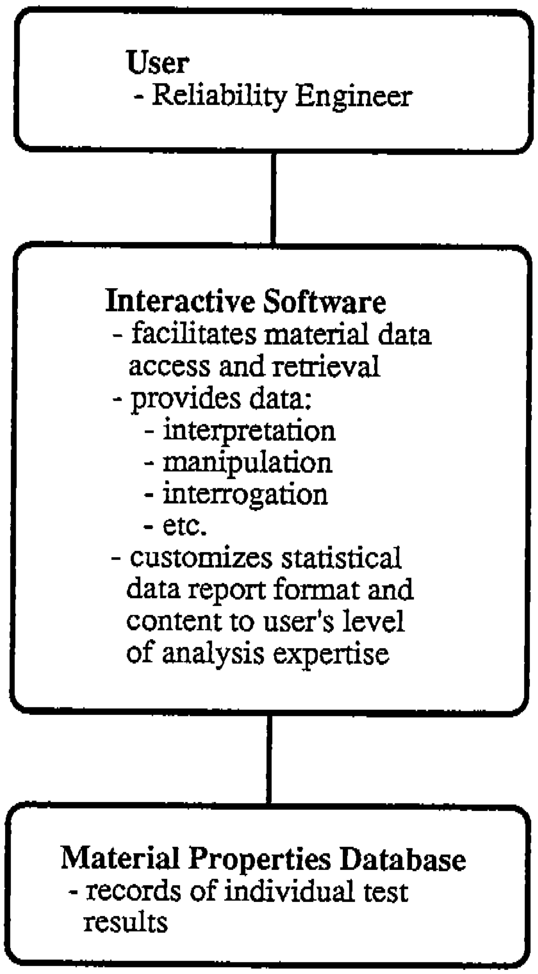

Figure 1.1: Project Objectives

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1.3 Overview of the Current Project

The material property data collection and recording format developed in the previous project (FORMAT.TXT) has been retained in general in order to facilitate the transfer of existing data. However, certain modifications have been incorporated based on the reviews carried out in this project.

The report which follows provides details of the project starting with a review of existing technology, including a critique of the existing database (Section 2.0) and a review of other material property databases, both from the literature and personal contact with their developers (Section 3.1). Further background information regarding the statistical requirements of reliability based design and statistical data quality control is discussed in Sections 3.2 and 3.3, which provides the basis for recommendations concerning the statistical calculations which the database should be capable of performing.

With a knowledge of the current state-of-the-art, the existing database or format was modified and the reasoning behind the modifications are described in Section 4.0. In order to help potential users identify the relative importance of the pieces of information in the data format, a data hierarchy was developed and is described in Section 5.0. Sections 6.0 reviews the statistical requirements of a database for use in reliability-based design in the form of a specification for the database program. Finally, the next steps to develop and have available a computerized material property database suitable for use in reliability based design are described in Section 7.0.

2.0 REVIEW OF THE EXISTING DATABASE FORMAT (SSC Report 352)

This task involved assessment of the material property data collecting and reporting formats. The review indicated that the important materials were marine steels and their weldments identified by the SSC. The material properties of interest are strength and toughness, which are also the primary properties of interest when employing the reliability approach to design.

In the data gathering format (FORMAT.TXT), importance is placed on material identification and processing associated with the test record. In the case of weldment testing, the fields for a detailed description of the welding information are included. Test records for tensile, fracture toughness, impact toughness, crack arrest toughness, drop weight and dynamic tear are also in the database. As will be seen in the next three sections, this approach is retained in the recommended format with some modifications.

The modifications that were identified as necessary to the data collecting format, (FORMAT.TXT) were generally for the following purposes:

i) statement of the purpose of the test (quality assurance, mill certificate, research and development or other),
ii) deletion of the section on total processing history (as final processing information is sufficient),
iii) modification of the fabrication details to include the hot rolling details and/or any subsequent heat treatment (i.e. normalizing, quenching and tempering),
iv) quality assurance (Q.A.) level identification of producer, and test data source ISO ratings; these fields will become important after the Q.A. of the source is ranked by ISO certification,
v) recognition of the availability of large data sets in statistical formats but without individual test records (for example from steel producers).

The primary reason for the above changes was to facilitate the establishment of a hierarchy of the fields of importance when recording data for a specific property (test procedure). This will help to select the important fields that should have common information before pooling. However, the recommended changes do not ignore the use of the database for other purposes, for example, as a deterministic material property data reference source, quality assurance purposes, etc. and therefore, more fields are included in the format than absolutely required for reliability analysis.

The data collecting formats for nil ductility transition temperature (NDTT) and dynamic tear were obtained from the authors of the report as they were not included in the SSC 352 report. These were also reviewed with the above objective.

3.0 DATA FORMAT AND STATISTICAL REQUIREMENTS: BACKGROUND

In this section the background information which is used as the basis for recommendations offered later in the report is reviewed. The background information which was collected can be divided into three groups:

i) existing material property data collection schemes;
ii) current approaches to reliability analysis and their statistical data requirements; and
iii) additional statistical requirements for data quality control.

3.1 Material Property Representation Formats

In this section, the salient features of *other* data collection (reporting) and representation formats are described. These formats can be categorized as either deterministic or statistical. Deterministic formats represent material properties by minimum specified values, whereas a statistical representation could take the form of a probability distribution expressing the likelihood of a specific material property being below or exceeding a specified value. Both, the form of the data and the requirements of the program associated with these forms of databases differ.

3.1.1 Deterministic Material Property Data Representations

Even though the objective of this project is develop a probabilistic material property database, deterministic databases were reviewed because they represent the majority of the existing ones. Furthermore, the specific material test data which are relevant to deterministic design are also relevant in reliability-based design. Therefore, in order to assess the state-of-the-art in data collection and representation, significant non-statistical or deterministic databases were studied. The following sections summarize the information gathered from each source.

3.1.1.1 Metals Data file and Met. D.B.

Both of these databases are available on-line from ASM International. The information contained in the "Metals Data file" is collected by the Editorial Committee of ASM International, while in "Met. D.B." information obtained from manufacturers is presented. These two databases are periodically updated.

3.1.1.2 Materials Property Data (MPD) Network

This database can be accessed on-line through STN International. In the "MPD Network" a number of databases are available for different categories of materials; for example, the database developed for SSC 352 is available as MARTUF.

3.1.1.3 Recommendations of ASTM Committee E 49 on Computerization of Material and Chemical Property Data

ASTM Committee E49 on Computerization of Material and Chemical Property Data has various sub-committees of which the relevant ones are the following:

i) E 49.01 on Material Descriptions
ii) E 49.02 on Material Properties
iii) E 49.05 on Data Quality
iv) E 49.04 on Data Exchange.

The E 49.02 Committee has established material property reporting (collecting) formats for tensile properties, fracture toughness, and notched impact testing which are of interest to this project. These are presented as appendices in ASTM E 1313 - 91a "Development of Standard Data Records for Computerization of Material Property Data".[2] These recommended standard data formats for the computerization of test data call for the complete record of the test procedure, results and analysis. A selected number of fields in this standard data format are further identified as essential fields, i.e., the input for these fields must be available for the property record to be included. Each committee considers the recommendations and standards produced by the other above mentioned sister sub-committees. For example, the fields concerning material identification in ASTM E 1313-91a should comply with ASTM E 1338 -90 "The Identification of Metals and Alloys in Computerized Material Property Databases"[3] which is the responsibility of the E 49.01 sub-committee. Most of the test and material identification fields are listed as essential.[2] The purpose of complete identification is to facilitate efficient storage and retrieval of information with a computer, and to allow meaningful comparison of data from different sources.[3] These requirements ensure the traceability of the raw data which is important requirements for the development of a statistical database.[4,5] The standardization of the reporting procedures ensures the establishment of a uniform format and also helps in data exchange, both of which are important requirements for the development of a statistical database.

The most recent document is ASTM E 1484 - 92 "Formatting and Use of Material and Chemical Property Data and Database Quality Indicators" [6] which is the responsibility of the E 49.05 sub-committee. The relevant quality indicators applicable to the present program are: source of data, statistical basis of data (reference is made to MIL-HDBK-5[7, 8]), validation, evaluation and certification status, completeness of materials information and completeness of test procedure description. These activities are on the leading edge of the developments in this area.

3.1.1.4 Recommendations of AWS Committee A9 on Computerization of Welding Information

In parallel with the activities of ASTM committee E 49 is the work of American Welding Society (AWS) Committee A9, leading to the publication of two standard formats for computerization of data:

i) ANSI/AWS A9.1-92 Standard Guide for Describing Arc Welds in Computerized Material Property and Nondestructive Examination Databases[8]
ii) ANSI/AWS A9.2-92 Standard Guide for Recording Arc Welds in Computerized Material Property and Nondestructive Examination Databases[9]

These standards adopt a similar approach and make frequent references to ASTM E 1313 and E 1338. In proposing modifications to the materials data reporting (collecting) format in this project, the information provided in ASTM and AWS documents was also considered.

3.1.2 Statistical Material Property Data Representations

In the following paragraphs, a brief review of the available material property data collection or statistical processing procedures will be presented. The concerns and approaches of each towards data quality and statistical parameter estimation will be presented to illustrate the state of the art of probabilistic data collection for material property estimation.

3.1.2.1 MIL-Handbook

The U.S. Military Handbook (MIL-HDBK 5F), "Metallic Materials and Elements for Aerospace Vehicle Structures"[4,7] outlines guidelines for test data presentation in two volumes. The first volume presents the statistically processed data values recommended for use in aerospace design, while the second volume describes the statistical methods and guidelines involved in the development of recommended design values. The guidelines ensure that the material properties to be compared with specified values reflect the actual material properties as closely as possible. Four characteristic values (basis categories) are defined as:

A	-	99th percentile with 95% confidence
B	-	90th percentile with 95% confidence
S	-	minimum industrial specification
Typical	-	average (without confidence interval)

To ensure that the A and B-bases represent the current processing capability associated with a material, all available test data for material that has been produced for the government, industry or equivalent company specification in question are included in the calculations whether or not the material meets the mechanical property requirements of the specification. Only positive proof of improper processing or testing is cause for exclusion of test data, except that the number of tests per lot shall not exceed the usual testing frequency for the product. It is recognized however, that extensive acceptance testing resulting in the elimination of low-strength product from the population may justify establishment of higher mechanical property values of the remaining material.

Current practice in the presentation of room temperature property values is as follows[4]:

i) Tensile ultimate and yield are presented in A or S-basis; 'A' values that are higher than 'S' values are given only in footnotes and are qualified as not for use in design, pending revision of specification requirements. However, 'A' values that are equal to or lower than 'S' values replace 'S' values in the document following approval.
ii) The S-basis is not used where property values are presented on an A-basis, except for elongation and reduction in area (R.A.).
iii) If an A value is presented for a strength property, then a B value is presented as well.
iv) Elongation and R.A. are presented on an S-basis only.
v) Design data for all other properties, such as modulus of elasticity (E), Poisson's ratio, creep, fatigue, and physical properties are presented on a typical basis unless indicated otherwise.

The remainder of the second volume describes the statistical methods, models and assumptions associated with the development of the A and B values. A well organized description of the recommended statistical process and a series of examples are used to illustrate sample pooling, distribution selection, parameter estimation and statistical significance testing of material properties. The MIL-HDBK indicates that the development of normal or Weibull statistical parameters is restricted to samples with 100 or more data points, whereas nonparametric (i.e. geometric series) estimation of characteristic values is restricted to data sets with more than 300 observations. The indirect methods of characteristic value estimation for small samples, use related data to help draw inferences concerning the sample data. The indirect methods are recommended for those material properties with well known relationships and statistical properties.

The statistical methods are similar to those needed for the SSC database of material properties. While the MIL-HDBK focused on the provision of representative deterministic material property values, the SSC database is being developed in part for users in need of frequency distribution information. The MIL-HDBK indicates that all material property information should be used in the development of statistical information regardless of whether it passes associated minimum specified industry standards. This requirement for the inclusion of complete data samples will alleviate the effects of distribution truncation, but will also limit the sources of test data for users of the MIL-HDBK. The MIL-HDBK's guidelines for recommended practice are restricted to the development of characteristic design values from normal or three parameter Weibull distributions and noncompliance with these distribution types necessitates the use of nonparametric statistics for large samples.

3.1.2.2 Modern Statistical Materials Selection

A series of five articles, "Modern Statistical Materials Selection"[10-14], introduced the significance of the statistical nature of material properties and the application of probabilistic design concepts. In the first article, "Some Basic Concepts"[10], material properties are introduced as random variables and the basic terminology and process of statistical representation is presented. The article presents the normal distribution and describes the use of confidence limits. The second installment of the series, "Random Variables and Reliability"[11], introduces probability and reliability analysis concepts and indicates how they are used in the material selection process. A "first order" approach to reliability analysis is described along with some definitions of probabilistic analysis terminology. The article is concluded by an indication of the limitations of reliability analysis based on a summary of the uncertainties which are non-statistical in nature and can not be described statistically. The third article, "The Price of Safety"[12], reviews the benefit/cost relationship inherent in the design of "fail safe" systems and the development of reliability based design standards. "Building a Database"[13], the fourth article of the series, outlines the statistical quality control tests (confidence intervals or hypothesis testing) which can be applied to sample data. Statistical tests which indicate statistically significant differences between groups of data and test the derived statistical parameters are presented. This review of statistical precision or quality, with reference to normally distributed data, indicated a desire to segregate significantly different data to ensure the quality of the resulting estimates. The final article of the series, "Correlation and Computers"[14], provides several basic programs to illustrate the role computers can play in the collection, presentation, analysis and interpretation of quantitative numerical data.

The series of articles is a good basic introduction to the statistics applied to engineering and reliability. The scope of the statistical analysis does not include distributions other than the normal distribution and the review of reliability analysis is very brief. The basic nature of the information and brevity of the series are understandable due to the target audience and the media through which it was presented. Subsequent to these articles, the author has published a book [15] which provides a more comprehensive review of the subject matter.

3.1.2.3 Creating a Common Materials Database

A database of material properties, similar to the focus of this project, developed for the aerospace industry was presented in "Creating a Common Materials Database"[5]. The goal of the database was to provide a statistical data source for advanced material properties for use in conventional design practice or reliability-based design analysis. The article highlighted the importance of data pedigree. To ensure the quality and integrity of the data, the database data collection procedure incorporates data pedigree certainty, anomalous data detection and standardized testing procedures incorporating specified data recording formats. Together these features serve to increase the confidence in derived statistical distributions and characteristic values. It was suggested that a minimum of 30 material property observations are required from at least three lots before any statistical information can be estimated. The sample size requirement is a subjective decision based on statistical measures which measure confidence for normal statistic estimation. As this article described a commercial software package, further details concerning the statistical data processing were not available.

As the above indicates, at least in the realm of high technology aerospace applications and advanced materials, a great deal of effort is being expended in the standardization of testing and data, data traceability and thus statistical parameter quality control.

3.1.2.4 ASTM Specifications and Committees

ASTM provides some guidance in the development of statistical data through its standards. ASTM E 177-90a[16] provides guidance concerning the use of the terms precision and bias in materials testing. According to the definitions provided, precision is a measure of test data variability which is represented by the reciprocal of the sample standard deviation $(1/\sigma)$. Bias is defined as the pattern of differences between a large sample of test data (minimum 30 observations) from a specified test procedure of a specific material from a unique source and an accepted set of reference values. Bias can be systematically removed from a sample based on comparison with the accepted reference values. A major difficulty in measuring bias is the lack of acceptable reference values.

As differences in test procedures between different laboratories affect test results, the ASTM developed a process to gauge the magnitude of this problem. ASTM E 691[17], involves the conduct of tests to determine the precision of the results of standardized test procedures. This standard outlines a round robin procedure and the statistics which should be used in the assessment of inter-laboratory test precision. The result of a study which employ this procedure would be of use as an indication of the minimum variation of test results from various testing facilities.

3.1.2.5 Material Property Data Collections

A wide variety of projects have been sponsored for the collection of material property data and the development of sample statistics. This type of project can be used as a source of information indicating the level of statistical accuracy or quality required by the sponsoring agency. Only a small number of the many available research reports are reviewed here for reasons of practicality.

A study of carbon steel plates and rolled shapes[18] investigated the variation of tensile properties at different locations of test plates and sections. The results of the study include a series of charts which indicate the probability of test specimens from various locations having strengths higher than a reference test specimen drawn from the same plate. The charts were developed based on test specimens taken from seven standardized locations on A-572, A-516 and A-537 plates. This study provides statistical information concerning the distribution of material tensile strength while drawing attention to the significance of material processing concerns by supplying a data reporting form to ensure complete specimen information. Multiple linear regression techniques were employed to identify relationships between the tensile strength data and mill practice.

A similar study[19] investigated the variation of Charpy V-notch impact toughness to develop similar performance probability charts for A-572, A-516 and A-537 steel plates. This testing program sought to create a database of test results for each of two specified test orientations of seven specimen locations tested at three temperatures. Gaussian (normal) test statistics were prepared to explain the variation of each sample subset (specimen orientation, test temperature, material property). Linear regression was used to define a relationship between absorbed energy and lateral expansion.

Both of these studies employed normal distributions and reported the data in discrete frequency distributions. The data and results of these studies draw attention to the fact that test data may only be available in grouped form (i.e. intervals or statistical measures).

Material properties presented in the Metals Handbook[20] are in the form of histograms. The yield and tensile strength, yield to tensile ratio, elongation and hardness histograms are based on specimens taken from one mill and include many heats. This data may present a problem owing to the potential uniqueness of mechanical properties resulting from the mill practice particular to the data collection location. The samples are tested according to appropriate ASTM specifications but no uniform data report format is indicated to provide any indication that data pedigree (i.e. testing, fabrication and metallurgical history) was considered.

3.2 Reliability Analysis

One of the objectives of this project is the assessment of the statistical requirements of probabilistic (reliability) analysis. In order to understand the statistical requirements of reliability analysis, it is important to have an idea of the types of processes which it employs. Reliability analysis can be thought of as a generic analysis tool similar to structural analysis techniques which can be applied with different levels of precision, each requiring different types of information. In this section, the basic theory of reliability analysis is presented in general terms so that it is applicable to any design or decision theory problem.

Because of the variety of reliability analysis techniques with different statistical requirements, a classification system has evolved to group the techniques based on the comprehensiveness of their analysis. Four general levels of reliability analysis, based on the amount of information employed, divide the spectrum of analysis procedures. In "Methods of Structural Safety"[21], the levels of reliability analysis are summarized as follows:

- Level I: These reliability methods are based on reliability analysis but are deterministic in form. They employ a design format and one "characteristic" value for each design variable. This probabilistic analysis type includes load and resistance factored design (LRFD) and limit states design (LSD) formats developed using Level II probabilistic analysis procedures.

- Level II: These reliability based design methods estimate probabilities of failure based exclusively on normal distributions. They employ two characteristics of each uncertain or random parameter (i.e. mean and variance) and a measure of parameter correlation. Reliability index methods[22,23] are examples of this type of analysis procedure.

- Level III: These probabilistic design methods estimate probabilities of failure based on the distribution types which best suit the design variables. They employ the joint distributions of all of the uncertain parameters to estimate the probability of failure. This type of analysis can be accomplished by evaluation of the convolution integral.

- Level IV: These reliability analysis techniques employ a global approach incorporating both event probabilities and their associated socio-economic benefits and costs. This type of analysis (i.e. expected cost minimization) is generally reserved for use in those projects whose failure has weighty consequences (i.e., significant economic loss and/or fatalities).

The above mentioned levels of reliability analysis are a general outline of the available design procedures. The fact that analysis methods which incorporate features of more than one of the levels exist does not invalidate the classification system. The system of classification is used as a general frame of reference for discussion and comparison.

The following sections describe: (1) characteristic value based design (Level I) which applies statistically derived resistance factors to minimum specified resistance values (material properties); (2) the development of the resistance factors used in Level I design (LSD or LRFD) and reliability analysis based on normal distributions; and (3) reliability analysis based on any statistical distribution type (Level III methods). The scope of this project does not include those methods involving intangible values (Level IV methods) as these methods are still being developed and rely heavily on subjective judgement. At the conclusion of each section describing a level of reliability analysis, a summary of the required statistical information is provided.

3.2.1 Level I Probabilistic Design

The objective of this type of analysis procedures is to incorporate the safety assurance of probabilistic methods into a design procedure while maintaining the simplicity of deterministic design practice. Level I probabilistic design employs a system of load and resistance factors, developed based on Level II or III reliability analysis methods, in conjunction with characteristic load and resistance values. Level I methods are simply limit states design (LSD) or load and resistance factor based design (LRFD) approaches. A set of load and resistance factors developed to ensure safety are called partial safety factors. The development or calibration of a Level I design standard can be formulated as a code optimization problem (see Section 3.2.2.2).

A code specified partial safety factor design procedure requires that the factored load effects be less than the factored resistance. Table 3.1 describes five code specified partial safety factor design formats. In the partial safety formats G_k, O_k and W_k represent the dead, superimposed (live) and wind load effects respectively. The load and resistance factors illustrated for the various code formats were developed based on Level II reliability methods. Some code formats are developed to provide the same measure of safety or economy as previous design standards while others are developed to provide a consistent reliability against failure.

The sole statistical analysis requirement of Level I design procedures is the identification of the characteristic (typical or specified) design values to be used in LRFD or LSD procedures. The use of characteristic values, in design, is the result of the realization that few design variables have well defined upper or lower bounds which can economically be used in design. Characteristic material property values represent specific material properties with prescribed probabilities of being exceeded. The characteristic value r_α of a random variable r is defined as the αth-fractile of the random variable. The probability of observing a resistance (material property) less than r_α is α, and for a normal distribution this probability is related to the number (k) of standard deviations (σ) from the mean (μ) by the inverse normal cumulative distribution function (Φ^{-1}(k)).

$$\begin{aligned} \mathit{Probability}[r<r_\alpha] &= \alpha \\ &= \Phi^{-1}(k) \\ \mathit{where;}\quad r_\alpha &= \mu_r - k\sigma_r \end{aligned} \tag{3.1}$$

Table 3.1: Code Specified Partial Safety Factored Design

a) Load Factor Formats

Loading Case	USD - Ultimate Strength Design				WSD
	CP110[24]	CEB-FIP Model Code[25]	ACI Building Code[26]	CSA Standards[27,28,29]	AISI - CFS[30]
1) Dead Load + Imposed Load	$1.4G_k + 1.8O_k$	$1.35G_k + 1.5O_k$	$1.4G_k + 1.7O_k$	$1.25G_k + 1.5O_k$	$G_k + O_k$
2) Dead Load + 2 Variable Imposed Loads		a) $1.35G_k + 1.5O_{k1} + 1.5\psi O_{k2}$ b) $1.35G_k + 1.5O_{k1} + 1.5\psi O_{k2}$			
3) Dead Load + Wind Load	$0.9G_k + 1.4W_k$	$G_k + 1.5W_k$	$0.9G_k + 1.3W_k$	$1.25G_k + 1.5W_k$	$G_k + W_k$
4) Dead Load + Imposed Load + Wind Load	$1.2(G_k + O_k + W_k)$	$1.2(G_k + O_k + W_k)$	$0.75(1.4G_k + 1.7O_k + 1.7W_k)$	$0.7(1.25G_k + 1.5O_k + 1.5W_k)$	$G_k + O_k + W_k$

b) Material (Resistance) Factor Formats

Material	CP110[24]	CEB-FIP Model Code[25]	ACI Building Code[26]	CSA Standards[27,28,29]	AISI - CFS[30]
Concrete	1.5 1.3 for accidental load or localized damage	1.5 1.3	No material safety factor but capacity reduction factor $\phi_{bending}=0.9$ $\phi_{shear}=0.85$ $\phi_{axial\ comp.}=0.7\text{-}0.75$	0.6	No material safety factor but capacity factors of safety $\Omega_{tension}=1.67$ $\Omega_{bending}=1.67$ $\Omega_{axial\ comp.}=1.92$
Steel	1.15 1.0 for accidental load or localized damage	1.15 1.0		0.9	

The identification of a characteristic value based on sample observations becomes increasingly uncertain as the number of observations (n) decreases. In the case of resistance values, the probability of the estimated characteristic value being lower than the true characteristic value is called the confidence interval (s) and is generally specified in design standards. Charts which tabulate values of a non-central student-t distribution with n degrees of freedom can be used to identify the characteristic value ($r_{\alpha s}$) with the prescribed confidence interval. When tables for the non-central t-distribution are not available or are not convenient, a close approximation for $r_{\alpha s}$ can be computed[31] as follows:

$$r_{\alpha s}(\textit{with an s\% confidence interval}) \approx \mu_r + k_{\alpha s}\sigma_r$$

$$\textit{where;} \quad k_{\alpha s} \approx \frac{\Phi^{-1}(\alpha) - \Phi^{-1}(s)\sqrt{\frac{1}{n}\left(1-\frac{(\Phi^{-1}(s))^2}{2(n-1)}\right)+\frac{(\Phi^{-1}(\alpha))^2}{2(n-1)}}}{1-\frac{(\Phi^{-1}(s))^2}{2(n-1)}} \tag{3.2}$$

Both the t-distribution and the approximation based approaches (3.2) employ the mean and the standard deviation of the design variable. It is assumed that the data is either normally distributed or has been transformed into a normally distributed data set by an appropriate mapping. If the parent distribution type is known a priori, the confidence of the characteristic value estimate will increase thus allowing the use of a design value closer to the mean, which is more economical. In general, the certainty with which a characteristic value is known is more sensitive to sample size than parent distribution identification.

With the procedure for selecting characteristic values known, the fractile (α) at which they are determined must be identified. There are a number of considerations which can influence the selection of a characteristic value fractile.

- characteristic values of loads should be values which are rarely exceeded while characteristic resistances (minimum specified material properties) should rarely be greater than the actual material resistance (strength).
- an observation of either the characteristic resistance or load should not be a so rare an event that they are never realized.
- often previously established characteristic or nominal values (i.e. from previous design standards or industrial practice) are used in order to simplify the adoption of the new design procedure.
- characteristic values can be chosen based on the reliability invariance they provide, as shown in Section 3.2.2.3).

3.2.1.1 Statistical Requirements of Level I Probabilistic Design

In order for the material property database to provide Level I designers with the information they require, it must be able to supply characteristic values defined by the user for use with specific LRFD design standards. The definition of the characteristic value or minimum specified material property (i.e. percentile, largest, smallest, n^{th} largest value, average, etc.) used in each LRFD design standard is defined when the load and resistance factors are calculated. To supply the user with a variety of characteristic values, the database program must be able to calculate sample statistics (i.e. means, standard deviations, largest or smallest observations, etc.). As described previously, knowledge of design variable parent distributions increases the certainty of the characteristic value estimate and thus allows less conservative approximations. The effect of parent distribution knowledge on the estimation of characteristic values is marginal compared to the potential effect associated with increasing numbers of random variable observations. As sample size is the most important feature in the confident selection of characteristic values, an emphasis should be put on the collection and pooling of large data sets.

3.2.2 Level II Probabilistic Design

This Level of probabilistic design employs random variable parameters (means and standard deviations) in approximate reliability analysis procedures. A Level II design procedure ensures that the probability of the applied load effects exceeding the resistance is inferior to the target (allowable) probability of failure, whereas Level I design methods ensure that factored load effects are inferior to factored resistances. The database of material properties would be used to provide material property (resistance) distribution parameters to compare with standardized load distribution parameters.

The reliability (probability of survival) of a design is generally expressed in terms of a reliability index (β) which is related to the reliability (P_s) and thus the probability of failure (P_f) by:

$$P_s = \Phi^{-1}(\beta) = 1-P_f = 1-\Phi^{-1}(-\beta) \tag{3.3}$$

where $\Phi^{-1}()$ is the inverse of the standard normal cumulative distribution function (CDF).

Several definitions of β have been developed and are explained in "Methods of Structural Safety"[21]. Cornell[22] provided the most basic definition of the reliability index (β_C) as the ratio of the expected value (E) and the standard deviation (D) of the safety margin or limit state function (M).

$$\beta_C = \frac{E(M)}{D(M)} = \frac{E(R-S)}{D(R-S)} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{3.4}$$

Traditionally, the safety margin (M) has been defined as the difference between the resistance and the load (R-S). M<0 indicates system failure while M≥0 indicates survival. Determination of the reliability index and thus system reliability, for the limit state expressed by M, is accomplished through Taylor series expansion of the load (S) and resistance (R) equations which define M. In order to understand the statistical measures required to calculate a reliability index, the form of the Taylor series expansions must be reviewed.

3.2.2.1 Taylor Series Approximation

The reliability of a design is assessed using a variety of methods of which Taylor series approximations are the most common. In these methods, the means and variances of functions of random variables are approximated with Taylor series expansions. A Taylor series expansion of a function Y=g(X) at the independent variable mean (μ_x) yields:

$$Y = g(x) = g(\mu_x) + (x-\mu_x)\frac{dg}{dx}\Big|_{x=\mu_x} + \frac{1}{2}(x-\mu_x)^2\frac{d^2g}{dx^2}\Big|_{x=\mu_x} + \cdots \tag{3.5}$$

For practical purposes only the first two or three terms of the expansion are considered. The Taylor series expansion of the mean (μ_y) of the function Y=g(x), at the independent variable mean (μ_x), can be estimated as follows:

$$\begin{aligned}
\mu_y \approx E[g(x)] &= \int_{-\infty}^{\infty}[g(\mu_x)+C_1(x-\mu_x)]\, f_x(x)\, dx, \qquad \textit{where: } C_1 = \frac{dg}{dx}\Big|_{x=\mu_x} \\
&= E[g(\mu_x)+C_1E(x-\mu_x)] \qquad (3.6a)\\
&= E[g(\mu_x)]+C_1(\mu_x-\mu_x) \\
\mu_y &\approx g(\mu_x) \qquad \textbf{\textit{First Order Approximation}}
\end{aligned}$$

Similarly;

$$\mu_y \approx g(\mu_x)+\frac{1}{2}C_2\sigma_x^2, \quad \textit{Second Order Approximation} \tag{3.6b}$$

where: $C_2=\frac{d^2g}{dx^2}|_{x=\mu_x}$

The variance (σ_y^2) of the function Y=g(x) can be estimated in the same way:

$$\begin{aligned}\sigma_y^2 &= E([g(x)-\mu_y]^2)\\ &= E([g(\mu_x)+C_1(x-\mu_x)-g(\mu_x)]^2)\\ &= C_1^2E(x-\mu_x)^2\\ &= C_1^2Var(x)\\ \sigma_y^2 &= C_1^2\sigma_x^2 \qquad \textit{First Order Approximation}\end{aligned} \tag{3.7}$$

A second order approximation of the variance requires the fourth moment of statistical information (kurtosis) of the independent random variable, which generally is not available or reliably calculated.

These approximations can be generalized for functions of many random variables. If the function being considered is $Y=g(x_1,x_2,x_3, \ldots ,x_n)$, the Taylor series approximations become:

$$\mu_y = g(\mu_{x1},\mu_{x2},\mu_{x3},\ldots,\mu_{xn}) \qquad \textit{First Order Approximation} \tag{3.8}$$

$$\mu_y = g(\mu_{x1},\mu_{x2},\mu_{x3},\ldots,\mu_{xn}) + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}(\frac{\partial^2 g}{\partial x_i \partial x_j})\ Covar(x_i,x_j) \tag{3.9}$$

Second Order Approximation

$$\sigma_y^2 = \sum_{i=1}^{n} C_{1i}^2\sigma_x^2+\sum_{i=1}^{n}\sum_{j=2}^{n}\rho_{ij}C_{1i}C_{1j}\sigma_{xi}\sigma_{xj} \quad [i\neq j] \quad \textit{First Order Approximation} \tag{3.10}$$

where the correlation coefficient $\rho_{ij}=0$ if x_i and x_j are statistically independent (uncorrelated).

The expressions developed above are frequently used in reliability analysis and can be called mean value, first- or second-order second moment reliability methods. Second moment reliability methods employ the expected values (first moments) and covariances (second moments) of the data, which are assumed to be normally distributed, to express all uncertainties of the system reliability. The first order approximations developed in (3.8) and (3.10) are the basis of what the current literature refers to as FORM (First-Order Reliability Methods). The second order approximation (3.9) is the basis of SORM (Second-Order Reliability Methods). SORM includes higher order terms in the Taylor series expansion for greater precision. The cost of using SORM is the extra effort required to estimate higher order statistical moments of the data.

3.2.2.2 Load and Resistance Factored Design Standard Calibration

The problem of determining the values of the load and resistance factors for a design standard (calibration) can be stated in the form of an optimization. The form and content of the objectives and constraints depends on the reasons behind the calibration. Design standards may be calibrated to ensure that a variety of designs have a consistent reliability or to ensure that the new code format provides designs with the same measure of economy or reliability as an existing code format.

The code optimization procedure is based on minimization of an objective function subject to the satisfaction of a group of constraints. An objective function, based on a reliability index probabilistic analysis procedure, can take the form:

$$\textit{Minimize: } \Delta = \sum_{materials} \; \sum_{limit\ states} \; \sum_{code\ formats} f_i(\beta_i^* - \beta_i)^2 \qquad (3.11)$$

In the above code optimization formulation the weighted average (f_i) difference between target reliability (β^*_i) and calculated reliability (β_i) of each associated material, limit state and code format combination is minimized. The estimated reliability of the design (β_i) is a function of material strength, applied loads, structural geometry and the optimization variables (load and resistance factors). It may be advantageous to specify the values of some of the load and/or resistance factors to ensure format continuity between different design standards as was done for the load factors in the Canadian design standards[27,28,29].

Code optimization requires a variety of information which depends on the level of reliability analysis used in its calibration (Level II reliability methods are most commonly employed). The first step in the optimization procedure is the definition of the scope of the optimization. The scope outlines the materials, limit states and code format(s) which will be used to determine the optimal load and resistance factors and code format. To further define the scope of the optimization procedure, expected ranges of live to dead load ratios and likely coefficients of variation are specified prior to optimization. The second step of the optimization process involves formulation of the objective function. An objective function, like (3.11), is likely to use target reliabilities and relative frequency factors (f_i) to develop a relative importance based, weighted performance measure (Δ). The target reliabilities may be drawn from previous design standards or benefit/cost analysis. The statistical requirements of the calibration depend almost entirely on the level of reliability analysis employed. Further code optimization procedure details are available in the literature[21,32-36].

3.2.2.3 Characteristic Value Design (Level I) Validation

In the use of a partial safety factor based design standard, Level I analysis, the single parameter used to represent each design parameter is called a characteristic or minimum specified value. The characteristic value (r_c) of a material strength (resistance) is generally designated as a specified fractile (α) of the strength (resistance) distribution. In other words, the characteristic strength is a specified number of standard deviations (k) below the mean strength value and for a normal distribution $k=\Phi(-\alpha)$; where $\Phi()$ is the normal cumulative distribution function (CDF).

The general partial safety factor based design equation states that the design resistance (r_d) $\geq$ factored load (w_f) which is equivalent to $\phi r_c \geq \lambda w_c$. The safety factor ϕ is generally smaller than one and if we assume that the design value (r_d) is k_d standard deviations below the mean strength, one can relate the material strength distribution, k values and safety factor in the following manner:

$$\mu_r - k_d\sigma_r = \phi(\mu_r - k\sigma_r)$$

then;

$$k_d = \frac{1-\phi(1-kV_r)}{V_r} \tag{3.12}$$

where: μ_r, σ_r and V_r are the strength mean, standard deviation and coefficient of variation respectively.

The characteristic value fractile can be chosen so that the design reliability is insensitive to distribution and parameter assumptions. This ensures that materials with the same design values but different distributions and parameters provide designs of equal reliability. To determine the required fractile it is assumed that one material has mean strength μ_r and standard deviation σ_r and a second material has a mean strength $\mu_r+\Delta\mu_r$ and standard deviation $\sigma_r+\Delta\sigma_r$. Since the design strengths are equal, $r_d=\mu_r-k_d\sigma_r=\mu_r+\Delta\mu_r-k_d(\sigma_r+\Delta\sigma_r)$ and it can be shown that:

$$\Delta\mu_r = k_d\Delta\sigma_r \tag{3.13}$$

By representing the load with a normal distribution (or a normal distribution tail approximation), with mean μ_s and standard deviation σ_s, the reliability of the design, expressed in terms of the reliability index (β), of the first material is $\Phi(\beta)$ and the second material is $\Phi(\beta+\Delta\beta)$. Employing a first order reliability index definition:

$$\beta = \frac{\mu_r-\mu_s}{\sqrt{\sigma_r^2+\sigma_s^2}} \tag{3.14}$$

and by neglecting higher order $\Delta\sigma_r$ terms:

$$\Delta\beta = \frac{\Delta\mu_r}{\sqrt{\sigma_r^s+\sigma_s^2}} - \beta\frac{\sigma_r}{\sigma_r^2+\sigma_s^2}\Delta\sigma_r \tag{3.15}$$

Using (3.15) and setting $\Delta\beta=0$ gives:

$$k_d = \frac{\beta}{\sqrt{1+\sigma_s^2/\sigma_r^2}} = \frac{\beta}{\sqrt{1+V_s^2/(\Theta V_r)^2}} \tag{3.16}$$

in which Θ is the central safety factor and is defined as:

$$\Theta = \frac{\mu_r}{\mu_s} = \frac{1+\beta\sqrt{V_r^2+V_s^2-\beta^2V_r^2V_s^2}}{1-\beta^2V_r^2} \tag{3.17}$$

Therefore, it can be said that the design value r_d, which equals μ_r-$k_d\sigma_r$, satisfies:

$$r_d = \mu_r-\frac{\beta}{\sqrt{1+V_s^2/(\Theta V_r)^2}}\sigma_r \tag{3.18}$$

Then r_d is the $\Phi(-k_d)$th characteristic value fractile at the design point of a Level II reliability analysis, based on normal tail approximations, with a safety margin having the form M=R-S. The reliability of a design based on the design value will remain constant for small variations in the parameters of the normal distribution (or normal tail approximation) as long as the $\Phi(-k_d)$th fractile of the strength distribution remains at the design point.

The statistical distribution of load changes from member to member with changes in the applied live and dead loads, which in turn changes the design point and thus the resistance characteristic value fractile. As the variation of the load's coefficient of variation is relatively small in reality, its effect on k_d can be ignored[21]. Therefore, the reliability of a Level I design using characteristic values calibrated with the design point algorithm can be treated as constant for changes in the random variable distribution. Thus the reliability calibrated Level I design is a form of probabilistic design (i.e. based on a target reliability).

3.2.2.4 Statistical Requirements of Level II Probabilistic Design

To aid a designer in the performance of Level II probabilistic design, the material property database program should be capable of estimating the statistical parameters which describe normal distributions. Normal (Gaussian) distributions are commonly described by their first and second moments (mean and standard deviation). For more precise Level II (Taylor series) reliability analyses, the relationships between random variables must be explored by calculating the correlation coefficients (ρ_{ij}). In a Level II analysis, ρ can vary from 0 to 1, indicating random variable independence or that a linear relationship exists. In many circumstances, an extreme case (i.e. independence or complete dependance) is assumed to simplify the analysis and reduce the volume of statistical information required. To develop a correlation coefficient matrix between each pair of random variables, observation groups must be compared in turn. In order for this systematic comparison to be done, all of the required material property data must be drawn from the database and processed together.

At this level of reliability analysis, the user may want an indication of the quality of the estimated distribution parameters. A variety of hypothesis testing procedures, providing parameter confidence measures, exist and should be made available. Along with evaluating the significance of the distribution parameters, it would be desirable to evaluate how well the normal distribution fits the data.

3.2.3 Level III Probabilistic Design

A Level III probabilistic design differs from Levels I and II in that it employs random variable probability distributions in the assessment of failure probabilities. In this level of reliability analysis a variety of probability distribution types and their associated measures are used, whereas a Level II design employs strictly normal distribution based analysis. If the database of material properties is intended for use in this level of probabilistic analysis, it must be capable of selecting the most appropriate distribution type for a set of data.

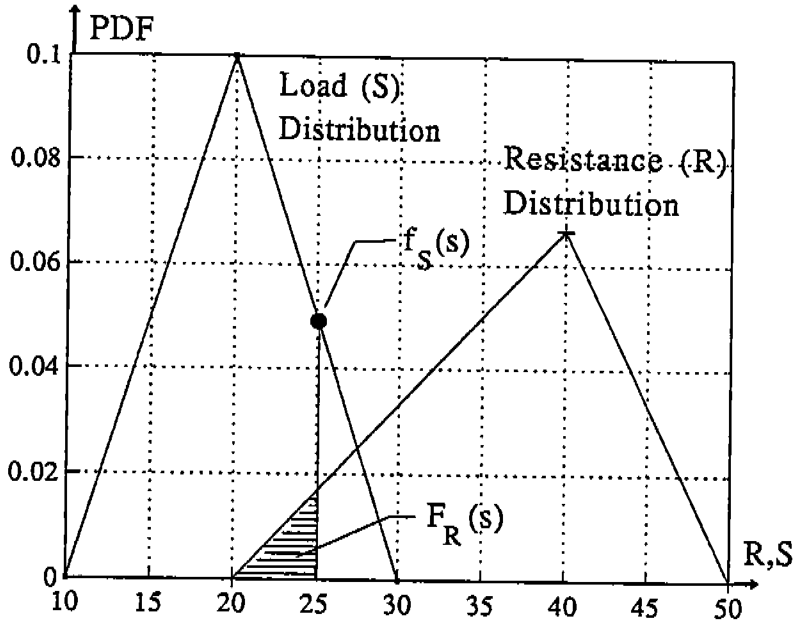
There are three common approaches to this level of analysis namely: Convolution Integral Evaluation, Taylor Series Approximation and Simulation. These three reliability analysis methods and their statistical data requirements will be described in the following sections.

3.2.3.1 Convolution Integral Evaluation

The probability of failure (P_f) or reliability (P_s) of a system can be calculated from the load and resistance distributions, shown in Figure 3.1, by a convolution integral evaluation procedure. If we assume that the load (S) has a fixed value (s) (Figure 3.1), the probability of failure (P_f) can be calculated by:

$$P_f = P(R \leq S) = F_R(s) \tag{3.20}$$

where: $F_R(x)$ = cumulative distribution function (CDF) for (R) evaluated at x
= $\int_{-\infty}^{x} f_R(r)\,dr$ and;
$f_R(r)$ = probability density function (PDF) for the resistance (R).



(Note: Area under each distribution = 1)

Figure 3.1: Convolution Integral Development

If the value of the load (S) is allowed to vary over all its values (weighted by its PDF, $f_S(s)$) the probability of failure can be calculated by:

$$P_f = P(R \leq S)\ F_S(s)\ ds = \int_{-\infty}^{\infty} F_R(s)\ f_S(s)\ ds \tag{3.21}$$

An expression for system reliability (3.22) can be developed by holding R at a value of r and following a similar same type of procedure as described above; except that the integral now gives the reliability (probability of non-failure or survival, i.e. R > S):

$$P_s = \int_{-\infty}^{\infty} F_S(r)\ f_R(r)\ dr \tag{3.22}$$

Equations (3.21) and (3.22) are expressions of the convolution integral.

The integration procedure may be generalized for a design with more than two random variables. Theoretically, the probability of a multi-variable limit state can be evaluated as:

$$P_f = \int\int\int_{g(x)\leq z} \cdots \int f_{x1}\, f_{x2}\, f_{x3} \cdots f_{xn}\, dx_1\, dx_2\, dx_3 \cdots dx_n \tag{3.24}$$

where; P_f is the probability of failure due to the limit state $g(x_i)$,
and $g(x)$ is the region of integration which is called the safety margin, limit state or performance function.

Realistically this evaluation method can only be applied to problems with small numbers of random variables (x_i) and simple limit state equations, $g(x_i)$. Evaluation of the convolution integral by other than approximate methods (i.e. numerical integration) is not practical. Further details concerning the development and use of the convolution integral can be found in reliability analysis textbooks[21,37].

3.2.3.2 Taylor Series Approximation

The use of Taylor series expansions to evaluate Level III reliabilities is an extension of the Level II procedure. Advanced Taylor series expansion approaches employ the design point algorithm which performs its Taylor series expansion at the most likely failure point instead of at the random variable means. The advanced Taylor series expansion methods are generalized at this level of reliability analysis, by a transformation of variables[39], to include correlated and non-normal random variable frequency distributions.

3.2.3.3 Simulation

The calculations involved in the approximate methods are complicated and the accuracy of their results is not well defined. Simulation techniques may be employed to estimate probabilities to a similar level of accuracy without much of the algebraic complexity associated with the approximate methods. Simulation techniques attempt to model the behavior of a system subject to various load conditions. Since the loads and resistances of a system are not unique values, but are distributions, a random sample of the various loads and resistances can be used to approximate the effects of the entire load and resistance combination spectrum. The quality of the simulated probability depends on several factors, of which the number of simulations is the most important.

The most basic simulation technique, Monte Carlo sampling, involves the following process:

1) Select a random value for each variable from its frequency distribution;
2) Using the random values ($\underline{X}$), determine if a failure has occurred by evaluating the safety margin or limit state equation ($g(\underline{X})$), i.e. $g(\underline{X})<0$ indicates failure;
3) Increase the failure occurrence counter according to the outcome of step 2;
4) Repeat steps 1 to 3 until the number of simulations provides the desired accuracy;
5) Estimate probability of failure (P_f) or reliability (P_s), where:
   P_f = Number of failures / Number of simulations, and
   P_s = Number of survivals / Number of simulations.

Using a Monte Carlo simulation approach, an element whose probability of failure is 1/10,000 will require, on average, the limit state function to be evaluated 10,000 times for a single failure event to be counted. Since the interesting events in a simulation are the failure events, the Monte Carlo simulation method should be modified to provide more failure information per simulation. Instead of drawing random samples from the entire range of each variable, sampling can be concentrated in regions which promote failure, and such approaches are collectively termed variance reduction techniques or advanced Monte Carlo methods. Variance reduction techniques increase efficiency by reducing the number of simulations required to obtain a specified level of accuracy. A description and comparison of variance reduction techniques (i.e. Importance Sampling and Latin Hypercube sampling) can be found in a paper by Schueller et. al.[40].

3.2.3.4 Statistical Requirements of Level III Probabilistic Design

Probabilistic design at this level requires the identification of both statistical distributions and their parameters. In order for the material property database program to support this level of reliability analysis, it must be able to fit distributions and their parameters as well as provide all of the information required for the previous levels of probabilistic design. An additional quality assurance measure describing the "goodness of fit" of the frequency distribution to the data should be provided.

3.3 Statistical Data Processing Requirements

This section describes the statistical calculations or quality assurance procedures that the material property database program will be required to perform in order to support the reliability analysis procedures described in the previous section. Since the methods for developing statistical measures and drawing inference from sample data are described in detail in many statistical reference books, this section will only indicate the required calculations. In the sections which follow, a review of the processing involved in the preparation of the material data observations for probabilistic analysis is presented. These sections describe the statistical processes involved in collecting material data, arranging the data, selecting a representative distribution, estimation of statistical measures of data variability and correlation, the development of data quality parameters and the implications of grouped data.

3.3.1 Data Collection

At the foundation of modern statistical, probabilistic and to some extent deterministic analysis is the assumption that several or a single observation can be used as representative of all similar observations. If all of the possible observations were known then *population* statistics could be developed for future predictions. For reasons of economy, portions of the *population* information termed *samples* are used to represent the population. Statistics embodies theory and procedures for using sample information (observations) to draw inferences about uncertain populations. As the sample statistics are based on incomplete information a potential for error exists, and there is no guarantee that the sample information is representative of the whole parent population.

3.3.1.1 Bias and Error in Sampling

A sample may be unrepresentative of the population from which it is drawn. Some of the unrepresentativeness which is encountered in any application of sample information can be characterized by: nonsampling error, sampling error and sampling bias.

Errors created in collection or processing of the data are considered as nonsampling errors. Engineering examples of nonsampling errors include collection of data with uncalibrated test equipment or simply erroneous data recording. Avoidance of this type of error is a talent acquired through experience or observation of the mistakes of others. The implementation of quality control programs as outlined by ISO 9000 would reduce this type of error.

Differences between the sample and population due to the nature of particular items used as observations are responsible for sampling errors. A sampling type of error would exist in the distribution of available steel strengths if the sample used as the basis of this measurement incorporated data from only one or two steel mills. This type of error is avoided by ensuring that the sample is drawn from the entire population (numerous manufacturers) so that all possible observations are equally likely.

A tendency to favor the observation of some population items over others is called sample bias. Sampling easily obtainable items can create bias if the items which are hard to observe are significantly different from the common observations. Sampling of the mechanical properties of marine steels will be biased if observations are taken exclusively from navy vessels since they incorporate steels not commonly used in commercial vessels.

It is frequently difficult to differentiate between the effects of these three types of errors. Since the population statistics are not known, it is generally difficult to determine how well the sample represents the population. For this reason, measures of statistical goodness of fit are generally focussed on describing the relationship between the sample statistics and data. Hypothesis testing (demonstrated in Appendix D) is a common approach to testing the quality of a sample statistic or a statistical assumption.

3.3.1.2 Qualitative Measures of Bias and Error

Bias and error of test data are comparative measures based on accepted reference values. Due to the relatively high level of uncertainty associated with the testing and measurement of material properties, the determination of reference data without the effects of other uncertainty sources is unlikely. For this reason, a modest qualitative approach to bias and error control, instead of the complex and possibly uncertain process of error measurement and removal, is suggested. When collecting sample data for a particular material property, the database should keep track of the testing and production facility. A large proportion of the data originating from a single source can be used as an indicator of potential bias and/or error.

3.3.2 Sample Statistical Parameter Estimation

In order to perform a statistical analysis based on sample distributions, the parameters of the distribution must be estimated. For example a sample mean and a standard deviation are parameters which completely define a normal or Gaussian distribution. Three methods which can be used to estimate sample distribution parameters are: method of moments, maximum likelihood and entropy minimization.

The method of moments is by far the most widely used method of parameter estimation. As the name indicates, parameters are estimated based on the relative distribution and frequency of observation of the sample data. Sample mean, expected value or average (3.25) are all names for the first moment of the sample observations about the origin. Variance (standard deviation) (3.26), indicative of sample variation, is the second moment of the observations about the mean. The third and fourth moments of the sample data which are less frequently used describe sample skewness (3.27) and kurtosis (3.28) respectively. Skewness is a measure of the asymmetry of a distribution; a symmetric distribution has a skewness of zero. Kurtosis represents the degree of "peakedness" of a distribution which describes the slope of the probability distribution function on either side of the most frequent observation.

$$E[x] = \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (3.25)$$

$$E[x-\bar{x}]^2 = \sigma^2 = \frac{1}{n}\sum_{i=1}^{n} (x_i-\bar{x})^2 \qquad (3.26)$$

$$E[x-\bar{x}]^3 = \gamma = \frac{1}{n}\sum_{i=1}^{n} (x_i-\bar{x})^3 \qquad (3.27)$$

$$E[x-\bar{x}]^4 = \kappa = \frac{1}{n}\sum_{i=1}^{n} (x_i-\bar{x})^4 \qquad (3.28)$$

These statistical parameters may be used directly to represent Gaussian distributions or can be transformed for use in non-Gaussian distributions.

The method of maximum likelihood is an intuitively appealing method of selecting distribution parameters which are, in general, equal to or better (in a mean squared error sense) than those estimates suggested by the method of moments. This method involves the selection of the distribution parameters (θ) which maximize the likelihood (3.29) of observing the sample data (x_i). The likelihood of each piece of the sample data is a function of the frequency ($f_x()$) with which the selected distribution predicts that the data item will be observed. The likelihood function, L(), employed in this method is, or is developed mathematically from, the probability density function (sample frequency distribution).

$$\textit{maximize} \qquad L(\theta \mid x_1, x_2, x_3, \ldots, x_n) = \prod_{i=1}^{n} f_x(x_i \mid \theta) \qquad (3.29)$$

The selection of distribution parameters based on entropy minimization[41] is similar to that used in the method of maximum likelihood. In this method of statistical parameter estimation, the fact that each piece of the sample data provides population distribution information is used. A less frequent observation is said to provide more information than a frequent observation. The information contained in a sample is derived to be a logarithmic function of the difference between the probabilities (P) of unique neighboring observations which are arranged in ascending order[41].

$$minimize \qquad D(\theta, x_1, x_2, x_3, \ldots, x_i) = -\sum_{j=0}^{n} \log(P_{j+1} - P_j) \qquad (3.30)$$

In (3.30), D is a measure of the entropy or disorganization of the data with respect to the statistical distribution being fitted, and P_j is the probability of an observation (x_j) which is given by the selected parameters (θ) and the probability distribution.

3.3.2.1 Parameter Quality

Parameter quality, confidence interval or hypothesis testing are used to ensure, in a probabilistic manner, that the sample statistics are representative of their associated population statistics. A hypothesis concerning the significance of each parameter is formulated and tested in turn. The conclusion of each hypothesis test is tempered by an associated confidence interval, i.e., the probability of the conclusion being correct. Higher levels of confidence are possible for sample statistics based on larger numbers of observations.

When testing the sample mean of a large sample, the normal distribution is used to develop the test statistic or confidence interval, whereas the student t distribution is used for small samples. The sample standard deviation or variance is tested in a similar fashion using the chi squared (χ^2) distribution which can be approximated by a normal distribution for large samples. Further information concerning parameter quality measurement can be found in most statistical analysis text books and examples of these procedures are provided in Appendix D.

3.3.2.2 Additional Statistical Measures

Beyond the statistical measures introduced in the previous section, additional statistical measures are commonly used to further characterize data samples and their relation to other samples. Statistical textbooks provide adequate descriptions of the meaning of mean, median and mode, among other statistical measures. In this section the measures particular to reliability based analysis will be described as they may be less familiar.

Reliability analysis procedures are commonly employed in sensitivity analysis and in design situations for which dimensionless constants are desirable. The dimensionless constant used to statistically describe a sample is the coefficient of variation (C.O.V.). The coefficient of variation is the ratio of sample variation to its most common value (σ/μ). The coefficient of variation quantifies the variability of a sample in terms of the sample mean, and is commonly used as a reference value in distributed parameter comparison.

The covariance (Cov.) of a pair of random variables defines the second central moment for joint random variables. The covariance can be defined as:

$$
\begin{aligned}
\sigma_{x,y} &= Cov[x,y] = E[(x-\mu_x)(y-\mu_y)] \\
&= \int_{-\infty}^{\infty}\int (x-\mu_x)(y-\mu_y) f_{x,y}(x,y)\, dx dy
\end{aligned} \tag{3.31}
$$

If the variance of a random variable sample corresponds to its moment of interia about the x and y axes through the distribution's centroid (mean), then the covariance corresponds to the product moment of inertia with respect to both axes.

The normalized version of the covariance, called the correlation coefficient $\rho_{x,y}$, is a more common expression of the relationship which exists between two random variables. The correlation coefficient is found by dividing the covariance of the two random variables by their standard deviations.

$$
\rho_{x,y} = \frac{Cov[x,y]}{\sigma_x\ \sigma_y} \tag{7.8}
$$

The advantage of the normalized correlation coefficient is its insensitivity to the units of the sample observations (x and y). The value of ρ, which expresses the relative strength of the association between the two samples, will remain constant regardless of the system of measurement used to scale the sample data.

3.3.3 Statistical Distribution Selection

A wide variety of statistical distributions are available to describe the statistical nature of data. The selection of the proper distribution for a data sample can be performed based on expertise and past experience, or based purely on statistical measures. Once the distribution has been selected, sample statistics can be estimated and the population is completely modelled. As the population statistical measures are not known and the sample's error with respect to the population can not be estimated, experience may be the only indicator of distribution type for relatively small data samples.

3.3.3.1 Theoretical Behavior and Experience Based Distribution Selection

Experience in statistical modelling of material behavior properties can provide information concerning the selection of the most appropriate statistical distribution type. For instance materials can behave as brittle, ductile or bundled systems. The strength of an ideal brittle material is governed by its weakest link as a system fails when the weakest link fails. The average strength of a brittle solid decreases with increasing specimen size and any material property which follows a similar pattern of behavior might be best represented by a type 3 extreme value (Weibull) distribution as shown by experience and theory. In an ideally plastic material, a particle will maintain its maximum load but redistribute any additional load. The strength of an ideally plastic material is thus the sum of its particle strengths. Through experience and theoretical derivations, it has become customary to represent any system comprised of many particles and which behaves plastically, by a normal distribution. Another common representation of material behavior is the fiber bundle which consists of many identical parallel elements. Each element is considered as a brittle system in which failure implies a loss of load carrying capacity. The strength of this type of system behavior has been shown to asymptotically approach a normal distribution as the number of elements increases to infinity, based on a linear load sharing rule.

3.3.3.2 Statistically Based Distribution Selection

Empirical studies based on the regression of material test data are available in the literature to correlate material behavior characteristics with particular frequency distributions. These studies focus on the development of statistical distributions of material properties for production quality control, reliability analysis, characteristic value selection and calibration of analysis procedures. Typically, the primary function of this type of study is to estimate the statistical parameters of sample data based on a predefined distribution model using one of the methods described in Section 3.3.1. If a distribution type is not predefined, the selection process can be carried out using either a satisficing or an optimization approach. The satisficing approach involves calibrating distributions and testing the statistical significance of the sample data and the statistical parameter relationship for a variety of distributions until an acceptable level of significance is obtained. The optimization technique involves calculating the likelihood or entropy parameters for all distributions and selecting the distribution which provides the largest likelihood or smallest entropy measure.

While the optimization approaches are appealing due to their objective nature, they are complex and require a great deal of computational effort. In order to limit the computational time involved in the selection of a distribution type, a combination of the two approaches is recommended. Sample data representing a familiar data type should be assumed to have a particular distribution type. The computational effort involved in the optimal selection of the most appropriate distribution type can be controlled by limiting the scope of the optimization (examine only the likely distributions).

3.3.3.3 Distribution Quality (Goodness of Fit)

Depending on how a statistical distribution is selected, additional measures of its representativeness or "goodness of fit" may be required. When mathematical means (i.e. least squares or entropy minimization) are used to select a distribution type, the value of the selection criteria can be used to gauge relative goodness of fit for different distribution types. If past behavior or personal preference is used in the selection of a distribution type, then a Chi squared

(χ^2) goodness of fit test can be used to compare the frequency distribution of the selected distribution with that of the sample data.

3.3.4 Combination of Data Samples

The objective of any database of material properties is to help identify expected material property values and their associated variation. As the confidence with which these statistical parameters are estimated varies directly with sample size, large samples are desirable. Therefore, the database should be able to combine sample data from various sources to improve the confidence in statistically derived parameters. Since the purpose of combining or pooling data is to increase the quality of the resulting parameters, the data used in this pooling process should be examined to ensure that it will in fact increase the confidence of the pooled statistical parameters.

3.3.4.1 Significance of Sample Differences

Before combining groups of data it is important to determine if they are statistically similar in order to avoid introducing inconsistencies into the data set. For instance, if two normally distributed data samples with significantly different means are combined, the resulting data set will be bi-modal, eg., the notch toughness distribution of conventional and very clean steels, that otherwise belong to the same specification. Similarly, samples with significantly different standard deviations or variances will result in a data set with an averaged standard deviation measure. Thus, it is important to identify any statistically significant reason for not combining sample data sets.

Comparison of the means of two normally distributed samples to identify significant differences in their expected values involves the use of the Student-t distribution. The procedure outlined in Appendix A uses the t-distribution to indicate if the difference between two means is significant with a specified level of confidence. Even though statistical analysis often employs non-normal distributions, which theoretically invalidates the use of the student-t distribution developed based on normally distributed data, it is accepted practice to use this procedure for all distribution types.

An approach used to identify significant differences in sample standard deviations, shown in Appendix D, is similar to that used for comparing means. The comparison of two sample standard deviations employs the F-distribution which is also based on normally distributed data, but has been accepted as a reasonable approximation for non-normal data.

3.3.5 Grouped Data

It is not uncommon to summarize data with either frequency distributions or statistical measures. Data which is represented (grouped) in this fashion has lost some of its descriptive ability, but when sample data is scarce it may have to be considered.

In order to include grouped data in statistical calculations with other non-grouped observations, the grouped data must be discretized based on its statistical measures. A discretization procedure would generate a series of data points with statistical measures (mean, standard deviation, goodness of fit measure, histogram, etc.) which match those of the summarized data. The series of data points would then be combined with non-pooled data as a representation of the summarized data.

If two sets of grouped data are to be combined it is possible to avoid generating two sets of representative data.. A weighted average based on sample size can be used to combine two sample means. Sample standard deviations can be combined based on a similar procedure which combines sample variances about the new mean.

4.0 PROPOSED MATERIAL DATA REPORTING FORMAT

The modified format is presented in Appendix A. The modifications are a result of considering the observations made in the previous two Sections.

All fields where information is essential at the data gathering stage in the present context, are identified by an asterisk (*). The remaining fields are included primarily for compatibility with other established formats, for example, ASTM requirements. Fields that are new compared to the previous format[1] are highlighted (in the text below, but not in the FORMAT) by bold lettering.

The rationale for the inclusion of each field in this format is outlined below. The format is organized so that the fields representing background information on the material are identified with the following sections:

i) Material Description and Processing, and
ii) Weld Description

Similarly, the fields describing test data are reported in separate sections as follows:

i) Format for tensile test data,
ii) Format for fracture toughness test data,
iii) Format for notched bar impact test data,
iv) Format for compact crack arrest fracture toughness test data,
v) Format for nil-ductility temperature test data, and
vi) Format for dynamic tear test data.

Within the above sections, each datum (information) field has been identified with specific sub-sections, so that entering information to this computerized format is simplified.

Material Description and Processing

Material Specification and Identification

0-1 Material code

Remains from the original format. It indicates the importance of the material, for design and fabrication of marine structures, as assessed by the SSC.[1] It also differentiates between the parent plate and the weldment, based on the usage of the material in critical applications.

0-1a* Common name

Describes the material in common terminology, for example, identification as HY80 or AISI 4140 makes the information available for data exchange. It is also an essential field in accordance with ASTM E 1338 guide for computerized Material Property Databases.[3]

0-1b*		UNS Designation

The unified numbering system (UNS) for metals and alloys as described in practice ASTM E 527 is the most comprehensive system available to describe metals by their composition. This is an essential field in accordance with ASTM E 1338 [3], and therefore it is retained in the same category.

**0-1c1*		Spec. organization, no. & year (made to)**

This is included as recommended in the ASTM guide, [3] to completely define the material (for example, ASTM A 572 Grade 60, 1985), and therefore is an essential material identification field. The addition *(made to)* here is specifically included to ensure that the material was indeed made to this specification. This is an important detail as all available original test data for material made to this specification should be included in calculating A and B-basis values using statistics, whether or not the material met the requirements of the specification.[4]

**0-1c2		Spec. organization, no. & year (passed)**

The difference between this field and the preceding one is the replacement of the word *(made to)* by the word *(passed)*. Therefore, this field is intended to obtain more information in case the material specification requirements were not met and the material was re-classified to another lower specification or grade. In most cases, this information may not be reported in two separate fields, as for example, manufacturers would not like to admit that when the target specification was not met, the product is consigned to a lower grade. However, it is included in the current format, in order to be aware of such re-classification, which may be ignored if only one field is present. The importance of these aspects on statistical measures have been outlined in Section 3.1.2.1.

**0-1c3*		Supplementary requirements**

The supplementary requirements to the standard specification may be stipulated by the user for a specific application; for example, Charpy notch toughness requirement for ASTM A36 steel when the specification does not call for it. This is an important detail as the Charpy data may not belong to the same population as for steels made to the standard specification. This field is therefore designated as essential.

0-1d		ASTM spec. no.
0-1e		AISI desig.
0-1f		Military spec.

The above three identification fields are retained from the original version[1] as these are specific to marine materials and should facilitate data exchange.

**0-1g		ISO desig.**

This is included in the current version for future requirements when ISO specifications may become universally applied. This identification field will enhance the data exchange capabilities of the database at that time. This rating identifies the level of quality assurance associated with the process but does not necessarily indicate the quality of the material property data.

Type and Geometry of Product

0-2a Test metal

This is retained as this field describes the processed condition of the material evaluated. The field name is modified from Base metal to the more appropriate Test metal.

0-2b* Basic form

This field is retained as it is an essential piece of information in accordance with ASTM E 1338.[3] This field assists in establishing the pedigree of the raw data and identifies the results to the product form. It is also an essential field that adds to the completeness of the material identification and therefore improves its quality level in accordance with ASTM E 1484. [6]

0-3* Thickness

This field is retained for the same reasons as the previous field, although perhaps it can be included in the information supplied with the basic form.

Composition

0-4* Composition type

This adds to the completeness of the data by specifying it as actual, nominal or referring to the material specification. In accordance with ASTM[3], this is an essential field if the compositional detail is not defined in the material specification.

0-4a Composition position

This field is retained as it clarifies the location from where the chemical analysis is obtained when the actual composition is given. This is specially important in the case of weld metals due to dilution effects.

0-4b Actual composition

This field is a key to record the composition and therefore has to be retained. It is an essential field if the actual composition is reported.

Fabrication History

0-5 Producer (name of the producing company)
0-5a Lot number
0-5b Year of production

These fields are retained as they assist in the traceability of the of the product for which the material property data are reported. These fields are also listed in the ASTM material identification guide.[3]

0-5c ISO 9000 certification

This is included in the current version for future requirements when producer ISO 9000 certification becomes universal. This rating identifies the level of quality assurance associated with the process but does not necessarily indicate the quality of the material property data.

0-6 Melting practice
0-7 Casting practice
0-8* De-oxidation practice

The above three fields are retained (0-7 is modified) as they describe the primary production process. These fields are classified as essential in the ASTM guide.[3] However, in the present context, only de-oxidation practice is defined as essential *after* developing the hierarchy in the next Section. Marine steel specifications (for example, American Bureau of Shipping (ABS), Lloyd's) do not require the casting practice to be reported on the mill test certificate. They only require continuously cast slabs to be reduced to at least one third of the as-cast slab thickness to break down the cast structure. The investigators have not seen any conclusive evidence that from the strength point of view, one practice is superior to the other. Only in the extreme cases of *chemical segregation* in continuously cast steels or *inclusion segregation* in ingots, are the toughness significantly affected. Therefore, the field is included but designated as non-essential.

0-9* Final rolling temp.
0-10 Rolling deformation

These two fields modify the three fields (Process temp., Process time and Rolling conditions) listed in the original version.[1] The two fields describe the rolling process employed and improve information on secondary processing.

0-11* Final processing steps

This field is retained as it indicates the final processing steps employed. This adds to the completeness of the processing history and is an essential field in the ASTM guide. [3] Modification has been made to precisely identify the process employed. The fields that follow describe any processes used after rolling.

0-12* Final heat treatment temp.
0-13* Final heat treatment time
0-14* Cold work strain
0-15* Stress relief or Aging temp.

The above fields are retained as they describe the secondary processes in detail and are considered essential as these treatments can have significant influence on the material properties. They add to the completeness of the processing information that is considered essential in the ASTM guide. [3] If these subsequent treatments are not performed after rolling then the information provided in 0-9* and 0-11* are important for the completeness of the data. The ASTM guide on quality indicators[6] lists processing history as one applicable indicator.

Data Quality

0-16* Source of data/laboratory
0-16a Source ISO 9000 certification
0-17* Source of data

Two of the above fields are retained, 0-16* and 0-17*, while the source ISO rating is included for future classification of the source of test information. However, they are moved to this more appropriate new section entitled "Data Quality" which considers the overall quality aspects following the lines of the ASTM guide[6] on quality indicators. These are important fields that indicate the reliability of the test data that were previously "hidden" in the processing domain. These fields assist in the ranking of the quality level of the data in accordance with ASTM.[6] The ratings identify the level of quality assurance associated with the process but do not necessarily indicate the quality of the material property data.

0-18 Completeness of material information

This addition is as recommended by the ASTM guide on quality indicators[6] and therefore included in this section. The fields rank the completeness of the information according to the guide and is a judgment on the quality. However, in the current context, these aspects are considered more appropriately by the hierarchy of the data fields developed in Section 5.0 and thus this field becomes less important.

Weld Description

W-0 Weld code

Remains from the original format as it identifies the priority of the parent material used in the fabrication of marine structures. This field also links the weld with the parent material and it identifies the test location with information from field W-17. However, it duplicates information provided in slot 0-1 of the section "Material Specification and Identification", if only the weldment is tested.

W-1* Welding process

This field is retained and modified according to AWS guide A9.1 - 92.[8] The abbreviations used are in accordance with AWS.

Welding Procedure

W-2 Spec. organization, no. & year

This field is included as required by AWS guide A9.1 - 92.[8] The field specifies the applicable standard, for example, AWS D1.1, Structural Welding Code - Steel.

W-3* Welding position

This field is retained from the original version and is defined as essential *after* developing the hierarchy in the next Section.

W-4 Preheat temp.
W-5 Interpass temp. (maximum)

These fields are retained from the previous version. However, the addition *(maximum)* for W-5 is a result of AWS guide A9.1 - 92.[8]

W-6 Post heat temp. & time (hydrogen outgassing)

This field is added according to AWS guide A9.1 - 92.[8] This is considered important information that together with the weld thermal cycle can affect the ductility and toughness.

W-7 Number of passes

Retained. "See" is included to describe other sequence details that may be provided in a weld data sheet.

W-8a Welding filler, Spec., no. & year
W-8b* Welding filler, Classification
W-8c UNS desig.

The above three fields replace Welding filler, Spec. & Grade in the original version taking into consideration the format in AWS guide A9.1 - 92.[8] These fields indicate broadly the characteristics of the filler, and anticipated weld metal properties and composition when deposited in a specified manner.

W-8d* Welding filler, trade name

This field is retained from the previous version. A product supplied to a given specification can have different toughness distributions. The field is therefore designated as essential.

W-9 Filler size

This field is retained as it is also included in the format described in AWS guide A9.1 - 92.[8]

W-10a Flux, Spec., no. & year
W-10b* Flux, trade name

These two fields which call for complete information of the flux used in the welding process are retained from the previous version. However, the field names are modified and their position is moved up to a more appropriate location in line with AWS guide A9.1 - 92.[8]

W-11a Shielding gas, Spec., no. & year
W-11b* Shielding gas, Composition/Common name

These two fields which call for complete information of the shielding gas used in the welding process represents one field in the previous version. The modified field names are in line with AWS guide A9.1 - 92.[8] W-11a is included as AWS specifications are being currently drafted. W-11b* is an essential variable because the oxygen potential of the shielding gas that influences the strength and toughness (see Section 5.2.1) and thus it is defined an essential field. (Similar rationale is used in making W-8b* and W-10b* essential fields.)

W-12a **Power source, Common name (trade name)**
W-12b Voltage
W-12c Amperage
W-12d Polarity

The above four fields describe the electrical characteristics of the arc, three of which are retained from the earlier version. The power source is added as it is included in AWS guide A9.1 - 92[8] and completes the information on this aspect of the welding procedure, noting that it usually has minimal effect on the properties.

W-13 Travel speed

The field is retained with a modification in the units in accordance with AWS guide A9.1 - 92.[8]

W-14* Heat input (range, average)

This is retained and modified from the previous version and is one of the most important fields that should be completed when mechanical properties of the weld and heat affected zone (HAZ) are recorded. The modification incorporates important information from a multi-pass weld.

W-15 **Cooling time**

This field is included to record the cooling time from 800° to 500°C (1472° to 932°F) as it covers the phase transformation temperature range for common structural steels. For a given welding process, plate thickness, preheat/interpass temperature and heat input determine the cooling time, which is an approach to describe the weld thermal cycle and can influence the toughness of the weld metal and the HAZ.

W-16a **Joint prep.**
W-16b* Groove type
W-16c Gap
W-16d **Backing, Spec. no. year**
W-16e **Back gouging**
W-16f Number of sides welded

The above fields represent the joint details and thus provide important information associated with the weld. W-16b* is an essential variable (see Section 5.2.1), thus it is designated as an essential field. Joint preparation, Backing and Back gouging are new fields included in line with AWS guide A9.1 - 92.[8], while the others are essentially retained from the previous format.

W-17* Weld specimen notch position codes; position relative to the fusion line (F.L.)

This field is retained and identifies the exact position of the test region with respect ot the F.L., (example, 02-Fusion line, 03-1 mm from the F.L. into the HAZ). The test region is where the notch or fatigue pre-crack is positioned. This is essential as welded regions contain a changing microstructure and therefore the test results are dependent on the exact position of the test region. These factors make this an essential field.

W-18* Location relative to the surface

This field indicates the location of the center axis of the test specimen in relation to the plate thickness, (example, 0/4T) is a sub-surface specimen. The different slots are standard locations and modified to include information if the specimen contains the weld root region. The field is retained from the previous format[1] but the notations modified according to standard terminology.

W-19* Postweld heat treatment temp.

W-20* Postweld heat treatment time

These two fields are retained, and they describe any heat treatment such as stress relief performed on the welds. They are essential fields if such treatment is carried out on the weld because the strength and toughness of the weld and HAZ would be changed. These two fields are included in the format in AWS guide A9.1 - 92.[8]

W-21* Is the actual weld deposit composition reported in 0-4 ?

Remains from the earlier version. This field is important, as in this format of arc weld description a field for the composition of the weld is not available. It is a combination of the filler metal and parent metal, depending on the amount of dilution from the parent metal.

W-0 Weld key code

This field is a key to record information on fields W-17 through W-20 if a number of specimens from a single weld are tested. This is retained as it is a convenient method to record specimen information.

Recommended Standard Format for Tensile Test Data

Background Information

1-0* Material key

This is a key to record information on test material identification (i.e. 0-1 Material code as it identifies the corresponding material description and processing), and is therefore an essential field as it links up the test record to the specific material. The information is available in the format "Material Description and Processing".

1-1 Type of test

Remains from the original format for completeness.

1-2* Purpose of test

This field is included as it is important to know the reason for carrying out the test, when the data is employed for developing statistical parameters. For example, if the test is carried out for Q.A. purposes or for supplying mill certificates, then they may not include test records of material that did not qualify.[7] In this situation the statistical parameters such as A and B-basis values will not include results that fail to qualify. This factor is considered in 0-1c where material specification data is addressed in "Material Description and Processing". This field is therefore essential in the present application.

Test Procedure

1-3* Standard

1-4 Date of applicable standard

These are retained from the previous version[1], and 1-3 is considered as an essential field as it provides information about the standard procedure employed. This field (which is also an essential field in ASTM guide 1313[2]) assists the exchange of computerized data as a result of the standard procedure adopted and also enhances the quality of data as it adds to the completeness of the test procedure.[6] These two fields are moved up from the previous format as they are information on the test procedure.

1-5a* Rate of loading to yield

1-5b Rate of loading from yield to fracture

These two fields report the rate of loading and are retained from the earlier format. However, compared to a single field in the previous format a modification to include two fields is recommended here. This is because test specifications[42-44] generally allow a higher rate after the yield point. As the yield point is critically dependent on the loading rate and the latter is specified in shipping regulations[43,44] it is defined as an essential field in the present context.

Specimen Information

1-6* Specimen location

This field is retained and modified in accordance with ASTM guide 1313.[2] This specifies the position of the axis of the test specimen in relation to the plate thickness in accordance with unified notation, and is an important field if the tensile properties change with through-thickness location.

1-7* Specimen orientation

This field is retained and modified in accordance with ASTM guide 1313[2] as applicable to the testing of wrought products. This specifies the direction of the axis of the test specimen in relation to the predominant rolling direction using standard abbreviations. In the case of welds, it is the direction of the specimen axis with respect to the axis of the weld. This is an essential field (also classified as an essential field in ASTM guide 1313) as the tensile properties change with the direction of load application and, therefore, cannot be grouped together even for the same material.

1-8* Specimen type

This field is retained from the original format. It specifies the cross-section of the machined tensile specimen and also if the load is applied on the full thickness. This data field is considered essential because tensile properties, especially elongation, are related to the cross-section and gage length of the specimen. It is also an essential field in ASTM guide 1313[2], and adds to the completeness of the test procedure which is a field in the quality indicators of the ASTM guide.[6]

1-9 Specimen diameter or thickness

This field is retained from the original format. It is also a field in ASTM guide 1313.[2] It indicates the load bearing area in relation to the product geometry in field 0-2 described in "Material Description and Processing".

1-10* Gage length

This field is also retained from the original version, and is defined as essential information in ASTM guide 1313.[2] The total elongation is a function of the gage length of the test specimen and is specified in the test procedure of standard methods.[43,44] Alternatively, if a different gage length is used, the elongation obtained can be converted to an equivalent value by applying empirical relationships.[43] This is an essential field if the elongation is used in design.

Test Results

1-11* Test temperature

This essential field is retained as the strength and ductility which are derived from the tensile test results are a function of the test temperature. Generally, the strength decreases and the ductility improves as the test temperature is increased.

1-12* Tensile strength

This field is retained from the original format. It is defined as essential information (as in ASTM guide 1313[2]). Together with the value of the yield strength, it can be used to determine the yield/tensile ratio, an important consideration in limit state based standards.

1-13a* Yield strength method

1-13b* Yield strength

Both these fields are retained from the original format.[1] However, 1-13a is modified in accordance with ASTM guide 1313 [2], because it specifies two standard methods; % off set and total (elastic and plastic) strain under load. The fields are considered as essential, because they define the yield strength precisely, following ASTM guide 1313, and together with the value of the loading rate to yield (1-5a) consider the strain rate sensitivity of the material. This is the most important information from a tensile test from a design standpoint.

1-14a Yield point method

1-14b Yield point

These two fields are considered together because the yield point load (stress) will depend on the method adopted for its determination from the test results. 1-14b is retained from the previous format and 1-14a is added following ASTM guide 1313 to describe the method (upper yield point) used for the determination of the numerical value.

1-15 Uniform elongation

This field is retained from the previous format because together with the yield/tensile ratio, it can be used when reliability of a structure is assessed through limit state design incorporating the work hardening exponent. The value is usually determined as the elongation at maximum load, and the equivalent true strain represents the work hardening exponent when the true stress-true strain curve is described by the standard power law equation.

1-16a* Total elongation

1-16b Fracture in the mid-half of the gage length

1-16a is retained from the previous format and is considered an essential field following the lines of ASTM guide 1313. 1-16b is included from ASTM guide 1313, as it validates the increase in the gage length measured from the broken test specimen. This information is important if the elongation value is used for the present application as described in 1-10*.

1-17 Reduction in area

This field is retained from the previous version. It is defined as an essential field in ASTM guide 1313, [2] as a record of completeness of the data for the tensile test.

1-18 Fracture location (weld)

This field is added in the present format, specifically to include the fracture location when a cross-weld tensile test is performed.

1-19a Number of test results

This new field is included primarily to reduce paper work in reporting information which is common to a number of data sets, for example, tests carried out under the same condition. It leads on to the next field. It is also very helpful if the reported data belongs to the same material key described in 1-0.

1-19b Method of presentation of results

This field allows results to be presented in a tabulated form, or alternatively in histograms and statistical distributions. However, in the latter case it is important to emphasize the usefulness of retaining the raw data in a tabular form, and a note to that effect is included in the format. This allows the designer/materials engineer access to data for further manipulation, and retains full traceability of the raw data.[5]

Data Quality

These new fields are important to indicate the reliability of the test data reported in this section describing the tensile results. The fields are specifically included to rank the data following the ASTM guide [6], and are classified according to the guide.

1-20 Statistical basis of data

This field is included to report group data when they are displayed in a statistical format, for example, A, B, and S-basis values are presented. Therefore, it is strictly not relevant when single values (raw data) are reported. However, it is recommended that the raw data be retained in the present application. The field is included as it will be among the most important as this type of data presentation becomes available.[6]

1-21a Validation status

1-21b Certification status

These two fields describe the quality of the data. Validation indicates if the data is independently assessed at source, or if there is no validation/review. Certification, on the other hand, is assessed by an expert body (American Bureau of Shipping (ABS) certification) or individual to determine the data applicability or appropriateness for the specific application.[6] Therefore, these fields can be adopted to assess the reliability of the data before approval for addition to a database.[5]

1-22 Completeness of the test procedure description

This new field does not indicate the details of the actual test, but rather ranks the procedure according to the ASTM guide.[6] Similar to field 0-18, in the current context, these aspects are considered more appropriately by the hierarchy of the data fields developed in Section 5.0 and thus this field becomes less important.

<u>Recommended Standard Format for Crack-Initiation Fracture Toughness Test Data</u>

Background Information

2-0* Material key
2-1 Type of test
2-2* Purpose of test

Test Procedure

2-3* Standard
2-4 Date of applicable standard

The description and justification for the above fields (2-0 to 2-4) were presented above in the format of the tensile test record, and therefore are not repeated here.

2-5* Type of loading

This field is retained from the previous format, and classifies three rates of loading: quasi-static, intermediate and high. The first is the most common testing rate. The intermediate and high rates are applicable for ship structures as they are exposed to dynamic and impact loads. This is defined as an essential field in the present context as the toughness depends on loading rate.

2-6 ($\dot{K}$) loading rate

This field is retained from the previous format, but modified to include the units (both SI and Imperial). The field reports the stress intensity rate ($\dot{K}$) determined from the specimen geometry and the exact loading rate employed for the test, thus supplementing information recorded in the previous field.

Specimen Information

2-7 Material yield strength

2-8 Material elastic modulus

These two fields are new inclusions to the format. They are used to determine K_{IC}, J and CTOD values.

2-9* Specimen location

This field is retained but modified in accordance with ASTM guide 1313[2]. It specifies the position of the axis of the test specimen in relation to the plate or weld thickness in accordance with the unified notation, and is an important field since the local toughness frequently varies with the through-thickness location. The standard notation used also considers weld specimens by indicating if the root region is contained in the test piece. Standard crack-initiation fracture toughness specimens include the full thickness of the plate or the weld and in this case, the specimen location is irrelevant. However, in research and development work, and especially in weld metal and HAZ toughness testing, specific locations may be tested using less than full thickness specimens. Therefore, in order to identify and separate these results from standard test data this field is made essential.

2-10* Specimen orientation

This field is retained and is essential in accordance with ASTM guide 1313[2]. In the standard abbreviations, the first letter is the direction normal to the plane of the crack and the second represents the direction of crack growth. This is an essential field as the toughness is different for each orientation, therefore, the results cannot be grouped together even for the same plate. In the case of weld metal and HAZ testing, the orientation is with respect to the axis of the weld, as for field 1-7* in the tensile test. This field also adds to the completeness of the test procedure which is a field in the quality indicators of the ASTM guide.[6]

2-11* Specimen type

This field is retained from the original format. It specifies the type according to standard abbreviations. This data field is considered essential because the toughness can be affected by specimen geometry.

2-12* Specimen thickness

This field is retained from the original format. It is also an essential field in ASTM guide 1313[2], because it is a primary measure for the validation of the test results, for example in accordance with ASTM E 399.[45] It is more important in the current format as the toughness values that can be reported include CTOD and the latter for most structural steels of interest is thickness dependent. As the toughness value used in fracture assessments must be appropriate for the specimen thickness, it must be recorded for the data to be useful.

2-13 Specimen width (W)

2-14 Average crack length (a)

2-14a* a/W

These are useful for determining the validity of the test result. W and a are defined as essential fields in ASTM guide 1313. As K_{IC}, J and CTOD values depend on a/W ratio, it is defined as an essential field. Fields 2-14 and 2-14a are retained from the previous format.

Test Results

2-15* Test temperature

This essential field is retained as the toughness which is calculated from the loading curve is a function of the test temperature. For steels used in marine structures, the fracture toughness improves as the test temperature is increased. In general, the scatter in the data is much less when the test temperature is in the lower or upper shelf regions. In the fracture transition range, the scatter is much larger. The transition temperature is also a function of specimen thickness and the rate of loading.

2-16* K_Q

2-17 K_{IC}

2-18* Valid measure of K_{IC} ?

These three fields are retained from the original format. Essentially, the three fields determine if the fracture toughness calculated (K_Q) is a valid measure of plain-strain fracture toughness (K_{IC}). The field 2-18 has the freedom of reporting the reason(s) for the invalidity if that is the case. A separate field for invalidity is not retained as the reasons are many more than those allowed for in the previous version.[1] The fields 2-16 and 2-18 are defined as essential following the lines of ASTM guide 1313[2]. ASTM test method E 399 "Plane strain fracture toughness testing" is the standard procedure for these determinations. Valid results can be employed in design and fitness for purpose analysis when flaws (cracks) are present in structural components using the principles of linear elastic fracture mechanics (LEFM).

2-19 J_{IC}

2-19a Valid measure of J_{IC} ?

2-20 Equivalent plane strain fracture toughness, K_{IC} (from J_{IC})

2-21 Method of J_{IC} calculation

Three fields are retained from the original format with the alternative units of reporting the values in fields 2-19 and 2-20 being included. 2-19a is added to record the validity following 2-18*. ASTM test method E 813 "J_{IC} A measure of fracture toughness"[46] describes the standardized procedure for these determinations.

2-22 Initiation J value

2-23 Maximum J value

2-23a No. of J specimens

These three fields are retained from the original format with the alternative units of reporting the values in fields 2-22 and 2-23 being included. These fields are moved up, in this format, as they are associated with testing according to ASTM test method E 813.

2-24 Initiation CTOD

2-25 Critical CTOD

2-25a Is reported CTOD c-cleavage, u-cleavage preceded by tearing, or m-fibrous (max. load)

2-25b Valid measure of CTOD ?

All of the above fields are associated with determination of fracture toughness from a measure of the crack tip opening displacement before fracture occurs. The method was first adopted in the U.K. as BS 5762 "Crack Opening Displacement (COD) Testing",[47] where COD is actually the CTOD. The parallel ASTM standard is E 1290 "Crack-tip Opening Displacement (CTOD) Fracture Toughness Measurement".[48] The method has found application in the elastic-plastic fracture mechanics (EPFM) domain when the conditions for linear elastic fracture mechanics (LEFM) are not satisfied. The most recent development in the application of CTOD toughness is in PD 6493 - 91 "Guidance on Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures"[49] (a BSI publication), where fitness for purpose analysis is the objective. (PD 6493 can use K and J data as well.) This CTOD method can also be used for material and weld procedure qualification purposes. Three of these fields are retained from the original version, while the validation is a new field. The last field is important from the assessment of the quality of the data in accordance with the ASTM guide.[6]

2-26a Number of test results

2-26b Method of presentation of results

The description and justification for these new fields are presented in the format of the tensile test record and therefore are not repeated here (see fields 1-19a and 1-19b).

Data Quality

2-27 Statistical basis of data
2-28a* Validation status
2-28b Certification status
2-29 Completeness of the test procedure description

The description and justification for these new fields are presented in the format of the tensile test record and therefore are not repeated here (see fields 1-20, 1-21a, 1-21b and 1-22, respectively). Validation is considered an essential field as plain strain fracture toughness and CTOD toughness results have to be checked for validity as described in fields 2-18 and 2-25b, respectively.

Recommended Standard Format for Notched Bar Impact Test Data

The information from these tests is currently not used in the application of reliability methods to design due to the absence of failure limit states in terms of CVN values, although empirical relations could be used to convert these to K or CTOD values. However, Charpy testing is the most common method of quality assurance that is currently adopted for toughness assessment. Therefore, the formats recommended in the previous work[1] are modified and justified along the lines employed in the tensile and initiation fracture toughness formats.

Background Information

3-0* Material key
3-1 Type of test
3-2* Purpose of test

Test Procedure

3-3* Standard
3-4 Date of applicable standard

The description and justification for the above fields are presented in the format of the tensile test record and therefore are not repeated here.

3-5a Testing machine capacity
3-5b Striker radius

These two fields can affect the results and are new inclusions following the recommended format in ASTM E 1313.[2]

Specimen Information

3-6* Specimen location
3-7* Specimen orientation
The description and justification for the above fields are presented in the format of the fracture toughness test record and are therefore not repeated here (see 2-9* and 2-10*, respectively). In this case, the field, Specimen location, is also defined as essential for this test in ASTM E 1313.

3-8* Specimen type
This field is retained from the original format[1] with specimen sizes referred to in ASTM E 23 "Test Methods of Notched Bar Impact Testing".[50] The fracture transition temperature decreases with the specimen thickness due to the decrease in constraint along the root of the V-notch. Thus results obtained will be a function of the specimen size and therefore, the field is defined as essential following ASTM E 1313.[2]

Test Results

3-9* Test temperature
For steels used in marine structures, the energy absorbed increases as the test temperature increases. In the fracture transition temperature range, these ferritic steels display a large scatter in energy absorbed, because the test specimen fractures contain varying amounts of brittle and ductile areas. In contrast, the scatter in the data is much less when the test temperature is in the brittle or ductile ranges. Therefore, this is defined as an essential field and is retained.

3-10* Total energy to fracture
3-11* Lateral expansion
3-12* Shear fracture
These three fields are retained from the previous format. They describe the results completely as recommended by ASTM E 23. These are also essential fields in the test result reporting format in ASTM E 1313.[2] The numerical values obtained for each are related; for example, the scatter in the energy absorbed results from the different proportions of brittle and ductile regions of the fracture surface.

3-13 Did specimen fracture completely
This field is retained form the previous format.[1] It is defined an essential field for the purpose of test validation in the recommended format of ASTM E 1313. This information is important in the upper shelf region when on occasion the specimen does not fracture into two pieces.

3-14a Number of test results
3-14b Method of presentation of results
The description and justification for these new fields are presented in the format of the tensile test record and therefore are not repeated here (see fields 1-19a and 1-19b).

Data Quality

These new fields are important to indicate the reliability of the test data reported in this section describing the notched bar impact results. The fields are specifically included to rank the data in accordance with the ASTM guide [6], and are classified according to the guide.

3-15 **Statistical basis of data**
3-16a **Validation status**
3-16b **Certification status**
3-17 **Completeness of the test procedure description**
The description and justification for these new fields are presented in the format of the tensile test record (see fields 1-20, 1-21a, 1-21b and 1-22, respectively).

Recommended Standard Format for Crack-Arrest Fracture Toughness Test Data

In the previous work[1] this test was referred to as the "MRL crack arrest" test. The test procedure has been standardized in ASTM E 1221 "Determining Plain-Strain Crack-Arrest Fracture Toughness, K_{Ia} of Ferritic Steels"[51]; therefore, it is identified as such in the current format. This test procedure has not so far been considered by the ASTM Committee E 49 on Computerization of Material and Chemical Property Data.

Background Information

4-0* Material key
4-1 Type of test
4-2* **Purpose of test**

Test Procedure

4-3* Standard
4-4 Date of applicable standard
The description and justification for the above fields (4-0 to 4-4) are presented in the format of the tensile test record and are therefore not repeated here.

Specimen Information

4-5 Specimen location
4-6* Specimen orientation
The description and justification for the above fields are presented in the format of the fracture toughness test record (see 2-9* and 2-10*, respectively). However, compared to initiation toughness where research and development work may involve testing specimens from diffferent locations, meaningful crack arrest values are only obtained using full-thickness specimens, thus the location is designated non-essential.

4-7 Specimen type

This field is retained from the original format[1] with an additional specimen type (compact crack arrest (CCA)) included following ASTM E 1221.

4-8* Specimen thickness

This field is retained from the original format. It is also an essential field, because it is a primary measure for the validation of the test results in accordance with ASTM E 1221.

Test Results

4-9* Test temperature

The description and justification for this field is similar to that presented in the format of the fracture toughness test record (see 2-15).

4-10* K_a

4-11 $\mathbf{K_{Ia}}$

4-12* Valid measure of K_{Ia} ?

The two essential fields (4-10* and 4-12*) are retained from the original format with a modification of the notations following those adopted in ASTM E 1221. Essentially, the three fields determine if the calculated crack arrest fracture toughness (K_a) is a valid measure of the plain-strain value (K_{Ia}). The field 4-12 has the freedom of reporting the reason(s) for invalidity. A separate field for invalidity is not retained as the reasons in ASTM E 1221 are many more than those allowed for in the previous version.[1]

4-13a Number of test results

4-13b Method of presentation of results

The description and justification for these new fields are presented in the format of the tensile test record (see fields 1-19a and 1-19b).

Data Quality

4-14 Statistical basis of data

4-15a* Validation status

4-15b Certification status

4-16 Completeness of the test procedure description

The description and justification for these new fields are presented in the format of the tensile test record (see fields 1-20, 1-21a, 1-21b and 1-22, respectively). Validation is considered an essential field as plain strain crack arrest toughness results have to be checked for validity as described in field 4-12.

Recommended Standard Format for Nil-Ductility Temperature Test Data

In the previous work[1] this format was not reported, thus, the fields described below are considered as 'new' additions, however, as all these fields are new they are *not* identified by bold lettering as for the previous formats. This format is included because there is renewed interest in the crack arrest behavior of steels and there weldments. This approach is an alternative to design based on crack *initiation* fracture toughness, and based on Pellini's work, nil-ductility temperature (NDTT) can be empirically related to crack arrest toughness. The NDT test procedure is standardized by ASTM E 208 "Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels"[52].

NDTT is not currently applied in reliability analysis, however, the present format is developed for completeness. The test is standardized for parent materials, although it is occasionally applied to weld metals and HAZ regions, therefore in the rationale developed the test as applied to parent plate only is considered. This test procedure has not been considered by the ASTM Committee E 49 on Computerization of Material and Chemical Property Data.

Background Information

5-0* Material key
5-1 Type of test
5-2* Purpose of test

Test Procedure

5-3* Standard
5-4 Date of applicable standard

The description and justification for the above fields (5-0 to 5-4) are presented in the format of the tensile test record and are therefore not repeated here.

5-5 Drop-weight energy

This energy level for the test is determined from the type of specimen (a field given below) and the yield strength of the material.[52] Drop-weight energy has to be raised as the yield strength increases.

Specimen Information

5-6 Specimen location
5-7 Specimen orientation

In contrast to fracture toughness these two fields are designated non-essential. This is because the standard test procedure (ASTM E 208) specifies that the specimen contain an original as-fabricated surface, and it is established that the NDTT is independent of the specimen orientation in wrought products. These fields are included in the test record.

5-8 Specimen type

The field specifies one of the standard specimen types. This field is related to 5-5.

5-9* Specimen thickness

This information will be available in the previous field if the test is performed in accordance with ASTM E 208.

Test Results

5-10 Test temperature

5-11 Break, No-break

These two fields are related to each other, and specify if a break or no-break occurred at the test temperature.[52] This is the basis for determining the NDTT of the material as described in the next field.

5-12* NDTT

This is the final outcome of the test and determines the maximum temperature at which a break occurs. Therefore, it is an essential field.

5-13a Number of test results

5-13b Method of presentation of results

The description and justification for these fields are presented in the format of the tensile test record (see fields 1-19a and 1-19b).

Data Quality

5-14 Statistical basis of data

5-15a* Validation status

5-15b Certification status

5-16 Completeness of the test procedure description

The description and justification for these fields are presented in the format of the tensile test record (see fields 1-20, 1-21a, 1-21b and 1-22, respectively).

Recommended Standard Format for Dynamic Tear Test Data

In the previous work[1] this format was not reported, thus, the fields described below are considered as 'new' additions. This format is included because the current 'Marine Structural Toughness Data Bank' presents data on this property.[1] The test procedure is standardized in ASTM E 604 "Dynamic Tear Testing of Metallic Materials"[53]. The information from these tests can not be used at present in the application of reliability methods to design due to difficulties in interpretation in terms of fracture mechanisms. However, the present format is developed for completeness. This test procedure has not been considered by the ASTM Committee E 49 on Computerization of Material and Chemical Property Data.

Background Information

6-0* Material key
6-1 Type of test
6-2* Purpose of test

Test Procedure

6-3* Standard
6-4 Date of applicable standard
The description and justification for the above fields (6-0 to 6-4) are presented in the format of the tensile test record.

Specimen Information

6-5* Specimen location
6-6* Specimen orientation
The description and justification for the above fields are presented in the format of the notched bar impact test record (see 3-6* and 3-7*, respectively).

6-7 Notch preparation
ASTM E 604 specifies the notch preparation procedure which involves machining followed by pressing of the notch root by a knife edge. If the pressing is not performed it can have an effect on the results, therefore, the field is included.

6-8* Specimen thickness
The dynamic tear energy and transition temperature are usually influenced by the specimen thickness. The fracture transition temperature increases with the specimen thickness due to differences in constraint along the notch root. Thus results obtained will be a function of the specimen size and therefore the field is defined as essential. Standard specimens are 16 mm thick, however non-standard thickness are also tested.

Test Results

6-9 Test temperature
The description and justification for this field is presented in the format of the notched bar impact test record (see 3-9*).

6-10* DT energy
6-11 Shear fracture
These fields describe the results completely in accordance with ASTM E 602. The numerical values obtained for each are related; the scatter in the energy absorbed result from the different proportions of brittle and ductile regions of the fracture surface. DT energy is the primary piece of information from this test, therefore, it is an essential field.

6-12 Did specimen fracture completely

This information is important in the upper shelf region when on occasion the specimen does not fracture into two pieces.

6-13a Number of test results

6-13b Method of presentation of results

The description and justification for these fields are presented in the format of the tensile test record (see fields 1-19a and 1-19b).

Data Quality

6-14 Statistical basis of data

6-15a Validation status

6-15b Certification status

6-16 Completeness of the test procedure description

The description and justification for these fields are presented in the format of the tensile test record (see fields 1-20, 1-21a, 1-21b and 1-22, respectively).

5.0 HIERARCHY OF THE DATA RECORDING FIELDS

In developing a statistical description from a sample population for a given property of a material in a specific condition, there would ideally be a large number of test records wherein all fields would display identical information, i.e., the material characteristics and test procedures would be identical. However, in practice this is unlikely. Data records may not include information for all of the fields or the database may be too small when all fields are required to display identical information.

It is proposed to overcome this drawback by developing a hierarchy of the data fields, i.e., ranking the various fields in different groups or levels in terms of the magnitude of the perceived influence that they have on the property value. The availability of a hierarchy can assist in enlarging the needed database by progressively ignoring the fields in the lowest ranked group.

For example, a tensile test record for a parent steel plate will usually contain the following information if performed according to ASTM E 8 "Tension testing of metallic materials" [42]:

i) Material specification
ii) Yield strength method
iii) Yield point method
iv) Gage length

The following information should be available on request:

i) Specimen type
ii) Specimen test section dimensions
iii) Speed of testing

Ideally, all of the above seven fields should display similar information when pooling tensile test results to develop a statistical sample population, however, information on the second set of fields may not be available. If there is insufficient numerical data in the ideal case to develop a statistical sample population, then the most important fields having similar information has to be *judged* so that sufficient numerical data is available for this purpose. For example, if we are pooling yield strength values, then the most important fields that should have similar information are: Material specification, Yield strength method, and Yield point method (if the yield point is considered as the yield strength). The fields that belong to the second level of importance are: Speed of testing and Specimen type (cylindrical, rectangular or full cross-section). Thus, in this example there are three judged levels of hierarchy: the two above and a third level which includes only Specimen test section dimensions. (Gage length will have no effect on yield strength). Therefore, to increase the database one should pool data with similar information in fields that belong to the first two levels. A further increase may be obtained if only the fields in the first level are considered.

5.1 Hierarchy for Parent Material

As described above, the ranking of the important fields is based on expert opinion. For parent material, the important fields can be inferred from two sources: i) standard test methods, and ii) material specifications. The information from the first has been considered in developing the rationale for the fields in Section 4.0. Here the essential fields include two types: background information on the materials and information on the test procedure that would affect the numerical value of the property. In the context of this project, the second source can include: marine steel specification requirements (for example, Materials for Hull Construction and Equipment in ABS Rules for Building and Classing of Steel Vessels [54] and similar codes and specifications from other ship building regulations). This is because reliable test data for marine materials will be obtained according to these codes and specifications, and thus these reports will include information on the required fields. (Codes and specifications include expert opinion on the important information on background of the material and changes in the test procedure that would affect the numerical value of the property.)

In general, the above factors have been considered in the hierarchy levels presented in Appendix B. The importance of each field, from the perspective of the influence on property value reported, is ranked from its indented position. The fields on the left have the most significance, thus the ranking of the fields decreases from left to the right in this hierarchy.

The basis for the proposed hierarchy for parent material properties is as follows:

i) The first two 'levels', i.e., fields in the extreme left and the first indentation, respectively, are the ones which are common to those identified as 'essential' in the data reporting (collecting) format, FORMATS.TXT, and those listed in the two sections on background information and test record described below.
ii) At the next three levels, all the remaining essential fields, and fields listed in the sections on background information and test record, which are known to have a second order influence on the property are included.

5.1.1 A Hierarchy for Pooling Tensile Data of Marine Structural Steels (Appendix B)

5.1.1.1 Fields Related to Background Information

Among the data fields in Appendix A, under material description and processing, the most important are the essential fields identified by an asterisk (*). The marine steel specifications, where the primary objective is quality assurance (Q.A.), call for the following information in certifying the test record; [43,44,54]

Specification designation *	Basic form *
Thickness *	Composition *
Producer (name of producing company)	Producer lot no.
Melting practice	De-oxidation practice *
Final processing steps *	

The fields with an asterisk (*) are essential according to Appendix A, thus these represent fields at levels L1 and L2 in the hierarchy following basis i). Specification designation (organization, no. & year) is the only field at L1 as it identifies the material and without this information the data cannot be pooled. With reference to basis ii), the remaining essential fields are included in L3 to L5. (From the point of view of the effects on tensile properties, only de-oxidation practice at level L2 is applicable and only for its influence on elongation.)

5.1.1.2 Fields Related to Test Record

In addition to background information described in the previous sub-section, the recommended format in Appendix A includes sections on test procedure, specimen information, test results and data quality.

It is known that test results are related to the procedure and specimen details, as considered in Section 4.0 in rationale for the fields. Marine steel specifications also outline the test procedure and specimen details with the objective of a uniform test method. Indirectly, through certification it ensures the quality of the data reported. In this context, information on the following fields are important.

Standard adopted *	Rate of loading to yield *
Specimen position	Specimen orientation *
Specimen type *	Specimen dimensions
Gage length *	Yield strength method *
Certification status	Completeness of test procedure

As before, the fields with an asterisk (*) are essential according to Appendix A and again these represent fields at levels L1 and L2 in the hierarchy. "Standard adopted" is placed at L1 as it specifies the test procedure. Test temperature is not present in the above list as it is usual to perform the test at room temperature, therefore as an exception to the basis i) above, this field which can have significant influence on tensile properties is placed at L1. It should be noted that gage length at L2 is *not* applicable when considering strength, and similarly, yield strength method and rate of loading to yield have little significance in relation to the tensile strength and elongation.

Among the remaining fields listed above, specimen position in relation to the plate dimensions and specimen dimensions may influence the test result. [55] The other two fields are associated with data quality. A study was carried out by the American Iron and Steel Institute (AISI) Technical Committee on the variability of the tensile properties of plates and shapes.[18] The variation of tensile data for a range of hot rolled plates, covering thickness of 25 mm (1") to 75 mm (3"), 570 heats and 11 producers in North America were analyzed. It was found that the variation in the properties as a result of test specimen position within a plate was less than the variation that was obtained for the same position in different heats. This justifies the omission of a field for the specimen position with respect to the plate dimensions in the current format (appendix A). As expected, the AISI study showed that the elongation values separated into two distributions for the two gage lengths (50 mm and 200 mm) of the specimens, confirming the importance of this field for hierarchy when considering elongation.

5.1.2 A Hierarchy for Pooling Crack -Initiation Fracture Toughness Data of Marine Structural Steels (Appendix B)

5.1.2.1 Fields Related to Background Information

Among the marine steel specifications, Lloyd's [43] has a provision for fracture toughness testing of the parent material, which calls for the following background information:

Specification designation *	Basic form *
Thickness *	Composition *
Producer (name of producing company)	Producer lot no.
Melting practice	De-oxidation practice *
Final processing steps *	Source of data/laboratory *

Again the fields with an asterisk (*) are essential according to Appendix A. When compared to the tensile test record, specific reference is made to 'a recognized test house in accordance with a nationally accepted standard', emphasizing the source of data.[43] Thus, the hierarchy on background information is similar to the tensile test data except for Source of data/laboratory which is at L2 following the basis i).

5.1.2.2 Fields Related to Test Record

Following similar lines as in the case of the tensile test record, outlined in section 5.1.1.2, the Lloyd's specification [43] requires information on the following fields for a uniform test procedure:

Standard adopted *	Type of loading *
Specimen orientation *	Specimen type *
Specimen thickness *	Specimen width
Average crack length	a/W ratio *
Test temperature *	Valid measure of CTOD ?
Certification status	Completeness of test procedure

The fracture toughness result considered here is the CTOD, because in structural applications, steels are normally expected to display elastic-plastic behavior. Further, CTOD can also account for both brittle and elastic-plastic behavior by specifying the value according to δ_c, δ_u, or δ_m (i.e. the mode of failure). In order to report data in the full range of brittle and ductile fractures, it is useful to have a field that describes the mode of failure in the CTOD test, i.e. δ_c, δ_u, or δ_m, and therefore, it is included in the hierarchy. The fracture toughness parameter considered here is CTOD, however, as an alternative, J values can also be considered as they can represent the EPFM domain.

Fields for the hierarchy levels L1 and L2 are arrived at using basis i). Compared to the hierarchy for tensile data, two more fields are included at L1, specimen orientation and thickness, because information on these two fields have greater effect on toughness compared to strength. With reference to basis ii), in addition to the remaining essential fields, the fields associated with CTOD and J values described in the previous paragraph are included in L3 to L5.

5.1.3 A Hierarchy for Pooling Notched Bar Impact Test Data of Marine Structural Steels (Appendix B)

5.1.3.1 Fields Related to Background Information

The marine steel specifications, where the primary objective is Q.A., call for the following information: [43,44,54]

Specification designation *	Basic form *
Thickness *	Composition *
Producer (name of producing company)	Producer lot no.
Melting practice	De-oxidation practice *
Final processing steps *	

As all of the specifications reviewed consider material Q.A. through both tensile and standard Charpy-V notch impact testing, the above fields are the same as those presented in section 5.1.1.1. These observations lead to the same hierarchy as for tensile data for background information.

5.1.3.2 Test Record

Following similar lines as in the case of the tensile test record, outlined in Section 5.1.1.2, review of marine steel specifications [43,44,54] leads to the following fields that are required to be addressed in the test report:

- Specimen position
- Specimen location *
- Specimen orientation *
- Specimen thickness *
- Test temperature *
- Certification status
- Completeness of test procedure

An AISI sponsored program, on "Variation of Charpy V-notch impact properties in steel plates" [19], following the lines of the previous one on tensile data [18], was carried out on three types of steel. The steels were in the as rolled (conforming to ASTM A572), normalized (ASTM A516) and quenched and tempered (ASTM A537) conditions. The test data (impact energy and lateral expansion) were obtained in a uniform procedure. Similar to the findings on the tensile properties, the test specimen position within the plate had an influence on the impact data (average of three values) when important fields such as orientation, location in relation to thickness and test temperature were fixed. However, the analysis does not determine if this variation within the plate is greater than the overall variation in the data of all the plates for a specific position and specimen location. A recent study on the "Notch toughness variability in bridge steel plates"[56] displayed, using the 'analysis of variance method', that a systematic variation in impact toughness (average of three values) occurs from the leading to the trailing edge of some as-rolled plates. The data from other as-rolled plates, however, because of the relatively large scatter at each position, did not lead to the same conclusion. In contrast, normalized plates had much lower scatter. These observations are related to the effects of final processing variables on properties and it is defined as an essential field in background information. Further, the inherent scatter in impact data does not justify defining the specimen position, in relation to the plate, as an important field that has a significant influence on the test results.

Similar to the method outlined in Sections 5.1.1.2 and 5.1.2.2, the hierarchy for pooling notch impact test data of marine materials has two levels (L1 and L2) following basis i) and is presented in Appendix B. There are no fields to be specified at the next three levels using basis ii).

5.2 Hierarchy for Weld Metal and Heat Affected Zone (HAZ)

The objective in this section is to develop a hierarchy of fields that influence weld metal and HAZ mechanical properties. The approach used here is to obtain a reliable assessment of the important variables by reviewing the essential variables for welding procedure qualification and steel pre-qualification in fabrication codes or other specifications. The essential variables represent a consensus expert opinion of knowledgeable and experienced personnel from research and industrial milieu vis a vis the important variables that might influence the soundness and mechanical properties of weldments. However, it should be noted that weld soundness (especially hydrogen induced delayed cracking, i.e 'cold cracking' in the weld metal and HAZ) is not to be considered in developing the present hierarchy as mechanical properties (toughness and strength) are the focus of attention here. It should be noted that there are no standard tests to directly measure the tensile properties of the HAZ and therefore, a hierarchy is not developed for this variant.

5.2.1 Determination of Essential Variables

The various fabrication codes and specifications reviewed in the context of requirements for welding procedure and steel pre-qualification included:

AWS D1.1 Structural Welding Code [57]
ABS [54], Lloyd's [43] and DnV [44] Requirements for procedure qualification
CSA W47.1 Offshore Supplement [58]
API Recommended Practice 2Z (RP 2Z) for offshore structures [59]

Offshore structures related documents have been included in this review because of their greater emphasis on fracture toughness of the weld zone, especially the HAZ. The essential variables identified in these documents are as follows:

- *change of steel-maker* (producer): For the same grade of steel, different steel-makers may have different target chemistries, thus influencing the heat affected zone microstructure and therefore its toughness. Similarly, the weld metal composition and mechanical properties can be affected due to the dilution from the parent material (e.g., effect of Al in base material on submerged arc weld metal toughness) and thus, the strength and toughness can be affected. If the weld metal composition is recorded, this field becomes less important.

- *change in steel making and/or finishing method*: These changes can influence features like extent of center-line segregation and in turn may influence the HAZ toughness.

- *change in steel specification and grade*: Affects the HAZ toughness as well as weld metal toughness and strength through dilution from the parent material.

- *change in thickness beyond a certain range*: This range is usually much narrower when toughness requirements are specified compared to its effect on strength. (In a proprietary document, this range is 0.7 to 1.25 times the thickness tested.) Increasing thickness up to a threshold value raises, i) the weld zone cooling rate for a given heat input, (ii) the hydrogen diffusion distance, (iii) the constraint in the full thickness fracture toughness specimens and iii) the number of weld passes which in turn can lead to tempering and/or embrittlement of the passes deposited earlier as well as changing the residual stress pattern in the weldment.

- *change in groove shape (type)*: Recently it has been found that weld beads deposited first, i.e., the root region can be susceptible to strain age embrittlement. A change in groove shape from a single-V to double-V can therefore, move the embrittled region from near the surface region to more constrained mid-thickness region and this can, in full thickness fracture toughness tests lead to lower fracture toughness values. In the context of HAZ toughness, a similar effect is again possible. However, here the more important parameter is the groove angle itself. Thus, HAZ fracture toughness (CTOD, for example) and Charpy V notch results are reported separately in literature for V-grooves and for grooves with one side perpendicular to the plate surface (for example, 'K' or half 'K' grooves). The specimen notches in the latter case sample a much greater proportion of the relatively brittle grain coarsened HAZ than is the case for HAZ specimens from welds made in V-grooves which would sample significant amounts of the base material and/or weld metal. Clearly, the HAZ toughness results from otherwise identically made welds but with significant differences in the groove shape can not be pooled or compared.

- *change of welding process*: A change of welding process necessarily implies a change in the weld metal composition (including elements such as oxygen) and therefore, a change in the weld metal strength and toughness values. Another possible change is in the arc efficiency so that nominally for the same heat input, two weldments might have different cooling rates (e.g., submerged arc process with an arc efficiency of 0.90 to 0.95 vs 0.6 to 0.7 for the shielded metal arc welding) influencing the HAZ toughness.

- *change of manufacturer/ trade name of consumable*: To achieve a given combination of weld metal properties different manufactures can use different approaches. This is especially true for processes involving weld pool shielding by molten slag, i.e., shielded metal arc, submerged arc, flux cored arc, etc. Also, within a given classification, the same manufacturer can have more than one product, intended for slightly different applications (e.g., E7018 electrode designed specifically to retain strength after stress relief). These different products should all meet the minimum requirements but with varying margins above the minimum, thus, the products would display different distributions for a specific property value.

- *change of classification of consumable* (weld filler classification): Minimum weld metal properties anticipated are usually reflected in the consumable classification itself.

- *welding position*: It was observed in earlier studies that for the SMAW process, welds made in the vertical up (3G) position, the weld metal had inferior toughness than in the flat (1G) position. This has been attributed to weaving and therefore, higher heat input in the 3G position welds and possible higher nitrogen content of the weld metal resulting from a longer arc. In contrast, recently it has been observed that for the flux cored arc welds, the welds made in the 3G position can have better weld metal toughness than those made in the flat position.

- *heat input/pass*: Heat input perhaps is one of the most important variables influencing the weld metal as well as the HAZ toughness. For example, a too high or a too low heat input lead to either soft and coarser microstructure or a hard microstructure, respectively, both having inferior toughness. Considering the weld metal, the 'optimum' heat input depends on weld metal composition as well as the weld zone cooling rate because these two fields determine the microstructure.

- *preheat/interpass temperature*: These two variables influence the cooling rate, especially at lower temperatures (below approximately 290°C (550°F) and therefore, have relatively no effect on weld zone microstructure. Higher preheat/interpass temperature enhances hydrogen diffusion which reduces the potential for cold cracking. These two fields are essential variables for weld zone soundness and are less important for weld zone properties and therefore in the present context, have lower priority in the hierarchy.

- *specimen orientation* (wrt. rolling direction): This variable is not expected to affect weld metal properties therefore, has low significance in the hierarchy. In contrast, it may influence the HAZ toughness as a result of directionality dependence retained from the parent material.

- *post weld heat treatment* (temperature and time): This procedure usually tempers (softens) both the weld metal and the HAZ, and thus, improves toughness. However, depending on actual composition of the specific region there is potential for embrittlement as well, for example, the known effect of vanadium (V) and nitrogen (N).

5.2.2 Hierarchies for Pooling Weld Metal and HAZ Test Data of Marine Structural Steels (Appendix C)

Following the procedures for developing hierarchies for tensile and toughness characteristics of the parent material, the essential fields include two categories; background information on the material and information on the test procedure that would affect the numerical value of the property. Considering the weld metal and HAZ, the first type and their importance has been outlined above as the essential variables, and the second type should generally be the same as for the parent material. Appendix C presents the recommended hierarchy for the various weld metal and HAZ properties, keeping in mind that some differences occur as the standard test procedures for weld metal and HAZ are different compared to those for the parent material as outlined below:

i) Tensile properties of the weld metal: The orientation of the specimen is identified with respect to the axis of the weld, whereas in the parent plate, it is described using standard notations (see Section 4). There are two standard methods for obtaining tensile properties; the first uses an all-weld metal test specimen where the gage length of the specimen contains only the weld metal, and in the second type the test load is applied transverse to the completed weld. Both methods have their disadvantages, considering the use of the property values in design; a) values derived from an all-weld metal test will vary much more than is the case of the parent material, depending on location and size of the specimen [55], b) the standard transverse test specimen usually verifies that the weld is stronger than the parent metal when loaded transverse to the weld; codes and specifications do not require yield strength to be reported for such specimens, and if reported the value is meaningless to a great extent as the gage length comprises different proportions of base metal, HAZ and weld metal.
In current research involving welding of high strength steels with 'undermatched' weld metals, there is no doubt that yield strength is being, and will be calculated for transverse specimens. The calculated value will depend on the gage length in relation to the weld width, and its meaningful assessment requires detailed analysis for which the approaches are still under development.[55] Until that time, gage length for *transversely* loaded specimens is not considered to be an essential field.

ii) Tensile properties of the HAZ: Standard test procedures are not available due to significant variations in the microstructure in this relatively small region. Thus no meaningful results can be obtained.

iii) Toughness of the weld metal and HAZ: Fracture toughness of the weld metal is commonly measured using through thickness notched specimens with their axes normal to the weld axis. However, in occasional cases, (for example, a need to perform fitness for purpose analysis for weld metal with transverse cracks) non-standard specimen orientations may be required. Since the statistical distributions are expected to be different for toughness obtained by specimens of different orientations; this field has been included at the second level (L2). The above comments regarding specimen orientation are also applicable to the toughness measurement of the HAZ.

iv) Dynamic tear tests for weld metal and HAZ: The hierarchies for the fields are similar to those proposed for the respective notched bar impact tests and therefore not separately presented in the Appendices.

In all of the above cases, there are three levels of hierarchy for background information on the material and five levels for information on the test procedure that would affect the numerical value of the property.

All of these proposed hierarchies are to be taken as a set of rules based on expert opinion and in light of the current state of knowledge. They may have to be modified as new research information becomes available.

6.0 PROPOSED DATABASE FORMAT AND DATABASE PROGRAM

6.1 Proposed Material Property Database Format and Hierarchy

The proposed material data reporting format is presented in Appendix A. The format is a modification of the one recommended in a previous SSC project[1] to incorporate the findings of Section 3.0 "Review of Existing Material Property Data Representation Formats" and the concerns of Sections 4.0 "Proposed Material Data Reporting Format" and 5.0 "Hierarchy of the Data Recording Fields". For example, when incorporating the findings from these three sections the number of essential fields in the data reporting format described in Section 4.0 had to be increased after the hierarchy was developed. Fields were added to ensure that all of the essential information was at levels L1 and L2.

6.2 Sample Application of the Material Property Database

The following section describes a potential scenario involving the use of the proposed materials database to illustrate its principal features. The flow of the proposed program is also described by the flow chart in Figure 6.1. In the scenario, it is assumed that the user is a designer with no special training in the fields of reliability or metallurgy. The user would like to perform a simple statistical study of the uniaxial yield strength of HY80 steels. The following is a description of a potential flow pattern of the database data retrieval program.

i) The first question the users must answer involves the level of statistical information they require or the level of reliability analysis they intend to perform with their data. Based on this response the database program will know the type of output (characteristic values, statistical measures, distribution types, etc.) the user is interested in. In this example, it is assumed that the user is interested in normal (Gaussian) statistical measures (a mean, standard deviation and some measure of the goodness of fit), therefore, level II statistical data is appropriate.

ii) The user must indicate which region of a structure is of interest (i.e. base metal, heat affected zone or weld metal) since the information required to describe each of these is different. In this example, it is assumed that the user is interested in base metal behavior.

iii) The next piece of information required involves specifying the desired material property. As previously mentioned, the user in this example requires uniaxial yield strength information.

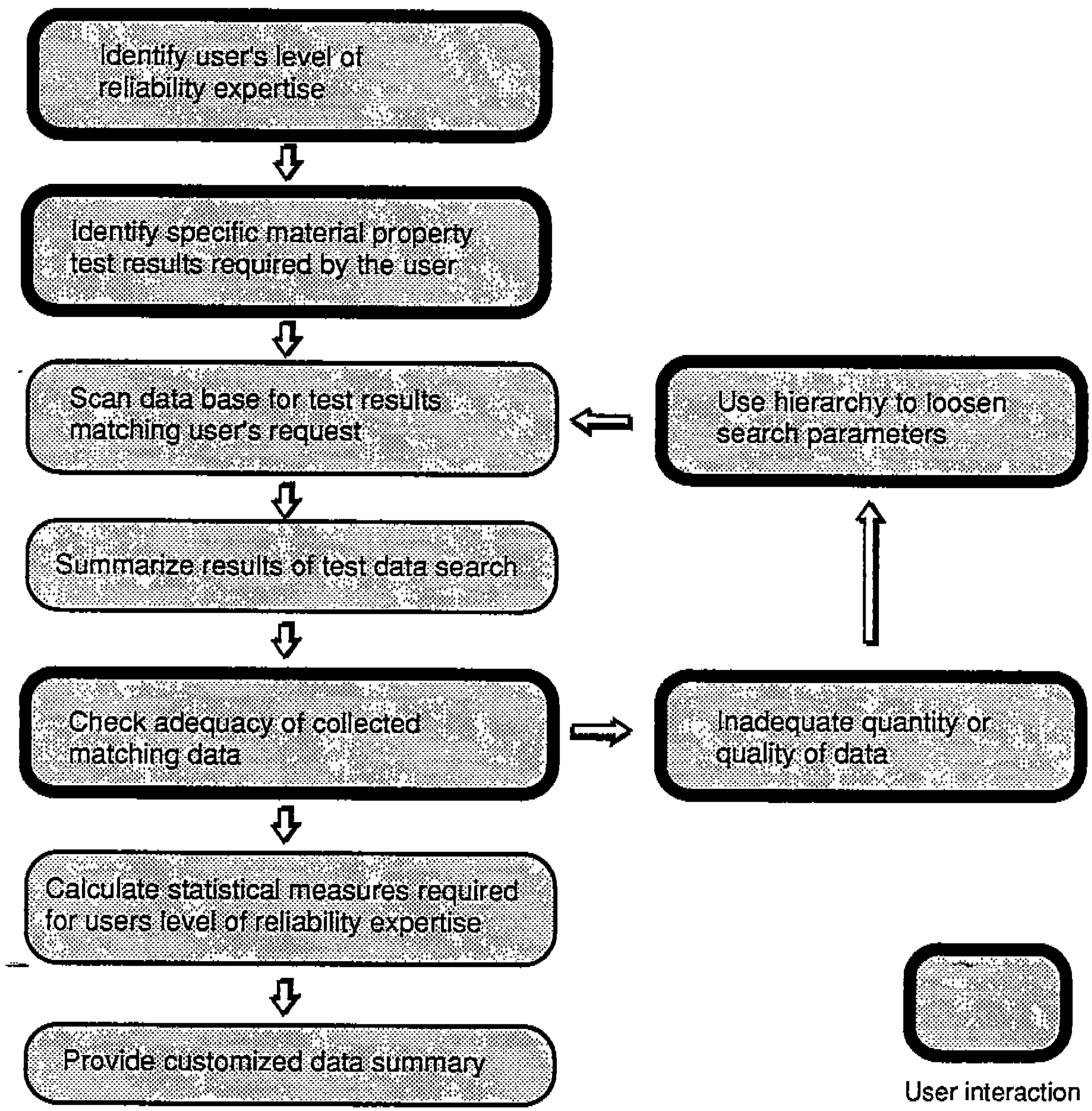


Figure 6.1: Proposed Material Property Database Program Flow Chart

iv) Based on the above information the user is presented with the fields of the appropriate hierarchy to supply information which he/she feels is important to keep constant in all of the data to be included in the material property sample information. The data field hierarchy's arrangement is such that it could be employed by a user who is not familiar with the importance of testing procedures, metallurgy and quality control to identify those fields which are most significant to the data being collected. In this example the user may request the yield strength, in the rolling direction, for half inch (12.5mm) HY80 plates that were tested based on quarter inch (6.25mm) diameter test specimens with a one inch (25 mm) gauge length, among other testing and material requirements particular to their application.

v) Using the responses provided by the user, the database program will search for all of the test results whose data fields match the user's requirements. A summary of the search results is presented to the user to assess if the search results were adequate. The summary, similar in form to Figure 6.2, would contain a list of test data sources, the number of pieces of data contributed by each and a description of the sample data statistical relations. The statistical relations, proposed in Figure 6.2, are measures of the statistical significance of the differences between each source group's mean and standard deviation, where a relationship of 1.0 indicates identical data and a value less than one indicates significant differences in the data sets.

vi) At this stage, the data is pooled based on either the user's selections of those data groups which are to be included in the statistical measures or the program could use a set of rules to disregard those sets of data which have significantly different means or standard deviations. The set of rules the program would use to select data which should be pooled could involve minimum inter-group correlation coefficients and sample size requirements.

vii) If a sufficient amount of information is found to supply the user's requested statistical measures with a reasonable level of certainty, then the information is calculated, summarized and provided. If there are too few test results in the database which match the user's material, testing and quality specifications, then the material hierarchy is consulted again to indicate those requirements which can be relaxed with the least effect on the quality of the requested material parameter. In this example, the hierarchy would indicate to the user that the diameter of the test specimen is one of the specified data requirements that will least effect the measurement of yield strength. With the revised search requirements, the database program will perform a new search starting at step v) in this summary until an adequate sample has been retrieved.

The flow outlined above for a data retrieval session could be altered significantly to suit different requirements without affecting the service provided by the database.

Source Sample Size and Correlation Table

Source	Sample Size	Source Group A	Group B	Group C	•••
Group A	50	1.0 1.0			•••
Group B	68	0.85 0.88	1.0 1.0		•••
Group C	175	0.93 0.90	0.68 0.75	1.0 1.0	•••
⋮	⋮	⋮	⋮	⋮	

Note: - The "matrix" of sample correlations is symmetric.
- Correlations presented for sample means and standard deviations.

Figure 6.2: Sample Database Program Material Property Data Pooling Results

6.3 Statistical Requirements of the Material Property Database Program

In order to effectively support the application of reliability analysis the database of material properties must be able to provide material statistical summaries of its data. The findings of this report suggest that the database should recognize that depending on the type of reliability-based design the user intends to perform, there will be different statistical data demands placed on the database program. In order to differentiate between the different user needs, the spectrum of reliability analysis techniques were classified into three levels for which typical data requirements were identified as follows:

- Level I - Reliability-Based Design in a Deterministic Format:
  - Requires characteristic (typical, specified, percentile) value.
  - Selection of characteristic value requires sample statistics (i.e. means, modes, medians, standard deviations, largest or smallest values etc.) and a distribution type assumption.

- Level II - Reliability-Based Design with Gaussian (Normal) Statistics:
  - Requires normal distribution parameters (i.e. mean, standard deviation) and a method for approximating the normal probability distribution.
  - Higher accuracy analysis requires correlation coefficients expressing material property relationships.

- Level III - Distribution Dependant Reliability-Based Design:
  - Employs the statistical distribution type which best fits the data.
  - Requires the tools to estimate the parameters for a variety of statistical distributions.

Based on the level of reliability analysis the user intends to employ, the database program should provide one of the three suggested data summaries or be capable of providing groups of data to users interested in performing their own statistical data analysis.

In addition to the statistical data necessary for reliability-based design, the database should also incorporate statistical features which ensure data quality. For this reason, a review of all of the statistical operations which could be expected of the database program was performed. Beyond the estimation of typical statistical distribution parameters (i.e. mean, standard deviation) some of the functions the program should be able to perform include:

- Statistical property estimation and quality assessment;
- Identification of characteristic values specified by the user;
- Statistical distribution selection and quality assessment;
- Identify statistical relations or lack there of between data from different sources;
- The ability to manipulate grouped data and combine it with non-grouped data.

Further details of the specific statistical requirements are included in the main body of this text or the reader could refer to standard statistical analysis reference literature.

7.0 RECOMMENDATIONS FOR FURTHER WORK

In making recommendations for further work, it should be recalled that the ultimate objective for project SR-1311 (SSC Report 352) and the current follow on project has been to develop a computerized material property database which with the help of a user - computer software interface could be employed for various levels of reliability based design and/or fitness for service analyses. As a result of the two above mentioned projects, a detailed and comprehensive data entry / presentation format has been developed and the statistical requirements for the software interface identified. The next stages to reach the goal defined above therefore are seen to be as follows:

A) DATABASE

- Screen Data

Currently, there is no restriction on quality of data that is included in the database, and a strategy is needed to assure the data quality. The database does have fields containing data quality measures which could be used for screening purposes. An alternative to electronic data quality screening might be to have a peer review committee as is done for Mat.D.B.

- Facilitate Data Entry

Currently, there are in excess of 190 data fields which can be associated with material properties of interest. The volume of information to be entered for a large scale database would make the data entry step very laborious and expensive. It is therefore suggested that a data entry hierarchy be developed to ensure that only the relevant fields associated with each piece of material property data are requested to be entered.

B) SOFTWARE INTERFACE

- Identify Efficient Statistical Procedures

In the current project the statistical needs of the database software package were summarized and various methods of satisfying these statistical needs were presented. In order to produce an efficient database management software system further investigation and experimentation of available statistical approaches are necessary.

- Collect Statistical Distribution Recommendations

The selection of statistical distributions to represent material properties based on past experience or theoretical basis is a practical alternative to purely mathematical approaches. In order for a user, unfamiliar with material property statistical distributions, to employ this theoretical or experience based selection process the software system managing the database should provide assistance in the form of distribution type recommendations.

Distribution type recommendations can be collected through a concentrated literature search and assessment of available data.

- Develop Statistical Acceptance Limits

In order to apply the statistical quality control procedures described in this report, threshold levels of accuracy (i.e. confidence limits) must be identified. These quality control requirements should be developed based on recommendations in the literature and experience derived from statistical experimentation.

Based on the interest expressed by the Ship Structure Committee in the evolution of the material property database into a universal design data resource consultation with other agencies is appropriate at this time. Both the American Society of Testing Materials (ASTM) and the Japanese Society for Materials Science (JSMS) were involved in similar projects and indicated an interest in this project.

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APPENDIX A: PROPOSED MATERIAL DATA REPORTING FORMAT

FORMATS.TXT (August 1993)

For File Use only
Entered into ______.WK1
lines____to____
Date____19_

Information included: Wld, Ten, FT, CV, CCA, NDT, DT
WORKSHEETS FOR SCC SR-1334 REQUIREMENTS FOR MATERIALS DATA GATHERING (Data fields with an asterisk (*) represent essential fields)

STRUCTURAL MATERIAL PROPERTIES FOR RELIABILITY ANALYSIS

MATERIAL DESCRIPTION AND PROCESSING

Material Specification and Identification

0-1 Material code __ __ __ . __ __ __ . __ __ __
0-1a* Common name ______________ __ not reported (n.r.) __ not available (n.a.)
0-1b* UNS desig. ____________________ __n.r. __n.a
0-1c1* Spec. organization, no. & year (made to) ________ __n.r. __n.a.
0-1c2 Spec. organization, no. & year (passed) ________ __n.r. __n.a.
0-1c3* Supplementary requirements ________ ___ See ____________ __n.r. __n.a.
0-1d ASTM spec. no. ____________________ __n.r. __n.a.
0-1e AISI desig. ____________________ __n.r. __n.a.
0-1f Military spec. ____________________ __n.r. __n.a.
0-1g ISO desig. ____________________ __n.r. __n.a.

Type and Geometry of Product

0-2a Test metal __ WM-Wrought metal __ CM-Cast metal __ WJ-Welded joint only
0-2b* Basic form __ P-Plate __ A-Angle __ C-Channel ___ WJ-Web of shape
__ T-Pipe __ B-Bar __ S-Shape ___ F-Flange of shape
__n.r. __n.a.
0-3* Thickness ______ mm ________ in. ___ See ____________
__ n.r. __ n.a.

Composition

0-4* Composition type ___ S-refer to specification ___ N-nominal (not measured)
___ A-actual
0-4a Composition position ___ T-Top ___ B-Bottom ___ L-Ladle, ___ W-Weld,
___ P-Product
__ n.r. __ n.a.
0-4b Actual composition ___ See ______________________

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Fabrication History

0-5 Producer (name of producing company) __ n.r. __ n.a.

____

0-5a Lot number ____________
__ n.r. __ n.a. See ________

0-5b Year of production ____ __ n.r. __ n.a.

0-5c ISO 9000 certification ____________

0-6 Melting practice __________________ __ n.r. __ n.a.

0-7 Casting practice __ ingot __ continuously cast __ n.r. __ n.a.

0-8* De-oxidation practice ________________ n.r. __ n.a.

0-9* Final rolling temp. ___°C ___°F ___K
__ n.r. __ n.a.

0-10 Rolling deformation ____ % reduction (total), __ n.r. __ n.a.

0-11* Final processing steps (use one or two letters)

___ A-austenitized ___ N-normalized
___ B-brine quenched from A ___ P-control rolled
___ C-cold working ___ K-aged
___ D-double normalized ___ Q-quenched
___ F-hot rolled ___ S-stress-relieved
___ G-hot forged ___ T-tempered
___ H-thermo-mechanical controlled processing

0-12* Final heat treatment temp. ___°C ___°F ___ K
__ n.r. __ n.a. See ______________

0-13* Final heat treatment time ___ hr __ n.r. __ n.a.
See ______________________

0-14* Cold work strain ____ % __ n.r. __ n.a. See ______________________

0-15* Stress relief or Aging temp. ___°C ___°F ___K
__ n.r. __ n.a. __ See ______________________

Data Quality

0-16* Source of data/laboratory __________________________

0-16a Source ISO 9000 certification ___________
__ n.r. __ n.a.

0-17* Source of data

__U-unpublished report __J-journal __H-handbook publication
__G-government report __P-producer brochure __S-source unknown

0-18 Completeness of material information

__F-full information on material form, condition and processing history
__C-information on material form and condition only
__X-no information on material form, condition or processing history

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WELD DESCRIPTION

W-0 Weld code __ __ __ . __ __ __ . __
W-1* Welding process
__SAW __NGGMAW __GMAW __GTAW __ESW
__SMAW __NGSAW __GMAW-P __GTAW-P __EBW
__FCAW __SAW-S __GMAW-S __SW __PAW
__n.r. __n.a.

Welding Procedure

W-2 Spec. organization, no. & year ________ __ n.r. __ n.a. See ________
W-3* Welding position ____________ __ n.r. __ n.a.
W-4 Preheat temp. ___°C ___°F ___K
W-5 Interpass temp. (Maximum) ___°C ___°F ___K
W-6 Post heat temp. & time (hydrogen outgassing) ___°C ___°F ___K ___s
W-7 Number of passes ______ __ n.r. __ n.a. See ________
W-8a Welding filler, Spec., no. & year ____________________
__ n.r. __ n.a.
W-8b* Welding filler, Classification ____________________
__ n.r. __ n.a.
W-8c UNS desig. ______________ __n.r. __n.a.
W-8d* Welding filler, trade name ____________________
W-9 Filler size __mm __in __ n.r. __ n.a.
W-10a Flux, Spec., no. & year ____________________ __ n.r. __ n.a.
W-10b* Flux, trade name ____________________
W-11a Shielding gas, Spec., no. & year ____________________
__ n.r. __ n.a.
W-11b* Shielding gas, Composition/Common name __ A __ He __ CO_2 __ O_2__Other__M-mixed __n.r.__n.a.
W-12a Power source, Common name (trade name) ____________________
W-12b Voltage ____________ volts __ n.r. __ n.a.
W-12c Amperage ____________amps __ n.r. __ n.a.
W-12d Polarity ____________________
W-13 Travel speed _____ in/min _____ mm/s __ n.r. __ n.a.
W-14* Heat input (range & average) __ kJoules/mm __ kJoule/in __ n.r. __ n.a.
W-15 Cooling time ($t_{8/5}$) __ s
W-16a Joint prep. __ M-Machined __ F-oxyfuel __ P-plasma
W-16b* Groove type __V __U __K __ double-V __ double-U __ half K ___N.G.
__ n.r. __ n.a.
W-16c Gap __mm __in __n.r. __n.a.
W-16d Backing, Spec., no. & year ________ __n.r. __n.a. See ________
W-16e Back gouging ____________ __n.r. __n.a.
W-16f Number of sides welded __1 __2 __ n.r. __ n.a.

W-17* Weld specimen notch position codes
Location relative to weld: (See below)
___09-Weld Metal
___02-Fusion Line
___03-1mm HAZ
___04-3mm HAZ
___05-5mm HAZ
___06-7mm HAZ
___07-9mm HAZ
___08-11mm HAZ
___10-Transverse Section Test (All Zones)
___11-50%WM-50%HAZ

W-18* Location relative to surface: (See below)
___ 0/4T (side 1) ___ 0/4T (side 2)
___ 1/4T (side 1) ___ 1/4T (side 2)
___ 1/2T ___ root of weld
___ N-Full cross-section
__ n.r. __ n.a.

W-19* Postweld heat treatment temp. (See below) ___°C ___°F ___K
__ n.r. __ n.a.

W-20* Post-weld heat treatment time ___ hr (See below)
__ n.r. __ n.a.

W-21* Is the actual weld deposit composition reported in 0-4 ? ___Yes ___No
__ n.r. __ n.a.

W-0 Weld key code (See total number below)

Weld code	W-17 Loc/Weld	W-18 Location	W-19 PWHT temp.	W-20 PWHT time
__ __ __.__ __ __.___	__ __	________	_____°___	________ hr.
__ __ __.__ __ __.___	__ __	________	_____°___	________ hr.
__ __ __.__ __ __.___	__ __	________	_____°___	________ hr.
__ __ __.__ __ __.___	__ __	________	_____°___	________ hr.
__ __ __.__ __ __.___	__ __	________	_____°___	________ hr.
__ __ __.__ __ __.___	__ __	________	_____°___	________ hr.
__ __ __.__ __ __.___	__ __	________	_____°___	________ hr.

STANDARD FORMAT FOR TENSILE TEST DATA

Background Information

1-0* Material key ______________________
1-1 Type of test-tension
1-2* Purpose of test __ Q.A. __ mill certificate __ R & D __ Other
___n.r. ___n.a. ___ See ________________

Test Procedure

1-3* Standard ____ ASTM ____________ or ___ other standard ______________
__n.r. ___n.a.
1-4 Date of applicable standard 19___ ___ __n.r. ___n.a.
1-5a* Rate of loading to yield ___ MPa/sec ___ksi/sec ___in/in/sec
___n.r. ___n.a. See ________________
1-5b Rate of loading from yield to fracture ___in/in/sec
___n.r. ___n.a. See ________________

Specimen Information

1-6* Specimen location ___n.r. ___n.a. __See_________
___ 0/4T
___ 1/4T
___ 1/2T
___ root of weld
1-7* Specimen orientation ___n.r. ___n.a. ___ See ______________
___ L (longitudinal) ___ T (long transverse) ___ S (short transverse)
1-8* Specimen type ___n.r. ___n.a. ___ See ______________
___ Cylindrical ___ Rectangular ___ Full cross-section
1-9 Specimen diameter or thickness ___ mm ___ in ___ See _______________
___n.r. ___n.a.
1-10* Gage length ___ mm ___ in ___ See ______________________
___n.r. ___n.a.

Test Results

1-11* Test temperature ___°C ___°F ___K ___ See ____________________
___n.r. ___n.a.
1-12* Tensile strength ___ MPa ___ ksi ___ See _______________
___n.r. ___n.a.
1-13a* Yield strength method ____ %Offset ____ % extension under load
See _______________ ___n.r. ___n.a.
1-13b* Yield strength ___MPa ___ksi ___ See ______________ __n.r. ___n.a.

1-14a Yield point method ___Half of load ___Autographic ___Strain rate
___extension under load ___ See _____________ __n.r. ___n.a.
1-14b Yield point ___ MPa ___ ksi ___ See _________________ __n.r. ___n.a.
1-15 Uniform elongation ______ % ___ See _________________
__n.r. ___n.a.
1-16a* Total elongation ______ % ___ See _________________
__n.r. ___n.a.
1-16b Fracture in the mid-half of gage length ___See ____________ __n.r. ___n.a.
1-17 Reduction of area ____ % ___ See _________________
__n.r. ___n.a.
1-18 Fracture location (weld) ___WM ___HAZ ___BM __See _________ __n.r. ___n.a.
1-19a Number of test results ___
1-19b Method of presentation of results ___Table ___Histogram
___Mean ___Standard deviation ___Type of distribution ___Parameters
___ See _________________ __n.r. ___n.a.
Note: Retain raw data in tabular form

Data Quality

1-20 Statistical basis of data
__ A-99th percentile with confidence of 95%
__ B-90th percentile with confidence of 95%
__ S-specification limit values
__ D-combination of A,B, and S values
__ M-mean values
__ P-statistical parameters
__ N-nominal or typical values
__ U-unprocessed single point values; raw data
__ X-unknown
1-21a Validation status
__ S-validated at source __ V-validated independently __ N-not-validated
1-21b Certification status
__ C-certified __ N-not certified
1-22 Completeness of test procedure description
__ S-standard test; documented
__ N-non-standard test; documented
__ X-test procedure(s) not documented

STANDARD FORMAT FOR FRACTURE CRACK-INITIATION TOUGHNESS TEST DATA

Background Information

2-0* Material key ______________________

2-1 Type of test-fracture toughness

2-2* Purpose of test __ Q.A. __ mill certificate __ R & D __ Other
___n.r. ___n.a. ___ See ________________

Test Procedure

2-3* Standard ____ ASTM ____________ or ___ other standard ______________
__n.r. ___n.a.

2-4 Date of applicable standard 19___ ___ __n.r. ___n.a.

2-5* Type of loading ___ Quasi-static ___ Intermediate ___ High Rate ___ n.r. ___ n.a.

2-6 (K) loading rate ___ MPa√m s^{-1}___ ksi√in s^{-1}___ See _______ ___ n.r. ___ n.a.

Specimen Information

2-7 Material yield strength ___MPa ___ksi See ________________ __n.r. ___n.a.

2-8 Material elastic modulus ___GPa ___psi x 10^6

2-9* Specimen location ___n.r. ___n.a. __See_____________
___ 0/4T
___ 0/4T (root)
___ 1/4T
___ 1/2T
___ 1/2T (root)
___ N-Full thickness

2-10* Specimen orientation ___ See ________________
___ L-T ___ L-S ___ L-C ___ L-R ___ T-L
___ T-S ___ S-L ___ S-T ___ C-L ___ C-R
___ R-C ___ n.r. ___ n.a.

2-11* Specimen type ___ n.r. ___ n.a. ___ See ______________
___ Compact ___ Side-grooved compact ___ Bend
___ Deep notch bend ___ DCB ___ WOL

2-12* Specimen thickness, B ___ mm ___ in
___ See _________________ ___ n.r. ___ n.a.

2-13 Specimen width (depth), W ___ mm ___ in
___ See _________________ ___ n.r. ___ n.a.

2-14 Average crack length, a ___ mm ___ in ___ See _________________
___ n.r. ___ n.a.

2-14a* a/W ______ ___ See __________________ ___ n.r. ___ n.a.

Test Results

2-15* Test temperature ___°C ___°F ___K ___RT ___ See___________ n.r. ___ n.a.
2-16* K_Q ___ MPa√m ___ ksi√in ___ See _______________ ___ n.r. ___ n.a.
2-17 K_{IC} ___ MPa√m ___ ksi√in ___See _______________ ___ n.r. ___ n.a.
2-18* Valid measure of K_{IC}? ___ yes ___ no ___ See ____________ ___ n.r. ___ n.a.
2-19 J_{IC} ___ MPa.m ___ ksi.in ___ See ________________ ___ n.r. ___ n.a.
2-19a Valid measure of J_{IC} ? ___ yes ___ no ___ See ____________ ___ n.r. ___ n.a.
2-20 Equivalent plane strain fracture toughness, K_{JC} (from J_{IC}) ____ MPa√m ___ ksi√in
___ See ________________ ___ n.r. ___ n.a.
2-21 Method of J_{IC} calculation ___ See ________________ ___ n.r. ___ n.a.
___ per Stand. ___ modified Stand. ___ other ________________________
2-22 Initiation J value ___ MPa.m ___ ksi.in ___ See __________ ___ n.r. ___ n.a.
2-23 Maximum J value ___ MPa.m ___ ksi.in ___ See _________ ___ n.r. ___ n.a.
2-23a No. of J specimens _________ See ____________________ ___ n.r. ___ n.a.
2-24 Initiation CTOD ___ mm ___ in ___ See _______________ ___ n.r. ___ n.a.
2-25 Critical CTOD ___ mm ___ in ___ See _______________ ___ n.r. ___ n.a.
2-25a Is reported CTOD ___ c-cleavage ___ u-cleavage preceded by tearing
___ m-fibrous (max. load) ___ See _______________ ___ n.r. ___ n.a.
2-25b Valid measure of CTOD? ___ yes ___ no ___ See ___________ ___ n.r. ___ n.a.
2-26a Number of test results ___
2-26b Method of presentation of results ___Table ___Histogram
___Mean ___Standard deviation ___Type of distribution ___Parameters
___ See _________________ __n.r. ___n.a.
Note: Retain raw data in tabular form

Data Quality

2-27 Statistical basis of data
__ A-99th percentile with confidence of 95%
__ B-90th percentile with confidence of 95%
__ S-specification limit values
__ D-combination of A,B, and S values
__ M-mean values
__ P-statistical parameters
__ N-nominal or typical values
__ U-unprocessed single point values; raw data
__ X-unknown
2-28a* Validation status
__ S-validated at source __ V-validated independently __ N-not-validated
2-28b Certification status __ C-certified __ N-not certified
2-29 Completeness of test procedure description
__ S-standard test; documented __ N-non-standard test; documented
__ X-test procedure(s) not documented

STANDARD FORMAT FOR NOTCHED BAR IMPACT TEST DATA

Background Information

3-0* Material key ___________________
3-1 Type of test-Notched bar impact __CVN-Charpy V __PCV-Precracked Charpy V
3-2* Purpose of test __ Q.A. __ mill certificate __ R & D __ Other
___n.r. ___n.a. ___ See ________________

Test Procedure

3-3* Standard ____ ASTM ____________ or ___ other standard ______________
__n.r. ___n.a.
3-4 Date of applicable standard 19___ ___ __n.r. ___n.a.
3-5a Testing machine capacity ___J ___ft-lbs ___ See ___________ ___ n.r. ___ n.a.
3-5b Striker radius ___mm ___in ___ See ___________ ___ n.r. ___ n.a.

Specimen Information

3-6* Specimen location ___n.r. ___n.a. __See_____________
___ 0/4T (side 1) ___ 0/4T (side 2)
___ 1/4T (side 1) ___ 1/4T (side 2)
___ 1/2T ___ root of weld
___ N-Full cross-section
3-7* Specimen orientation ___ See ___________________ ___ n.r. ___ n.a.
___ L-T ___ L-S ___ L-C ___ L-R ___ T-L
___ T-S ___ S-L ___ S-T ___ C-L ___ C-R
___ R-C ___ n.r. ___ n.a.
3-8* Specimen type ___ See ______________ ___ n.r. ___ n.a.
____ Full: full-width Charpy V ____ 1/2W: One-half width Charpy V
____ 2W: Twice-width Charpy V ____ 1/4W: One-quarter width Charpy V

Test Results

3-9* Test temperature ___°C ___°F ___K ___RT
___ See ____________________ ___ n.r. ___ n.a.
3-10* Total energy to fracture ___ J ___ Ft-Lb ___ See ____________
___ n.r. ___ n.a.
3-11* Lateral expansion ____ mm ____ in ___ See _____________ ___ n.r. ___ n.a.
3-12* Shear fracture ____ % Brittle fracture ____ % ___ See ____________
___ n.r. ___ n.a.
3-13 Did specimen fracture completely ___ yes ___ no ___ assumed
___ See _________________ ____ n.r. ___ n.a.

3-14a Number of test results ___
3-14b Method of presentation of results ___Table ___Histogram
___Mean ___Standard deviation ___Type of distribution ___Parameters
___ See ________________ __n.r. ___n.a.
Note: Retain raw data in tabular form

Data Quality

3-15 Statistical basis of data
__ A-99th percentile with confidence of 95%
__ B-90th percentile with confidence of 95%
__ S-specification limit values
__ D-combination of A,B, and S values
__ M-mean values
__ P-statistical parameters
__ N-nominal or typical values
__ U-unprocessed single point values; raw data
__ X-unknown
3-16a Validation status
__ S-validated at source __ V-validated independently __ N-not-validated
3-16b Certification status
__ C-certified __ N-not certified
3-17 Completeness of test procedure description
__ S-standard test; documented __ N-non-standard test; documented
__ X-test procedure(s) not documented

STANDARD FORMAT FOR CRACK-ARREST FRACTURE TOUGHNESS TEST DATA

Background Information

4-0* Material key ________________
4-1 Type of test-Crack arrest fracture toughness
4-2* Purpose of test __ Q.A. __ mill certificate __ R & D __ Other
___n.r. ___n.a. ___ See ________________

Test Procedure

4-3* Standard ____ ASTM ____________ or ___ other standard ______________
__n.r. ___n.a.
4-4 Date of applicable standard 19___ ___ __n.r. ___n.a.

Specimen Information

4-5 Specimen location ___n.r. ___n.a. __See_____________
__ 0/4T
__ 0/4T (root)
__ 1/4T
__ 1/2T
__ 1/2T (root)
__ N-Full thickness
4-6* Specimen orientation ___ See ___________________ ___ n.r. ___ n.a.
___ L-T ___ L-S ___ L-C ___ L-R ___ T-L
___ T-S ___ S-L ___ S-T ___ C-L ___ C-R
___ R-C ___ n.r. ___ n.a.
4-7 Specimen type ___ CCA ___ DCB ___ See ______________ ___ n.r. ___ n.a.
4-8* Thickness of specimen ___ mm ___ in
___ See ________________ ___ n.r. ___ n.a.

Test Results

4-9* Test temperature ___°C ___°F ___K ___RT
___ See ____________________ ___ n.r. ___ n.a.
4-10* K_a ___ MPa$\sqrt{m}$ ___ ksi$\sqrt{in}$ ___ See ______________ ___ n.r. ___ n.a.
4-11 K_{1a} ___ MPa$\sqrt{m}$ ___ ksi$\sqrt{in}$ ___See ______________ ___ n.r. ___ n.a.
4-12* Valid measure of K_{1a}? ___ yes ___ no ___ See __________ ___ n.r. ___ n.a.
4-13a Number of test results ___
4-13b Method of presentation of results ___Table ___Histogram
___Mean ___Standard deviation ___Type of distribution ___Parameters
___ See ________________ __n.r. ___n.a.
Note: Retain raw data in tabular form

Data Quality

4-14 Statistical basis of data
- __ A-99th percentile with confidence of 95%
- __ B-90th percentile with confidence of 95%
- __ S-specification limit values
- __ D-combination of A,B, and S values
- __ M-mean values
- __ P-statistical parameters
- __ N-nominal or typical values
- __ U-unprocessed single point values; raw data
- __ X-unknown

4-15a* Validation status
- __ S-validated at source __ V-validated independently __ N-not-validated

4-15b Certification status
- __ C-certified __ N-not certified

4-16 Completeness of test procedure description
- __ S-standard test; documented __ N-non-standard test; documented
- __ X-test procedure(s) not documented

STANDARD FORMAT FOR NIL-DUCTILITY TEMPERATURE TEST DATA

Background Information

5-0* Material key ________________
5-1 Type of test-Nil ductility temperature
5-2* Purpose of test __ Q.A. __ mill certificate __ R & D __ Other
___n.r. ___n.a. ___ See ________________

Test Procedure

5-3* Standard ____ ASTM ____________ or ___ other standard ______________
__n.r. ___n.a.
5-4 Date of applicable standard 19___ ___ __n.r. ___n.a.
5-5 Drop-weight energy __ J __ ft-lbf ___n.r. ___n.a. __See_____________

Specimen Information

5-6 Specimen location ___n.r. ___n.a. __See_____________
__ 0/4T
__ 0/4T (root)
__ 1/4T
__ 1/2T
__ 1/2T (root)
5-7 Specimen orientation ___ See ___________________ ___ n.r. ___ n.a.
___ L-T ___ T-L ___ n.r. ___ n.a.
5-8 Specimen type ___ P-1 ___ P-2 ___ P-3 ___ See ___________ ___ n.r. ___ n.a.
5-9* Specimen thickness of ___ mm ___ in
___ See ________________ ___ n.r. ___ n.a.

Test Results

5-10 Test temperature ___°C ___°F ___K ___ See __________ ___n.r. ___ n.a.
5-11 Break ___ No-break ___
5-12* NDTT ___°C ___°F ___K ___ See __________ ___ n.r. ___ n.a.
5-13a Number of test results ___
5-13b Method of presentation of results ___Table ___Histogram
___Mean ___Standard deviation ___Type of distribution ___Parameters
___ See ________________ __n.r. ___n.a.
Note: Retain raw data in tabular form

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Data Quality

5-14 Statistical basis of data
- __ A-99th percentile with confidence of 95%
- __ B-90th percentile with confidence of 95%
- __ S-specification limit values
- __ D-combination of A,B, and S values
- __ M-mean values
- __ P-statistical parameters
- __ N-nominal or typical values
- __ U-unprocessed single point values; raw data
- __ X-unknown

5-15a Validation status
- __ S-validated at source __ V-validated independently __ N-not-validated

5-15b Certification status
- __ C-certified __ N-not certified

5-16 Completeness of test procedure description
- __ S-standard test; documented __ N-non-standard test; documented
- __ X-test procedure(s) not documented

STANDARD FORMAT FOR DYNAMIC TEAR TEST DATA

Background Information

6-0* Material key ________________
6-1 Type of test-Dynamic tear
6-2* Purpose of test __ Q.A. __ mill certificate __ R & D __ Other
___n.r. ___n.a. ___ See ________________

Test Procedure

6-3* Standard ____ ASTM ____________ or ___ other standard ______________
__n.r. ___n.a.
6-4 Date of applicable standard 19___ ___ __n.r. ___n.a.

Specimen Information

6-5* Specimen location ___n.r. ___n.a. __See_____________
___ 0/4T (side 1) ___ 0/4T (side 2)
___ 1/4T (side 1) ___ 1/4T (side 2)
___ 1/2T ___ root of weld
___ N-Full cross-section
6-6* Specimen orientation ___ See ___________________ ___ n.r. ___ n.a.
___ L-T ___ T-L ___ n.r. ___ n.a.
6-7 Notch preparation-Pressed ___ yes ___ no ___ See _________ ___ n.r. ___ n.a.
6-8* Thickness of specimen ___ mm ___ in
___ See ________________ ___ n.r. ___ n.a.

Test Results

6-9* Test temperature ___°C ___°F ___K ___ See __________ ___ n.r. ___ n.a.
6-10* DT energy ___ J ___ Ft-Lb ___ See ____________ ___ n.r. ___ n.a.
6-11 Shear fracture ____ % Brittle fracture ____ % ___ See ____________
___ n.r. ___ n.a.
6-12 Did specimen fracture completely ___ yes ___ no ___ assumed
___ See _________________ ____ n.r. ___ n.a.
6-13a Number of test results ___
6-13b Method of presentation of results ___Table ___Histogram
___Mean ___Standard deviation ___Type of distribution ___Parameters
___ See _______________ __n.r. ___n.a.
Note: Retain raw data in tabular form

Data Quality

6-14 Statistical basis of data
__ A-99th percentile with confidence of 95%
__ B-90th percentile with confidence of 95%
__ S-specification limit values
__ D-combination of A,B, and S values
__ M-mean values
__ P-statistical parameters
__ N-nominal or typical values
__ U-unprocessed single point values; raw data
__ X-unknown

6-15a Validation status
__ S-validated at source __ V-validated independently __ N-not-validated

6-15b Certification status
__ C-certified __ N-not certified

6-16 Completeness of test procedure description
__ S-standard test; documented __ N-non-standard test; documented
__ X-test procedure(s) not documented

APPENDIX B: HIERARCHY OF THE DATA RECORDING FIELDS - PARENT MATERIAL

HIERARCHY FOR POOLING TENSILE DATA OF MARINE STRUCTURAL STEELS (for convenience the field numbers from the recommended format in Appendix A are retained)

The significance of each field decreases with indentation to the right (L1 through L5).

L1	L2	L3	L4	L5
Background Information				
		0-1a* Common name		
				0-1b* UNS desig.
0-1c1* Spec. organization, no. & year (made to)				
		0-1c3* Supplementary requirements		
	0-2a* Basic form			
	0-3* Thickness			
	0-4* Composition type			
	0-8* De-oxidation practice			
	0-11* Final processing steps			
				0-16* Source of data/laboratory
				0-17* Source of data
		1-2* Purpose of test		
Test Procedure				
1-3* Standard				
	1-5a* Rate of loading to yield			
Specimen Information				
		1-6* Specimen location		
	1-7* Specimen orientation			
	1-8* Specimen type			
			1-9 Specimen diameter or thickness	
	1-10* Gage length			
Test Results				
1-11* Test temperature				
	1-13a* Yield strength method			

Note: When pooling yield strength values, the de-oxidation practice and gage length hierarchy levels are moved to the right making them less significant. Similarly, when elongation values are pooled, the rate of loading to yield and yield strength method have no significance.

HIERARCHY FOR POOLING CRACK-INITIATION FRACTURE TOUGHNESS DATA OF MARINE STRUCTURAL STEELS

L1	L2	L3	L4	L5
Background Information				
		0-1a* Common name		
				0-1b* UNS desig.
0-1c1* Spec. organization, no. & year (made to)				
		0-1c3* Supplementary requirements		
	0-2a* Basic form			
	0-3* Thickness			
	0-4* Composition type			
	0-8* De-oxidation practice			
	0-11* Final processing steps			
	0-16* Source of data/laboratory			
				0-17* Source of data
		2-2* Purpose of test		
Test Procedure				
2-3* Standard				
	2-5* Type of loading			
Specimen Information				
		2-9* Specimen location		
2-10* Specimen orientation				
	2-11* Specimen type			
2-12* Specimen thickness				
	2-14a* a/W			
Test Results				
2-15* Test temperature				
				2-18* Valid measure of K_{IC}?
				2-19a Valid measure of J_{IC}?
		2-21 Method of J_{IC} calculation		
		2-23a No. of J specimens		
		2-25a Is reported CTOD ___ c-cleavage ___ u-cleavage preceded by tearing ___ m-fibrous (max. load)		
		2-25b Valid measure of CTOD ?		
				2-28a* Validation status

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HIERARCHY FOR POOLING NOTCHED BAR IMPACT DATA OF MARINE STRUCTURAL STEELS

L1 L2 L3 L4 L5

Background Information

0-1a* Common name

0-1b* UNS desig.

0-1c1* Spec. organization, no. & year (made to)

0-1c3* Supplementary requirements

0-2a* Basic form

0-3* Thickness

0-4* Composition type

0-8* De-oxidation practice

0-11* Final processing steps

0-16* Source of data/laboratory

0-17* Source of data

3-2* Purpose of test

Test Procedure

3-3* Standard

Specimen Information

3-6* Specimen location

3-7* Specimen orientation

3-8* Specimen type

Test Results

3-9* Test temperature

APPENDIX C: HIERARCHY OF THE DATA RECORDING FIELDS - WELD METAL AND HEAT AFFECTED ZONE

HIERARCHY FOR POOLING TENSILE DATA OF WELD METALS IN MARINE STRUCTURAL STEEL WELDMENTS

L1	L2	L3	L4	L5
Background Information				
	0-1c1* Spec. organization, no. & year (made to)			
	0-3* Thickness			
0-4* Composition type				
		0-5 Producer (name of producing company)		
W-1* Welding process				
	W-3* Welding position			
		W-4 Preheat temperature		
		W-5 Interpass temperature (Maximum)		
W-8b* Welding filler, Classification				
	W-8d* Welding filler, trade name			
W-10b* Flux, trade name				
W-11b* Shielding gas, Composition/Common name				
W-14* Heat input (range and average)				
	W-16b* Groove type			
W-17* Weld specimen notch position codes				
W-19* Postweld heat treatment temperature				
	W-20* Post-weld heat treatment time			
W-21* Is the actual weld deposit composition reported in 0-4 ?				
		1-2* Purpose of test		
Test Procedure				
1-3* Standard				
	1-5a* Rate of loading to yield			
Specimen Information				
	1-6* Specimen location			
	1-7* Specimen orientation			
	1-8* Specimen type			
			1-9 Specimen diameter or thickness	
	1-10* Gage length			
Test Results				
1-11* Test temperature				
	1-13a* Yield strength method			

Note: When pooling elongation values, the rate of loading to yield and yield strength method have no significance.

HIERARCHY FOR POOLING CRACK-INITIATION FRACTURE TOUGHNESS DATA OF WELD METAL IN MARINE STRUCTURAL STEEL WELDMENTS

L1	L2	L3	L4	L5
Background Information				
	0-1c1* Spec. organization, no. & year (made to)			
0-3* Thickness				
0-4* Composition type				
		0-5 Producer (name of producing company)		
	0-16* Source of data/laboratory			
W-1* Welding process				
	W-3* Welding position			
		W-4 Preheat temperature		
		W-5 Interpass temperature (Maximum)		
W-8b* Welding filler, Classification				
	W-8d* Welding filler, trade name			
W-10b* Flux, trade name				
W-11b* Shielding gas, Composition/Common name				
W-14* Heat input (range & average)				
	W-16b* Groove type			
W-17* Weld specimen notch position codes				
W-19* Postweld heat treatment temperature				
	W-20* Post-weld heat treatment time			
W-21* Is the actual weld deposit composition reported in 0-4 ?				
		2-2* Purpose of test		
Test Procedure				
2-3* Standard				
	2-5* Type of loading			
Specimen Information				
		2-9* Specimen location		
	2-10* Specimen orientation			
	2-11* Specimen type			
2-12* Specimen thickness				
	2-14a* a/W			
Test Results				
2-15* Test temperature				
				2-18* Valid measure of K_{Ic}?
				2-19a Valid measure of J_{Ic}?
		2-21 Method of J_{Ic} calculation		
		2-23a No. of J specimens		
		2-25a Is reported CTOD ___ c-cleavage ___ u-cleavage preceded by tearing ___ m-fibrous (max. load)		
		2-25b Valid measure of CTOD ?		
				2-28a* Validation status

HIERARCHY FOR POOLING NOTCHED BAR IMPACT DATA OF WELD METAL IN MARINE STRUCTURAL STEEL WELDMENTS

L1	L2	L3	L4	L5
Background Information				
	0-1c1* Spec. organization, no. & year (made to)			
	0-3* Thickness			
0-4* Composition type				
		0-5 Producer (name of producing company)		
W-1* Welding process				
	W-3* Welding position			
		W-4 Preheat temperature		
		W-5 Interpass temperature (Maximum)		
W-8b* Welding filler, Classification				
	W-8d* Welding filler, trade name			
W-10b* Flux, trade name				
W-11b* Shielding gas, Composition/Common name				
W-14* Heat input (range & average)				
	W-16b* Groove type			
W-17* Weld specimen notch position codes				
W-19* Postweld heat treatment temperature				
	W-20* Post-weld heat treatment time			
W-21* Is the actual weld deposit composition reported in 0-4 ?				
		3-2* Purpose of test		
Test Procedure				
		3-3* Standard		
Specimen Information				
3-6* Specimen location				
	3-7* Specimen orientation			
3-8* Specimen type				
Test Results				
3-9* Test temperature				

HIERARCHY FOR POOLING CRACK-INITIATION FRACTURE TOUGHNESS DATA IN HEAT AFFECTED ZONE OF MARINE STRUCTURAL STEEL WELDMENTS

L1	L2	L3	L4	L5
Background Information				
0-1c1* Spec. organization, no. & year (made to)				
0-3* Thickness				
0-4* Composition type				
		0-5 Producer (name of producing company)		
	0-8* De-oxidation practice			
	0-16* Source of data/laboratory			
	W-1* Welding process			
		W-3* Welding position		
		W-4 Preheat temperature		
		W-5 Interpass temperature (Maximum)		
W-14* Heat input (range & average)				
W-16b* Groove type				
W-17* Weld specimen notch position codes				
W-19* Postweld heat treatment temperature				
	W-20* Post-weld heat treatment time			
W-21* Is the actual weld deposit composition reported in 0-4 ?				
		2-2* Purpose of test		
Test Procedure				
2-3* Standard				
	2-5* Type of loading			
Specimen Information				
		2-9* Specimen location		
	2-10* Specimen orientation			
	2-11* Specimen type			
2-12* Specimen thickness				
	2-14a* a/W			
Test Results				
2-15* Test temperature				
				2-18* Valid measure of K_{IC}?
				2-19a Valid measure of J_{IC}?
		2-21 Method of J_{IC} calculation		
		2-23a No. of J specimens		
		2-25a Is reported CTOD ___ c-cleavage ___ u-cleavage preceded by tearing ___ m-fibrous (max. load)		
		2-25b Valid measure of CTOD ?		
				2-28a* Validation status

HIERARCHY FOR POOLING NOTCHED BAR IMPACT DATA OF HEAT AFFECTED ZONE IN MARINE STRUCTURAL STEEL WELDMENTS

L1 L2 L3 L4 L5

Background Information

0-1c1* Spec. organization, no. & year (made to)

0-3* Thickness

0-4* Composition type

0-5 Producer (name of producing company)

W-1* Welding process

W-3* Welding position

W-4 Preheat temperature

W-5 Interpass temperature (Maximum)

W-14* Heat input (range & average)

W-16b* Groove type

W-17* Weld specimen notch position codes

W-19* Postweld heat treatment temperature

W-20* Post-weld heat treatment time

W-21* Is the actual weld deposit composition reported in 0-4 ?

3-2* Purpose of test

Test Procedure

3-3* Standard

Specimen Information

3-6* Specimen location

3-7* Specimen orientation

3-8* Specimen type

Test Results

3-9* Test temperature

APPENDIX D - STATISTICAL PROPERTY ESTIMATION EXAMPLES

Test for Significant Difference Between the Means of Two Samples

Required Information:

Sample Statistics	Sample 1	Sample 2
Number of Observations	n_1	n_2
Mean	μ_1	μ_2
Standard Deviation	σ_1	σ_2

This significance test involves the use of the t-distribution.

Solution Process:

1)Identify test hypothesis

Hypothesis:No significant difference exists between the means of samples 1 and 2 at a α% confidence level.

2)Calculate test statistic ($\Delta\mu$)

$$\Delta\mu = \mu_1 - \mu_2$$

3)Calculate number of degrees of freedom (v) for samples and test

$$v_1 = n_1 - 1, \quad v_2 = n_2 - 1 \quad \text{and} \quad v = v_1 + v_2 = n_1 + n_2 - 2$$

4)Estimate bounds for test statistic

$$U = t_{\alpha,v}\sqrt{\frac{v_1\sigma_1^2 + v_2\sigma_2^2}{v_1 + v_2}}\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}$$

$$\textit{where:} \quad t_{\alpha,v} \approx x_\alpha + \frac{g_1(x_\alpha)}{v} + \frac{g_2(x_\alpha)}{v^2} + \frac{g_3(x_\alpha)}{v^3} + \frac{g_4(x_\alpha)}{v^4}$$

$$g_1(x) = \frac{1}{4}(x^3+x)$$

$$g_2(x) = \frac{1}{96}(5x^5+16x^3+3x)$$

$$g_3(x) = \frac{1}{384}(3x^7+19x^5+17x^3-15x)$$

$$g_4(x) = \frac{1}{92160}(79x^9+776x^7+1482x^5-1920x^3-945x)$$

$$x_\alpha = \textit{Normal deviate for upper tail probability } \alpha$$

(REF: eq. 26.7.5, Handbook of Mathematical Functions)

5)Check results of hypothesis

If $\Delta\mu \leq U$ then no significant difference exists between the means of the two samples with α% confidence.

Test for significant difference between the variances of two samples

Required Information:

Sample Statistics	Sample 1	Sample 2
Number of Observations	n_1	n_2
Standard Deviation	σ_1	σ_2

This significance test involves the use of the F-distribution.

Solution Process:

1) Identify test hypothesis

   Hypothesis: No significant difference exists between the variances of samples 1 and 2 at a α% confidence level.

2) Calculate test statistic (F_{test})

   $F_{test} = \sigma_1^2 / \sigma_2^2$

3) Calculate number of degrees of freedom (v) for samples

   $v_1 = n_1 - 1$ and $v_2 = n_2 - 1$

4) Estimate bounds for test statistic

   $F_\alpha(v_1,v_2)$ and $F_\alpha(v_2,v_1)$

   F-distribution values can be taken from tables or approximated as follows:

$$F_\alpha(v_1,v_2) \approx e^{2w}$$

where:

$$w = \frac{x_\alpha\sqrt{h+\lambda}}{h} - \left(\frac{1}{v_2-1} - \frac{1}{v_1-1}\right)\left(\lambda + \frac{5}{6} - \frac{2}{3h}\right)$$

$$h = 2\left(\frac{1}{v_1-1} + \frac{1}{v_2-1}\right)^{-1}$$

$$\lambda = \frac{x_\alpha^2 - 3}{6}$$

x_α = *Normal deviate for upper tail probability* α

(REF: eq. 26.6.16, Handbook of Mathematical Functions)

5) Check results of hypothesis

   If $1/F_\alpha(v_2,v_1) \le F_{test} \le F_\alpha(v_1,v_2)$ then no significant difference exists between the variances of the two samples with α% confidence.

Required Sample Size for Estimating the Mean

Required Information:

Sample Statistics	Sample
Standard Deviation	σ

This significance test involves the use of the normal distribution.

Solution Process:

1) Identify desired statistical quality measures

   Precision: maximum error δ

   Reliability: in terms of normal deviate for two sided probability $x_{\alpha/2}$ (i.e. $\alpha = 0.95\%$ ==> $x_{\alpha/2} = 1.96$)

2) Identify sample standard deviation

   σ = assumed population standard deviation

   - based on previous statistical experience; or
   - collected sample data; or
   - based on knowledge that 99.7% of normally distributed information lies within μ 3σ range. Therefore, the 1 st and 99.9th percentile, which are practical upper and lower bounds on the data can be used to estimate σ by the following relationship: σ_{approx} = (99.9th - 1st percentiles) / 6

3) Calculate required sample size

$$n \geq \frac{x_{\alpha/2}^2 \sigma^2}{\delta^2}$$

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Project Technical Committee Members

The following persons were members of the committee that represented the Ship Structure Committee to the Contractor as resident subject matter experts. As such they performed technical review of the initial proposals to select the contractor, advised the contractor in cognizant matters pertaining to the contract of which the agencies were aware, and performed technical review of the work in progress and edited the final report.

Mr. Allen Manuel	Naval Sea System Command
Mr. John E. Allison	Naval Sea System Command
Mr. Tom Montemarano	Carderock Division, Naval Surface Warfare Center
Mr. Gaeten Labbe	Director Ship Engineering, Canada
Mr. Zbigniew Karaszewski	U. S. Coast Guard
Dr. Neil Pegg	Defence Research Establishment Atlantic, Canada
Mr. Stephen Arntson	American Bureau of Shipping
Dr. Keith Ortiz	Sandia National Laboratories
Dr. John R. Rumbel	National Institute of Standards
Mr. William Siekierka	Naval Sea Systems Command, SSC Contracting Officer's Technical Representative
Mr. Alex Stavovy Dr. Robert Sielski	National Academy of Science, Marine Board Liaison
CDR Mike Parmelee CDR Steve Sharpe	U.S. Coast Guard, Executive Director Ship Structure Committee

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