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Consideration of Human and Organization Factors in Development of Design, Construction, and Maintenance Guidelines for Ship Structures

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Abstract

This paper summarizes results from two SSC projects that have addressed human and organization factors associated with design, construction, and maintenance of ship structures (SSC 365, SSC 378). Results from these studies indicate that such consideration is particularly important as the requirements for improved quality in ship structures are changed. The use of complex and sophisticated computer based analytical processes, application of advanced load and resistance factor based design methods, increased pressures to minimize initial and maintenance costs while increasing the reliability of the ship structures, the use of innovative structure, material, and construction systems, and an industry that is undergoing rapid organizational and financial changes all combine to make this a high priority concern for the profession. This paper summarizes how human and organization factors in design, construction, and maintenance of ship structures might be formulated and addressed. Key aspects of this formulation and approach includes a focus on the life-cycle quality characteristics of the ship structure system, the team performance and organization aspects of developing and maintaining adequate quality, providing effective quality assurance and control measures in development of design guidelines, and developing life-cycle ship structure quality information databases and communication systems. A critical challenge in implementing the approach is to improve the overall efficiency of the system so that initial costs are not increased and long-term costs are decreased. Ways in which this challenge might be addressed are suggested.

1. Introduction

Present experience in the design, construction, operation and maintenance of ship structures clearly indicates that the primary threats to the quality of ship structures are associated with human and organization errors (HOE). The Ship Structure Committee (SSC) project titled "The Role of Human Error in Design, Construction, and Reliability of Marine Structures," addressed four key questions:

#1 *What is Human and Organization Error (HOE)?*

#2 *Can HOE be defined and classified?*

#3 *Can HOE be quantified and analyzed?*

#4 *Should HOE be reflected in design codes and criteria?*

This paper summarizes the answers that were developed to each of these questions. The approach will be illustrated with application to the fatigue durability design and construction of an example fleet of oil tankers.

2. What is HOE ?

Any activity that involves people is subject to flaws and defects. These flaws and defects (malfunctions) are generally identified as errors.

HOE that occur during the life-cycle of a ship structure can be related first to the individuals that design, construct, operate and maintain these structures. These are the *system operators*.

The actions and inactions of these operators are influenced to a very significant degree by five components (Fig. 1):

a) *the organizations that they work for and with,*

b) *the procedures (formal, informal, software) that they use to perform their activities,*

c) *the structures and equipment (hardware) that are involved in these activities, and*

d) *the environments (external, internal, social) in which the operator activities are performed.*

There are error producing potentials in each of the components and at their interfaces.

Human error can be characterized as a departure from acceptable or desirable practice on the part of an individual that can result in unacceptable or undesirable results. Human error refers to a basic event involving a lack of action or an inappropriate action taken by individuals that can lead to unanticipated and undesirable quality.

Analysis of the history of failures of ship structures provides many examples in which organizational malfunctions have been primarily responsible for failures. Organization error is defined as a departure from acceptable or desirable practice on the part of a group of individuals that results in unacceptable or undesirable results.

3. Can HOE be Defined and Classified ?

Yes, human errors can be defined and classified in a variety of ways (e.g. action class, mode, mechanism, effect). The classification and definition needs to be appropriate for a particular descriptive or analytical purpose. There is no single "best" system to classify HOE.

3.1 Operator Malfunctions

In one scheme, human errors or *operator malfunctions* can be organized into two categories: 1) those that develop from states, and 2) those that develop from actions [1]. States are those influences that induce individuals, teams, and organizations to make errors. Incentives, environment, and information are some of the primary factors that influence state determined errors. Lapses or slips, mistakes, and unsafe acts are the primary factors that influence actions determined errors.

A slip or error of omission is a human error in which what is performed was not intended. A mistake is a human error where the intention was erroneous and was purposefully executed. Unsafe acts are unreasonable or unlawful actions (violations). States can lead to human error in actions, and actions can lead to undesirable states.

Mistakes can develop where the action was intended, but the intention was wrong. Circumventions (violations, intentional short-cuts) are developed where a person decides to break some rule for what seems to be a good (or benign) reason to simplify or avoid a task. Mistakes are perhaps the most significant because the perpetrator has limited clues that there is a problem. Often, it takes an outsider to the situation to identify mistakes.

Based on studies of information from databases on marine systems in which their acceptable quality has been compromised, the primary factors that lead to operator malfunctions are summarized in Table 1 [2]. The sources of mistakes or cognitive malfunctions are further detailed in Table 2.

Table 1 Classification of Operator Malfunctions

Communications - ineffective transmission of information
Slips - accidental lapses
Violations - intentional infringements or transgressions
Ignorance - unaware, unlearned
Planning & Preparation - lack of sufficient program, procedures, readiness
Selection & Training - not suited, educated, or practiced for the activities
Limitations & Impairment - excessively fatigued, stressed, and having diminished senses
Mistakes - cognitive malfunctions of perception, interpretation, decision, discrimination, diagnosis, and action

Table 2 Classification of Mistakes

Perception - unaware, not knowing
Interpretation - improper evaluation and assessment of meaning
Decision - incorrect choice between alternatives
Discrimination - not perceiving the distinguishing features
Diagnosis-incorrect attribution of causes and or effects
Action- improper or incorrect carrying out activities

3.2 Organization Malfunctions

The goals promulgated by an organization may induce operators to conduct their work in a manner that management would not approve if they were aware of their reliability implications. Excessive risk-taking problems are very common in marine systems. Frequently, the organization develops high rewards for maintaining and increasing production; meanwhile the organization hopes for safety (*rewarding "A" while hoping for "B"*). The formal and informal rewards and incentives provided by an organization have a major influence on the performance of operators and on the reliability of offshore ships. A classification system for organization malfunctions is given in Table 3.

One of the most pervasive problems that has resulted in failures of ship structures regards organizational communications. In many cases, due to incentives provided by the organization, there are tendencies to filter information, making the bad seem better than it was. Information is power. Frequently, within the organization and amongst the interfacing organizations information is manipulated to achieve and maintain power. In development of programs to improve management of HOE, careful consideration should be given to information integrity (collection, communications, and learning), particularly as they affect the balancing of several objectives such as costs and reliability.

Table 3 Classification of Organization Malfunctions

Communications - ineffective transmission of information
Culture - inappropriate goals, incentives, values, and trust
Violations - intentional infringements or transgressions
Ignorance - unaware, unlearned
Planning & Preparation - lack of sufficient program, procedures, readiness
Structure & Organization - ineffective connectedness, interdependence, lateral and vertical integration
Monitoring & Controlling - inappropriate awareness of critical developments and utilization of ineffective corrective measures
Mistakes - cognitive malfunctions of perception, interpretation, decision, discrimination, diagnosis, and action

Several examples of organizational malfunctions recently have developed as a result of down-sizing and out-sourcing as a part of re-engineering organizations. Loss of corporate memories (leading to repetition of errors), creation of more difficult and intricate communications and organization interfaces, degradation in morale, unwarranted reliance on the expertise of outside contractors, cut-backs in quality assurance and control, and provision of conflicting incentives (e.g. cut costs, yet maintain quality) are examples of activities that have lead to substantial compromises in the intended quality of systems [3,4].

Experience indicates that one of the major factors in organizational malfunctions is the culture of the organization. Organizational culture is reflected in how action, change, and innovation are viewed; the degree of external focus as contrasted with internal focus; incentives provided for risk taking; the degree of lateral and vertical integration of the organization; the effectiveness and honesty of communications; autonomy, responsibility, authority and decision making; rewards and incentives; and the orientation toward the quality of performance contrasted with the quantity of production. The culture of an organization is a product of its history and environment. It is for these reasons that the culture of an organization is so difficult to change.

3.3 System Malfunctions

Human errors can be initiated by or exacerbated by poorly engineered systems and procedures that invite errors (Fig. 1). Such systems are difficult to construct, operate, and maintain. Such systems are “error inducing.” Table 4 summarizes a classification system for hardware (equipment, structure) related malfunctions.

New technologies compounds the problems of latent system flaws [5,6]. Complex design, close coupling (failure of one component leads to failure of other components) and severe performance demands on systems increase the difficulty in controlling the impact of human errors even in well operated systems.

Table 4 Classification of Hardware Malfunctions

Serviceability - inability to satisfy purposes for intended conditions
Safety - excessive threat of harm to life and the environment, demands exceed capacities
Durability - occurrence of unexpected maintenance and less than expected useful life
Compatibility - unacceptable and undesirable economic, schedule, and aesthetic characteristics

The issues of system robustness (defect or damage tolerance), design for constructablity, and design for IMR (Inspection, Maintenance, Repair) are critical aspects of engineering ship structures that will be able to deliver acceptable quality [7]. Design of the structure system to assure robustness is intended to combine the beneficial aspects of redundancy, ductility, and excess capacity (it takes all three). The result is a defect and damage tolerant system that is able to maintain its serviceability characteristics in the face of HOE. This has important ramifications with regard to structural design criteria and guidelines.

3.4 Procedure & Software Malfunctions

Table 5 summarizes a classification system for procedure and software malfunctions. These malfunctions can be embedded in engineering design guidelines and computer programs, construction specifications, and operations manuals [2]. They can be embedded in how people are taught to do things. With the advent of computers and their integration into many aspects of the design, construction, and operation of marine structures, software errors are of particular concern because "*the computer is the ultimate fool*" [8].

Software errors in which incorrect and inaccurate algorithms were coded into computer programs have been at the root cause of several major failures of marine structures [2]. Guidelines have been developed to address the quality of computer software for the performance of finite element analyses. Extensive software testing is required to assure that the software performs as it should and that the documentation is sufficient.

Table 5 Classification of Software & Procedure Malfunctions

Incorrect - faulty
Inaccurate - untrue
Incomplete - lacking the necessary parts
Excessive Complexity - unnecessary intricacy
Poor Organization - dysfunctional structure
Poor Documentation - ineffective information transmission

Of particular importance is the provision of independent checking procedures that can be used to validate the results from analyses. High quality procedures need to be verifiable based on first principles, results from testing, and field experience.

Given the rapid pace at which significant industrial and technical developments have been taking place, there has been a tendency to make design guidelines, construction specifications, and operating manuals more and more complex. In many cases, poor organization and documentation of software and procedures has exacerbated the tendencies for humans to make errors. Simplicity, clarity, completeness, accuracy, and good organization are desirable attributes in procedures developed for the design, construction, and operation of ship structures.

3.5 Environmental influences

Environmental influences can have important effects on the performance characteristics of individuals, organizations, hardware, and software (Fig. 1). Environmental influences include:

a) external (e.g. wind, temperature, rain, fog),

b) internal (lighting, ventilation, noise, motions), and

c) sociological factors (e.g. values, beliefs, mores).

4. Can HOE be quantified and analyzed?

Yes, if and as desirable, HOE can be quantified and analyzed. There are two complementary approaches to the quantification of HOE in the life-cycle of ship structures. The first approach is based on the use of objective data that has been gathered on the incidence of HOE [9, 10, 11].

The six years of research on which this paper is based has not been able to identify any well organized, definitive, long-term effort in which a substantial body of objective data has been developed on HOE in the life cycle of ship structures [12, 13]. Objective data can be developed by the direct gathering of data on the job of interest, information from similar jobs, real-time simulations or experiments with the actual tasks. Limited information is available for some types of activities (Fig. 2) [9, 10].

The second approach is based on the use of expert judgment [2, 14]. Subjective data can be derived from extrapolations of objective data and the scaling of expert judgment [11]. The quantitative information that is available is extremely valuable in that it provides a place to start the processes of quantification. *However, primary reliance in making quantification of HOE in the life-cycle of ship structures must be placed on the use of qualified expert judgment.*

The approaches that can be used to help develop engineering evaluations of HOE in the life-cycle of ship structures can be organized into three general categories:

1) *qualitative,*

2) *quantitative, and*

3) *combined qualitative - quantitative.*

4.1 Qualitative

The first approach can be identified as *subjective* or *qualitative*. This approach uses *soft* linguistic variables to describe systems and procedures and HOE. Integration of the evaluations generally is subjective. This approach may or may not involve detailed structuring of systems and the related HOE events, decisions, and actions that may influence the quality of these systems. The qualitative approaches generally focus on general categories of operations performance. General good practice guidelines are given. General rather than detailed studies of the systems are developed. The focus is on performance rather than processes.

Qualitative approaches have been developed for the evaluation of HOE in the life-cycle of ship structures. Specific systems can be evaluated based on scales and attributes developed to reflect the potentials for good or bad operating performance. Hazop (Hazard and operability) procedures have been employed in evaluating a wide variety of marine systems. Qualitative approaches have also been identified as Failure Mode and Effect Analysis (FMEA) [15]. This approach focuses on both functional analysis and the evaluation of potential consequences. The objective of these analyses is to identify the combination of events that could lead to compromises in the desired safety of a ship.

The method is structured only in how it is performed. It focuses on a logical analysis of the system and its functions. FMEA attempts to assess the criticality of a component or function of a system on the basis of the minimum number of failures in the failure modes involving the component or function. If a failure mode (sequence of events leading to low quality) consists of one component or function failure, this component or function is indicated to be criticality #1, and so forth. In this manner, the most critical components and functions in a system are identified. These components and functions then become the primary options for quality assurance and control measures.

4.2 Quantitative

The second approach can be termed *objective* or *quantitative*. This approach is generally utilized for higher consequence systems and processes in which undesirable levels of quality have potentially severe ramifications [10, 11, 15]. This approach generally examines in much greater detail the systems and the events, decisions, and actions that influence the quality of these systems.

This approach utilizes numerical models to provide quantitative indications of the effects of changes in quality management systems and procedures. This approach generally focuses on the critical aspects of systems that have been evaluated using more general qualitative methods. This approach uses *hard* numerical variables to describe systems and procedures. The analytical models provide for a structured integration of the effects and variables.

The second approach is oriented to detailing how the operating system works or might not work and quantifying the likelihood associated with performance. This approach is generally very structured in that probabilistic Event Tree, Fault Tree, and Influence Diagram type analyses are used [11, 15]. Such analyses are frequently identified as Probabilistic Risk Analyses (PRA), Quantified Risk Analyses (QRA), or Formal Safety Analyses (FSA) [16]. These procedures and processes have been highly developed, particularly by the nuclear power and chemical processing industries.

4.3 Combined

The third approach is a mixed qualitative and quantitative process. It is identified here as a Safety Indexing Method (SIM). Linguistic variables are translated to numerical variables. A mathematical process is provided to perform analytical integration of the effects and variables. Groeneweg, et al. utilized this approach in development of the Tripod Delta evaluation process [17]. This process has been used very successfully in identifying critical elements on ships that need to be addressed to improve safety. This method was used in development of HESIM (*Human Error Safety Index Method*) to assist in the quantitative evaluations of HOE in operations of ships [12]. This method also was used in development of the assessment instrument FLAIM (Fire and Life safety Assessment Indexing Method) to evaluate the influences of HOE on fire and explosions in marine systems [18].

This method has been applied in evaluations of tanker loading and discharge operations [18]. This method is currently being tested in the field in assessments of potentials for fires and explosions on offshore platforms [20]. This development is addressing the human and organization aspects of the ISM (International Safety Management) code [21] and the SEMP (Safety and Environmental Management Programs) guidelines [22].

4.4 Strengths and Weaknesses

Each of the three approaches possess strengths and weaknesses. The qualitative approach does not attempt to capture details of the systems and processes. Rather it focuses on a general evaluation of the systems and processes and attempts to identify the critical elements in these systems and how they might be improved. Given the extremely complex and frequently irrational nature of the systems and processes that are involved in the life-cycle of ship structures, the qualitative approach offers some significant advantages. *As for any of the approaches, the quality of the approach depends directly on the experience, skill, and motivations of the assessors.*

The quantitative approach is frequently viewed as one that is able to capture the details of systems and processes, and to a certain extent this is true. For well defined and "behaved" systems and processes, the quantitative approach offers some significant advantages and attractions. However, for ill-defined systems, and particularly those that involve significant and complex HOE interactions, then one might question the reality of the results produced by the quantitative approach.

Viewed in the context of their life-cycle, HOE influences on the quality of ship structures are extremely complex. Many of the HOE interactions during the life-cycle fundamentally are not predictable. Based on recent experience in attempting to apply this approach in the field [19], it is contended that quantitative approaches generally are not able to sufficiently capture the complexities and HOE interactions. Yet, the approach appears to capture the complexities and interactions. Added to the poor quality of information and data that is available to provide objective information on HOE, one is left with a feeling that application of quantitative approaches produces results that have severe limitations.

In addition, multiple PRA / QRA / FSA performed on the same system or even a given accident often do not produce reasonably consistent results [17, 12]. Many of these evaluations tend to treat human performance characteristics in the same manner as the characteristics of the ship structure and its equipment. As ship systems become more complex, then the analyses must become more complex. This spiral results in computational and analytical nightmares that almost defy comprehension and validation. Yet, we have the numbers and because we have invested so much in developing these numbers we are tempted to believe them.

The third approach offers some significant advantages in performing evaluations of HOE in the life-cycle of ship structures. At this time, it is not as well developed as the first two approaches. The approach does not require that the full complexity of the system and process are reduced to analytical models. However, the approach does require an identification of the priorities or hierarchy of the concerns and elements involved in the system and processes, and an evaluation of their relative safety. Various numerical methods can be used to combine the priorities (weightings) and gradings. The approach can be developed so that it encourages interactions with those that have direct responsibilities for the systems and processes.

Proper use of any of these approaches requires experience, expertise, and sufficient direct exposure to the ship structure "system" and its processes so that reasonable evaluations can be developed to help provide insights into the strengths and weaknesses of a given ship structure. The most critical elements in any of the approaches are the motivations and qualifications of the evaluator or assessor. All three approaches have their respective roles and should be used in appropriate combinations to help improve the safety of ship structures.

It is contended that the fundamental objective of the applications of these approaches should be to develop improvements in the quality of ship structures during their life-cycle and not to produce elegant analytical constructs. *The most essential ingredient in such improvements is the integration of the experience, insights, and judgment of those that have direct and daily responsibilities for ship structures*. Selection of an approach must take into account the skills and knowledge of these people. Any safety assessment process that does not account for implementation in and by the field rarely is beneficial to safety. *Whatever method is used should facilitate interactions with the people in the field, and should result in the empowerment of those in the field.*

The fundamental purpose of engineering evaluations of HOE can not be prediction. The fundamental purpose of these evaluations should be to provide a disciplined framework with which one can describe and evaluate the potential effects of HOE in the life-cycle of ship structures. The objective of these analyses is to make assessments of the potential benefits and costs associated with alternative measures that can improve the quality of ship structures. The objective of these analyses is to provide insights into how best to improve the quality of ship structures and to optimize the use of the resources that can be made available to improve quality.

5. Should HOE Be Reflected in Design Codes and Criteria ?

Yes, HOE should be reflected in ship structure design codes and criteria in two primary ways. First, in the form of explicit and defined Quality Assurance and Quality Control (QA/QC) measures (Fig. 3).

Second, in the form of explicit and defined measures to make the ship structure less likely to promote errors during its design, construction, operation, and maintenance, and to make the ship structure more tolerant of the human errors and accidents that can occur during the life of the ship.

There are three fundamental HOE risk management approaches:

1) *reduce the incidence and severity of HOE,*

2) *reduce the effects of HOE, and*

3) *increase the detection and remediation of HOE.*

Experience indicates that a good HOE management program will employ all three approaches in a balanced way.

5.1 Incidence and Severity Reduction

The first approach is very difficult. It requires fundamental changes in how operators are selected, trained, audited, and evaluated. Incidence and severity reduction directly addresses the qualifications and training of those that design, construct, operate, and maintain ship structures, the formation of quality oriented teams, the elimination of unnecessary complexity in guidelines, codes, and procedures, and the verification and validation of guidelines, procedures, and software [2].

Current experience with major compromises in the quality of ship structures indicates that in many cases, the particular set of circumstances and breakdowns that resulted in the accident could not have been predicted. While not lessening the importance of and necessity for proactive management to assure adequate quality, this recognition highlights the necessity for "real time" HOE incidence and severity management strategies.

It has been estimated that there are approximately 100 "alerts" and 10 "near-misses" for every accident. This indicates that system operators are generally responsible for keeping systems "out of harms way." Improvements in early warning systems, provision of support and safety systems, and development of emergency management teams and strategies are fruitful ways to reduce the incidence and severity of accidents [23, 24].

5.2 Effects Reduction

The second approach has proven to be very effective. This approach can be characterized as engineering or technical fixes that addresses designing, constructing, operating, and maintaining *systems that have inherent stability and robustness* [7, 25, 26]. *Stability* means that as the system is brought to its operating boundaries, that it tends naturally to maintain or increase stability rather than become unstable.

Robustness means inherent defect and damage tolerance. Robustness is developed from the combination of redundancy (spare components), ductility (ability to redistribute excessive demands), and excess capacity (ability to carry redistributed demands). The ship structure likely will not be ideally designed, constructed, operated, and maintained. Through provision of stability and robustness the ship structure should be designed to retain a desirable level of quality even though it is subjected to "normal abuse."

5.3 Detection and Remediation

The third approach is focused on internal and external assessments and auditing. QA/QC measures have traditionally addressed detection and remediation of hazards and flaws. *QA are those practices and procedures that are designed to help assure that an acceptable degree of quality (safety, durability, serviceability, compatibility) is obtained*. QA is focused on prevention of errors.

QC is associated with the implementation and verification of the QA practices and procedures. Quality control is intended to assure that the desired level of quality is actually achieved. Quality control is focused on reaction, identification of errors, rectification, and correction [2, 3].

QA/QC measures are intended to assure that a desirable and acceptable quality and reliability of the ship is achieved throughout its life. Quality is initiated with the conception of a ship, defined with design, translated to reality with construction, and maintained with high quality operations. Achieving quality goals is primarily dependent on people. QA/QC efforts are directed fundamentally at assuring that human and system performance is developed and maintained at acceptable levels.

QA/QC strategies include those put in place before the activity (prevention), during the activity (checking), after the activity (inspection), after the manufacture or construction (testing), and after the ship has been put in service (monitoring and detection). The earlier QA/QC measures are able to detect the lack of acceptable quality, then the more effective can be the remediation.

Of all of the QA/QC measures, the most effective are those associated with prevention. As factors leading to lack of desirable safety are allowed to become more and more embedded in first the design, then the construction, and then the operation of a ship, then the more difficult they are to detect and correct. Personnel selection, training, and verification; the formation of cohesive teams and encouragement of teamwork, and the elimination of unnecessary complexity in procedures and structure - equipment systems are examples of effective QA/QC measures.

Control QA/QC measures consist of procedures and activities that are implemented during activities to assure that desirable quality is achieved. Self-checking, checking by other team members, and verification by activity supervisors are examples of such activities.

Inspection and verification QA/QC measures consist of procedures and activities that are implemented after an activity has been completed.

Detection QA/QC measures consist of procedures and activities that are implemented after the ship has been put in service to assure that desirable and acceptable quality and safety are maintained.

It is surprising how often correction of flaws and errors is under-estimated. Intense efforts are devoted to QA and QC, but little and frequently no planning or efforts are devoted to corrections. Often, provisions are not made for correcting errors and flaws when they are found, and the fixes become problematic. Detailed planning and evaluations are necessary to properly define what should be done when major errors are detected.

Effective QA/QC requires certain types of resources: *sufficient time, money, positive incentives, knowledge, experience, insight, respect, and wisdom* [7]. Of all of the resources, knowledge, experience, and positive incentives are the most critical.

Present experience indicates that much QA/QC is not very effective [2]. In many cases, it becomes a "paper chase" and results in a seemingly endless series of unneeded and perfunctory meetings. QA/QC becomes part of the problem of achieving safety and is not effective at determining what the real problems are and how they might best be solved. Much more attention needs to be given to keeping the good, discarding the bad, and adopting clearly needed improvements in QA/QC processes. This can lead to improving the effectiveness of the QA/QC processes and reducing its costs.

6. Quality and Reliability

Quality is defined as freedom from unanticipated defects. Quality is fitness for purpose. Quality is meeting the requirements of those that own, operate, design, construct, and regulate ship structures. These requirements include those of serviceability, safety, compatibility, and durability [27].

Serviceability is suitability for the proposed purposes, i.e. functionality. Serviceability is intended to guarantee the use of the system for the agreed purpose and under the agreed conditions of use.

Safety is the freedom from excessive danger to human life, the environment, and property damage. Safety is the state of being free of undesirable and hazardous situations. The capacity of a structure to withstand its loadings and other hazards is directly related to and most often associated with safety.

Compatibility assures that the system does not have unnecessary or excessive negative impacts on the environment and society during its life-cycle. Compatibility is the ability of the system to meet economic and time requirements.

Durability assures that serviceability, safety, and environmental compatibility are maintained during the intended life of the marine system. Durability is freedom from unanticipated maintenance problems and costs.

Quality is freedom from unanticipated defects in the serviceability, durability, compatibility, and safety of the ship structure.

6.1 Reliability

Reliability is closely related to quality. *Reliability is defined as the probability or likelihood that a given level of quality will be achieved during the design, construction, and operating life-cycle phases of a ship structure*. Reliability is the likelihood that the system will perform in an acceptable manner. Acceptable performance means that the system has desirable serviceability, safety, compatibility, and durability.

The compliment of reliability (Ps) is the likelihood or probability of unacceptable performance; the probability of "failure" (Pf = 1 - Ps). Success is the ability to anticipate and avoid failure. Failure is an undesirable and unanticipated outcome; the lack of meeting expected performance; the significant loss of utility. Experience has amply demonstrated that the single largest factor responsible for failure of ship structures is *human error* [2, 28].

Likelihoods of not realizing a desirable level of quality arise because of a wide variety of uncertainties. During the design phase there is a likelihood of not realizing the intended quality due to causes such as an analytical flaw embedded in a finite element program or an error made in interpreting a design loading formulation. During the construction phase, unrealized quality might be developed by the use of the wrong materials or use of inappropriate alignment and welding procedures. During the operating phase, unrealized quality might be developed by accidental loading from collisions or dropped objects or neglect of planned maintenance of coatings and cathodic protection.

Generally, ship structural reliability has been defined as the likelihood that the ship structure's capacity is exceeded by the dead, live, and environmental loading. This definition has been criticized because of its limited scope. Conventional structural reliability analysis fails to address the other key issues associated with the quality of the marine structures. The conventional definition fails to address the other key hazards to the quality of the structure that develop during the life-cycle of the structure.

Unreliability is due fundamentally to three types of uncertainties . The first is inherent or natural randomness (aleatory). The second is associated with analytical or professional uncertainties (epistemic). The third is associated with HOE.

While conventional ship structural reliability assessments have explicitly addressed the first two types of uncertainty, in general they have not addressed the third category of uncertainty. At best, the third category of uncertainty has been included implicitly. It has been incorporated in the background of data and information that is used to describe the uncertainties and variabilities.

7. Risk and Risk Management

Risk is defined as the product of the likelihood that adequate or acceptable quality is not achieved and the consequences associated with the lack of achieved quality.

Risk results from uncertainties. Some uncertainties are random (aleatory) and some are systematic (epistemic). Some uncertainties can be managed (information sensitive, epistemic, predictable) and some uncertainties can not be managed (information insensitive, aleatory, unpredictable). Some uncertainties are essentially static (unchanging in time) and others are essentially dynamic. Some uncertainties can be identified and quantified and some uncertainties can not be identified and quantified.

Consequences result from unrealized expectations and unanticipated lack of sufficient quality. Consequences can be expressed in terms of their frequency, their severity, their impacts (on site and off site), and their predictability.

Consequences can be expressed in a variety of ways and with a variety of metrics. Monetary costs are one metric to measure and express consequences. Time (schedule, availability), injuries to humans, and injuries to the environment are other ways to express and measure consequences.

Some consequences can be proactively managed or controlled (hazard mitigation measures). Some consequences can not be proactively managed or controlled. Some consequences can be evaluated objectively and quantitatively and some consequences can not be evaluated objectively and quantitatively.

Generally, there are significant uncertainties associated with the results of evaluations of consequences. This is particularly so as one projects the consequences of insufficient or unacceptable quality far into the future.

Evaluations of consequences are difficult to make and express. Evaluations of consequences are very susceptible to the values, views, and biases of the assessors.

Some consequences are essentially static. Other consequences are very dynamic in that they change markedly with time.

An identified risk is an engineering and management problem. A faulty or bad definition of a risk can result in additional risk and result in bad management of quality. A risk management framework should be based on intelligent and perceptive risk identification, classification, analysis, evaluation, and response. Risk management attacks both the likelihoods of compromises in quality and the consequences associated with these compromises.

Risks have sources, are translated to reality with events, and are felt with effects. There are initiating events (direct causes), contributing events (background causes), and compounding events (propagating or escalating or arresting causes). *Risk management attempts to identify and remedy causes, detect potential and evolving events and bring them under control, and minimize undesirable effects*.

Risks are independent and dependent. Risks can have partial dependence. If the occurrence of one risk does not influence the occurrence of another risk, then it is independent. If the magnitude of one risk is related to the magnitude of another risk then these two risks are correlated. Independence and correlation are critical issues in risk analysis, evaluation, and management.

Risks are controllable and uncontrollable. Controllable risks are those that are within the direct control of those that own, operate, design, classify, regulate, and build ship structures. Uncontrollable risks are those that are not within the direct control of these groups. Proactive risk management is concerned primarily with predictable and controllable risks. Real-time risk management is concerned primarily with unpredictable risks. Inherent risk and uncontrollable risk must be recognized, evaluated, and managed in the process of making decisions regarding the activities and ventures associated with the quality of ship structures.

A risk management system should be practical, realistic, and must be cost effective. Risk management need not be complicated nor require the collection of vast amounts of data. *Excellent risk management results from a combination of uncommon common sense, qualified experience, judgment, knowledge, wisdom, intuition, and integrity.* Mostly it is a willingness to operate in a caring and disciplined manner in approaching the critical features of any activity in which risk can be generated. *Risk management is largely a problem of doing what we know we should do and not doing what we know we should not do.*

The purpose of a risk management system should be to enable and empower those that have direct responsibilities for the designing, building, maintaining, and operating ships. The engineer can play a vital role in this empowerment. If technology is not used wisely, scarce resources and attention can be diverted from the true factors that determine the safety of a ship, and less safe systems developed. The purpose of a risk management system should be to assist the front line operators to take the right (sensible) risks and to achieve acceptable quality. To try to completely eliminate risk is futile. To help manage risks and make appropriate use of technology should be one of the key objectives of engineering and management.

8. Cost Justification of HOE Risk Management Alternatives

An important objective HOE risk management should be to help enhance the quality of the ship structure while at the same time enhancing the long term profitability of the operations: *Quality must be good business.*

Experience indicates that some quality related activities should be discarded and more effective and efficient methods adopted. Thus, some improvements in how quality is achieved can be realized without increasing costs.

Providing adequate quality in the design, construction, maintenance, and operation of a ship structure can result in lower life-cycle costs, be safer, increase income. A “systems” approach to quality can result in significant economic benefits: there can be both short-term and long-term savings. Experience has amply demonstrated that it is on the basis of economics that justifications for improvements in the quality of ship structures must be based. Only when this is done will there be adequate and sustained support to achieve this quality.

The costs to correct insufficient quality (errors) are a function of when the deficiencies are detected and corrected (Fig. 4). The earlier they are caught and fixed, then the less the costs. The most expensive time to fix quality errors is after the system is placed in service. This places a large premium on early detection and correction of errors. Not only are there large direct future costs associated with fixing errors, but as well there are large indirect costs associated with loss of business, image, and credibility.

Assuming that the costs of quality varies linearly with the logarithm of the probability of insufficient quality, the "optimum" reliability (annual) that produces the lowest total of initial costs and future costs can be shown to be [7]:

$$P_s = 1 - \frac{0.4348}{CR\ pvf} \tag{1}$$

where *CR* is a cost ratio and *pvf* is a present value discount function.

The cost ratio is the ratio of the costs associated with not realizing the desired level of quality (*CF*) to the costs required to reduce the likelihood of not realizing the desired level of quality by a factor of ten (ΔC_i). For a continuous discount function and long-life structures (life >= 10 years), $pvf \approx r$-1 where *r* is the monetary net discount rate (investment rate minus inflation rate). For short-life structures (life ≤ 5 years), $pvf \approx L$, where *L* is the life in years.

As shown in Fig. 5, as the costs associated with development of insufficient quality increases, the reliability must increase. As the initial costs to achieve quality increases, the optimum reliability decreases.

The marginal probability of insufficient quality is double the optimum quality probability. It is the quality in which the incremental investment to achieve quality equals the incremental future benefit (cost / benefit = 1.0).

The optimum reliability of a ship structure element, component, and system is a function of its *criticality* expressed by the product of *CR* and *pvf*.

HOE risk management strategies must address their effectiveness at reducing the likelihoods of insufficient quality in the ship structure and in reducing the costs associated with the inadequate quality. All of the attributes of quality during the life-cycle of the ship structure need to be brought into the evaluation.

Quality can be a substantial competitive aspect in industrial activities. If a purchaser or user recognizes the benefits of adequate quality and is able and willing to pay for it, then quality can be a competitive advantage. If a purchaser or user does not recognize the benefits of adequate quality or is unable or unwilling to pay for it, then quality can be a competitive disadvantage. Purchaser/owner quality goals must be carefully defined so that uniformity can be developed in the degrees of quality offered in a product or service sector. Once these goals have been defined, then the purchaser/owner must be willing to pay for the required quality.

It is here that cooperation and communication between the primary organizations that have responsibilities for the quality of a ship structure during its life-cycle must be developed. It is critical that all of these organizations clearly understand, agree to, and discharge their responsibilities [2, 7, 30]. Given the global and fragmented nature of the international commercial shipping industry, this poses a major challenge.

It is important to recognize that the society being served by the ship owner also has a stake in quality. The ship owner must have adequate profitability to have the necessary resources to invest in achieving adequate quality. Corporate desires for quick or excessive profits should not be allowed to divert the resources required to achieve adequate quality. The public that is served by the ship owner must be pay for the quality that it demands.

9. Example Evaluation

This example illustrates application of some of the key aspects of the foregoing developments [31]. The example is intended to be illustrative of how HOE analyses can be performed. The case history used in this example focuses on critical structural details (CSD) in a class of commercial tankers. A CSD is a section of the structure that experiences very high stress concentrations in comparison with the rest of the structure, and therefore requires special attention in the design and construction phases, and should receive close scrutiny in inspections and maintenance.

The example CSD are the side shell longitudinal to webframe connections (Fig. 6) in a class of single-hull tankers of 165,000 dwt. The mid-body transverse framing of this class of ships is shown in Fig. 7.

9.1 Background

This class of tankers suffered severe fatigue cracking problems in the CSD. The class of 4 ships were designed and built by a U. S. shipyard during the 1970's. This class of ships developed more than 4,000 major fatigue cracks during a period of 20 years. Several hundred of the CSD had to be repaired three times during the 15 year life.

The questions posed in the analysis of this example are:

1) What were the causes of the fatigue problem?

2) Could these causes have been anticipated? and

3) What could have been done to prevent the problems?

This analysis addresses the major sources of fatigue susceptibility in order of their occurrence, beginning with the existing climate in ship design and construction and carrying through operation of the ships. The problems that developed with these ships during the design and construction phases are addressed and a coarse qualitative evaluation of the major factors developed. The system is analyzed using a coarse quantitative method based on event trees [2, 31].

9.2 Design

The most obvious source of fatigue susceptibility in this class of ships was the lack of explicit design for fatigue durability. No fatigue analyses were performed during the design. Was fatigue a known risk in engineered structures at this time? The answer is clearly yes. Fatigue and fatigue analysis was well-known at the time of design of these ships. A major error in the design of these ships was the lack of utilization of existing technology. The apparent reason for this exclusion was that fatigue analysis was not required by regulatory and classification authorities and the ship owners wanted the ship to meet "class minimums". The general climate in shipbuilding was to build to minimum requirements only.

The lack of fatigue analysis requirements was due to the relationship between the ship owners, builders, operators, and the regulatory and classification societies. The owner, builder, and operator believed that by building the ships to existing rules, sufficient safety and durability was ensured. However, the regulatory and classification societies considered only safety to be their responsibility, not durability. They did not include fatigue in their guidelines. This situation existed because durability had not been a problem historically; ships built with adequate safety also had adequate durability. But, as will be seen, things had changed that would endanger the relationship between safety and durability of the ship structure.

In the case of these ships, a new material (HTS, or high tensile steel) was used in the structure to achieve weight savings. The circumstances that had resulted in the durability of the previous generations of ships were changed. It was well understood at the time that while the fatigue strength of the parent or base material could be expected to increase with the yield strength, the fatigue strength of the welded material in a corrosive environment could not be expected to increase with the yield strength. As this material was different from that which the classification societies had based their stance on durability, durability was not ensured with the new material.

Another factor figured in the lack of sufficient durability. Classification Societies had changed rules to comply with the interests of ship owners to build cheaper ships (Fig. 8) without substantially compromising the safety of the ship structure [7]. Another problem was the intense economic pressure applied in ship construction. HTS was relatively untried in marine applications, but economic pressures to increase payload per deadweight ton implicated its use.

This error can be classified as one of organizational error. It can further be defined as an error in communications and culture. Communications was a problem because the rule-making bodies did not make clear that durability was not their responsibility when non-standard materials were used in a design. Culture was a problem because both the regulatory agencies and the classification societies had been reducing requirements to comply with ship builders and owners requirements for "low cost tonnage", as well as to increase the economy of designs by lowering safety factors which may have seemed excessive in light of their previous success.

Finally, the ships were to be operated on a trade route with very severe wave conditions, which increased their susceptibility to fatigue problems. This fact was not considered during the design phase. The prevailing thought was that design of a ship for the "North Atlantic trade route" conditions would assure adequate strength and hence adequate fatigue durability. This error is considered to be one of organizations culture. It was known that the planned route for the ships was one with severe environmental conditions for most of the year, much more severe than that of the North Atlantic, but the designers failed to take this fact into account, assuming that if the design passed the classification requirements, fatigue would not be a problem.

This error should not be considered one of ignorance. Fatigue was a well-known risk in ship design at the time these ships were conceived. The 1967 edition of **Principles of Naval Architecture** contains a section on "Fatigue in Ship Structures", which discusses the use of HTS and describes the potential problems in "details subject to repeated reversal of high stress" (such as CSD) [32]. This advice would have been within easy reach of most naval architects at the time. By this time, fatigue in offshore platforms had been widely recognized and formal fatigue design and analysis procedures were developed and applied to design of fatigue sensitive structures. This technology was founded on similar technology developed for design of airframes [7].

It is also interesting to note the historical relationship between required safety factors and major failures. As a result of an in-depth study of the historic failures of engineered systems, Petroski points out that periods of prolonged success tend to inevitably invite failures, as prolonged success leads to a lowering of safety factors [33]. This is because prolonged success seems to imply over-design to many engineers, owners, and operators. These lowered safety factors eventually lead to failure.

In this case, the safety factors had been successful for fatigue, even if only because loading safety factors coincidentally insured fatigue success, which led to this type of failure when loading safety factors were (reasonably) lowered. This example also illustrates another point of Petroski's study of historic failures of engineered systems: apparently correct answers may be reached for the wrong reasons [32]. Just because the ships in the recent past had not experienced fatigue problems by following loading safety factors did not ensure that future designs would also escape fatigue problems without undergoing fatigue analysis. An incorrect understanding of the system, which incidentally gives correct answers, can easily lead to failures.

In a recent article titled "Victory's Pipeline" Hannan cited three categories of problems that resulted in the structural failures that occurred in 521 T2 tankers built during World War II: design, workmanship, and material. Hannan observed [34]:

"Abrupt changes in section, or elements added to the ship as an afterthought, for example, often became troublemakers, initiating cracks and raising local stresses."

"Imperfect welds were the point of origin for many failures. The imperfections originated as often the manner of preparing the joint for welding as in the quality of the metal deposited."

"The fatigue limit of various structural steels is approximately proportional to the ultimate tensile strength of the material and not to the yield point. Therefore, fatigue may become an important consideration as higher yield strength steels are used."

Many of the same problems encountered in the T2 tankers were repeated in the example class of ship structures. This is an indication of the slowness and inefficiency of "organizational learning."

The configuration of the ships made them fatigue-prone. Ship scantlings were reduced from historically average sizes and high tensile steel (HTS) was used. This was done to lighten the ship, as high strength steel allowed for a lighter ship than normal steel, increasing the amount of cargo per ton of displacement. However, the fatigue properties of HTS are not proportionally higher than that of mild steel, as discussed in the previous section. Therefore, the design of the CSD made the ships fatigue-prone. The CSD design did not adequately account for stress concentrations, which exacerbated this fatigue problem.

This can be classified as an individual human error. The design of the details was carried out by the design team, a relatively small group. This error can be further classified as one of selection and training. The error is considered of this type because stress concentrations were known and predictable, and the problem should have been detectable by a ship designer.

9.3 Construction

The climate of ship construction at the time was one of low-bid to win contracts [35]. This attitude resulted in attempts by the designer and builder to minimize costs at every opportunity. This led to cost-cutting in design as well as construction. Cost cutting in the shipyard lead to misalignments, poorly prepared plate edges, and in several cases, incompletely welded CSD. This is an organizational problem, and is classified as an organizational error in culture (incentive system). The existing culture did not promote or reward work of high quality, but work of low cost.

The state of the shipyards also lead to errors in the design and construction of the ships. Shipyards bid on the "minimum initial cost" ship to win contracts. This emphasis on initial cost drew attention away from life-cycle thinking, which lead to overlooking fatigue, corrosion and maintenance concerns.

The tankers had to be built in the U. S. because of the Jones Act, a piece of legislation which went into effect in 1921 and states that ships used on routes between domestic ports must be built in the U.S. Therefore, the owners were forced to have the ship construction done by an industry that was not "up to par", as U.S. shipyards were clearly inferior to foreign yards in terms of productivity, quality, and technology [35]. This can be proven by one single statistic: 3760 new commercial ship orders were placed between 1988 and 1992, with only 5 going to U. S. yards. The Jones Act ensured that the U. S. shipyards would not have to compete against foreign shipyards for this type of ship. This act removed some of their incentive for continuous improvements.

In terms of commercial ship building, U. S. shipyards were behind the times in terms of organization and construction facilities. This had a substantial effect on the quality problems associated with this class of ships. Foreign yards were employing techniques such as modular construction, process lanes and zone outfitting. These methods allowed for simplified critical paths, greater quality control, and superior monitoring. In one study [35], it was found that a Japanese yard, producing the same ship design as a U. S. shipyard, required only 27% of the labor hours, and only 65% of the material cost.

The errors due to the climate of U. S. ship construction are classified as organizational errors. Specifically, they are errors of culture, planning and preparation, structure and organization, and monitoring and controlling.

The construction quality of this fleet of ships was generally poor. Misalignments, poor fit-up, incomplete and poor quality welding, hand flame-cut edges, and poorly applied, low durability coatings were found. Poor edge preparation of CSD was also common. Commissioning inspections performed by the shipyard, the regulatory agency, the classification society, and lastly, the owner all disclosed incompletely welded CSD. Each of these inspections disclosed different numbers and locations of incompletely welded details. Existing QA/QC measures failed to detect and correct the wide variety of problems that arose during construction.

The errors which occurred in construction are considered to be individual human errors. They are due to ignorance, selection and training, slips, and planning and preparation. Most of these errors can be attributed to the state of U. S. shipyards at the time.

9.4 Qualitative Evaluation

Based on the design and construction characteristics of these ships, a qualitative quality profiling instrument was developed to help evaluate the general fatigue durability expected of the CSD. An objective of this profiling instrument was to highlight the factors which could be expected to have the greatest impacts on fatigue durability. The evaluation instrument and results are summarized in Fig. 9.

The ships were given low marks for materials, as HTS was relatively new to ship construction and this shipyard. Construction quality was poor, as mentioned earlier, so scores were low for construction - procedures and systems. The structure was not analyzed for fatigue, so both the structure and the design - procedures and systems were given low scores. Personnel and management were typical of a U. S. shipyard, so construction - personnel and management and design - personnel and management were given slightly below-average scores. Available technology (compared to foreign yards) was not employed, so the technology score was low. Finally, financial resources, personnel resources, time resources and quality incentives were all given low scores due to the climate at the shipyards at the time of construction.

The evaluation shows that in all of the categories, the ship structure quality factors were judged to be below average. The ship structures were obviously prone to low quality: excessively low durability. The material (HTS) is the area of greatest concern. However, design, construction, and organization related issues lead to low quality scores. The provision of below average technology, time, personnel, and financial resources is a critical issue that is reflected in the low quality incentives. It is these key issues that will become the focus of the second part of this example; the quantitative analyses.

In this evaluation, it is important to point out that it would have taken an experienced and diligent assessor that was relatively independent of the circumstances that resulted in the low fatigue durability in these ships. Incentives would need to be in place to encourage the assessor to come forward with “bad news.” It would have taken a ship owner that wanted to acknowledge the potential for undesirable durability, and realized its implications on the long-term ship serviceability and compatibility.

The qualitative analysis and quality profile highlighted four factors in design and construction which were major contributors to HOE. These four factors, and their specific type of HOE, are summarized in Table 6.

9.5 Quantitative Analysis - Original System

The example was first analyzed quantitatively for the original conditions. Each of the four factors was analyzed using event trees (Figs. 10 - 13) [31]. This required establishing baseline error rates for each factor. The baseline error rate for Factor I (error in the fatigue analysis) was evaluated to be 1E-2. This rate was selected because the error occurred in the omission of proper communication of responsibility.

Factor II (error in CSD design) was evaluated to have an error rate of 1E-3, as the design of CSD for fatigue was not well developed at the time. Factor III has an was evaluated to have an error rate of 1E-3 also, as the state of shipbuilding was the result of a confused set of relationships and dependencies, where errors could occur without much chance of being noticed. Factor IV was assigned an error rate of 1E-3, as the construction process was slightly more complex than usual (HTS), and there were time and economic pressures.

The probabilities of the situations to induce errors being present were divided equally in this analysis. In the analysis of the re-configured system, these values may be reduced, as indicated by the multipliers for performance shaping factors [36] and relative strengths of error-producing conditions [9, 37].

9.6 Quantitative Analysis - Improved System

By the use of quality improvement measures the probability of occurrence of situations inducing HOE can be reduced. These measures are described for each factor in this section, and then quantitatively evaluated in the following section.

Table 6 Major Factors and Causes Resulting in Low Durability CSD

FACTOR I - Fatigue Design	
	Organizational error, Communications
	Organizational error, Culture
FACTOR II - CSD Configuration	
	Human error, Selection and Training
FACTOR III - Construction Environment	
	Organizational error, Culture
	Organizational error, Planning and Preparation
	Organizational error, Structure and Organization
	Organizational error, Monitoring and Control
FACTOR IV - Construction Process	
	Human error, Ignorance
	Human error, Selection and Training
	Human error, Slips
	Human error, Planning and Preparation

Factor I can be ameliorated by several organization modifications. Establishing clear lines of communication and responsibility between the various agencies at work in shipbuilding would greatly improve the problem and reduce the occurrence of conflicts of interest. An example of how responsibility can be defined is given below for the four agencies involved in ship design, construction, and operation: regulatory bodies, classification and inspection groups, designers and builders, and owners and operators [7, 30]:

- Regulatory: definition and verification of compliance with goals and policies of quality.
- Classification and inspection: development of classification rules that will guide and verify design, construction, and operation of durable and reliable structures that meet regulatory and owner requirements.
- Design and construction: designing and producing structures with appropriate quality.
- Owners and operators: design and maintenance of high quality structures and the economic operation of structures.

Focusing on the life-cycle costs of the ship could provide incentives for improvement in the fatigue durability. When the economics are examined for the life-cycle, the advantages of initially robust design versus design for light weight and low initial cost should be obvious. This will be addressed in the following section of this paper.

Factor II can be improved by focusing on fundamentals and identification of failure modes. Ellingwood describes this type of error prevention measure [38]:

"Technical measures include independent reviews of fundamental design concepts and assumptions, which have been identified as the root of many failures. Such reviews should be performed on all major projects. Even simple equilibrium and stability checks frequently reveal fundamental errors in design concepts and assumptions."

Employees should be selected by their command of basic concepts and training should be carried out to help retain the fundamentals. Also, the recognition of "hazard scenarios" or failure modes should be emphasized. As Petroski points out, a designer can only design against failure modes which he or she recognizes. Other failure modes may be covered incidentally, but this can lead to dangerous situations. QA/QC measures towards improved designs would include licensing, verification and testing procedures, incentives, accountability, and job design [2].

Factor III is a complicated problem. The state of U. S. shipyards and the climate of construction in the U. S. is a product of many factors that have developed over a long period of time. However, it is clear that most U. S. shipyards have not kept up with modern advances in construction of commercial ships. Although some of the lag can be attributed to lack of series ship orders and cost of equipment, much of the modernization in foreign shipyards has been in the form of organization. A basic reorganization of shipyard labor into more efficient units could greatly improve productivity.

There are four steps towards modern ship building practice which the shipyard that built the example class of ships could implement to improve quality and productivity [35]:

1) Modular construction techniques should be employed. This serves to simplify planning and reduce interference between groups of outfitters.

2) Process lanes should be implemented. These consist of fixed workstations which process items or units of similar construction. This enables workers to progress along the learning curve of construction and makes possible the use of statistical control in the production process. It also provides greater tool utilization, simpler material handling, and the tolerances necessary for successful modular construction. It can serve as a basis for implementing continual improvement and modern management techniques such as work teams and participative management.

3) Zone outfitting should be executed. This consists of outfitting by module, block, or unit. It has been esti-

mated that outfitting by block saves 30% in labor, while outfitting by unit saves 70% over conventional outfitting. This improvement is the result of simplified coordination and scheduling and less time moving material through areas under construction.

4) Use standardized tested designs for subassemblies and units. This would work well with process lanes and zone outfitting. If plans were created and stored electronically, maximum utilization of information and computing technologies could be obtained. There would also be benefits due to re-use.

Establishing goals of quality and good customer relations over low-bid would go a long way towards improving the state of ship construction. Construction should also be viewed in terms of life-cycle costs.

Factor IV is also a challenging problem. The example of foreign shipyards could be followed for training, selection and organization. Reorganization would bring about the greatest quality change. However, reorganization would require workers with flexible skills. This would be a problem, as U. S. shipyards are currently approximately 90 % unionized, with the unions being craft-based. Without flexibly-skilled workers, the advantages of techniques such as zone outfitting cannot be fully realized.

Following the principles of design for constructability, inspectability, and repairability would be beneficial to the quality that could be achieved during the construction phase.

Based on the projected effects of the system reconfigurations, the system was again analyzed by event trees, with new probabilities of occurrence (but the same base error rates).

In Factor I, the communications and culture induced error probabilities were reduced by half.

Available information indicated that Factor II would experience greater improvement through QA/QC measures. Focusing on fundamentals and failure modes would give designers a much better chance to detect large errors. Therefore, the probability of error due to selection and training was reduced by a factor of five.

It was difficult to assess the impacts of improved QA/QC for Factor III. It was judged that focusing on life-cycle costs and quality would improve the culture problem, reducing it by a factor of two. Adopting modern shipbuilding methods of organization, selection, and training could have a similar effect on planning and preparation and structure and organization. Implementing statistical control methods would have a large impact on monitoring and control, reducing its probability of contributing to error by a factor of five.

Factor IV was handled in the same manner as Factor III. Improved selection and training can be expected to cut error probabilities in half, if modern shipbuilding methods are employed. Probabilities of error due to ignorance and slips should also be decreased by the same amount. The greatest benefit would be in adopting modern methods of labor organization and construction planning. By using these methods, a reduction in error due to planning and preparation of a factor of five could be realized.

9.7 Results

Table 7 summarizes the quantitative results for both the original and reconfigured systems. The evaluations indicate that in the initial state, the likelihood of experiencing less than desirable fatigue durability in this class of ships CSD due to HOE problems was about 3 E-2. The total likelihood of fatigue failures in the CSD was about 1 E-1 (for a 20 year operating period). This class of ships were obviously a problem waiting to happen.

Given the reconfigured system, the likelihood of experiencing less than desirable fatigue durability was about 1 E-2 (for a 20 year operating period).

The largest contributors to the CSD durability problem were due to construction related issues, both of which had their roots in organizational issues. The construction related issues indicated a probability of durability failure of 2 E-2 while the design related issues indicated a probability of durability failure of 1 E-2.

As discussed, each of the four factors has means for improvement. Addressing the design issues, Factor I would be the most important element to concentrate improvement efforts on, as it has the highest baseline error rate of the design related issues. Development of fatigue design guidelines and requirements would clearly address this factor.

In the other factors, a new QA/QC effort for hiring and training, for both designers and yard workers, would have positive and significant impacts on quality. Some type of reorganization of shipyard labor will be necessary for improved quality control in construction, which will be a difficult problem, but is necessary to improve construction quality.

However, it appears the greatest problems are those which are classified as organizational and cultural. Changing these categories would have the best chance of changing the overall system from one which is considered error prone or low quality inducing to one that is acceptable quality inducing, robust, and error-tolerant. The positive interactions of the cooperating agencies (owner / operator, regulatory, classification, shipyard) oriented toward achieving acceptable quality in the ship structures are perhaps the most important change that could be made.

Technical changes such as improved durability design guidelines are less important than organizational issues such as requirements that they be used and the provision of adequately trained personnel and other design resources. Similarly, it is organizational issues related to construction that are the most important; most of these are rooted in provision of sufficient resources (personnel, time, money) to achieve adequate quality in the ship CSD.

10. Economics Analysis of Improved Fatigue Durability

An example application of these developments is illustrated in Fig. 14. for the CSD in the 165,000 dwt tankers. The numbers of fatigue failures (through thickness fractures) that could be anticipated in a ship hull structure during 5 year periods throughout a service life of 20 years are shown. The analyses were performed for the ship hull structure that had CSD whose fatigue durability was determined by fatigue design Safety Indices (B_D's) ranging from 1.0 to 3.0 [7, 29]. The probability of fatigue failure in a CSD is approximately $Pf \approx 10^{-BD}$.

The fatigue life evaluation indicated that the original example tankers had a fatigue design and construction reliability of about B_D = 1.0. The measures outlined in Section 9 were evaluated to develop a fatigue design and construction Safety Index of about B_D = 2.0.

This evaluation was used to estimate the total life-cycle costs associated with CSD fatigue fractures in the example tankers (Fig. 15). It was assumed that the inspection process was capable of detecting the through-wall fractures that were developed at 5-year intervals, and that these fractures were immediately repaired to the initial condition. Based on current shipyard estimates (28, 31), the initial cost differential between designing and constructing for a CSD B_D = 1.0 to CSD B_D = 3.0 was evaluated to be $10 millions. It was evaluated that the total present valued cost associated with each fatigue fracture was $10,000 (this included inspection, repair, and out-of-service costs).

The results indicated a fatigue design reliability of about B_D = 2.0 would be optimum or result in the lowest total life-cycle cost. These results indicated that the costs of the improvements defined in Section 9 would be warranted from an economics standpoint.

Table 7 Summary of Results of Quantitative Analyses

FACTOR I Baseline Error Rate	1.00E-02	
	As Configured	Re-configured
P Communications	*0.50*	0.25
P Culture	*0.50*	0.25
P Error - Communications	5.00E-03	2.50E-03
P Error - Culture	2.50E-03	6.25E-04
Total P Error	7.50E-03	3.13E-03
	Net Change	**58%**
FACTOR II Baseline Error Rate	1.00E-03	
	As Configured	Re-configured
P Selection and Training	*0.50*	0.10
P Error - Selection	5.00E-03	1.00E-03
Total P Error	5.00E-03	1.00E-03
	Net Change	**80%**
FACTOR III Baseline Error Rate	1.00E-03	
	As Configured	Re-configured
P Culture	*0.50*	0.25
P Planning and Preparation	*0.50*	0.25
P Structure and Organization	*0.50*	0.25
P Monitoring and Control	*0.50*	0.10
P Error - Culture	5.00E-03	2.50E-03
P Error - Planning	2.50E-03	6.25E-04
P Error - Structure	1.25E-03	1.56E-04
P Error - Monitoring	6.25E-04	1.56E-05
Total P Error	9.38E-03	3.30E-03
	Net Change	**65%**
FACTOR IV Baseline Error Rate	1.00E-03	
	As Configured	Re-configured
P Ignorance	*0.50*	0.25
P Selection and Training	*0.50*	0.25
P Slips	*0.50*	0.25
P Planning and Preparation	*0.50*	0.10
P Error - Ignorance	5.00E-03	2.50E-03
P Error - Selection	2.50E-03	6.25E-04
P Error - Slips	1.25E-03	1.56E-04
P Error - Planning	6.25E-04	1.56E-05
Total P Error	9.38E-03	3.30E-03
	Net Change	**65%**

11. Implications for Design of Ship Structures

A large number of cases have been studied in detail in which errors made during the design of the marine structure lead to the failure (lower than desired quality) of the structure. Table 9 summarizes the key causes of these failures.

Table 9 Key Causes of Structure Design Related Failures

- New or complex design guidelines and specifications
- New or unusual materials
- New or unusual types of loading
- New or unusual types of structures
- New or complex computer programs
- Limited qualifications and experience of engineering personnel
- Poor organization and management of engineering personnel
- Insufficient research, development and testing background
- Major extrapolations of past engineering experience
- Poor financial climate, initial cost cutting
- Poor quality incentives and quality control procedures
- Insufficient time, materials, procedures, and hardware

The single dominant cause of structure design related failures has been errors committed, contributed, and / or compounded by the organizations that were involved in and with the designs. At the core of many of these organization based errors was a culture that did not promote quality in the design process. The culture and the organizations did not provide the incentives, values, standards, goals, resources, and controls that were required to achieve adequate quality.

Loss of corporate memory also has been involved in many cases of structure failures. The painful lessons of the past were lost and the lessons were repeated with generally even more painful results.

The second leading cause of structure failures is associated with the individuals that comprise the design team. Errors of omission and commission, violations (circumventions), mistakes, rejection of information, and incorrect transmission of information (communications) have been dominant causes of failures. Lack of adequate training, time, and teamwork or back-up (insufficient redundancy) has been responsible for not catching and correcting many of these errors.

The third leading cause of structure failures has been errors embedded in procedures. Traditional and established ways of doing things when applied to structures and systems that "push the envelope" have resulted in a multitude of structure failures. There are many cases where such errors have been embedded in design guidelines and codes and in computer software used in design. Newly developed, advanced, and frequently very complex design technology applied in development of design procedures and design of marine structures has not been sufficiently debugged and failures have resulted.

Another important concept has developed from these failure cases. This concept is that making the structures stronger or utilizing larger factors of safety in its design is not an effective or efficient way to achieve sufficient and desirable quality in the structures. Resources are best focused at the sources of the quality problem which in this case are the humans involved in the structure design activities.

This is not to say that one should not consider the human aspects directly in the structure design procedures and processes. Human errors will occur during design, construction, and operations. One key objective of the design process should be to make the ship structure so that it can better tolerate such errors and the defects and damage that it brings with it. This is design for robustness. This is design to minimize the effects of inevitable human error (fault tolerance).

Another key objective of the design process should be to make the ship structure not invite or promote human errors. This is the development of design procedures and processes that will promote quality in the work to be performed by designers, constructors, and operators of ship structures (fault avoidance). The design process should promote detection and removal of errors throughout the life-cycle of the ship structure (fault detection and removal) [7].

This insight indicates the priorities of where one should devote attention and resources if one is interested in improving and assuring sufficient quality in the design of ship structures:

1) *organizations (administrative and functional structures),*

2) *individuals (the design team), and*

3) *procedures (the design processes and guidelines).*

11.1 Organizations

Even though it may be the most important, the organization aspects of ship structure design quality are perhaps the most difficult to define, evaluate, and modify. Because of their pervasive importance in determining the quality which is achieved in the design of ship structures, some critical aspects of quality in design organizations will be addressed.

The ship structure design process should be viewed in the context of the multiplicity of organizations that influence the quality of that process. The organizations and their activities form a "mega-system" [6] that should be recognized and addressed. These mega-systems and their organizational components must be understood as "organisms, living systems that relate to each other" [6].

The implementation of Total Quality Management and International Standards Organization guidelines in design organizations is a current example of efforts directed at the organization aspects associated with design of ship structures. Critical flaws to avoid in implementing these approaches is *development of minimum compliance mentalities and making them an unnecessarily burdensome paper chase.*

Studies of HRO (High Reliability Organizations) [39] has shed some light on the factors that contribute to risk mitigation in HRO [40]. HRO are those organizations that have operated nearly error free over long periods of time. A variety of HRO ranging from the U. S. Navy nuclear aircraft carriers to the Federal Aviation Administration Air Traffic Control System have been studied [39].

Reduction in error occurrence in HRO is accomplished by:

1) *command by exception or negation,*
2) *redundancy,*
3) *procedures and rules,*
4) *training,*
5) *appropriate rewards and punishment,*
6) *the ability of management to see the big picture.*

Command by exception (management by exception) refers to management activity in which authority is pushed to the lower levels of the organization by managers who constantly monitor the behavior of their subordinates. Decision making responsibility is allowed to migrate to the persons with the most expertise to make the decision when unfamiliar situations arise (employee empowerment).

Redundancy involves people, procedures, and hardware. It involves numerous individuals who serve as redundant decision makers. There are multiple hardware components that will permit the system to function when one of the components fails.

Procedures that are correct, accurate, complete, well organized, well documented, and are not excessively complex are an important part of HRO. Adherence to the rules is emphasized as a way to prevent errors, unless the rules themselves contribute to error.

HRO develop constant and high quality programs of training. Training in the conduct of normal and abnormal activities is mandatory to avoid errors. Establishment of appropriate rewards and punishment that are consistent with the organizational goals is critical.

Lastly, Roberts [40] defines HRO organizational structure as one that allows key decision makers to understand the big picture. These decision makers with the big picture perceive the important developing events, decisions, and actions and properly integrate them, and then develop high reliability responses.

In recent organizational research reported by Roberts and Libuser [41], five hypotheses that defined "risk mitigating and non-risk mitigating" organizations were developed:

1) Risk mitigating organizations will have extensive process auditing procedures. Process auditing is an established system for ongoing checks designed to spot expected as well as unexpected safety problems. Safety drills would be included in this category as would be equipment testing. Follow ups on problems revealed in prior audits are a critical part of this function.

2) Risk mitigating organizations will have reward systems that encourage risk mitigating behavior on the part of the organization, its members, and constituents. The reward system is the payoff that an individual or organization gets for behaving one way or another. It is concerned with reducing risky behavior.

3) Risk mitigating organizations will have quality standards that meet or exceed the referent standard of quality in the industry.

4) Risk mitigating organizations will correctly assess the risk associated with the given problem or situation. Two elements of risk perception are involved. One is whether or not there was any knowledge that risk existed at all. The second is if there was knowledge that risk existed, the extent to which it was acknowledged appropriately or minimized.

5) Risk mitigating organizations will have a strong command and control system consisting of five elements: a) migrating decision making, b) redundancy, c) rules and procedures, d) training, and e) senior management has the big picture.

11.2 Design teams

The activities of the individuals that are directly responsible for the design of ship structures will be placed in the context of the structure design team.

There are two primary lines of defense to prevent and / or detect and correct design team errors. The first line of defense is centered in the individuals performing the design analyses; the design team. The second line of defense is identified as QA/QC. These are activities of those outside the design team.

The first line of defense is associated with prevention and minimization of errors made and not corrected by the individuals that perform the design processes. The quality of the structural design is a direct function of the quality of the design team that performs the design. Table 10 summarizes the key factors that are need to be addressed to develop a high reliability ship structure design team. Many of these factors relate directly to the attributes of HRO and risk mitigating organizations.

Table 10 Key Factors the in Development of High Reliability Ship Structure Design Teams

Communications	Procedures
Personnel selection	Organization
Training	Leadership
Planning	Monitoring
Preparations	Information seeking, observations
Discipline	Controlling
Quality resources	Information evaluation
Appropriate operation strategies	Distributed decision making
	Quality incentives and rewards

Past problems associated with design of ship structures indicates that effective communications, personnel selection, training, provision adequate resources to achieve the desired quality, and provision of quality incentives and rewards are essential elements that determine the frequency and intensity of human factor related problems in structure design.

Communications has been identified as a major human factors problem in many other individual and team situations. The way in which information is presented, information distortion (biasing), and the formatting of the information can have dramatic affects on the effectiveness of the communications within the design team.

Training of design personnel must also match the job to be done. To enhance the performance of a specific task, the more repetition that occurs, then the lower the likelihood of error. To enhance problem solving, experience in a variety of tasks is needed.

Training of design personnel will be particularly important as a new ship structure design process is implemented. There will be a loss of “feel” during the early phases of applying such a new design process. If errors are to be prevented or caught and corrected, this intuitive feel must be quickly re-established in those that will apply the new guidelines.

Training of design personnel to understand the effects of biases and heuristics on their decisions is important. Decision makers involved in the design of complex structural systems need to be taught about confirmation bias; the tendency to seek new information that supports one’s currently held belief and to ignore or minimize the importance of information that may support an alternative belief. Rigidities in perceptions, ignoring potentially critical flaws in complex situations, rejection of information, and minimizing the potentials for errors or flaws result from confirmation bias.

A very important aspect of minimizing designer error regards team work. Team-work on the front lines of the design process can provide a large measure of internal QA/QC during these operations [24]. Team-work can be responsible for interrupting potentially serious and compounding sequences of events that have not been anticipated. It is such team-work that is largely responsible for “near misses.”

QA/QC measures are focused both on error prevention and error detection and correction. There can be a real danger in excessively formalized QA/QC processes. If not properly managed, they can lead to self-defeating generation of paperwork, waste of scarce resources that can be devoted to QA/QC, and a minimum compliance mentality.

In design, adequate QC (detection, correction) can play a vital role in assuring the desired quality is achieved in a marine structure. Independent, third-party verification, if properly directed and motivated, can be extremely valuable in disclosing embedded errors committed during the design process.

In many problems involving insufficient quality in marine structures, these embedded errors have been centered in fundamental assumptions regarding the design conditions and constraints and in the determination of loadings. These embedded errors can be institutionalized in the form of design codes, guidelines, and specifications.

It takes an experienced outside viewpoint to detect and then urge the correction of such embedded errors. The design organization must be such that identification of potential major problems is encouraged; the incentives and rewards for such detection need to be provided.

It is important to understand that adequate correction does not always follow detection of an important or significant error in design of a structure. Again, QA/QC processes need to adequately provide for correction after detection. Potential significant problems that can degrade the quality of a structure need to be recognized at the outset of the design process and measures provided to solve these problems if they occur.

Knoll's study of structure design errors and the effectiveness of QA/QC activities in detecting and correcting such errors lead to the checking strategies summarized in Table 11 [8].

Table 11 Design QA/QC Strategies

WHAT TO CHECK ?	HOW TO CHECK ?
• high likelihood of error parts (e.g. assumptions, loadings, documentation) • high consequence of error parts	• direct toward the important parts of the structure (error intolerant) • be independent from circumstances which lead to generation of the design • use qualified and experienced engineers
WHEN TO CHECK ?	
• before design starts (verify process, qualify team) • during concept development • periodically during remainder of process • after design documentation completed	• provide sufficient QA/QC resources and incentives • assure constructability and IMR
	WHO TO CHECK ?
	• the organizations most prone to errors • the design teams most prone to errors • the individuals most prone to errors

The structure design checking studies performed by Knoll [8], the series of studies performed by Melchers and Stewart [42-44], and the studies of failures marine structures [2, 12] indicate that there is one part of the design process that is particularly prone to errors committed by the design team. That part of the process is the one that deals with the definition of design loadings that are imposed on and induced in the structure. Given the complexities associated with performing loading analyses, the complexities associated with the loading processes and conditions, and the close coupling between the structure response and the loading environment, it is little wonder that loading analyses are probably the single largest source of structure design errors. What is somewhat disturbing is that many designers of ship structures do not understand these complexities nor have been taught how to properly address them in structure design.

Again, given the development of an LRFD ship design process that will involve new loading factors and new loading combinations associated with these factors, training of ship structure design engineers will be particularly important.

The intensity and extent of the design checking process needs to be matched to the particular design situation. Repetitive designs that have been adequately tested in operations to demonstrate that they have the requisite quality do not need to be verified and checked as closely as those that are "first-offs" that may push the boundaries of current technology.

11.3 Design Guidelines and Codes

There are three HOE minimization strategies that should be considered in development of ship design guidelines and codes:

- Strategy 1 - QA/QC the design procedures and processes (fault avoidance),
- Strategy 2 - QA/QC is integrated as a requirement directly in the design procedures and processes (fault detection and correction), and
- Strategy 3 - Measures are introduced into the design procedures and processes that will minimize the effects of HOE on the quality of the ship structure (fault tolerance).

Strategy 1

Development of a design code or guideline is no simple undertaking. Not only is complex technology involved, but as well complex organization and political issues are involved. In the struggle to develop the technical and organizational consensus that should be represented in a design code, technical completeness, correctness, and crispness can be compromised.

In one recent development, an objective that was defined to achieve "a more efficient structure" by balancing the reliabilities of the elements that comprised the structure. To the guideline developers, it did not make sense that some components in the structure should have very low probabilities of failure while other components had much higher probabilities of failure. It was only after the need for damage and defect tolerance (robustness) in the structure was recognized, that the need for unbalanced design became apparent. This recognition not only influenced the design processes to assure adequate strength (capacity) in the structure, but as well its ductility and fatigue durability characteristics. Recognition of the needs for "fail-safe" design of the structures had major effects on the structure design guideline developments.

Current experience indicates that if not properly developed and documented, a design guideline can enhance the likelihood of significant errors being made by even experienced structural designers (*radar assisted collisions*). These errors can lead to important compromises in the intended quality of the structure. The errors arise primarily because of the dramatically increased complexity of the design guideline, its similarly increased opaqueness (frequently caused by associated computer software), and the lack of sufficient training.

Research has shown that the difficulty of a particular task is influenced by five primary factors [24]:

1) *structure of the task,*
2) *task goals and performance criteria,*
3) *quality, format and modality of information,*
4) *cognitive processing required, and*
5) *characteristics of the input / output devices.*

The more difficult a task is made, then the more likely that there will be errors. Those charged with development of ship structure design guidelines should be sensitized to these factors. Design guidelines should be developed that will minimize the difficulty of the tasks to be performed and thereby enhance the likelihood of high quality design results.

Strategy 2

The second strategy is to embody QA/QC directly and explicitly into the ship structure design guideline. In this case, requirements for assuring adequate quality in the designers are spelled out. Checking procedures are defined that are appropriate for the particular ship structure. Explicit provisions are made for the correction of errors committed during the design process. Of particular importance is the guiding principle of checking "high likelihood of error parts" such as loading analyses, and checking "high consequences of error parts" of the design process such as design documentation.

Also of importance is the need to be independent from the circumstances which lead to the generation of the design. This refers directly to the need for independent, third-party verification to disclose embedded errors and flaws in the design. Research and experience both indicate that given that it is done properly, third party verification is the most effective way to detect potential problems in the structure design process.

Ship structure design procedures need to incorporate intuitive, first principles, and empirical verifications. Intuitive verifications are derived from the designer "feel" cited earlier. Such feel is based on adequate experience with the design procedures and analyses. This feel is responsible for a majority of quality problems that are detected and corrected (design near misses).

First principles verification is needed so that complexity is not allowed to over-shadow realism. This means first that design engineers need to be well trained in these first principles, and second, that the design process must allow and encourage their use in verifying the results from the process.

Experience has indicated that results from simplified methods that employ first principles can play an important role in identifying problems in results from complex methods. Yet, there is often little respect given to such methods by engineers. They feel that complex methods are more reliable and give more realistic results. Simplified methods can not be expected to develop the details developed by complex methods. However, sophistication in analytical design methods does not assure either reliability or realism in results. There is an important need to further develop simplified design methods that can be used to help verify the fundamental results from complex design analyses.

Empirical or experimental verification is needed because of the inherent inadequacies and limitations of most engineering analytical procedures when applied to design of ship structures. This is particularly true when it comes to loading analyses, but it also applies to most structure analyses. The question is the extent of experimental verification that is required. This becomes a problem in trading off the costs involved in providing the verification versus the costs involved when insufficient quality is obtained due to the lack of the verification.

Strategy 3

The third strategy that should be incorporated directly into the design guidelines and their development regards design of the structure to be tolerant or forgiving of human errors. These human errors can and probably will occur in design, construction and operation of a ship structure; even one that has been designed by the most advanced technology available today.

It is rare to find explicit structure design guidelines that address the need for obtaining human error tolerance in the life-cycle of any type of structure. Some have begun to appear, but more work is needed to develop such guidelines. The results of the Marine Structural Integrity Project (MSIP) [7] indicated that there were four general approaches that should be considered in developing human error tolerant structure design guidelines. These were design for:

1) *damage or defect tolerance (robustness),*

2) *constructabilty,*

3) *inspectability, and*

4) *maintainability and repairability.*

The first approach is focused on providing fault tolerance in the ship structure system. The last three approaches are focused on providing fault avoidance, detection, and removal in the ship design process. Structure robustness can be achieved with a combination of redundancy, ductility, and excess capacity in the structure system. Robustness implies much more than redundancy (degree of indeterminacy) [25, 26]. Fail-safe design is one aspect of this approach [7].

Robustness needs to be placed in those areas of the ship structure that have high probabilities of damage or defects and high consequences associated with such damage or defects.

Design for constructability is focused on configuration and proportioning the structure to promote / facilitate high quality materials, cutting and forming, and assembly. Design for inspectability is focused on the same structure design activities, but this time the objective is to maximize the inspectability of the ship structure during its operation. Design for maintainabilty and reparability is meant to direct the structure design engineers attention to the long-term life-cycle phase of the ship structure. Corrosion management and buckling and fracture repairs are key issues.

All of these design approaches are intended to minimize the incidence of and effects of human errors that can occur in design, construction, and operation of a ship structure.

12. Conclusions

There are three primary aspects that should be addressed in achieving quality in ship structures: designers, constructors, and operators of the structure (humans), the groups that are responsible for the management of the systems (organizations), and the physical elements (system including structure, hardware, and software). A thorough understanding of ship structure systems indicates that there literally are no separate parts. There are only relationships and interactions. This understanding is at substantial variance with the historic separation and compartmentation of ship structure design, construction, and operation.

High consequence compromises in quality of ship structures result from a multiplicity or compounding sequence of break-downs in the human, organization, and system; often there are precursors or early warning indications of the break-downs that are not recognized or ignored.

The physical components of ship structure systems are generally the easiest of the three components to address; design for human tolerances and capabilities (ergonomics), provision of redundancy and damage / defect tolerance, and effective early warning systems that provide adequate time and alerts so that systems can be brought under control are examples of potential measures. Error inducing systems are characterized by complexity, close coupling, latent flaws, small tolerances, severe demands, and false alarms.

Humans are more complex in that error states can be developed by a very wide series of individual characteristics and states including fatigue, negligence, ignorance, greed, folly, wishful thinking, mischief, laziness, excessive use of drugs, bad judgment, carelessness, physical limitations, boredom, and inadequate training. External (to the system) and internal (in the system) environmental factors such as adverse weather, darkness, smoke, heat provide additional influences.

Selection (determination of abilities to handle the job), training (particularly crisis management), licensing, discipline, verification and checking, and job design provide avenues to improve the performance of front-line operators. The formation of motivated and cohesive design and construction teams can do much to improve the quality of ship structures.

While the human and system aspects are very important, the organization aspects frequently have over-riding influences [45]. Corporate cultures focused on production at the expense of quality, ineffective and stifled communications, ineffective commitment and resources provided to achieve quality, excessive time and profit pressures, conflicting corporate objectives, and counter-quality and integrity incentives are often present in low reliability organizations. Generally, these aspects are the most difficult to address. Experience indicates that high reliability organizations tend to improve, while low reliability organizations do not improve rapidly, if at all.

To take any action with a ship structure design, construction, or operation system without an intimate and thorough knowledge of that system is tampering. Deep knowledge of a system includes a detailed understanding of the system, an understanding of qualitative and quantitative evaluations, a knowledge of psychology (individuals, organizations), and an understanding of the limitations of our abilities to describe and analyze complex systems.

Without a deep knowledge of the system, one can be seriously mislead.

Many engineers are very uncomfortable with two things: uncertainty, and people. The challenges of design, construction, and operation of ship structures involves both. Neither can or should be avoided. Engineers have much to learn about how to improve their role and activities in helping develop engineered systems that will have desirable and adequate quality. A vast field of human factors related technology has developed. The analytical thinking and processes of engineering needs to absorb the technologies of ergonomics, human psychology, management, and cognitive psychology.

If their work is to be meaningful, engineers must learn as much about people as they presently know about the physical and mechanical aspects of the elements that comprise and affect engineered systems. Recognition of and education in human factors are two of the primary obstacles to integration of human factors into engineering.

The historic development of design guidelines has had as one of its foundations probability methods. These methods attempt to address some of the uncertainties. In almost all cases, this historic development has fallen short of explicitly addressing one of the primary sources of uncertainty and hazards to quality: people. Many of the experienced engineers that have objected to probability based design guideline developments have objected to this development primarily for this reason. They sense that something important is missing, and it is. But, the same thing is also missing from the more traditional methods. And, in the main, it is for this reason that we are now recognizing the reasons for the majority of compromises in the quality of both marine and non-marine structures are firmly rooted in HOE.

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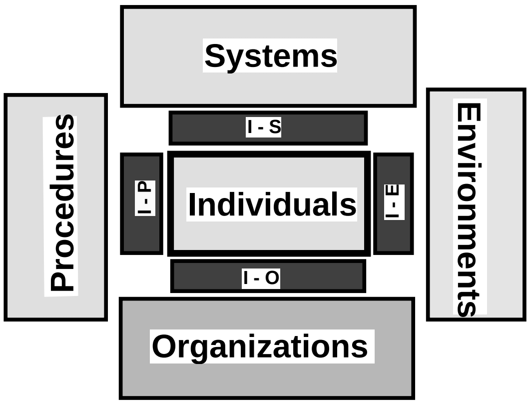

Figure 1
Components and Interfaces That Can Lead to Human Errors

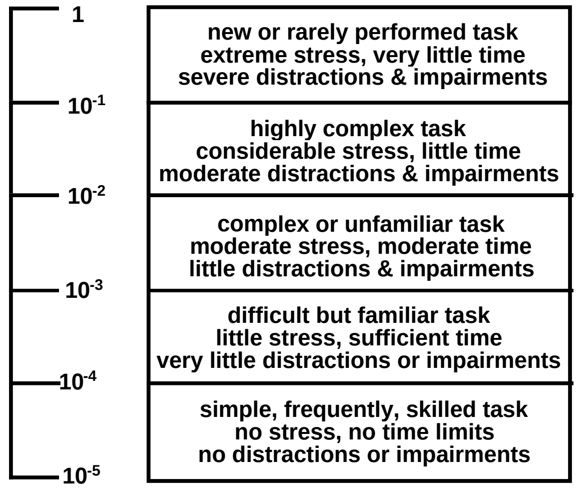

Figure 2
General Task Human Error Probabilities

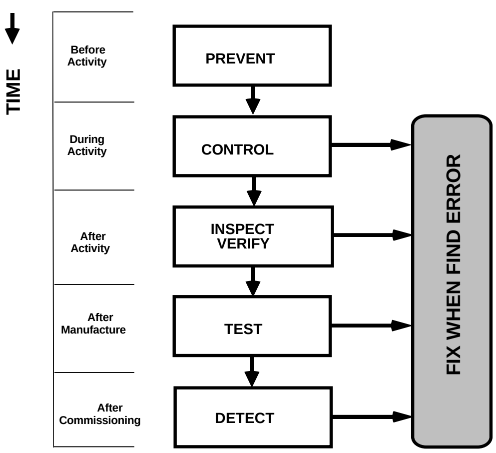

Figure 3
QA/QC Life-Cycle Activities

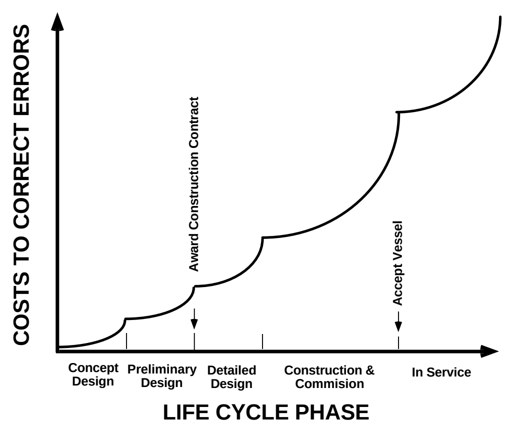

Figure 4
Life Cycle Costs to Correct Errors

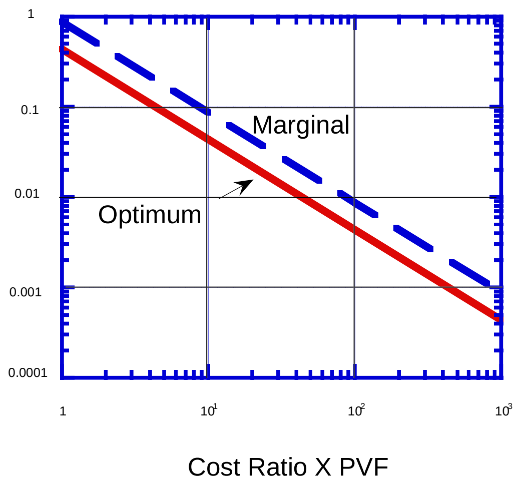

Figure 5
The Economics and Likelihood of Insufficient Quality

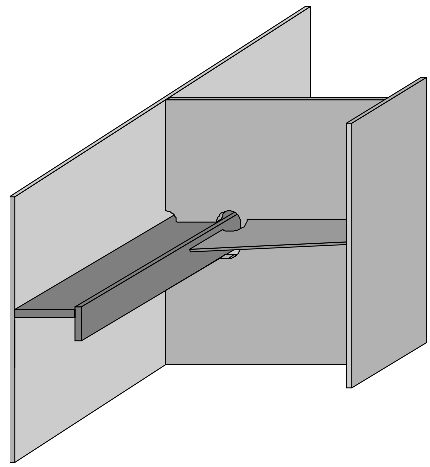

Figure 6
Example CSD Side Shell Longitudinal to Webframe Connection

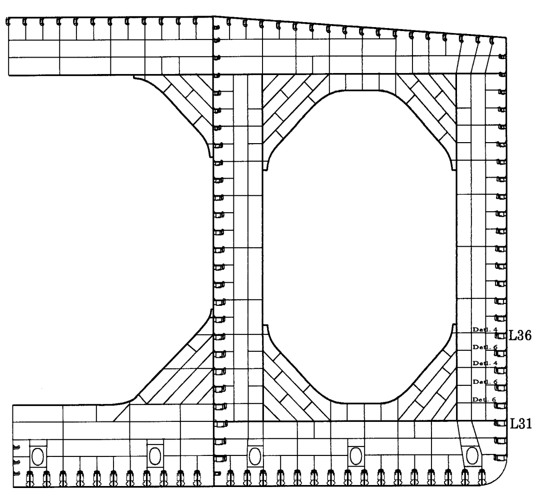

Figure 7
Transverse Midships Frame of Example Tankers

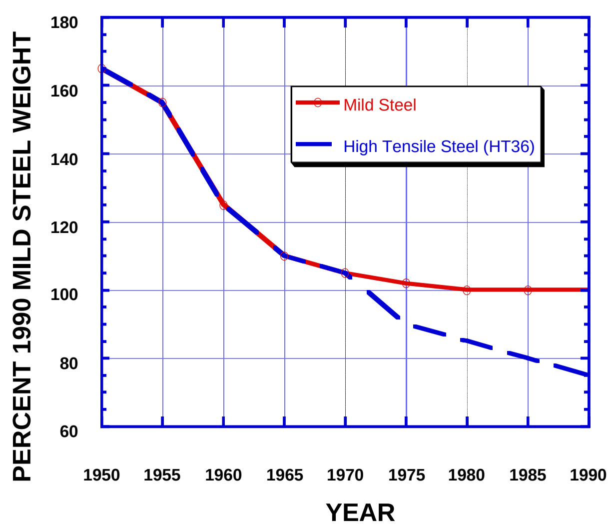

Figure 8
Reduction in Required Minimum Ship Structure Weight (100,000 dwt tanker) as a Function of Time

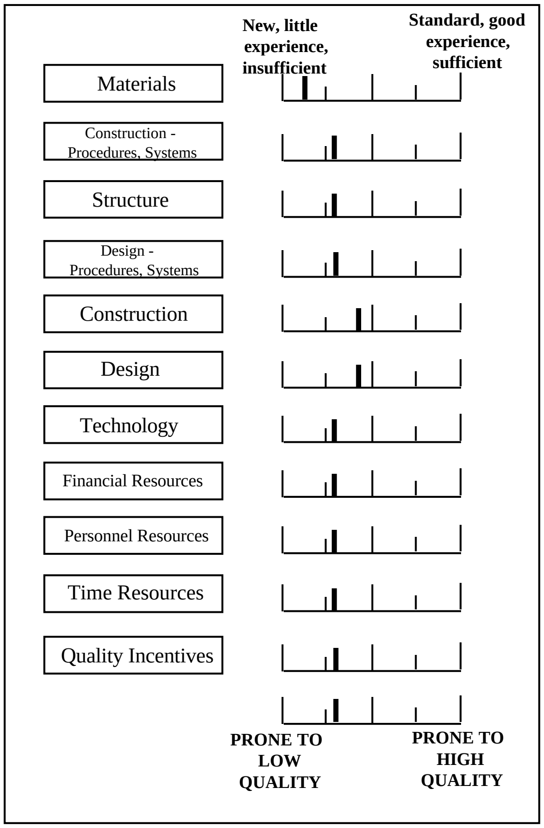

Figure 9
Quality Profiling for CSD Fatigue in Example Tankers

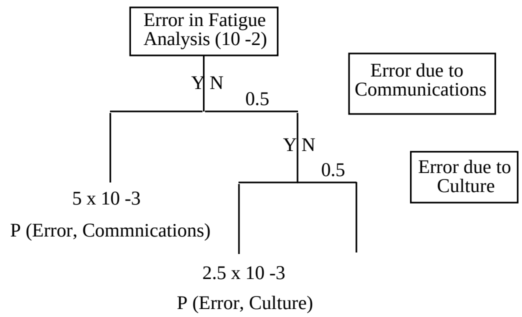

Figure 10
Event Tree for Factor I

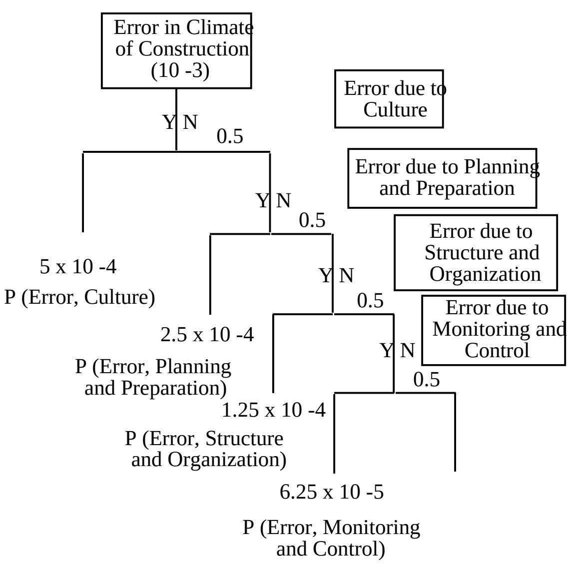

Figure 11
Event Tree for Factor II

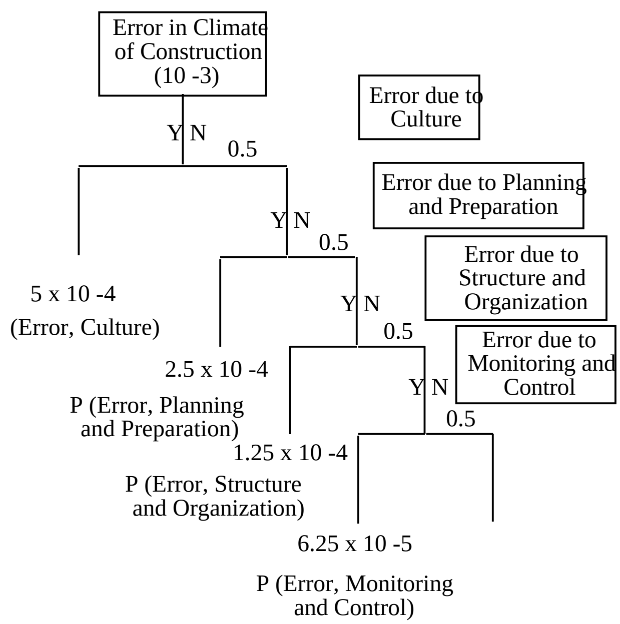

Figure 12
Event Tree for Factor III

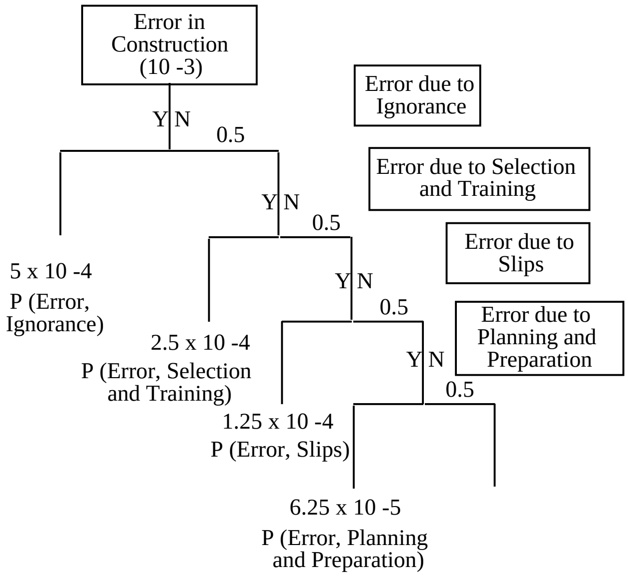

Figure 13
Event Tree for Factor IV

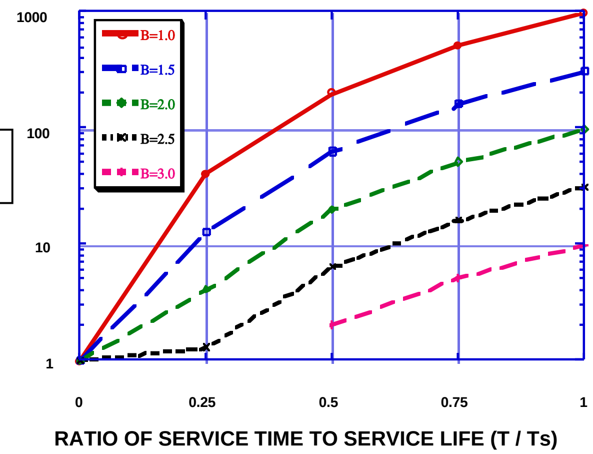

Figure 14
Number of Fatigue Fractures in Example Tankers as a Function of Time and Fatigue Design Reliability

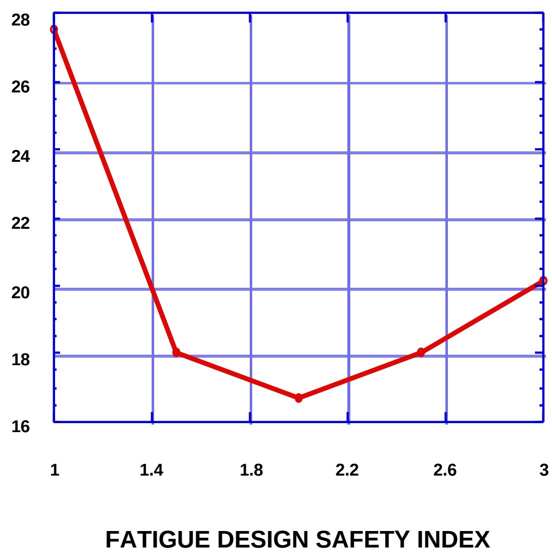

Figure 15
Lifetime (20 Year) Costs in Example Hull Structure as a Function of the Fatigue Design Safety Index

Discussion

by Dr. Robert Sielski
Marine Board, National Research Council

I have a different perspective on the fatigue problems with tankers, and would like to discuss it because it points out how we need to apply the type of approach that is suggested by this paper. Fatigue cracking of tanker structures was not a new problem. Tankers, as any owner will tell you, have always been prone to cracking, but the degree to which it was controlled was a subject of owner preference. One of the most common causes of fatigue failures was the use of lapped structural details. Some owners understood the significance of this type of detail, and specified fitted details, but very few were willing to pay this additional expense. The change to higher tensile steel did not introduce a new problem, it only exacerbated an existing problem.

The two factors, fitted structural details, and higher-strength steels are not new to ship construction; they have been used in naval ship construction since the 1930's. The naval use, however, brought an important human factors issue. The military was viewed as "gold plating" the structure by those who thought that they were building practical ships. perhaps this can be viewed as he prescriptive minimum standard versus the alternative compliance viewpoint of self-regulation.

The U. S. Navy, in fact, was no better than the commercial tanker industry in looking at fatigue. Since its introduction as a structural material for deckhouses in the 1940's, aluminum had always been subject to fatigue. Although the technology for fatigue analysis was developed in the aircraft industry, naval ship designers viewed this technology as inapplicable to combatant ship design, even when it was demonstrated for high performance ships, such as the Boeing-designed hydrofoils. Rather than viewing the problem as one of design procedures, these structural designers of whom I was a principal, viewed the problem of deckhouse cracking as a problem of the material - aluminum - that could be solved by reverting to the good old steel. However, all the problems of fatigue were not fully addressed, and I understand that the new steel deckhouses are not free from fatigue defects. The human factor here is an unwillingness to apply existing technology on the part of the designer, or at the inability of the designer to justify the cost of application of that technology to management.

There have been other structural problems that could have been anticipated, but somehow were not. The failures of bulk carriers came not through a radical change in technology, but because the technology of inspection and analysis were not properly applied.

My question to the author is whether the process of consideration of human and organizational factors will enable us to predict the next big problem in ship structures? For example, there is a wide difference between the standards for crack-arrest strakes of the U. S. Navy and those of classification societies. The U. S. Navy requires HY-80 in all cases, but the classification societies permit grade A steel in thin plate. Someone must be wrong, but the current state of fracture mechanics analysis, despite the work of the Ship Structure Committee over the last 50 years does not provide the answer. Extensive research is still required, but the U. S. Navy does not want to undertake the cost of research because the additional material cost is minor in proportion to the total ship cost. Commercial ship builders and classification societies do not want to undertake such a multi-million dollar research program because they have no perceived need.

Is fracture of ship structure under some new circumstances as new design concepts or operating conditions a human and organizational disaster waiting to happen? Do we have the tools to determine what other subjects need emphasis? I have mentioned fracture only because it is a potential problem of which I am aware. *How can I become aware of something I have ignored and no one seems to care about but may be a major problem in the future?*

Author's Reply

The unwarranted rejection of applicable technology has been a problem in other fields of engineering. Sowers (1990) cites this type of human error as one of the major sources of failures in geotechnical engineering. Similar observations have resulted from studies of the design initiated failure of conventional structures such as bridges and buildings. The reader is referred to SSC 378 for further details on this type of human and organizational error.

The purpose of human and organizational factor (HOF) analyses or studies should not be prediction. The purpose of HOF analyses or studies should be detection and remediation of potential "critical flaws" in ship structures that can originate in design, construction, operation, and maintenance. It is on this point that many risk and reliability analyses come to grief. People become preoccupied with the results from quantitative risk and reliability analyses. They fail to recognize that in reality it is impossible to predict the future actions of people and organizations. They fail to recognize that in reality "systems" are much more organic and dynamic than static. It is the process of analysis and evaluation that is important. And, this process must intimately involve those that have daily responsibilities for the safety of our ship structures. The analysis and evaluation processes need to encourage their interaction and input. Beware of risk and reliability analysts that fail to recognize these realities. Risk and reliability "tampering" can produce some very serious side effects that can degrade rather than improve the safety of systems.

Yes, fracture of ship structure under some new circumstances as new design concepts or operating conditions is a human and organizational disaster waiting to happen. Dr. Sielski's background in this area spans more than three decades and his discussion indicates that this is a real possibility because of the reluctance of those responsible for future ships to make the necessary investments in technology to prevent such problems. It has happened before, and it will probably happen again.

Yes, we have the tools to determine what other subjects need investigation before we create problems that can be prevented. These tools are utilized in high technology areas such as airframe and space vehicle design. Extensive and exhaustive testing, analysis, and highly qualified personnel provide the necessary tools. It is rare to see these tools fully mobilized in the marine industries. Our organizational histories and cultures do not seem to encourage the full use of these tools. We seem to boldly go where no one has gone before without making full use of "the lessons of history." Ship structures that do not have desirable and acceptable serviceability, compatibility, durability, and safety are the result of this boldness.

Awareness of potential problems is a critical issue in helping solve these problems before they become real problems. Some engineers have what I like to call "perverse imaginations." These engineers have a special talent for detecting how systems may not work. Many of these engineers are the old grizzled veterans of past "mistakes" and they remember these lessons. Most engineers have talents for making systems work and it is difficult for them to detect potentially critical flaws in these systems. Frequently, the engineers that have perverse imaginations are frequently not highly regarded by their colleagues because they are seen to be "gloom and doom" and "not positive." Group think problems that degrade "situational awareness" develop when the requisite variety for the problem to be addressed is removed or excluded. Complacency replaces vigilance and trouble soon follows. Pride and wishful thinking precede folly. This is why "inside" checking has been shown to be relatively ineffective at detecting basic critical flaws in systems. It takes someone relatively independent from the circumstances that result in the development of the hidden critical flaws to detect these flaws. It is one of the fundamental purposes of HOF assessments and evaluations to help introduce new insights and perspectives to help create awareness of potential problems. The most important ingredient in successful HOF assessments and evaluations is the experience, knowledge, skills, and motivations of the people that perform these assessments and evaluations.

The author would like to thank Dr. Sielski for his detailed review of this paper, a very stimulating discussion of some of its critical aspects, and his thoughtful questions.