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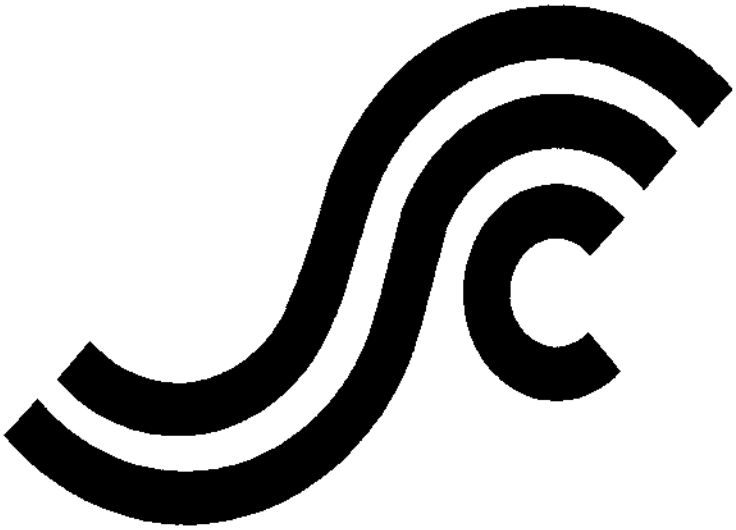
FAILURE DEFINITION FOR STRUCTURAL RELIABILITY ASSESSMENT



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This study begins with a review and description of structural reliability methodologies as they have been applied to ship structure. Uncertainty types are then explored for information and tools used in a reliability prediction. Types of failure modes are described as reported in literature. These types are then expanded upon to establish classes of failure modes, leading to a methodology for formulating the range of failure definitions. Failure definition examples are provided for the hull girder and structural components at both the ultimate and serviceability types of failure. Finally, recommendations are made to provide guidance on applications and future research in this topic area.

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inches	meters	divide	39.3701
inches	millimeters	multiply by	25.4000
feet	meters	divide by	3.2808
VOLUME			
cubic feet	cubic meters	divide by	35.3149
cubic inches	cubic meters	divide by	61,024
SECTION MODULUS			
inches^2 feet^2	centimeters^2 meters^2	multiply by	1.9665
inches^2 feet^2	centimeters^3	multiply by	196.6448
inches^4	centimeters^3	multiply by	16.3871
MOMENT OF INERTIA			
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inches^2 feet^2	centimeters^4	multiply by	5993.73
inches^4	centimeters^4	multiply by	41.623
FORCE OR MASS			
long tons	tonne	multiply by	1.0160
long tons	kilograms	multiply by	1016.047
pounds	tonnes	divide by	2204.62
pounds	kilograms	divide by	2.2046
pounds	Newtons	multiply by	4.4482
PRESSURE OR STRESS			
pounds/inch^2	Newtons/meter^2 (Pascals)	multiply by	6894.757
kilo pounds/inch^2	mega Newtons/meter^2 (mega Pascals)	multiply by	6.8947
BENDING OR TORQUE			
foot tons	meter tons	divide by	3.2291
foot pounds	kilogram meters	divide by	7.23285
foot pounds	Newton meters	multiply by	1.35582
ENERGY			
foot pounds	Joules	multiply by	1.355826
STRESS INTENSITY			
kilo pound/inch^2 inch$^{1/2}$(ksi$\sqrt{\text{in}}$)	mega Newton MNm$^{3/2}$	multiply by	1.0998
J-INTEGRAL			
kilo pound/inch	Joules/mm^2	multiply by	0.1753
kilo pound/inch	kilo Joules/m^2	multiply by	175.3

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ADMINISTRATIVE INFORMATION

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1. INTRODUCTION

Surface ships encounter numerous structural loads, for example, wave bending, whipping, slamming. The magnitudes and times of occurrence of these loads are highly uncertain. Some of these loads or combinations of loads are capable of severely damaging the ship's structure. Damage often results in a reduction or loss of structural integrity, or otherwise adversely affects ship system performance. Traditional design criteria use deterministic safety factors in equations to guard against the possibility of structural damage and ship system degradation and failure. Unfortunately these methods provide an undetermined level of safety and performance which experience has shown is not always adequate. Structural reliability methods allow the prediction of an occurrence likelihood for a particular event of interest (for example, structural failure), allowing the designer to limit the probability of undesirable events. Calculating the probability that a failure event will not occur provides a performance measure termed reliability.

The Society of Naval Architects and Marine Engineers (SNAME) publishes a book entitled the *Principles of Naval Architecture*. The chapter on the "Strength of Ships" (MacNaught, 1967) describes the ship structure "as the material which provides the strength and stiffness to withstand all the loads which the ship may reasonably be expected to experience." Inability to fulfill this function, partially or completely, may constitute failure of the ship structural system.

The degree to which ship system performance deteriorates as a result of some structural response or load effect could range from insignificant to catastrophic. Such deterioration could impact the ship safety and survivability, and the ship's ability to continue its mission. The qualitative or quantitative effect of this deterioration will be subsequently referred to as the cost or consequence of the structural response. When the cost or consequence exceeds some accepted level, the structure has failed.

An example of structural failure is the permanent deformation of an unstiffened plate. Excessive permanent set may misalign some mechanical system rendering it inoperable; reduce the strength of a larger structural system beyond acceptable levels and endanger more critical systems; or be cosmetically unappealing. The consequence of the permanent deformation may also be an increase in the likelihood of greater system failures. The point at which the deformation level becomes unacceptable for the designer or surveyor is the onset of failure for the plate. The failure definition for the permanent set of unstiffened plating depends on the acceptability of the consequences of the permanent set. When the consequences are no longer acceptable, the plate has failed. A designer would attempt to limit the likelihood of the plate experiencing such plastic deformation. A surveyor could identify such deformation as excessive and needing repair. Differences in the level of permanent set considered excessive by the designer and surveyor may exist due to modeling uncertainty and bias in the predictive tools used by the designer and the subjective nature of the surveyor's observations. This study is predicated on treatment of failure from the point of view of the designer, analyst, or decision-maker, where predictive tools are required, but can be extended to operational applications.

Risk resulting from a particular hazard scenario, is the combination of the likelihood of failure due to the hazard (for example, seaway loads), and the consequences of failure. This is commonly expressed as a mathematical product of the failure likelihood and consequences, as done in hazardous industry's use of Probabilistic Risk Assessment (PRA). Acceptability of a certain level of risk or performance requires the mapping of the decision maker's judgment and values into an expression, which is comparable to a quantitative or qualitative performance measure of the system or process in question. The decision-maker represents the community that may be impacted by the decision. The measure may be either qualitative (subjective) or quantitative (objective). Qualitatively, the criteria must take into account the need for the risk exposure, the amount of dependable controls over the risk producing process, and the fairness in which the costs, risks, and benefits are distributed (Reid, 1992). Quantitatively, the criteria must take into account uniformity of standards and efficiency (Reid, 1992). Modarres (1993) proposes that fair, balanced and consistent risk criteria must be based upon comparison of the risks and benefits associated with other activities.

Traditionally, the designer applies his judgment to decide what structural behavior constitutes failure. This approach contains an implicit treatment of the consequence of the event, with the designer deciding acceptable and unacceptable behavior of the system in question such that he feels the design will be adequate. The threshold of design acceptability is molded into a limit state equation for use in decision making. The limit state equation provides a threshold formulation where the system/component capability (strength) must be greater than the demand (load) by some margin such that an acceptable structure results. Risk and performance based design approaches allow explicit, formal treatment of these safety margins that are traditionally matters of judgment.

There are many modes by which the hull of a ship can experience damage. Designers attempting to preclude these failure modes are highly dependent upon a physical prediction method for characterization of the response leading to failure. Due to the complexity of the ship structural system, the currently available physical prediction models are based on a component view, where the components are the hull girder, stiffened and unstiffened panels, and details. In both deterministic and classical reliability-based design and analysis, the structural responses for each component must have an associated limiting value, which defines the transition from survival to failure.

Arriving at an appropriate limiting value for a structural response requires the designer to decide what constitutes a failure event. Failure may or may not result from an easily identifiable change in state of the structure or response model. The failure definition depends on the structural response models, and the cost or consequence corresponding to the response. Each of these factors has an inherent uncertainty, which must be assessed prior to predicting the reliability of the structure.

This study provides methodologies for defining failure for reliability-based, marine structural design and analysis. A structural failure event is a change in state such that the structure no longer provides a required capability (load-carrying or otherwise) or impacts some specified system performance to an unacceptable degree. Examples, discussion and taxonomies of failure events are explored for the different levels of the ship structural system (hull girder, stiffened panels and grillages, unstiffened panels and details). Changes to the traditional serviceability failure definitions are not possible without addressing the costs associated with the failures, either subjectively or objectively. The basis for the consideration of changes to traditional serviceability failure thresholds and implementation of new serviceability failure modes/criteria is provided in this report. The approach is predicated on treatment of failure from the point of view of the designer, analyst, or decision-maker, where predictive tools are required, but can be extended to operational applications.

This study begins with a review and description of structural reliability methodologies as they have been applied to ship structure. Uncertainty types are then explored for information and tools used in a reliability prediction. Types of failure modes are described as reported in literature. These types are then expanded upon to establish classes of failure modes, leading to a methodology for formulating the range of failure definitions. Failure definition examples are provided for the hull girder and structural components at both the ultimate and serviceability types of failure. Finally, recommendations are made to provide guidance on applications and future research in this topic area.

2. STRUCTURAL RELIABILITY AND RISK ASSESSMENT

In reliability predictions of electronic or mechanical systems, much of the work has been carried out with the extensive use of failure databases, which allow the prediction of the time-to-failure, or failure rate, for each component of the system. Combining the failure rates of all the components to arrive at the system failure rate provides a means of finding the reliability of the system (Ayyub and McCuen, 1997; Kumamoto and Henley, 1996; Modarres, 1993). Studies such as Hawkins, et al. (1971), Jordan and Cochran (1978), Jordan and Knight (1979), and Akita (1982) provide the beginnings of a structural failure database for ship structures for use in this manner. Extensive testing of details for both fatigue and strength has provided a means by which the reliability of similar structural details may be predicted. This approach has lead to a catalog of structural details and members for use in design.

The extensive range of structural configurations and the large costs of testing at a statistically significant level have contributed to the development of structural reliability theory from an approximate “physics of failure” perspective. This approach propagates basic (input) variable uncertainty through an approximate model of the system under inspection, to provide the analyst with an estimated likelihood that the structural strength will be exceeded by the load, over the designated lifetime and under predetermined operating conditions.

Structural reliability theory has been developed with the assumption of crisp delineation of success and failure, and this approach has been applied to structural systems. The traditional load-strength interference calculation relies upon the simple relationship whereby a failure event is an overload of the structure. The classical definition is $g = R - L$, where R represents the capability, or resistance, and L represents the demand, load, or load effect. The failure event is considered to be when $g<0$, or rather when the load, L, exceeds the resistance, R (Ang and Tang, 1984; Ayyub and McCuen, 1997; Thoft-Christensen and Baker, 1982; Madsen et al., 1986; White and Ayyub, 1985). This definition depends upon a resistance model that represents the ultimate strength of the structural component where the component is unable to carry any increase in load and is considered to have failed.

The resistance and load are both represented by random variables that are functions of the ship's environment and structural geometry and material properties. The uncertainties in the strength and load basic variables and models have been discussed in Galambos and Ravindra (1978), Hess et al. (1994), Hess, et al. (1998), Hughes et al. (1994), Mansour and Faulkner (1973), Nikolaidis and Kaplan (1991), and White and Ayyub (1993). These basic variables require continued investigation to maintain accuracy over time and to decrease the uncertainty surrounding their probabilistic characterizations.

Traditionally, three methods are discussed and used in structural reliability predictions. These are referred to as Levels 1, 2 and 3, with complexity and amount of required information increasing with level number (Madsen et al., 1986; Mansour, 1990).

Level 1 describes the use of design equations with partial safety factors developed using reliability techniques (Levels 2 and 3). This approach is also termed Load and Resistance Factor Design (LRFD). The factors may also be developed without use of reliability methods and are an extension of the traditional, factor of safety, design approach. The limit state equation is usually some variant of Equation 2-1. On the left-hand side of the equation, the resistance is denoted as R and the strength reduction factor is f, which is generally less than unity. The right-hand side, or loads side of the equation is the sum of the n loads or load effects, L_i, amplified by g_i, which is generally greater than unity. R and the L_i's are singular values developed using nominal, or design, basic variable values and prediction tools. Variability and uncertainty in the information and predictions are used to define the values of the partial safety factors using Levels 2 or 3, structural reliability techniques, to ensure a minimum safety level is met.

$$fR \geq \sum_{\mathrm{i=1}}^{\mathrm{n}} g_i L_i \qquad (2\text{-}1)$$

The strength of the Level 1 approach is that the designer can efficiently use a reliability-based, LRFD code without potential errors resulting from the complexity of the higher-level reliability techniques. Reliability-based, LRFD codes are currently in use by the American Institute of Steel Construction (AISC, 1993), American Association of State Highway and Transportation Officials (AASHTO, 1998), American Petroleum Institute (API, 1993b), and NORSOK (1998). Discussion of Level 1 methods and their development may be found in structural reliability texts and papers including Lee and Son (1989), Madsen et al. (1986), Mansour (1990), Thoft-Christensen and Baker (1982), White and Ayyub (1985).

Level 2 denotes approximate methods that use only the means and variances of variables in the limit state equation to predict the reliability and are termed First Order Reliability Methods (FORM). Extensions to FORM have been developed to allow approximate inclusion of the basic variable probability density functions. This modified approach is termed the Advanced Second Moment (ASM) method and can provide a substantial increase in accuracy. The reduction in needed information and computational power for a Level 2 reliability analysis makes it quite appealing and so it is frequently used. Level 2 methods are discussed in structural reliability texts and papers including Ang and Tang (1984), Ayyub and Haldar (1984a), Ayyub and McCuen (1997), Chao (1995), Der Kiureghian, Lin and Hwang (1987), Hasofer and Lind (1973), Madsen et al., (1986), Mansour (1990 and 1993), Modarres (1993) and White and Ayyub (1985).

Level 3 reliability assessment requires and uses complete probabilistic characterizations of all basic load and strength variables to capture the uncertainty inherent in the strength and the load predictions. The exact solution involves integration over the surface formed by the strength and load, joint probability distribution. A popular method of solving this problem is Monte Carlo simulation, as closed form solutions to the convolution integral are rarely possible. Efforts to improve the efficiency of Monte Carlo simulation include conditional expectation and antithetic variates variance reduction techniques (Ayyub and Haldar, 1984b), Latin Hypercube Sampling (Ayyub and Lai, 1989; Ayyub and

Lai, 1992), and other techniques such as importance sampling as outlined in Ang and Tang (1984), Bjerager (1988), Casciati and Faravelli (1980), and Harbitz (1986).

Limit state equations are essential for conducting Level 2 and Level 3 reliability analyses, and are the means by which a definition of failure is articulated mathematically. These equations are an objective function, define the point at which capability equals demand, and can simply be described as $g = R - L$. Level 2 methods measure the distance between the origin in standard normal space to the point on the limit state surface closest to the origin. This distance is the safety index, or $\boldsymbol{b}$. For normally distributed variates, $\boldsymbol{b}$ can be converted to the probability of failure using the standard normal variate transformation as $p_f = 1 - \Phi(\boldsymbol{b})$. This procedure becomes approximate with the introduction of non-normal, probabilistic descriptions of the basic variables. Level 3 methods compute the probability of failure directly.

The inclusion of risk in an analysis or design is informally considered Level 4 (Madsen, et al., 1986). To achieve this quantitatively, probabilities of occurrence must be attached to the failure event and the consequences corresponding to the failure must be identified and assigned some value. The ability to predict the likelihood of failure does not allow the designer to modify the failure definition beyond what was previously used, as the consequences may not have remained constant. A more relaxed definition of failure, or one that allows more structural damage or performance degradation prior to being considered a failure event, would reduce the probability of occurrence while bringing with it greater consequences.

Structural reliability techniques at all levels have been developed in such a way that ultimate failure, or failure modes resulting from overload conditions, are implicitly assumed. Specific techniques, such as the use of extreme value analysis in treating the expected loading conditions, result in reliability predictions that are not necessarily usable in a risk context. These reliability predictions are conditioned on experiencing an extreme event. Simplifications such as this must be acknowledged and considered in deciding on acceptable reliability and risk levels.

The idea of calculating the risk, or expected loss, associated with a design, is to provide a normalized value which is transportable beyond the specific system, sub-system, or component under study. For comparison or aggregation of structural sub-systems, a metric is needed. This metric may be found in probabilistic risk predictions. The acceptable reliability levels associated with structural components throughout a structural system may not be constant, but could vary as the importance of the components vary. This importance may be measured by considering the consequences and likelihood of component failures, thereby providing the risk associated with the component.

3. UNCERTAINTY CHARACTERIZATION

There has been much work done in many different disciplines to develop methods for classifying and quantifying types of uncertainties found in physical system models and their basic variables (see Ayyub, 1992 and 1994; Ayyub and Lai, 1992; Ayyub and McCuen, 1997; Brown, 1979a and 1979b; Cai, 1996; Chao, 1995; Gupta, 1992; Ibrahim and Ayyub, 1992; Klir and Folger, 1988; Kruse, et al., 1991; Twisdale 1979; Tyler, 1993). Klir and Folger (1988) define two general classes of uncertainty as ambiguity and vagueness. Ambiguity may also be considered objective or non-cognitive, while vagueness may be considered subjective or cognitive.

3.1 TYPES OF UNCERTAINTY

3.1.1. Ambiguity

The ambiguity type of uncertainty is considered the result of non-cognitive sources such as (1) physical randomness; (2) statistical uncertainty due to use of limited information to estimate the characteristics of these parameters; and (3) modeling uncertainties due to simplifying assumptions in analytical and prediction models, simplified methods, and idealized representations of real performances. Ambiguity associated with the physical behavior (mechanisms) in structural reliability predictions is and has been the subject of much research (for example, Ang and Tang, 1975 and 1984; Ayyub and Haldar, 1984b; Daidola and Basar, 1980; Galambos and Ravindra, 1978; Hess, et al., 1994; Hess et al., 1998; Hughes, et al., 1994; Mansour and Faulkner, 1973; Mansour, 1993; Nikolaidis and Kaplan ,1991; Schrader et al., 1979; Thoft-Christensen and Baker, 1982; White and Ayyub 1985; White and Ayyub, 1993). The uncertainties associated with the load and structural response or strength predictions and the basic variables upon which these predictions depend may be considered to be of the ambiguity type.

Using current deterministic methods the design strength of a structure is based on nominal values of basic strength variables, both material and geometric, such as yield strength of the material, plate thickness, modulus of elasticity, and so forth. Random behavior of the basic strength variables can cause the strength of the structure to vary beyond acceptable levels. The use of structural response predictions in a reliability-based design format requires accurate characterization of the uncertainty inherent in the basic strength and load variables. Preceding the development of any reliability-based design procedure, relevant variables must be identified and their statistical characteristics need to be defined. As shown in Hughes, et al. (1994), the strength prediction of a longitudinally stiffened panel may be shown to have coefficients of variation ranging as high as 10%. Quantifying the uncertainty, or randomness, found in the basic strength variables allows the designer to account for this variability in the strength of the structure. The uncertainty associated with the strength prediction may be estimated using simulation techniques, such as Monte-Carlo simulation, which allow the values for the basic strength variables to be generated based on their statistical distributions (probability density functions). Hess et al. (1998) expanded the available database and performed analyses to better statistically characterize the uncertainty for material and geometric basic strength variables as used in naval ship construction.

3.1.2. Vagueness

The vagueness type of uncertainty is the result of cognitive sources such as (1) the definition of certain parameters, for example, structural performance (failure or survival), quality, deterioration, skill and experience of construction workers and engineers, environmental impact of projects, conditions of existing structures; and (2) inter-relationships among the parameters of the problems, especially for complex systems. Treatment of vagueness or cognitive uncertainties has been discussed in Alvi, Ayyub and Lai (1992), Brown (1979a and 1979b), Chao (1995), Dong, et.al. (1989), Furuta (1994), Gupta (1992), Klir and Folger (1988), Shiraishi and Furuta (1983) and Yao (1980).

The uncertainty associated with defining the structural change in state from complete survival to complete failure may be considered to be a form of vagueness uncertainty. Reliability predictions are highly dependent upon the underlying level of damage and the uncertainties associated with the failure definition. The acceptable levels of damage for one system may not be acceptable at all for another. Allowances for vagueness in the failure mode definition provides the designer with a procedure for incorporating subjective judgment into the design process. This uncertainty, or vagueness, is due to lack of knowledge of the component's function in the system context and the impact of degradation on the parent system. Capturing and quantifying vagueness requires the application of measures able to deal with subjective information. Two different theories, discussed in Section 5.3, may be used in this regard: possibility (fuzzy set) theory and subjective probability (Bayesian) theory.

3.2. INFORMATION UNCERTAINTY IN SYSTEM DEFINITION

Analysis of structural systems commonly starts with a definition of a system that can be viewed as an abstraction of the real system. The abstraction is performed at different epistemological levels as shown in Figure 3.2-1 (Ayyub, 1992 and Ayyub and Chao 1997). The resulting model can depend largely on an analyst or engineer; hence the subjective nature of this process. During the process of abstraction, the engineer needs to make decisions regarding what aspects should or should not be included in the model. These aspects are shown in the Figure 3.2-1. These aspects include the previously identified uncertainty types. In addition to the abstracted and non-abstracted aspects, unknown aspects of the system can exist, and they are more difficult to deal with because of their unknown nature, sources, extents, and impact on the system.

Uncertainty modeling and analysis for the abstracted aspects of the system need to be performed with a proper consideration of the non-abstracted aspects of a system. The division between abstracted and non-abstracted aspects can be a division of convenience, which is driven by the objectives of the system modeling, or simplification of the model. However, the unknown aspects of the systems are due to ignorance and lack of knowledge. These aspects depend on the knowledge of the analyst and the state of knowledge about the system in general. The effects of the unknown aspects on the ability of the system model to predict the behavior of the real system can range from none to significant.

Approximations and assumptions are explicitly used in reliability predictions due to lack of knowledge. These are necessary to conduct the calculations, but are often made without a complete understanding of their implications. When interpreting the results of a reliability analysis, it is vital that the analysts recognize the non-abstracted aspects of the system and understand that the resulting information is qualitative at best, should it be taken out of context. For purposes of comparison, reliability predictions can prove to be effective measures when used in a consistent manner.

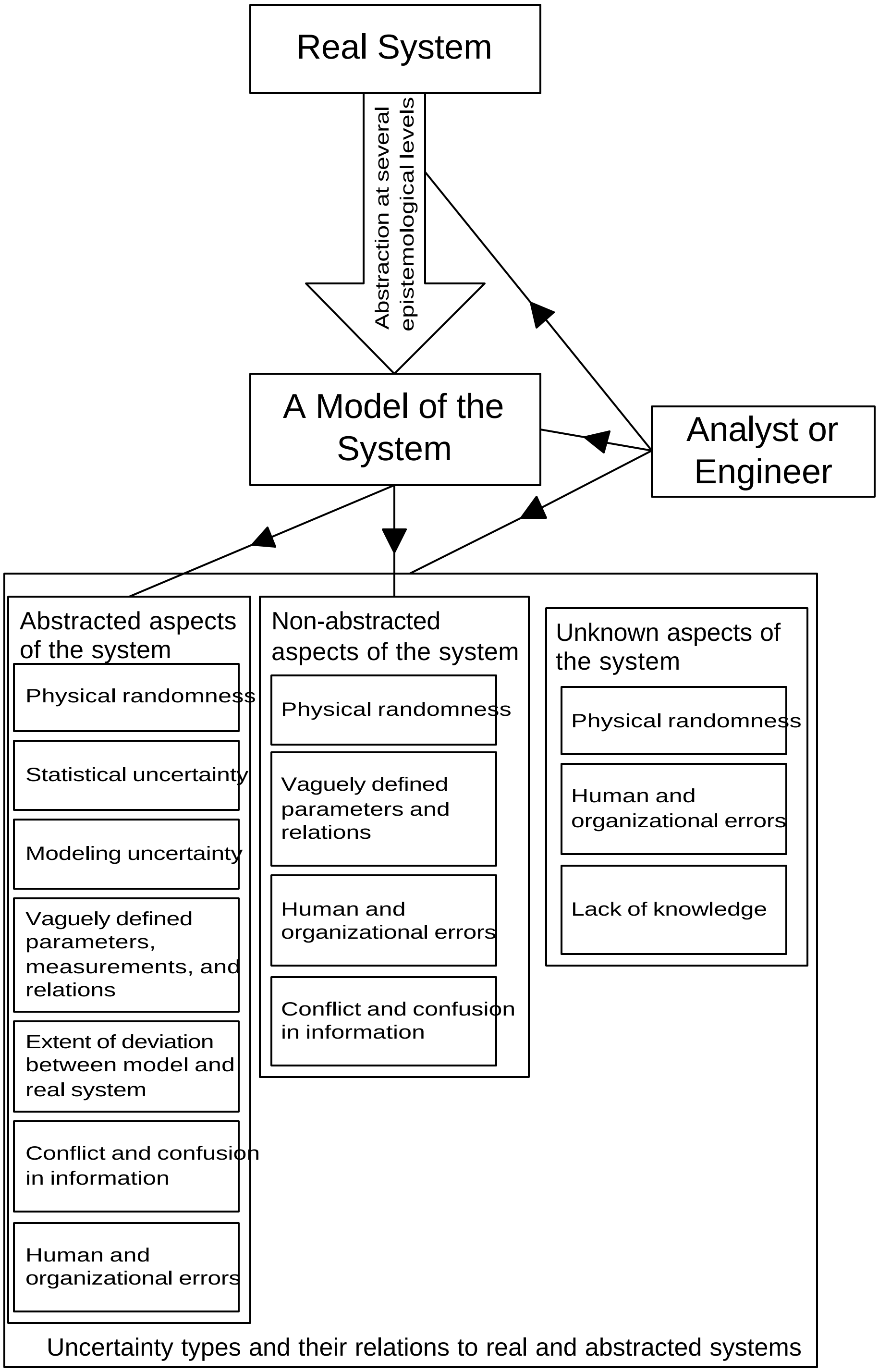


Figure 3.2-1. Uncertainty Types for Engineering Systems (Ayyub 1992, Ayyub and Chao 1997)

4. TYPES OF FAILURE MODES

Failure modes can be based on whether they represent structural or non-structural failure. The structural failure modes may again be divided into ultimate and serviceability types of failure. Ultimate failure modes are representative of a strength limit, beyond which the component loses effectiveness or ability to carry additional load. Ultimate failure modes are quantified though the use of Ultimate Limit States (ULS). Serviceability failure modes are lower energy states and imply structural failure without exceeding load-carrying capability which would occur prior to an ultimate failure. Serviceability failure modes are quantified though the use of Serviceability Limit States (SLS). Failures driven by non-structural system performance are classed as serviceability failure modes as they would not necessarily be in-phase with an ultimate failure, and are traditionally guarded against with serviceability limit states. The two categories may be depicted using a load-shortening curve for a structural member undergoing progressive failure as shown in Figure 4-1.

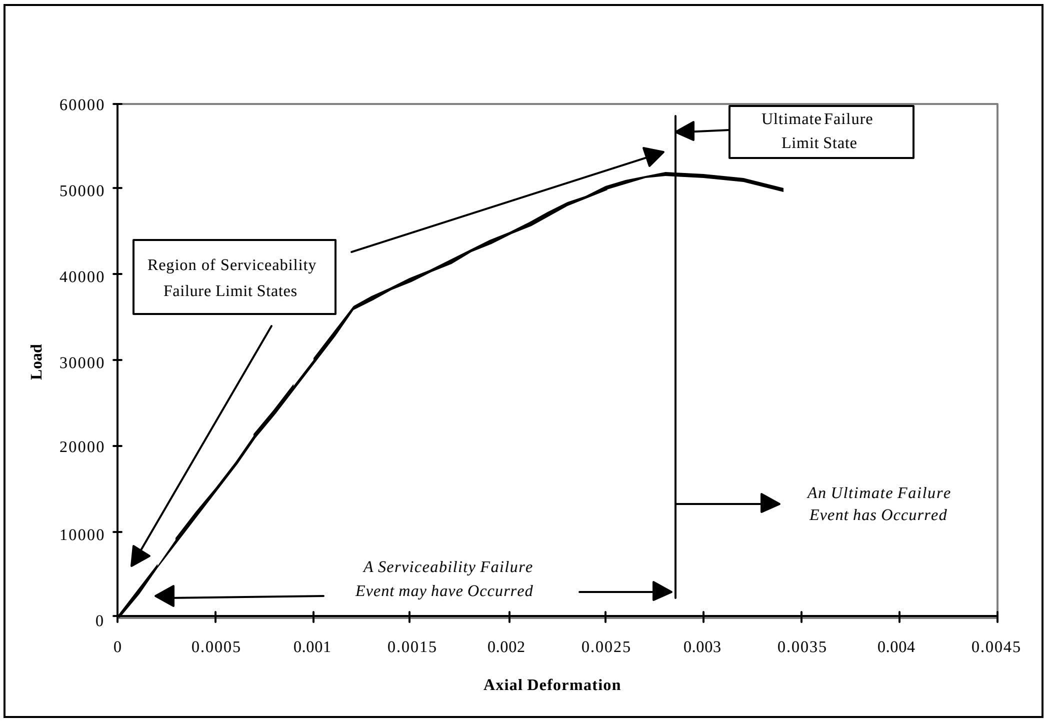


Figure 4-1. Types of Failure Modes vs. Structural Response

The lower energy region is associated with serviceability failure modes, while the peak of the curve represents the ultimate failure of the structural member. Failure modes corresponding to an ultimate strength limit are considered without uncertainty due to vagueness; either they can or cannot carry additional load and therefore are considered bivalent. Limit states for serviceability failures are prone to vagueness uncertainty as they are based on factors such as unacceptable degradation of structural system performance, parent system impacts, and tradition.

4.1. FAILURE DEFINITIONS FROM LITERATURE

Report of ISSC Committee V.I (Planeix et al., 1982), in a description of failure modes and limit state design, states:

> A structure in a limit state is a structure on the verge of going into an unwanted ("unsafe") situation with respect to some effects. One distinguishes ultimate limit states (ULS) relating to the structural safety of a design (trespassing the limit state results in collapse) and serviceability limit states (SLS) relating to the ability of a design to fulfill its functions… There is no limitation to the list of limit states of each category which may be adopted.

The report goes on to discuss the idea of "state parameters" that provide a quantified representation of the system/component status. Consistency between the demand and capability state parameters allows identification of a failure event. Examples of demand and capability state parameters for a jacket platform are shown in Table 4-1. The demand state parameter is the load, load effect or structural response. The capability state parameter is the ultimate strength or some other limiting value.

Table 4.1-1. State Parameters for a Jacket Platform (Planeix et al., 1982)

Component	Demand	Capability
Bracing	Stress	Yield Strength
Bracing	Crack Length	Limit Crack
Underside of Platform	Wave Elevation	Air Gap
Quarters	Acceleration	Human Acceleration Limit

The categories and descriptions of ULS and SLS are consistent with those provided in Ellingwood et al. (1980), which presents an LRFD format for the design of buildings and other structures with respect to ultimate failure modes. The report defines two categories of limit states as:

> <u>Ultimate Limit States</u>: are related to a structural collapse of part or all of the structure. Such a limit state should have a very low probability of occurrence, since it may lead to loss of life and major financial losses.
>
> <u>Serviceability Limit States</u>: are related to the disruption of the functional use of the structure and/or damage to or deterioration of the structure.

In SSC-392 (Mansour et al., 1996), examples of failure definitions for each structural level are presented for use with Level 2 methods of reliability analysis. This includes hull girder buckling, unstiffened plate yielding and buckling, stiffened plate buckling, and fatigue of details. The authors provide both ultimate and serviceability limit states. The serviceability failure modes depend on traditional limit states.

SSC-375 (Hughes, et al., 1994) presents a discussion of structural failure modes and strength assessment models relevant to ship structural design. The focus of the work is the estimation of the modeling and random uncertainty associated with structural response models. The failure modes of principal members are listed along with appropriate response prediction models and the degree to which test data is available for validation. This list is shown in Table 6.2.1-1. The linking of structural system failure modes with structural response models is necessary for structural reliability assessment.

The 8th ISSC, "Lessons Learned from Failure and Damage of Ships" (Akita, 1982) presents a discussion of structural damage and its frequency as found in ships classed by Nippon Kaiji Kyokai between 1973 and 1978. The modes of structural damage to the ship's hull are dent, buckling, crack and wastage. The dominating failures were classified as:

1) Fatigue crack due to repeated stress (including vibration) in discontinuous structure,
2) Buckling due to high stress level or distortion,
3) Dent and buckling due to wave impact force,
4) Crack, dent and buckling due to corrosion,
5) Crack and deformation due to workmanship,
6) Crack due to improper material,
7) Crack and buckling due to improper cargo handling, and
8) Sea casualties such as collision, contact to quay, fire, explosion, and grounding due to improper operation.

The first and second classes occurred most frequently, and are also the most readily handled in the design of the structure. No explanation is provided as to what constitutes failure for each identified class, except that these were observed failures. The database is therefore a compilation of visible cracks and deformation ("buckling") that were deemed unacceptable by the surveyor, according to experience and inspection procedure. This listing is important as it provides failure modes needing further attention, but it is also important to emphasize the need for corresponding predictive tools and failure thresholds developed for reliability assessment analysis and reliability-based design. It is important to have a significant degree of correlation between the definitions of failure of the analyst and the surveyor. The traditional failure modes and predictive models described in SSC-375 and shown in Table 6.2.1-1, have limiting values defined as yielding, localized buckling or collapse that may be improved, modified or updated as a result of close integration with surveyor or owner observations.

Hawkins, et al. (1971) provide the beginnings and guidelines for a structural failure database for ship structures. Surveys of ship damage reported to the U.S. Coast Guard, the Maritime Administration, and the Military Sealift Command were conducted in order to build a database by which to better understand the types of failures occurring in service, and assess the possibility of minimizing such failures. SSC-272 (Jordan and Cochran, 1978) and SSC-294 (Jordan and Knight, 1979) contain survey results for detail failures. These information sources can be used to address weaknesses in current design approaches as discussed above regarding Akita et al. (1982), but should not be used to predict rates of failure as the data populations are pooled without knowledge of all influencing factors.

The U.S. Coast Guard produced a classification of structural failures for surveyor use in NVIC 15-91 (U.S. Coast Guard, 1991), which classifies failure for reporting procedures as follows:

Class 1 Structural Failure

A fracture that occurs during normal operating conditions (i.e., not as a result of a grounding, collision, allision, or other casualty damage), that is:

1. A fracture of the oil/watertight envelope that is visible and any length or a buckle that has either initiated in or has propagated into the oil/watertight envelope of the vessel; or
2. A fracture 10 feet or longer in length that has either initiated in or propagated into an internal strength member.

Class 2 Structural Failure

A fracture less than 10 feet in length or a buckle that has initiated in or propagated into an internal strength member during normal operating conditions.

Class 3 Structural Failure

A fracture or buckle that occurs under normal operating conditions that does not otherwise meet the definition of either a Class 1 or Class 2 structural failure.

Any failures reported under this system would constitute damage beyond the failure thresholds assigned for design in ultimate limit states for buckling, and fatigue limit states, providing qualitative evidence of events occurring outside the scope of the design assumptions. The design and owner communities should respond to this evidence and improve the information in the design assumptions for high-cost failures, and declare the low-cost failures as acceptable, leaving the design process unchanged. The distinction between high and low-cost failure is up to the owners of the vessel.

Budd, et al. (1981), in SSC-308, discuss the impact of hull structure flexibility on propulsion machinery. The authors cite the following reasons for the decreasing stiffness of hull girders:

i) Increased length.
ii) Use of high-strengths steels.
iii) Less stringent corrosion or wastage allowances.
iv) Increased knowledge of structural response, encouraging less conservative designs.
v) Wider use of optimization techniques, in particular weight minimization, leading to smaller scantlings.
vi) Use of aluminum for superstructure construction.

SSC-308 describes the effects of decreasing structural stiffness can result in the following dynamic and static modes of failure:

Dynamic

a) Personnel discomfort from propeller induced or other steady-state vibration and noise.
b) Malfunction of electronic or mechanical equipment, including main shafting, bearing and gear failures from vibration or excessive displacement.
c) Unacceptable high-frequency stress peaks in primary structure due to impact loads such as slamming.
d) Fatigue of primary hull structure from the steady-state vibratory response of springing.

Static

e) Excessive curvature causing premature structural instability in the primary hull structure.
f) Excessive deformation when loaded resulting in reduced payload capacity in the sagging condition, or lower bottom clearance.

g) Excessive hull deformation imposing structural loads on non-structural items such as joiner bulkheads, piping, propulsion shafting, hatch covers, etc.
h) Second-order effects introducing inaccuracies into many of the customary naval architecture calculations.

Each of the failure modes listed above (except the last) require the specification of acceptability limits on the structural response, or definitions of failure, to allow reliability analysis and ensure acceptable performance.

The effects of hull structure flexibility on the propulsion shafting [a portion of (g) above], is the focus of SSC-308 and is a serviceability failure type. This flexibility may impact the main propulsion machinery components by eclipsing the required operational tolerances. According to SSC-308, manufacturers of ship machinery assume a concrete foundation, requiring the structural designer to create foundations accordingly. SSC-308 provides methodologies useful in evaluating the relationship between the structural design and machinery manufacturer's requirements, with failure defined as excessive hull girder flexibility. These methodologies are useful in performing trade-off studies in the preliminary design phase. The requirements of the manufacturers for different propulsion arrangements may be compared to the predicted structural response to determine the likelihood of propulsor failure due to hull girder flexibility.

4.2. ULTIMATE FAILURE MODES

Ultimate failure is the point at which a structural member is unable to continue to carry additional load as shown in Figure 4-1. Analytical approaches to assessing a structure either predict a response due to loading (for example, stress or displacement) or predict the ultimate strength (for example, collapse strength). To predict an ultimate failure, the designer may either choose a simple model which gives only the collapse or buckling strength, or a more complex model which shows the progression to ultimate collapse and beyond (post-buckling regime). The simpler model provides a very crisp threshold between survival and failure that is easily accommodated by structural reliability analysis techniques. The more complex model of the structural response portrays the progression from no damage to ultimate collapse, with the failure event threshold coinciding with the point of maximum load capacity. The modeling bias and uncertainty are required to achieve accurate results as is discussed in Hughes et al. (1994) and Hess et al. (1994).

For illustrative purposes, one may consider the Euler buckling equation as a simple model of an ultimate strength failure mode for a column due to elastic (bifurcation) buckling. Euler's equation is:

$$s_{CR} = \frac{p^2 EI}{L^2 A} \tag{4.2-1}$$

where s_{CR} = the critical buckling stress; E = Elastic (Young's) modulus; I = moment of inertia; L = column length; and A = cross-sectional area. If the axial load on the column divided by the cross sectional area is greater than σ_{CR}, the limit state is exceeded and a failure event is considered to have occurred. The amount of disagreement between the predicted strength from Equation 4.2-1 and the actual failure stress of a slender column is the modeling bias. The variation of the strength prediction due to variability in E, I, L and A may be considered the random uncertainty.

Reliability analysis Levels 2 and 3 account for the ambiguous uncertainty surrounding the reliability prediction by treating the basic load and strength variables as random variables and can include measures of the strength and load, modeling bias and uncertainty. Ambiguity can also be accommodated in Level 1 reliability codes (for example, LRFD) if included in the derivation of the partial safety factors.

The complexity and redundancy found in the ship structural system forces the designer to make assumptions and simplifications. Strength predictions of the ship structural components (for example, hull girder, stiffened panel, unstiffened panel, detail) are calculated using algorithms developed with empirical relations, which do not necessarily match the ship structural system being analyzed. Component tests rarely are able to capture the influence of the surrounding structure for the smaller components, forcing conservative boundary conditions to be assumed. To design components based on an ultimate strength formulation assumes that the connected structure does not influence the ultimate strength. This could lead to an overly conservative design. If consequences to the greater ship system and progressive damage are ignored, potentially high risk failure modes corresponding to lower energy (serviceability failure), pre-collapse structural response effects may be left out of the design formulation, resulting in a non-conservative design.

4.3. SERVICEABILITY FAILURE MODES

We may consider serviceability failure to be an event that increases the risk of ultimate failure to unacceptable levels, or degrades non-structural systems in an unacceptable manner. Knowledge about the functional roles that a component/system plays in its parent system (structural and non-structural) is embodied in serviceability failure modes. The availability of such knowledge is often lacking to the degree that it may be accurately used in design. A quantitative system model is required to completely understand the influence of the structural response, short of ultimate failure, on the parent system as a whole. As this system model, and quantitative awareness, is traditionally unavailable, approximations are required. Current serviceability limit states are based on experience, tradition, convenience or narrowly focused insight into the system role of a particular component. Figure 4.3-1 shows the range of approaches available for defining serviceability failure modes for reliability analysis.

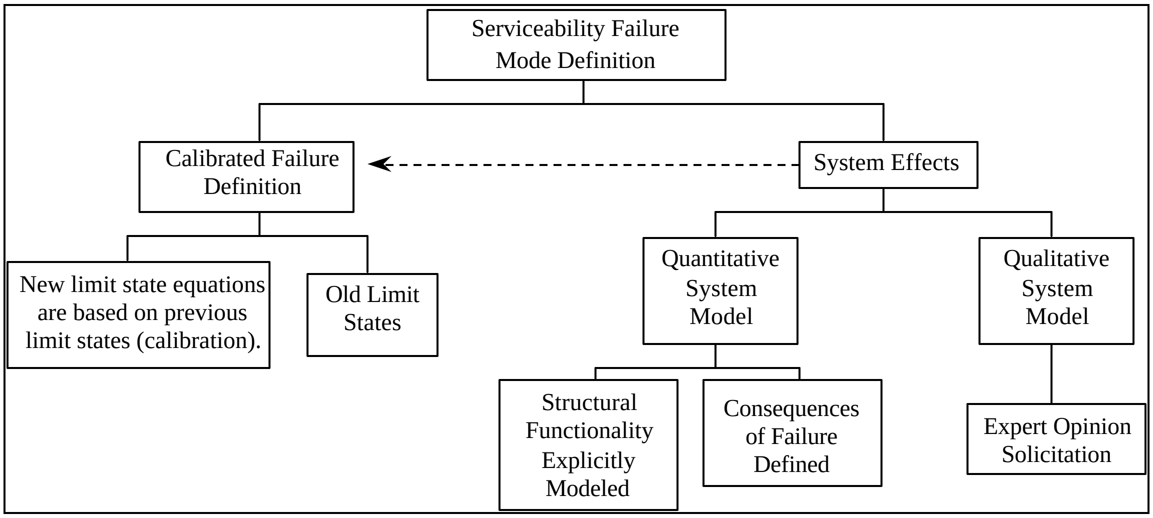


Figure 4.3-1. Approaches to Serviceability Failure Definition

Realistic serviceability limit states depend on the degree to which the greater system is degraded by the structural response. This system degradation must exceed some acceptable limit before being considered failure. The use of probabilistic risk analysis to quantify the risk associated with the degradation scenario allows comparison to some governing risk criteria, which is the delineation between acceptable and unacceptable risk. The interdependence of the rational limit-state and the overall risk acceptability is discussed in Appleyard (1995) as risk negotiation. Risk negotiation is the communication and decision processes, which the designer conducts with the client to arrive at a design with acceptable levels of risk. The comparison of the costs and benefits associated with the different risk levels helps decide acceptability. Therefore, a complex and difficult, but more progressive way of defining serviceability failure is to assess the increase in risk or decrease in performance, associated with the structural response, and choose the limit state as the response corresponding to the onset of unacceptable risk or performance. Without the means of conducting a full system risk assessment, the structural designer is left to develop approximate serviceability failure definitions such that work can progress.

Serviceability failure modes of the structural component are traditionally based on perceived component functions. Due to the lack of information and communication with the design of the parent system in which the structural component exists, the component's design must be based on tradition or engineering judgment. This information is embodied in the current written and unwritten design criteria, and in the minds and past decisions of the owners, operators, and inspectors for whom the idea of failure is multi-faceted and system-based.

A simple way to define a serviceability failure mode is to base new failure definitions upon those used in past designs. These limiting values, which correspond to the onset of a failure event, may be applied to a new structural response model. This allows adoption of a new model while attempting to maintain the implicitly accepted level of risk associated with the old model, essentially a calibration of the new response model to prior knowledge.

A traditional serviceability failure definition has been the onset of yield in the extreme fibers of the structural material. The structural response under consideration is the stress, which is then compared to the nominal yield strength of the structural material as derived from coupon testing. The idea of the loaded structure experiencing the onset of yield, or fraction thereof as in allowable stress, is an abstraction of convenience. This abstraction allows a limit to be placed on the allowable structural behavior such that higher energy, collapse mechanisms or fatigue cracking are prevented. Progressive damage resulting from consecutive near overloads (stresses higher than yield), may weaken the structure such that the collapse strength is markedly less than originally assumed, forcing the structure into the elasto-plastic domain. The unloaded structure, after such an overload, may not return to its original strength or geometry. Defining serviceability failure as the onset of inelastic behavior allows prevention of more uncertain, higher energy failures that have much higher associated consequences. The likelihood (probability of failure) deemed acceptable for the occurrence of yielding should be higher than the likelihood for collapse. It is important to note that the risk associated with yielding failure versus collapse failure may be the same or more if the acceptable probability of failure is chosen without consideration of the failure consequences. For example, if the likelihood of experiencing yield is 0.001 and the likelihood of experiencing collapse is 0.0001, and the consequences are 100 times greater for collapse than yield, the risk associated with yield failure would be ten times greater than the risk from collapse. Conversely, if the likelihood of yield failure is 0.01, then the risks are equivalent. For elastic buckling, where the critical stress is less than the yield strength, the probability of exceeding the yield strength can be set at a very low value to preclude buckling failure at an acceptable likelihood.

Traditional design equations developed to prevent structural serviceability failure are functions of the geometry, material properties and/or predicted design loads and load effects. Criswell (1979) discusses the uncertainty inherent in traditional, serviceability failure thresholds due to their dependence upon the predictive tools with which they are paired. The discussion is of deflection limit imposed on wood flooring, implicitly assuming a traditional predictive technique as compared to reality. Improvement or change in the structural response prediction requires a change in the failure definition, or limiting response, to reflect a different modeling bias and uncertainty. Probabilistic treatment of these uncertainties in a reliability framework allows the designer to map the historic failure threshold to a new value in line with the improved response model. The new failure threshold can be treated as uncertain with it’s own probabilistic characterization.

Probabilistic aggregation of (uncertain) limit states from different sources along with expert opinions allows the development of a probabilistically characterized failure definition. Treatment of the system dependencies on the component response, which are not clearly linked to the existing limit states, may be modeled using expert opinion. A probability distribution can be created which represents the likelihood of the failure threshold taking on a particular value of response. The probabilistically characterized failure threshold and structural response can be compared using reliability analysis to calculate the likelihood of failure.

Inclusion of new information into previous failure definitions (whether actual or calibrated expressions) may be achieved using probabilistic characterization of the limit states. Updating the limit state model is possible by using Bayesian probabilistic techniques for incorporating new knowledge and expert opinion into the existing model.

4.4. NON-STRUCTURAL, SYSTEM FAILURE MODES

Non-structural ship systems may experience failure where structural behavior is the root-cause. These failure modes should be considered in the design of the structure. The system performance impacts due to structural behavior (response) must be assessed and compared to acceptability criteria to declare the response event a failure. A greater amount of response can be allowed if the predicted response event provides a higher system performance, or lower risk level, than required by the governing criteria. Appleyard (1995) alludes to the process by which greater responses, and greater potential for damage, are allowed due to risk negotiation. This approach would provide the most rational framework in which to judge serviceability issues, but may also be implausible.

The lack of knowledge about the functional role of the structural component forces the designer to make an approximate model. This model may take the form of a functional mapping, taking the structural response and linking it to parent system behavior. Use of uncertainty measures and functions to allow for the lack of knowledge may provide a formalized method of approximation. Mapping of response to the parent or dependent system may be done using physical interaction models, or fuzzy approximations. This area may prove to be amenable to approaches based on possibilistic or fuzzy set theories.

The model proposed by Ayyub and Lai (1992) is useable in this context. This model uses a linear belief function to transition from complete success to complete failure. The response corresponding to the transition from complete survival to partial failure serves as the lower limit. The response corresponding to the transition from partial to complete failure serves as the upper limit. This approach is discussed further in Section 5.1. The transition model can represent an abstraction of the system's performance degradation in terms of the structural response, allowing the approximate model of the component's function to be considered in the design process. The Ayyub and Lai (1992) model is also discussed in broader terms in Alvi, et al. (1992) and mentioned with respect to design methodology development in Ayyub et al. (1995).

As the process of approximating the system interactions may prove too burdensome, formal aggregation of experience and previous practice can allow treatment of non-structural serviceability failure at the structural component level.

5. METHODOLOGY TO FORMULATE FAILURE DEFINITIONS

5.1 THE DAMAGE SPECTRUM

The progression from success to failure for a structural system failure mode may be termed a damage spectrum. While some failures may be considered crisp events, others are more gradual. This damage spectrum may be partitioned to reflect different levels of failure. Crisp failures are those for which the community agrees upon the definition such as ultimate collapse or fracture. Non-crisp (vague) failure are those for which the community does not have an agreed upon definition. This could include elastic and plastic deformation, critical crack size or crack initiation, excessive vibration, or other unacceptable performance degradation.

A reliable system or component is one that performs its intended function under stated conditions for a specified period of time. Failure of the system or component is an inability to fulfill its function. Failure may also be considered an unacceptable lack of performance, where the threshold of acceptability is determined by formal or informal consideration of the associated risk. The identifiable ways in which a system or component may fail are considered failure modes. The occurrence of a failure mode is a failure event. Quantitative assessment of system/component failure likelihood requires the analyst/designer to define failure such that it is possible to calculate the probability of occurrence for each failure event. Defining a failure threshold requires understanding of the physical causes (structural response) responsible for each mode and explicitly considering the uncertainties found in both the failure mode definition and its associated physical cause(s).

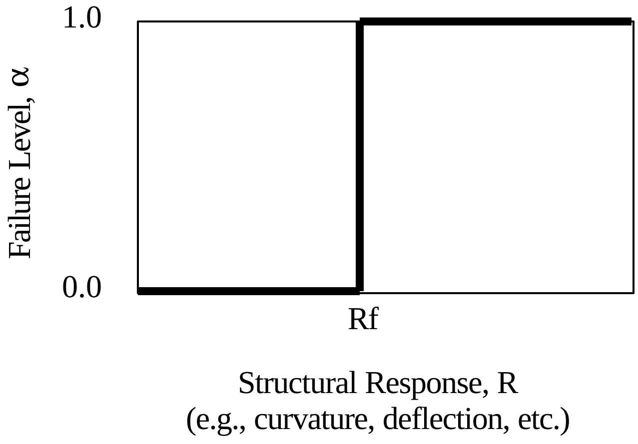
5.2. CRISP FAILURE DEFINITION

Classical reliability approaches treat the failure mode as a limiting point found in the physical behavior, delineating between success and failure, traditionally agreed upon by the community involved with the design process. This limiting point is mapped into a limit state equation born out of a model of the physical behavior and modified to reflect a crisp transition from success to failure. Analytical and numerical tools allow the designer to effectively model the structural response. These models are also able to incorporate ambiguous or objective uncertainty using simulation and other numerical techniques. Ambiguity is an uncertainty in the predictive models resulting from physical randomness of the model parameters, limited information about these parameters, and simplifications, assumptions, or idealizations found in the predictive models themselves.

Current structural failure definitions, both for deterministic and reliability-based design, are based upon an assumed crisp transition from survival to failure, with only two, mutually exclusive events, complete survival and complete failure. This may be expressed as

$$U \rightarrow A = \{0, 1\} \qquad (5.2\text{-}1)$$

where U = the universe of all possible outcomes; A = failure level scale; 0 = failure level of the event *complete survival*; 1 = failure level of the event *complete failure*. Figure 5.2-1 shows a crisp failure definition, R_f, for some structural response R. The threshold where a failure state begins is not necessarily based upon a structural collapse event, but may be a point beyond which structural or non-structural performance is affected (for example, permanent set of plates and beams). In this case, the limit state threshold is often chosen based on past experience and available predictive tools.



Rf = structural response at failure
R < Rf : complete survival (α = 0)
R = Rf : limit state
R > Rf : complete failure (α = 1)

Figure 5.2-1. Crisp Failure Model

Convenience failure definitions may be used to address serviceability limit states such that the initiation of failure is deemed the failure point. Such as case may be found in crack initiation versus crack growth. If models are used to predict the formation of a crack, such as the cumulative damage model, the predictive tools will not lead the designer or analyst to a prediction of the size of the crack. The testing conducted will only predict the onset of damage. It is at this point that the event is classed as a failure, due to modeling limitations.

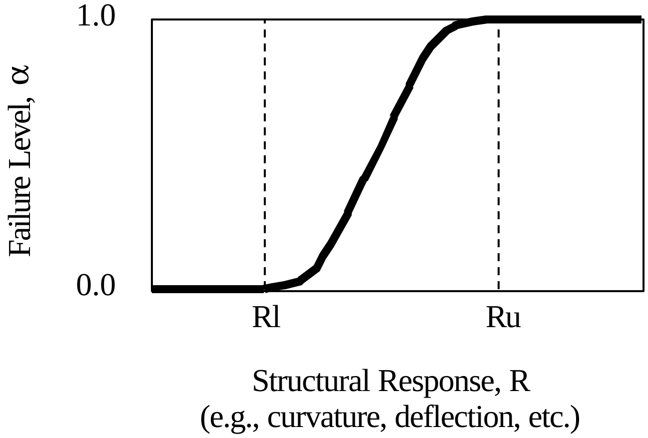
5.3. VAGUE LIMIT STATES

The choice of a failure threshold is highly important in determining the reliability of a system. Unfortunately in the case of structures, there is not necessarily an easily identifiable change in physical state that corresponds to the change in state judged to constitute failure by the engineer or operator. The inability to provide for the subjective view of failure is a weakness in traditional methods. This uncertainty in defining what constitutes failure may be considered subjective and is a result of vagueness. Vagueness is an uncertainty in the definition of certain parameters such as structural performance, quality, deterioration, and definitions of the interrelations between the parameters of a system, particularly for complex systems such as a ship structure.

Structural system or component failure is rarely an all-or-nothing event. While the complete failure of a system may be easily defined, it is less likely to occur than a partial failure or unacceptable deterioration of system performance. A subjective index, failure level α, is introduced to represent the intermediate levels of damage. Equation 5.2-1 may be revised to reflect this new type of failure as:

$$U \rightarrow A = \{ \alpha : \alpha \in [0, 1] \} \qquad (5.3\text{-}1)$$

where U = the universe of all possible outcomes; A = failure level scale; $\alpha = 0$ is complete survival; $0 < \alpha < 1$ is partial failure; and $\alpha = 1$ is complete failure. Figure 5.3-1 shows the relationship between the failure level and the structural response R. R_l and R_u represent the lower and upper bounds, respectively, of the partial failure zone. When R is less than R_l, α is zero, and the structure is considered to be in a state of complete survival. When R is greater than R_u, α is one, and the structure is considered to be in a state of complete failure. For values of R between R_l and R_u, α takes values between 0 and 1 reflecting the level, or degree of failure. A failure level of 0.5 would denote a structure that is 50% failed in the mode of interest.



R < Rl : complete survival (α = 0)
Rl < R < Ru : α is the degree of failure
where 0 < α < 1
R > Ru : complete failure (α = 1)

Figure 5.3-1. Vague Failure Model

Decisions based on the risk of failure and cost/benefit measures are highly dependent upon the underlying level of damage and the associated uncertainties. The acceptable levels of damage for one system may not be acceptable for another. Allowances for vagueness in the failure mode definition provide the designer with a procedure for incorporating subjective judgment into the design process.

Ayyub and Lai (1992) discuss the presence of failure levels from low serviceability to complete collapse. The paper suggests a treatment of the thresholds for each level as fuzzy boundaries whose properties are estimated through the use of expert testimony. Different weighting methods for aggregating expert opinion have been developed using both probabilistic (for example Modarres, 1993) and fuzzy set (for example Hadipriona, 1989) theories. Jovanovic, et al. (1989) suggests an artificial intelligence approach and has developed a computer code toward this end. It is possible that a more timely estimation of these boundaries between success and failure would result from a calibration based on the different design and acceptance criteria currently in use. This could be updated with improved knowledge or use of expert testimony.

Treatment of non-crisp structural failure modes has also been explored in the context of damage assessment of existing buildings by Yao (1980) and Dong, et al. (1989). Shiraishi and Furuta (1982) bring attention to other types of failure such as mistakes, omissions, modeling errors and construction errors and incorporate them into the reliability analysis using fuzzy sets. Bourgund, et al. (1989) discuss a damage index, which acknowledges the damage spectrum without introducing the use of fuzzy sets. The failure level, α, discussed in Ayyub and Lai (1989) and the damage index of Bourgund, et al. (1989) are similar in that a value of zero represents success and unity represents complete failure. The use of a structure function, ϕ, in system analysis (see Høyland and Rausand, 1994, or other system reliability references) is the reverse of the failure level, where success is unity and failure is zero, for use in Boolean analysis of system models. Ming-zhu and Guang-yuan (1989) propose a structure function and solution methodology, which allows multiple states beyond the binary, success/fail approximation to failure, for analyzing structural systems.

The structural designer, or the creator of the design process, may choose probabilistic or possibilistic techniques to address the vagueness uncertainty accompanying the definition of structural serviceability failure or non-structural system performance failure. The primary focus of research into vague failure definitions in the structural design community appears to be aimed toward incorporation of fuzzy failure definitions into damage assessment and reliability calculations, with some efforts leading toward a blend of possibilistic (fuzzy) and probabilistic (Bayesian) approaches.

5.3.1. Possibilistic Vague Failure Model

The uncertainty surrounding whether a failure event did or did not occur can be characterized by treating the boundary between the two events as fuzzy. The use of fuzzy sets would assign a degree of belief regarding whether a failure event did or did not occur for each response.

Ayyub and Lai (1992) view the failure probability prediction as fuzzy, a methodology treated by Cai (1996) as fuzzy probist theory. Cai presents an extensive discussion of system reliability prediction with the use of possibility theory and fuzzy sets. A classification of the potential methods useable for reliability prediction are presented as follows (from Cai, 1996):

- *Probist* Reliability Theory: The system failure behavior is fully characterized in the context of probability measures and assumes that the state of the system is binary with crisp delineation between success and failure.
- *Profust* Reliability Theory: The system failure behavior is fully characterized in the context of probability measures and assumes that success and failure are characterized by fuzzy states.
- *Posbist* Reliability Theory: The system failure behavior is fully characterized in the context of possibility measures and assumes that the state of the system is binary with crisp delineation between success and failure.
- *Posfust* Reliability Theory: The system failure behavior is fully characterized in the context of possibility measures and assumes that success and failure are characterized by fuzzy states.

Cai gives a very brief discussion of the utility of *posfust* theories for mechanical and structural reliability, but devotes the greater portion of the book to the use of *probist*, *profust* and *posbist* theories.

The work of Ayyub and Lai (1992) entitled “Structural Reliability Assessment with Ambiguity and Vagueness in Failure” presents a demonstration of a methodology for the treatment of the vagueness type of uncertainty as it relates to the definition of structural failure. This uncertainty is of the cognitive, subjective, or fuzzy type. The paper also uses probabilistic techniques to consider the ambiguity type of uncertainty, which may be considered non-cognitive, objective or random. Ayyub and Lai (1992) propose to incorporate the use of non-crisp failure modes into a structural reliability analysis using fuzzy sets to define the threshold of a failure event.

The methods used in Ayyub and Lai (1992) include the uncertainty in the failure mode definition in the calculated probability of failure, p_f. The probability of occurrence is calculated for different amounts of structural response (curvature: ϕ). Each curvature may have membership in one or more failure event. The curvatures and their associated failure likelihood’s are then assembled according to the degree of membership in each event (α). Ayyub and Lai (1992) extract one value for the probability of failure for each performance event by finding the arithmetic and geometric averages of the probabilities of failure for the curvatures that are members of each performance event fuzzy set.

Ayyub and Lai (1992) explore the use of three failure models incorporating vagueness in their definition portraying the sensitivity of the probability of failure (reliability) to the definition of failure. The performance events are associated with a fuzzy index which is interpreted as either: 1) the level of damage ($\alpha=0$ for complete survival, $0<\alpha<1$ to represent progressing degrees of failure and $\alpha=1$ for complete failure); 2) a degree of belief that a performance event has occurred as a function of ϕ; 3) a degree of belief that "at least" a performance event has occurred as a function of ϕ. For the latter two, the authors partitioned the damage spectrum into six levels, from survival through increasingly damaging serviceability failure events, to ultimate failure. This gave results that are consistent with traditional engineering experience, with the likelihood of failure decreasing as the severity increased. Scientific and mathematical methods are presented which have allowed this analysis to be demonstrated. The application of this methodology to the hull girder under vertical, longitudinal bending will be discussed in Section 6.1.

A reliability formulation by Holicky (1997) proposes vague, performance (serviceability) failure to be defined as the condition where the action effect (response) exceeds some limiting performance requirement (limit-state). Holicky goes on to discuss a fuzzy-probabilistic representation of the limit-state as it applies to floor vibration in offices. For each limit state, a range is proposed which defines the failure threshold. This fuzzy range is mapped into the probabilistic domain and is input into an optimization procedure based on cost. Each level of response has an accompanying consequence/cost. The optimum design corresponds to the lowest cost, where cost is the sum of the initial construction cost and the expected cost due to the predicted response distribution. This approach is a form of risk negotiation as discussed above.

5.3.2. Probabilistic Vague Failure Model

Bayesian analysis is an extension of classical probability theory, which gives the analyst a structured and mathematically rigorous approach to incorporating subjective knowledge into a probabilistic format. The axioms of probability are applicable and so the techniques join easily into the classical probability methods used in reliability assessment. The probability measure is considered a degree of belief founded in subjective knowledge, much like the approach used in fuzzy theory. Bayesian techniques are used in many different ways, including characterization of expert knowledge.

The construction of a database of events considered failure in the past may be used to assess events in the future. Future events deemed to be failure (by experts), which do not prove similar to past events, may be used to update the database in a formalized manner using Bayesian techniques. This would be particularly appropriate for detail design, where databases have been in use for some time.

The lack of knowledge about the system functions of a structural component requires the designer to assign a degree of belief to a response level corresponding to whether or not the particular response represents serviceability failure for the component. Given a full, quantitative system model, the response failure threshold for the structural subsystem/component would be known. If a probability distribution is derived for the response failure threshold, this may be compared to the response probability distribution to arrive at a prediction of the likelihood of the failure threshold being exceeded. This approach has the same failure formulation as discussed in Holicky (1997), but with probabilistic characterizations of both the action effect (responses) and performance requirement in place of possibilistic (fuzzy) characterizations.

This method allows the failure likelihood to be calculated using the same techniques as would be used for classical structural reliability analysis, such as the Monte Carlo simulation and approximate methods (ASM). The response failure threshold distribution may be considered the resistance, and the predicted response distribution may be considered the load. In classical structural reliability, when the load exceeds the resistance, failure is considered to have occurred. For the framing of the serviceability failure likelihood discussed above, when the response exceeds the failure threshold, failure is considered to have occurred.

Creation of the predicted response distribution depends on quantifying the uncertainty in the load and strength models and basic variables, as in classical structural reliability. The analytical method of combining the load and strength into a response measure is required, and not necessarily always available, nor accurate.

Approximation of the response failure threshold distribution may be done using a combination of traditional failure definitions and experience (expert opinion and historical failure identifications). Subjective (Bayesian) probabilistic methods are recommended for the development of the failure threshold distribution. The traditional failure definitions as used by different designers may be combined with expert opinion from ship structural inspectors to produce a probabilistic failure definition for immediate use. The probabilistic combination of failure thresholds for excessive permanent set of unstiffened plates is explored in Section 6.2.3.

The creation of a database of unacceptable structural behavior for which prediction tools exist would allow future analysis of the associated structural response measures, and probabilistic characterization. This response distribution may then be used to update the failure threshold distribution used in design to obtain a more meaningful failure definition. The existing reliability-based design process could immediately incorporate this improved knowledge.

5.3.3. Vague Failure Recognition and Classification

Prediction of the response of ship structural components or systems could require the use of nonlinear structural analysis. In such cases, failure definitions need to be expressed using deformations or resonant frequencies, rather than forces or stresses. Also, the recognition and proper classification of failures based on a structural response within the simulation process need to be performed based on deformations. The process of failure classification and recognition needs to be automated in order to facilitate its use in a simulation algorithm for structural reliability assessment. Figure 5.3-2 shows a procedure for an automated failure classification that can be implemented in a simulation algorithm for reliability assessment. The failure classification is based on matching a deformation or stress field with a record within a knowledge base of response and failure classes. In cases of no match, a list of approximate matches is provided, with assessed applicability factors. The user can then be prompted for any changes to the approximate matches and their applicability factors. In the case of poor matches, the user can have the option of activating the failure recognition algorithm shown in Figure 5.3-3 to establish a new record in the knowledge base. The adaptive or neural nature of this algorithm allows the updating of the knowledge base of responses and failure classes. The failure recognition and classification procedure shown in the figure evaluates the impact of the computed deformation or stress field on several systems of a ship. The impact assessment includes evaluating the remaining strength, stability, repair criticality, propulsion and power systems, combat systems, and hydrodynamic performance. The input of experts in ship performance is needed to make these evaluations using either numeric or linguistic measures. Then, the assessed impacts need to be aggregated and combined to obtain an overall failure recognition and classification within the established failure classes. The result of this process is then used to update the knowledge base.

A prototype computational methodology for reliability assessment of continuum structures using finite element analysis with instability failure modes is described in Ayyub (1996). Examples were used to illustrate and test the methodology. Geometric and material uncertainties were considered in the finite element model. A computer program was developed to implement this methodology by integrating uncertainty formulations to create a finite element input file, and to conduct the reliability assessment on a machine level. A commercial finite element package was used as a basis for the strength assessment in the presented procedure. A parametric study for stiffened panel strength was also carried out. The finite element model was based on the 8-node doubly curved shell element, which can provide the non-linear behavior prediction of the stiffened panel. The mesh was designed to ensure the convergence of eigenvalue estimates. Failure modes were predicted on the basis of elastic non-linear analysis using the finite element model.

Reliability assessment was performed using Monte Carlo simulation with variance reduction techniques that consisted of the conditional expectation method. According to Monte Carlo methods, the applied load was randomly generated, finite element analysis was used to predict the response of the structure under the generated loads in the form of a deformation field. A crude simulation procedure can be applied to compare the response with a specified failure definition, and failures can then be counted. By repeating the simulation procedure several times, the failure probability according the specified failure definition is estimated as the failure fraction of simulation repetitions. Alternatively, conditional expectation was used to estimate the failure probability in each simulation cycle in this study, then the average failure probability and its statistical error were computed.

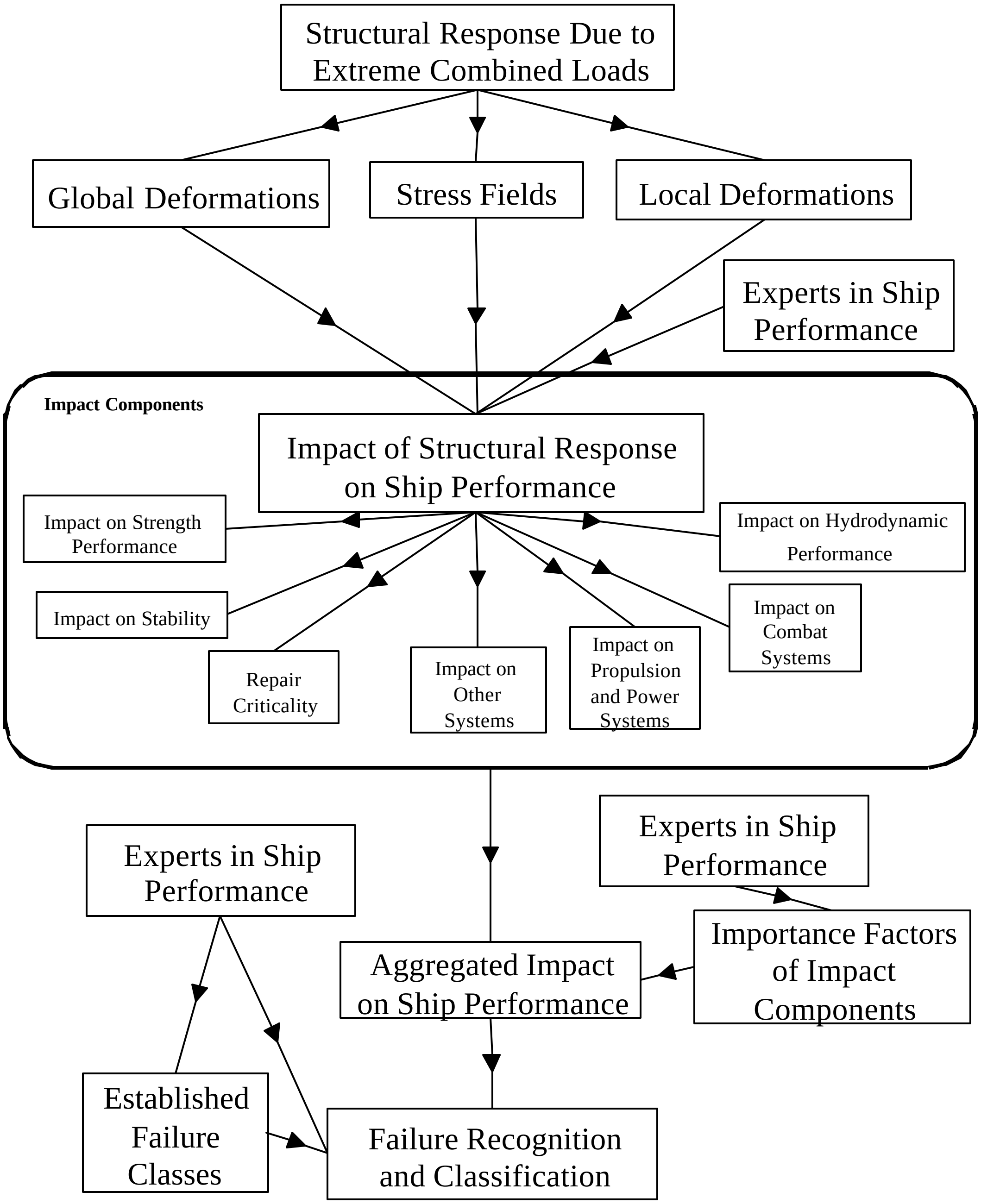


Figure 5.3-2. Failure Recognition and Classification Procedure (Ayyub, et al. 1995, Ayyub 1996)

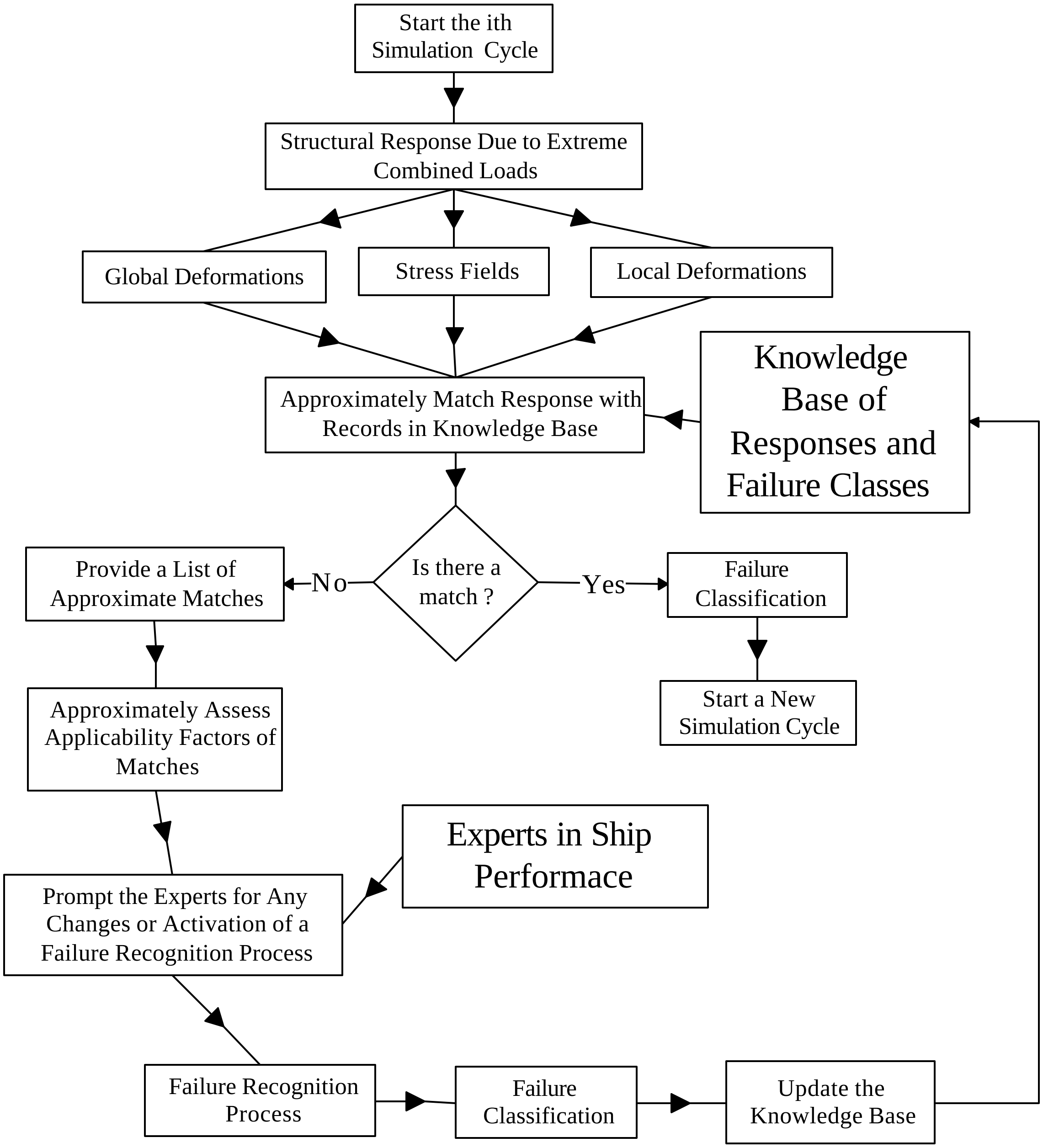


Figure 5.3-3. Failure Recognition Algorithm (Ayyub, et al. 1995, Ayyub 1996)

6. FAILURE DEFINITIONS FOR SHIP STRUCTURES

The traditional levels of a surface ship structural system, each having sets of failure modes, are primary (hull girder), secondary (grillage and stiffened panel), and tertiary (unstiffened panel and local details). Current reliability-based design tools and methodologies for surface ship structures treat the different levels in a structural system as a set of components, each of which have their own particular modes of failure, or as a series system of independent components where the first component failure constitutes system failure. To be incorporated in the design methodologies currently in place or being developed, each level of the structural system must be addressed. Potential failure events must be identified and the structural response to the environment or loads, which lead to the failure event, must be characterized to include uncertainty, allowing application of these methods and enhancements to the design process.

6.1. HULL GIRDER

6.1.1. Discussion of Hull Girder Failure

As quoted in SSC-299 (Mansour and Thayamballi, 1980), the 1967 International Ship Structures Congress defines failure of a hull girder as follows:

> "This occurs when a structure is damaged so badly that it can no longer fulfill its function. The loss of function may be gradual as in the case of lengthening fatigue crack or spreading plasticity, or sudden, when failure occurs through plastic instability or through propagation of a brittle crack. In all cases, the collapse load may be defined as the minimum load which will cause this loss of function."

SSC-299 and SSC-392 provide a taxonomy of possible failure modes for a hull girder under seaway loads, as well as techniques for calculating the hull girder strength under vertical bending, lateral bending and torsion, alone and combined. Fatigue and brittle fracture were excluded from the list. While brittle fracture of the hull is also possible and does occur, it is generally prevented by inspection, material choice and proper choice and treatment of structural details in accordance with fatigue considerations. The cited hull girder failure modes are as follows:

1) Failure due to yielding and plastic flow:
    a) The plastic collapse moment;
    b) The shakedown moment;
    c) The initial yield moment;
2) Failure due to instability and buckling:
    a) Failure of the plating between stiffeners;
    b) Panel failure mode (flexural buckling or tripping of longitudinals);
    c) Overall grillage failure mode.

Failure due to instability and buckling is usually the governing mode. Multiple models of the ultimate strength of a hull girder under bending have been developed, but not in a reliability framework. SSC-299 presents detailed strength or capability models for each of the modes listed above. Failure is defined as the structural bending response in a seaway exceeding the calculated resisting moment, capability or strength as defined in the list above. Each of these failure modes is assumed to be crisp with the limiting value being the result of direct calculation, though the capabilities and corresponding failure thresholds are not equivalent, representing unique failure definitions.

In a reliability-based context, SSC-398 (Mansour et al., 1997) describes primary failure as the occurrence of one of three failure modes for the hull girder: the fully plastic moment mode, the initial yield moment mode, and the instability collapse moment mode. Each failure mode defines failure as the exceedance of a specified hull girder resisting moment. The plastic moment can be considered an upper bound on the instability collapse moment. SSC-398 also includes a description of simplified methods for predicting the instability collapse moment mode as well as a description of the computer code ALPS/ISUM (Paik, 1993). Each method presumes to predict the maximum load-carrying moment of the hull. A comparison of these methods to experimental and full-scale data is included and discussed. Multiple predictive models for the instability collapse moment are compared based on analysis of a 1/3-scale frigate in the 1994 ISSC Committee III.1 report (Jensen et al., 1994), showing the possible range of modeling uncertainty.

SSC-398 presents reliability analysis results for four ships in each of three different failure modes: primary, secondary and tertiary. Two failure definitions for primary failure of the hull girder are applied in the analysis. The first is when the seaway bending moment exceeds the initial yield moment, which is the product of the extreme fiber yield strength and the section modulus. The second is when the seaway loads exceed the ultimate collapse moment of the hull girder as calculated using ALPS/ISUM. The resulting ranges of safety indices (β) are shown in Table 6.1-1. The ratios of collapse over initial yield, safety indices and probabilities of failure, are shown in Table 6.1-2. The range of ratio values show the inconsistency between these two definitions of failure. The simplicity of the initial yield moment failure definition makes it appealing for use in early design, but the scatter in the margin between the results of the two failure definitions signifies the need for added conservatism. This needed conservatism may invalidate the utility of highly simplified tools in reliability-based design. SSC-398 addresses this issue, concluding: "Designing a ship's structure based on yield strength criteria is unlikely to produce designs with a consistent level of reliability."

Table 6.1-1. Hull Girder Reliabilities from SSC-398 (Mansour et al., 1997)

Ship	Failure Definition	Short Term				Long Term			
		Sagging		Hogging		Sagging		Hogging	
		beta	Pf	beta	Pf	Beta	Pf	beta	Pf
Cruiser 1	Yield	10.29	0.00E+00	10.45	0.00E+00	7.92	1.22E-15	7.40	6.86E-14
	Collapse	6.47	4.92E-11	6.75	7.43E-12	4.27	9.78E-06	4.09	2.16E-05
Cruiser 2	Yield	6.75	7.43E-12	7.77	4.00E-15	4.67	1.51E-06	4.54	2.82E-06
	Collapse	5.10	1.70E-07	6.22	2.50E-10	3.09	1.00E-03	3.18	7.36E-04
SL-7	Yield	6.26	1.93E-10	6.58	2.36E-11	4.20	1.34E-05	5.88	2.06E-09
	Collapse	5.83	2.78E-09	3.32	4.50E-04	3.84	6.15E-05	2.67	3.79E-03
Tanker	Yield	5.87	2.19E-09	5.01	2.73E-07	3.31	4.69E-04	4.03	2.81E-05
	Collapse	3.02	1.26E-03	2.82	2.40E-03	0.81	2.08E-01	2.03	2.14E-02

Table 6.1-2. Primary Failure Definition Ratios of Reliabilities from SSC-398 (Mansour et al., 1997)

Ship	Short Term				Long Term			
	Sagging		Hogging		Sagging		Hogging	
	$\frac{b_{IY}}{b_{Ult}}$	$\frac{P_{f\,IY}}{P_{f\,Ult}}$	$\frac{b_{IY}}{b_{Ult}}$	$\frac{P_{f\,IY}}{P_{f\,Ult}}$	$\frac{b_{IY}}{b_{Ult}}$	$\frac{P_{f\,IY}}{P_{f\,Ult}}$	$\frac{b_{IY}}{b_{Ult}}$	$\frac{P_{f\,IY}}{P_{f\,Ult}}$
Cruiser 1	0.63	-	0.65	-	0.54	8.0E+09	0.55	3.1E+08
Cruiser 2	0.76	2.3E+04	0.80	6.3E+04	0.66	6.6E+02	0.70	2.6E+02
SL-7	0.93	1.4E+01	0.50	1.9E+07	0.91	4.6E+00	0.45	1.8E+06
Tanker	0.51	5.8E+05	0.56	8.8E+03	0.24	4.4E+02	0.50	7.6E+02

SSC-392 (Mansour et al., 1996) provides an approximation of the ultimate (instability collapse) moment capacity of the hull girder using a reduced initial yield moment. This approach assumes a consistent margin between onset of extreme fiber yield and the occurrence of buckling or instability failure. The margin is expressed as a knockdown factor *c*, which is based on material type. The knockdown factor may be calculated as the ratio of the instability collapse moment to the initial yield moment. The instability collapse moment is then calculated as the product of the knockdown factor, the extreme fiber yield strength and the section modulus. Failure is said to have occurred when the bending moment experienced due to waves, exceeds the maximum bending resistance of the hull girder. The knockdown factor approach outlined in SSC-392 shifts the initial yield strength prediction in a consistent manner, but would not significantly reduce the variation in the calculated reliabilities such that yield-based strength criteria may be used in design.

Should the margin between the initial yield moment and the ultimate bending moment be consistent, the desired reliability levels for hull girder collapse can be adjusted to allow for simplified capacity models without the use of a knockdown factor. As the occurrence of buckling precedes the onset of yield, a higher reliability can be associated with the initial yield moment (lower probability of failure) than the collapse moment due to buckling. The reliability levels for hull girder, instability collapse failure can be chosen based upon more realistic considerations. The artificial target reliability levels chosen for the simplified failure definition and tools can be calibrated to assure some level of confidence in meeting the desired, realistic target reliability. The result allows simplified tools to be used in early design with adjusted target reliabilities set such that when more sophisticated tools are applied, the reliability targets assigned to realistic failure modes are met. The adjustment of target reliabilities to account for modeling simplifications, but calibrated against more complex analyses, can be used at any level of a structure to minimize complexity early in the design, but may not always be possible as shown in Table 6.1-2. It is important to emphasize the complete correlation between the target or assessed reliabilities, and the tools, information and especially the failure definitions used to develop them or to which they are applied.

6.1.2. Hull Girder Ultimate Strength

Hull girder ultimate strength is conventionally considered the maximum bending moment the hull girder is able to resist and can be considered a crisp event. Table 9-1 in the Appendix shows the two possible ultimate strength failure definitions limit values as yield strength and the maximum bending resistance. The dominant and most realistic failure mode is instability collapse. Failure is defined as the occurrence of an applied bending moment greater than the instability collapse moment. The other hull girder failure modes discussed above are a result of simplified modeling or should be considered in the context of hull girder serviceability failure or lower level, component failure.

Due to the seriousness of hull girder failure, the most realistic predictive tools available to the analyst or designer should be used. These include the incremental strain approaches such as ALPS/ISUM, ULTSTR, and others as discussed in Jensen et al. (1991). Lack of information at an early design stage may necessitate more simplified approaches, but the inaccuracies resulting from these models, particularly those based on yield strength formulations, must enforce greater conservatism on the part of the designer. Simple models more advanced than the yield strength-based models use similar amounts of information as computer codes such as ALSP/ISUM and ULTSTR, tending to reduce their utility to the designer. Failure modes such as the initial yield moment mode or the plastic moment mode are simplifications that may not provide consistent measures of hull girder safety, and are probably not appropriate for use in reliability-based, design and analysis.

6.1.3. Hull Girder Serviceability Failure

As shown in Table 9-1, hull girder serviceability failure modes include excessive of vibration, damage and deformation. Vibratory response due to insufficient stiffness can negatively impact equipment and machinery, as well as human comfort. The limiting value is most easily taken as the natural frequency, to guard against resonance. The onset of damage to stiffened and unstiffened panels in the hull girder is not acceptable for in-service conditions and is a serviceability failure mode. This limit state is defined by the onset of non-linearity in the plot of bending moment to curvature, or the bending moment resulting in the first component failure.

The ability to assess the hull girder bending load at the onset of damage, or first failure, as well as ultimate collapse, is afforded by the use of such computer codes as ALPS/ISUM and ULTSTR. The point of initial failure can be predicted with these codes and compared to the ultimate bending resistance. The degree of separation of these loads is an indicator of the reserve strength and provides a measure of safety. For a description and exploration of the idea of reserve strength see Nikolaidis and Kapania (1990). Of course, the target reliability associated with first failure, must be less than that for ultimate collapse.

The range of possible intermediate failure thresholds between first failure and ultimate collapse due to hull girder bending is discussed and explored in Ayyub and Lai (1992). Ayyub and Lai (1992) provide a methodology for incorporating other intermediate failure modes into reliability-based design and analysis. The failure thresholds are portrayed using fuzzy membership functions, which would be developed using expert solicitation. The focus of the study is the midship cross-section of a cruiser and its response to seaway bending loads. The computer program used to calculate the ultimate strength of the hull girder under primary loading is ULTSTR (Adamchak, 1982). The manner in which ULTSTR assesses the ship ultimate strength is to apply a curvature, ϕ, to the hull girder, and evaluate the resisting moment provided by the cross-section of the hull. This method incorporates algorithms for progressive failure mechanisms at the component level, enabling the program to be used as a predictive tool for developing the cross-sectional structural system response.

For a particular hull girder cross section, the curvature of the hull girder is directly correlated with the structural bending resistance. When compared with the structural bending response due to seaway loads, it is possible to predict the probability that the seaway load exceeds the resisting moment and associated curvature. Figure 6.1-1 shows the relation between the curvature and the probability that the curvature is exceeded by seaway bending response, based on data reported in Ayyub and Lai (1992). For a chosen limiting value of curvature, such as could be prescribed by shafting requirements, a probability of failure can be determined from the plot.

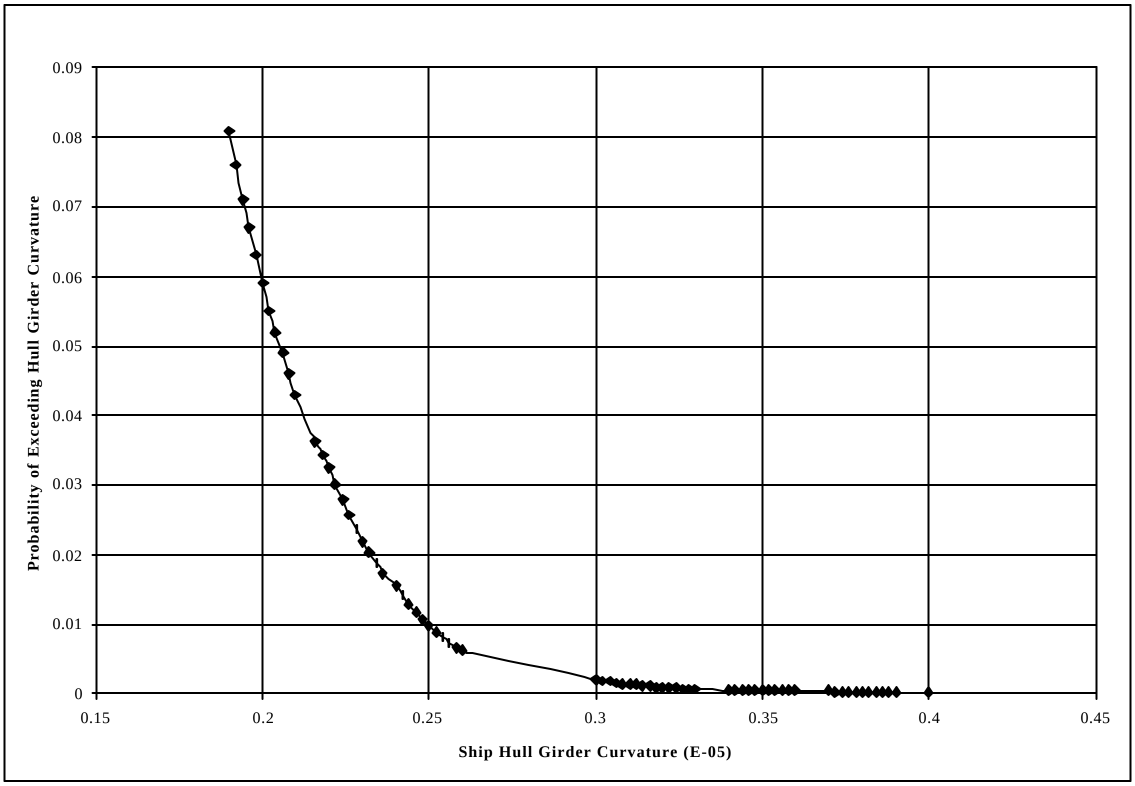


Figure 6.1-1. Probability of Exceeding Ship Hull Girder Curvature vs. Ship Hull Girder Curvature for Reported Damage Spectrum from Ayyub and Lai (1992)

Deformation or curvature of the hull girder resulting from response to bending loads can impact the effectiveness of ship systems dependent upon proper alignment such as the propulsor shaft. This failure mode and other stiffness related failure modes are discussed in SSC-308 (Budd et al. 1981) as described earlier. The limits in cases of stiffness and deformation would be prescribed by the experts involved with those systems. Figure 6.1-1 shows the importance of choosing limiting values of structural response using risk negotiation or uncertain failure definitions as outlined in Ayyub and Lai (1992). If the system relying on the structure (i.e. shafting) can be designed to withstand greater amounts of curvature, the probability of exceedance decreases substantially beyond a curvature of 0.3E-05. Greater and more formal interaction between the structures community and the other ship system communities would provide the basis for better understanding of the performance needs of the ship, as impacted by the structure. The resulting failure thresholds should be provided by these non-structural communities in order to be included in the structural reliability assessment.

6.2. STRUCTURAL COMPONENTS

Stiffened and unstiffened panels, beams and structural details are the components comprising a ship structural system. Much research and testing has gone into the development of models to predict component behavior over the life of the ship in both overload and fatigue. Summaries of failure definitions are listed in the appendix. Failure definitions for grillages are in Table 9-2, stiffened panels in Table 9-3, unstiffened panels in Table 9-4, beams in Table 9-5 and details in Table 9-6. The strength and serviceability of plate panels will be addressed in the following section , followed by consideration of structural details under fatigue and fracture. An example of a vague failure definition for an unstiffened plate under lateral pressure is explored in Section 6.2.3.

6.2.1. Stiffened and Unstiffened Panels

Table 6.2.1-1 presents a listing of failure modes and capability models for stiffened and unstiffened panels as presented in SSC-375 (Hughes, et al., 1994). A more general summary of failure definitions for grillages, stiffened and unstiffened panels are shown in Tables 9-2, 9-3, and 9-4, respectively. The model used to predict the limit value is not specified in these tables. Table 6.2.1-1 relates failure modes and limit values to a set of first principles prediction models providing limit values for the ultimate failure strength and local plate buckling failure modes. These failure thresholds are fairly well defined and represent an effective approach for reliability-based analysis and design. Certainly other strength models exist for these failure modes. The differences in these models are not a result of uncertainty in the failure definition, but of uncertainty in the models relative to actual structural behavior. The prediction models for the remaining serviceability failure modes provide a structural response, or load effect, to be compared with a limiting value of either the yield strength, or the permanent set of the unstiffened plate. The use of yield strength as a failure threshold is a traditional approach for localized material behavior, and is uncertain only with respect to the randomness found in the material given consistent and standardized testing regimes. Questions do remain with regard to whether the testing regime adequately mimics reality such as with strain rate effects. Issues regarding specification of a permanent set failure threshold, and the inherent uncertainties, will be discussed in Section 6.2.3.

Table 6.2.1-1. Failure Modes and Response Models of Principal Structural Members (after Hughes, et al., 1994)

Principal Member	Failure Modes	Failure Category	Prediction Model
PANEL	**Collapse**		
	Stiffener Flexure	Ult.	SSD Sec. 14.2
	Combined Buckling	Ult.	SSD Sec. 13.2-13.4
	Membrane Yield	Ult.	SSD Sec. 12.5
	Stiffener Buckling	Ult.	SSD Sec. 13.1 & 15.5
	Stiffener Serviceability (Initial Yield)		
	Tension, Flange	Serv.	Beam Theory & SSD Sec. 8.6
	Tension, Plate	Serv.	“
	Compression, Flange	Serv.	“
	Compression, Plate	Serv.	“
	Plate Serviceability		
	Yield, Plate Bending	Serv.	SSD Sec. 9.1-9.2
	Local Buckling	Serv.	SSD Sec. 12.6
	Allowable Permanent Set	Serv.	SSD Sec. 9.3-9.5 & (H&C 91)
BEAM	**Collapse**		
	Tripping	Ult.	SSD Sec. 13.1
	Flexural-Torsional Buckling	Ult.	SSD Sec. 15.4-15.5
	Plastic Hinge	Ult.	SSD Sec. 16.1-16.2
	Serviceability (Initial Yield)		
	Bending	Serv.	Beam Theory
	Web Shear	Serv.	“
GRILLAGE	**Collapse**		
	Overall Buckling	Ult.	SSD Sec. 10.2 & 13.5-13.6
	Plastic Hinge	Ult.	SSD Sec. 16.1-16.4

Note: SSD represents *Ship Structural Design*, by Hughes, 1988.

The stiffened panel represents the secondary structural level and is comprised of panels containing unidirectional stiffening members (such as a longitudinally stiffened sub-panel) and multidirectional stiffening members (considered a grillage). Appendix E of SSC-392 (Mansour et al., 1996) provides a discussion of failure modes and associated limit state equations for stiffened panels in the context of reliability design. Reliability-based consideration of all identified failure modes, such as those outlined in Table 6.2-1, depends upon the formulation of a complete set of limit state equations as demonstrated in SSC-392.

Unstiffened panels, or plates, are a fundamental building block of ship structures, but whose load-carrying capability is shared with adjoining structure. This sharing can take the form of a plate-stiffener combination as found in a longitudinally stiffened panel, or a hard corner configuration where multiple plates join as in a double bottom. Therefore, in primary loading, the unstiffened panel performs the role of a strength member until the decreasing stiffness of the plate allows load shedding to the usually stiffer, adjoining structure. In the case of uniaxial or biaxial stress, the plate undergoes elasto-plastic buckling. Numerous strength models have been formulated to allow calculation of the plate buckling strength. For reliability analysis, the plate's strength under in-plane, axial pressure, can be taken as the maximum resisting force, averaged across the loaded edge of the plate. Beyond this stress, the resistance of the plate declines, and the load is shed into adjoining structure.

In the case of lateral pressures, the plate deforms elastically and ultimately plastically in response to the load. The stiffness of the plate determines the amount of deflection due to lateral pressure, as well as the vibration response. Limitations on these responses must be specified for the designer, as they must be determined according to non-structural concerns. SSC-392 provides two limit states for a plate under lateral pressure. The first considers failure the onset of yield at plate center due to lateral loads according to the Von Mises stress criterion. The second considers elastic/plastic deformation beyond some specified limit value as failure. Neither of these failure modes corresponds to an ultimate failure event, and can be considered of a form of serviceability failure. Rupture of a plate is rarely considered explicitly in design, as the analytical formulations cannot predict this event. To arrive at a rational limiting value for the permanent set, subjective analysis of expert opinion should be coupled with quantifiable, objective analysis. An unstiffened plate is usually a component in a stiffened panel, which has a much greater load-carrying role. The consequences of plate deformation should be outlined quantitatively prior to defining failure for unstiffened panels.

The serviceability failure threshold may be mapped onto a two dimensional space which includes structural response versus probability of exceedance. To include risk, a third dimension is needed to address consequence. Staying with the two dimensions, the threshold beyond which failure is assumed to occur may be viewed as a limiting value of the response function or failure likelihood. This approach is discussed for hull girder bending in Section 6.1.2.

6.2.2. Structural Details

Structural details are components whose primary function is in support of the structural system, by maintaining continuity between the larger structural members. The degree to which this performance is degraded is purely from the view of structural functionality. A secondary role is to ensure that the performance of equipment or machinery is not impinged. A summary of failure definitions for structural details is shown in Table 9-6. Should the detail be unable to fulfill its obligation to dependant structural or non-structural systems, then it may be considered to have failed. The criteria by which the assessor would decide failure or non-failure may be either crisp or vague, depending on the function of the detail. Failure modes for details include yield, buckling, deformation and cracking. For ship structure, designing for low, local stresses to reduce fatigue damage usually prevents the types of overload that would lead to yielding, buckling, or permanent deformation. Reducing the likelihood of crack initiation due to cyclic loading is a primary consideration in detail design.

For most purposes, the appearance of deformation (i.e. buckling) or a crack in a structural detail may be considered failure, as the point of maximum strength has most likely been violated prior to the damage exposure. As a detail is designed to provide rigidity and continuity to the parent structure, the presence of a visible crack or deformation will alter its ability to perform as intended. For reliability-based design, the designer must be able to predict the likelihood of the detail cracking or buckling. Detail failure surveys can be found in SSC-220 (Hawkins, et al., 1971), SSC-272 (Jordan and Cochran, 1978), and SSC-294 (Jordan and Knight, 1979), which present damage data from ship surveys.

Traditionally, the design of structural details is often based upon past experience and experimental testing. Due to the multi-dimensional nature of many structural details, analysis is not feasible without resorting to numerical methods, as closed form, analytical solutions are unavailable. The impracticality of applying computationally intense, numerical prediction methods to arrive at the probable structural response makes the use of physics-of-failure reliability methods unlikely at this structural member level. The traditional manner of guarding against cracking due to fatigue is based upon empirical data from cyclic testing to failure. The resulting S-N curves may then be used to estimate the lifetime of the detail under normal operating conditions. Failure modes that result from overloading, including buckling and deformation, may be predicted by conducting experimental tests and analysis of past experience.

Convenience failure definitions may be used to address serviceability limit states such that the initiation of failure is deemed the failure point. Such a case may be found in crack initiation versus crack growth. If models are used to predict the formation of a crack, such as the cumulative damage model, the predictive tools will not lead the designer or analyst to a prediction of the size of the crack. The testing conducted will only predict the onset of damage. It is at this point that the event must be classed as a failure, due to modeling limitations. Planeix et al. (1982) discuss the need for a more clearly specified definition of failure in testing, giving examples of a 50% reduction in load carrying capacity and crack extension greater than 80-90% of a joint circumference. An approach for basing the design on test data is to assume that complete fracture of the specimen reflects crack initiation in the full-scale structure. This allows for scalability problems with fatigue testing but remains an approximation based on engineering knowledge.

6.2.3. Example of Vague Failure Definition

Design of an unstiffened plate to withstand lateral loading requires an accurate structural response model. The dominating limit for unstiffened plating tends to be allowable permanent set. Consideration of elastic flexure of the plate is not included in design formulations concerned with strength, but this may prove important if ship system effects such as vibration are considered. An ultimate failure mode for lateral pressure loading would require rupture of the panel, which cannot be efficiently predicted using analytical means. The following example is provided to demonstrate the considerations associated with assigning a limiting value to the permanent set, and show a means by which vague failure definitions may be addressed.

Consider a plate of 96 inches in length and 24 inches in breadth, for an aspect ratio (a) of 4. This plate may be part of a stiffened panel subject to hydrostatic pressure in the lower shell of a ship. The panel is to be made from ordinary steel (σ_Y=34000psi). The U.S. Navy Design Data Sheets provide an easy algorithm for determining the appropriate plate thickness based on C values according to the following equation:

$$\frac{b}{t} \leq \frac{C}{K\sqrt{H}} \qquad (6.2.3\text{-}1)$$

where b is the short dimension of the plate (stiffener spacing) in inches; t is the plate thickness in inches. H is the design head of sea water in feet, which for demonstration purposes we will take as 30 feet (for a pressure of 13.33 pounds per square inch or psi). K is a shape factor determined by the inverse of the aspect ratio, b/a or $1/\alpha$, which for $b/a \leq 0.5$ is unity. The C factor is found in Table 6.2.3-1 for ordinary steel to be 550. This gives a required plate thickness of 0.239 inches, requiring the use of the next available plate thickness, which is ¼ inch. The U.S. Navy design pressure corresponding to this thickness is 14.59 psi. The plate slenderness ratio, B, is 3.2536 where B is defined by:

$$B = \frac{b}{t}\sqrt{\frac{\sigma_Y}{E}} \qquad (6.2.3\text{-}2)$$

Table 6.2.3-1. C values for Steel Types and Locations of a Ship (U.S.N Manual 1976)

Material Type	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Top Side	Lower Shell/Tank	Flooding/ Damage Control
MS (OS)	60	34	350	550	700
HTS	72	47	400	630	800
HY-80 (HSLA80)	100	80	500	750	900
HY-100	115	100	550	800	1000

The C factors are derived from a rearrangement of simple beam theory using Equation 6.2.3-3, with the stress due to the lateral pressure given by f_a. For topside regions, the stress is limited to the allowable working stress of the material, which, for ordinary steel, is 27 ksi resulting in C = 350, with the intent of preventing any permanent set. For lower shell regions, the C values are calculated by allowing f_a to go to twice the yield strength, resulting in a moderate degree of permanent set. The tank regions allow the formation of membrane stresses, with a f_a approximately twice the ultimate tensile strength according to Equation 6.2.3-3.

$$f_a = \frac{12\,\gamma\,H\,b^2 t}{12 * 144 * 2\,t^3} \qquad (6.3.2\text{-}3)$$

The plastic structural response of an unstiffened plate subjected to a uniform lateral load may be modeled with a variety of approximations, three of which will be discussed below. The example plate will be used to show the response as a function of load for each of the three formulations, along with traditional limiting values for the permanent set.

The American Petroleum Institute’s (API) 1987 Bulletin 2V gives the formulation for finding the lateral pressure associated with a specified permanent set (w_p) shown by Equation 6.3.2-4. Rearrangement provides Equation 6.2.3-5, which shows the permanent set as a function of lateral pressure. These equations provide a linear relationship between pressure and permanent set.

$$p_u = \boldsymbol{s}_Y \left(\frac{t}{b}\right)^2 \frac{6}{\sqrt{\boldsymbol{a}}}\left[1+\frac{2\,w_p}{\boldsymbol{a}\;t}\right] \qquad (6.2.3\text{-}4)$$

$$w_P = \frac{\boldsymbol{a}t}{2}\left[\frac{p}{\boldsymbol{s}_Y}\left(\frac{b}{t}\right)^2\frac{\sqrt{\boldsymbol{a}}}{6}-1\right] \qquad (6.2.3\text{-}5)$$

A second, more complex formulation for finding the lateral pressure associated with a permanent set is presented in Hughes (1988, equation 9.4.1), and is shown in Equation 6.2.3-6.

$$Q = Q_Y + T(R_w)[\Delta Q_0 + \Delta Q_1 R_w] \qquad (6.2.3\text{-}6)$$

$$Q = \frac{PE}{\boldsymbol{s}_Y^2}$$

$$\Delta Q_0 = \frac{2}{\sqrt{1-\boldsymbol{n}+\boldsymbol{n}^2}\;\boldsymbol{b}^2}\left[1+0.6\left(\frac{b}{a}\right)^4\right]$$

$$\Delta Q_0 = \frac{1+0.5\,\boldsymbol{b}\frac{b}{a}\left[1+\frac{b}{a}\left(3.3-\frac{1}{\boldsymbol{b}}\right)\right]}{\sqrt{1-\boldsymbol{n}+\boldsymbol{n}^2}\;\boldsymbol{b}^2}$$

$$\Delta Q_1 = 0.32\left(\frac{b/a}{\sqrt{\boldsymbol{b}}}\right)^{1.5}$$

$$
\begin{aligned}
T(R_w) &= \left[1-(1-R_w)^3\right]^{1/3} && R_w \le 1 \\
&= 1 && R_w > 1
\end{aligned}
$$

$$R_w = w_P \left[\frac{0.07\boldsymbol{b}^2}{3}\right]^{-1}$$

A third formulation is provided from a study done by Bruchman and Dinsenbacher (1991) using non-linear finite element methods to arrive at the empirical relation shown in Equation 6.2.3-7.

$$w_u \; = \; b\left(\frac{pEB^2}{2.222\boldsymbol{s}_Y^2} \; - \; 1\right)^3 \left[0.00356 + 0.0198\tanh\left(\frac{B}{60}\sqrt{\frac{E}{\boldsymbol{s}_Y}}\right)\right] \qquad (6.2.3\text{-}7)$$

The API (1987) limiting value for permanent set is shown by Equation 6.2.3-8, resulting in an allowed permanent set of 0.163 inches for the example plate.

$$w_{p,\max} \; = \; 0.2tB \qquad (6.2.3\text{-}8)$$

Hughes (1988) provides two limiting values of permanent set:

$$w_{p,\max} \; = \; 0.01b \;\; \text{for Cargo Vessels} \qquad (6.2.3\text{-}9)$$

$$w_{p,\max} \; = \; 0.02b \;\; \text{for Naval Vessels} \qquad (6.2.3\text{-}10)$$

For the example plate, the limiting values for the commercial and naval applications are 0.24 and 0.48 respectively.

The plot of the three formulations as permanent set as a function of applied lateral pressure is shown in Figure 6.2.3-1. It can be seen that the three formulations provide different values of permanent set for a given lateral pressure. It is interesting to note that the limiting value of permanent set from Equation 6.2.3-8 (API, 1987) is almost equivalent to the response due to the U.S. Navy's design pressure as predicted by Equation 6.2.3-4 (API, 1987). Similarly, the limiting permanent set found using Equation 6.2.3-9 (Hughes, 1988) corresponds closely to the response predicted using Equation 6.2.3-7 (Bruchman and Dinsenbacher, 1991) under the U.S. Navy design pressure.

The variation of the lateral pressures associated with each failure definition is rather large as shown in Table 6.2.3-2. This variation is due to vagueness of the failure definition. The Navy requirement shown as a limiting lateral pressure for the panel allows for the permanent set predicted by the three algorithms to range from 0.07 to 0.25 as shown in Table 6.2.3-3. The limiting response, or failure threshold, is therefore highly dependent on the model chosen for it's prediction.

Table 6.2.3-2. Pressures Predicted by Three Response Models for Three Failure Definitions of Example Unstiffened Panel under Lateral Loading

Failure Definition (allowable permanent set)	Lateral Pressure from Eq. 6.2.3-4 (API, 1987)	Lateral Pressure from Eq. 6.2.3-6 (Hughes, 1988)	Lateral Pressure from Eq. 6.2.3-7 (Bruchman and Dinsenbacher, 1991)
Eq. 6.2.3-8 (API, 1987)	14.67 psi	15.74 psi	13.73 psi
Eq. 6.2.3-9 (Cargo Vessels, Hughes, 1988)	16.38 psi	16.05 psi	14.51 psi
Eq. 6.2.3-10 (Naval Vessels, Hughes, 1988)	21.69 psi	16.68 psi	16.15 psi

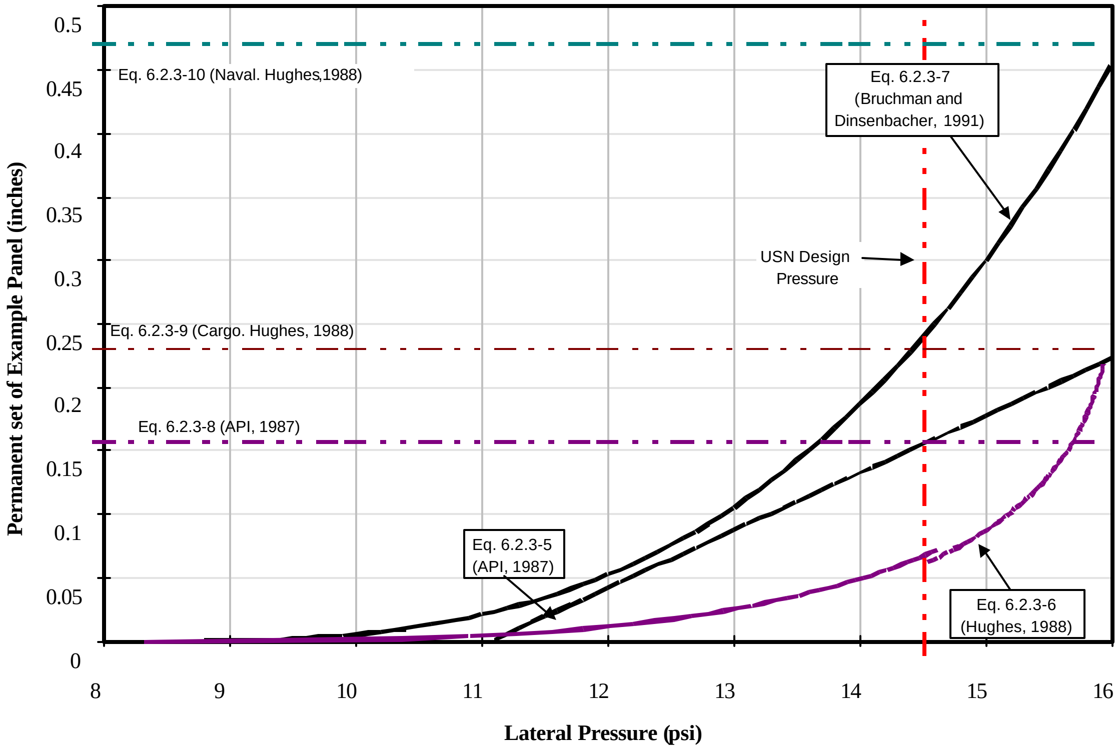


Figure 6.2.3-1. Permanent Set Predictions versus Lateral Pressure for Example Unstiffened Panel

Table 6.2.3-3. Permanent Set Associated with the Design Pressure of 14.59 psi, Predicted by Three Response Models

Response Model	Eq. 6.2.3-4 (API, 1987)	Eq. 6.2.3-6 (Hughes, 1988)	Eq. 6.2.3-7 (Bruchman and Dinsenbacher, 1991)
Permanent Set	0.159 in.	0.071 in.	0.249 in.

The methodology for probabilistic characterization of the failure definition, or threshold, mentioned in Section 5.3.2 will be applied to the reliability analysis of an unstiffened plate under lateral pressure. To demonstrate a limiting value to the permanent set, consider the plate analyzed in the previous section.

Development of a new, probabilistic limit state, which combines the limit states presented in equations 6.2.3-8, 6.2.3-9, and 6.2.3-10, may take place with the use of Bayesian theory. To simplify the example, one may assume the limit states are normally distributed allowing the combination of the three limit states into one, normally distributed random variable.

Equation 6.2.3-11 shows Bayes' Theorem, which is the means for aggregating the limit state distributions.

$$\Pr(A \mid E) = \frac{\Pr(E \mid A)\Pr(A)}{\Pr(E)} \qquad (6.2.3\text{-}11)$$

Pr(*A*) is the prior distribution of random variable *A*; Pr(*A*|*E*) is the posterior distribution of *A* after being updated with the evidence *E*; and Pr(*E*|*A*)/Pr(*E*) is the likelihood of the evidence given the occurrence of *A*. If the prior and the likelihood are normally distributed random variables, the posterior is normal as well. This relationship between the prior and likelihood is called a conjugate pair, and allows easy calculation of the posterior distribution parameters. Other conjugate pairs exist for non-normal distributions. The means to accomplish aggregation of two normally distributed random variables is through the use of Equations 6.2.3-12 and 6.2.3-13.

$$m_P = \frac{s_0^2}{s_0^2 + s_1^2}\, m_0 + \frac{s_1^2}{s_0^2 + s_1^2}\, m_1 \qquad (6.2.3\text{-}12)$$

$$s_P = \frac{1}{\sqrt{\frac{1}{s_0^2} + \frac{1}{s_1^2}}} \qquad (6.2.3\text{-}13)$$

The mean and standard deviation of the random variables being combined are μ_0 and σ_0 for the first (prior) and μ_1 and σ_1 for the second (likelihood). The posterior, or the distribution of the combined random variables, is normal with a mean of μ_P and standard deviation of σ_P. The three distributions may be combined in any order, as Bayes' Theorem is not affected by sequencing effects (additive property). The results of the combining process are shown in Table 6.2.3-4. The chosen uncertainty levels shown in the table are for demonstration purposes.

Table 6.2.3-4. Permanent Set Failure Threshold

Failure Threshold Formulation	Mean (in.)	Standard Deviation (in.)	Coefficient of Variation
Eq. 6.2.3-8 (API, 1987)	0.163	0.0163	10%
Eq. 6.2.3-9 (Cargo Vessels, Hughes, 1988)	0.24	0.024	10%
Eq. 6.2.3-10 (Naval Vessels, Hughes, 1988)	0.48	0.024	5%
Combined	0.2655	0.01174	4.42%

Note: failure thresholds are based on nominal values of the plate scantlings as discussed previously.

The two response models shown in Equations 6.2.3-5 and 6.2.3-7 are used to calculate the probability of exceeding each limit state for the example plate under lateral loading discussed earlier in this Section. Equation 6.2.3-6 was not used due to the complexity involved in predicting the permanent set as a function of pressure. A Monte Carlo simulation with Latin-Hypercube sampling was conducted with 1000 cycles for each response mode and limit state pairing.

The lateral pressure, P, distribution for local seaway on a ship's hull may be modeled using an exponential distribution with the design pressure as its mean. (This approximation is realistic and used in practice according to discussions with Mr. J. Sikora of the Naval Surface Warfare Center Carderock Division.) The mean in this case is the U.S. Navy design pressure of 14.59 psi, which gives an exponential distribution parameter, λ, value of 0.06854 psi^{-1}.

The biases and uncertainties associated with the strength variables in the permanent set formulation have been characterized probabilistically as discussed in Hess et al. (1998). These biases are reported as a ratio between the nominal value and the mean of the material samples, and an uncertainty surrounding the bias characterized by a probability density function (p.d.f.). The simplest probability density function provided in the paper for each basic variable, is chosen for this exercise. The yield strength, σ_Y, is reported as lognormally distributed with a reported ratio bias of 1.1746 and a standard deviation of 0.1214. For mild steel, the mean yield strength is 39940 psi and has a standard deviation of 4128 psi. The Young's Modulus, E, is reported as being normally distributed and having a mean bias of 0.9868 and a standard deviation of 0.07520. For the mild steel used in this example, the Young's Modulus has a mean of $29.2*10^6$ psi and a standard deviation of $2.22*10^6$ psi. The panel width, b, is reported as normally distributed with a mean bias of 0.9921 and a standard deviation of 0.02816. The panel width in this example has a resulting mean of 23.81 inches and a standard deviation of 0.6758 inches. The plate thickness, t, is reported as lognormally distributed with a mean bias of 1.013 and a standard deviation of 0.04337. The plate thickness used in this example has a resulting mean of 0.2533 inches and standard deviation of 0.01084 inches.

The reliability analysis of the response predictions versus the four failure thresholds provides exceedance probabilities ranging from 15.9 to 30.2 percent, as shown in Table 6.2.3-5. The average of the exceedance probabilities for Equation 6.2.3-5 is 22.83 percent, while for Equation 6.2.3-6 the average is 27.6 percent. These are very close to the probabilities shown for the combined limit state case, and are likely the result of assuming the limit states are normally distributed. The choice of non-normal distributions will likely cause the probability of exceeding the combined limit state to differ from being just the average of the probabilities of exceedance calculated for the independent limit states.

The higher amount of permanent set for a given pressure load given by Equation 6.2.3-7 results in higher exceedance probabilities for all limit states as compared to the probability predictions using Equation 6.2.3-5. The correlation between the failure threshold selection and the choice of response model has a significant influence on the results of a reliability analysis.

The analytical representation of the response model is very important as well. The example response model in Equation 6.2.3-5 predicts a linear relation between the load and the permanent set. This is not indicative of the plastic, non-linear behavior associated with the material. The use of stochastic finite element methods for a numerical response model would be appropriate for detailed studies and calibration, but not useable for design purposes.

Table 6.2.3-5. Probabilities of Exceeding the Maximum Permanent Set According to Different Failure Thresholds and Response Models

Failure Thresholds	Response Models	
	Eq. 6.2.3-5 (API, 1987)	Eq. 6.2.3-7 (Bruchman and Dinsenbacher, 1991)
Eq. 6.2.3-8 (API, 1987)	28.1 %	30.2 %
Eq. 6.2.3-9 (Cargo Vessels, Hughes, 1988)	24.5 %	27.9 %
Eq. 6.2.3-10 (Naval Vessels, Hughes, 1988)	15.9 %	24.7 %
Combined	23.1 %	27.8 %

More accurate probabilistic limit state definitions can be formulated through aggregation of historical failure data, traditional limit states and expert opinion. A probabilistic characterization of historic deformation failures may be blended with the traditional design goals (limiting permanent set) in order to improve future designs. The use of expert opinion is implicit in using historical data as the degree of deformation considered as failure, tends to be subjective in practice. The importance of "flat" surfaces in naval applications may be a future source of rational, quantitative allowable permanent set prescriptions that would benefit from probabilistic characterization.

7. CONCLUSION

Current design criteria use deterministic safety factors in design equations to guard against the possibility of structural damage and ship system degradation and failure. Unfortunately these methods provide an undetermined level of safety and performance that experience has shown is not always adequate. Traditionally, the designers apply their judgment to decide what structural behavior constitutes failure. This approach contains an implicit treatment of the consequence of the event, with the designers deciding acceptable and unacceptable behavior of the system in question such that they feel the design will be adequate. The threshold of design acceptability is molded into a limit state equation for use in decision making. The limit state equation provides a threshold formulation where the system/component capability (strength) must be greater than the demand (load) by some margin such that an acceptable structure results. Risk and reliability based design approaches allow explicit, formal treatment of these safety margins that are traditionally matters of judgment. This formality is important in order to counter cost and other ship system demands that tend toward reduced structural safety levels.

Arriving at an appropriate limiting value for a structural response requires the designer to decide what behavior constitutes a failure event. Failure may or may not result from an easily identifiable change in state of the structure or response model. The failure definition depends on the state variable chosen to describe the failure, the structural capability and response models, and the cost or consequence corresponding to the structural behavior. Each of these factors has an inherent uncertainty, which must be assessed prior to predicting the reliability of the structure. The correlation between the limit state, state variable, and response model has a significant influence on the results of a reliability analysis. There are many modes by which the hull of a ship can experience damage. Designers attempting to preclude these failure modes are highly dependent upon a physical prediction method for characterization of the response leading to failure. Due to the complexity of the ship structural system, the currently available physical prediction models are based on a component view, where the components are the hull girder, stiffened and unstiffened panels, and details. In both deterministic and classical reliability-based design and analysis, the structural responses for each component must have an associated limiting value, which defines the transition from survival to failure.

The degree to which ship system performance deteriorates as a result of some structural response or load effect could range from insignificant to catastrophic. Such deterioration could impact the ship safety and survivability, and the ship's ability to continue its mission. The qualitative or quantitative effect of this deterioration can be considered the cost or consequence of the structural response. When the cost or consequence exceeds some acceptable level, the structure has failed.

Risk resulting from a particular hazard scenario, is the combination of the likelihood of failure due to the hazard (for example, seaway loads), and the consequences of failure. This is commonly expressed as a mathematical product of the failure likelihood and consequences, as done in hazardous industry's use of Probabilistic Risk Assessment (PRA). Acceptability of a certain level of risk or performance requires the mapping of the decision maker's judgment and values into an expression, which is comparable to a quantitative or qualitative performance measure of the system or process in question. The decision-maker represents the community, which may be impacted by the decision. The measure may be either qualitative (subjective) or quantitative (objective).

This study begins with a review and description of structural reliability methodologies as they have been applied to ship structure. Uncertainty types are then explored for information and tools used in a reliability prediction. Types of failure modes are described as reported in literature. These types are then expanded upon to establish classes of failure modes, leading to a methodology for formulating the range of failure definitions. A structural failure event is a change in state such that the structure no longer provides a required capability (load-carrying or otherwise) or impacts some specified system performance to an unacceptable degree.

Failure definition examples are provided in the Appendix for the hull girder and structural components at both the ultimate and serviceability types of failure. Summary tables of failure definitions are listed in the Appendix. Hull girder failure definitions are shown in Table 9-1. Two strength failure modes are listed: yield and collapse. Three serviceability failure modes are shown for hull girder, grillage, stiffened panel, unstiffened panel and beam as exceedance of design limits placed on vibration, elastic curvature/deformation and plastic curvature/deformation. Grillage failure modes are listed in Appendix Table 9-2. Grillage strength failure definitions are plastic hinge formation and overall buckling. Stiffened panel failure definitions are listed in Table 9-3. Stiffened panel strength failure definitions tensile and compressive yield, compressive collapse, stiffener tripping and fracture. Unstiffened panel failure definitions are listed in Table 9-4, with strength failure modes: bending and membrane yield, local plate buckling and fracture. Beam failure is shown in Table 9-5 with strength failure modes of compressive or tensile yield, and compressive collapse. Detail failure modes are shown in Table 9-6. Detail strength failure is a result of material yield, buckling collapse or fracture. Serviceability failure of details can occur due to crack initiation, and elastic or plastic deformation.

Changes to the traditional serviceability failure definitions are not possible without addressing the costs associated with the failures, either subjectively or objectively. The basis for the consideration of changes to traditional serviceability failure thresholds and implementation of new serviceability failure modes/criteria is discussed herein. The approach is predicated on treatment of failure from the point of view of the designer, analyst, or decision-maker, where predictive tools are required, but can be extended to operational applications.

An example is presented of structural serviceability failure of an unstiffened plate experiencing permanent deformation due to lateral pressure. Excessive permanent set may misalign some mechanical system rendering it inoperable; reduce the strength of a larger structural system beyond acceptable levels and endanger more critical systems; or be cosmetically unappealing. The consequence of the permanent deformation may also be an increase in the likelihood of greater system failures. The point at which the deformation level becomes unacceptable for the designer or surveyor is the onset of failure for the plate. The failure definition for the permanent set of unstiffened plating depends on the acceptability of the consequences of the permanent set. When the consequences are no longer acceptable, the plate has failed. Different response prediction models and failure thresholds are presented and compared to show their importance in a reliability-based design process.

Assigning failure definitions to all possible failure modes in design must be considered for each structure in question. Generalized failure definitions are limited to ultimate failure modes, where the collapse strength of a member is concerned. These types of failure are addressed to a large extent in current criteria and predictive formulations. Serviceability failure must be described based upon the associated consequences of the behavior using risk negotiation, expert testimony, or traditional failure thresholds.

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9. APPENDIX – FAILURE DEFINITION SUMMARY TABLES

Table 9-1. Hull Girder Failure Definitions

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Yield	Ultimate	Stress	Yield Strength	Material Failure
Collapse	Ultimate	Bending Moment	Maximum Bending Resistance	Hull Girder Collapse and Rupture
Onset of Damage	Serviceability	Curvature	Onset of Nonlinearity in Bending Moment to Curvature Plot	Corresponds to onset of permanent structural damage
Vibration	Serviceability	Frequency	Natural Frequency	Human Comfort, Equipment/Machinery
Elastic Curvature	Serviceability	Curvature	Elastic Curvature Corresponding to Operational Shafting Tolerance	Impact on non-structural items such as joiner bulkheads, piping, propulsion shafting, hatch covers, etc.
Plastic Curvature	Serviceability	Curvature	Plastic Curvature Corresponding to Emergency Shafting Tolerance	Impact on non-structural items such as joiner bulkheads, piping, propulsion shafting, hatch covers, etc.

Table 9-2. Grillage Failure Definitions

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Plastic Hinge Formation	Ultimate	Stress	Plastic Hinge Formation Stress	Reduction of Strength
Overall Buckling	Ultimate	Stress	Buckling Strength	Instability and reduction in load carrying ability
Vibration	Serviceability	Frequency	Natural Frequency	Human Comfort, Equipment/machinery performance
Elastic Deformation	Serviceability	Displacement	Max Allowed Elastic Displacement	Equipment/machinery performance
Plastic Deformation	Serviceability	Displacement	Max Allowed Plastic Displacement	Equipment/machinery performance, Strength Reduction, Stealth

Table 9-3. Stiffened Panel Failure Definitions

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Tensile Yield of Flange	Ultimate	Stress	Yield Strength	Material Failure
Tensile Yield in Plate	Ultimate	Stress	Yield Strength	Material Failure
Compressive Yield of Flange	Ultimate	Stress	Yield Strength	Material Failure
Compressive Yield of Plate	Ultimate	Stress	Yield Strength	Material Failure
Compressive Collapse	Ultimate	Stress	Strength (Plate-induced, stiffener-induced, or combined)	Instability and reduction in load carrying ability
Stiffener Tripping	Ultimate	Stress	Strength	Instability and reduction in load carrying ability
Fracture, Crack Propagation	Ultimate	Crack Length	Critical Crack Length	Prevention of Fracture
Vibration	Serviceability	Frequency	Natural Frequency	Human Comfort, Equipment/machinery performance
Elastic Deformation	Serviceability	Displacement	Max Allowed Elastic Displacement	Equipment/machinery performance
Plastic Deformation	Serviceability	Displacement	Max Allowed Plastic Displacement	Equipment/machinery performance, Strength Reduction, Stealth

Table 9-4. Unstiffened Panel Failure Definitions

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Plate Bending Yield	Ultimate	Stress	Yield Strength	Material Failure
Membrane Yield	Ultimate	Stress	Yield Strength	Material Failure
Local Plate Buckling	Ultimate	Stress	Buckling Strength	Strength Reduction
Fracture, Crack Propagation	Ultimate	Crack Length	Critical Crack Length	Prevention of Fracture
Vibration	Serviceability	Frequency	Natural Frequency	Human Comfort, Equipment/machinery performance
Elastic Deformation	Serviceability	Displacement	Max Allowed Elastic Displacement	Equipment/machinery performance
Plastic Deformation	Serviceability	Displacement	Max Allowed Permanent Set	Equipment/machinery performance, Strength Reduction, Stealth

Table 9-5. Beam Failure Definitions

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Compressive Yield	Ultimate	Stress	Yield Strength	Material failure
Tensile Yield	Ultimate	Stress	Yield Strength	Material failure
Collapse	Ultimate	Stress	Strength	Instability and reduction in load carrying ability
Fracture, Crack Propagation	Ultimate	Crack Length	Critical Crack Length	Prevention of Fracture
Vibration	Serviceability	Frequency	Natural Frequency	Human Comfort, Equipment/machinery performance
Elastic Deformation	Serviceability	Displacement	Max Allowed Elastic Displacement	Equipment/machinery performance
Plastic Deformation	Serviceability	Displacement	Max Allowed Plastic Displacement	Equipment/machinery performance, Strength Reduction

Table 9-6. Detail Failure Definitions

Failure Mode	Failure Type	State Variable	Limit Value	Reasons
Material Yield	Ultimate	Stress	Yield Strength	Reduction in Strength
Buckling Collapse	Ultimate	Stress	Buckling Strength	Reduction in Strength
Crack Initiation	Serviceability	Fatigue Damage	Cumulative Damage Limit	Prevention of Fracture
Fracture, Crack Propagation	Ultimate	Crack Length	Critical Crack Length	Prevention of Fracture
Elastic Deformation	Serviceability	Displacement	Max Allowed Elastic Displacement	Equipment/machinery performance
Plastic Deformation	Serviceability	Displacement	Max Allowed Plastic Displacement	Equipment/machinery performance, Strength Reduction


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