Paper No. OMAE 95 1233 Proposed for Publication
Safety and Reliability Symposium
14th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 1995)
Copenhagen, Denmark, June 1995

EVALUATION OF HUMAN AND ORGANIZATION FACTORS IN DESIGN OF MARINE STRUCTURES: APPROACHES & APPLICATIONS

Robert Bea

Department of Civil Engineering and
Department of Naval Architecture & Offshore Engineering
University of California
Berkeley, California

ABSTRACT

This paper addresses evaluation of human and organization factors in design, reliability, and quality of marine structures. Complimentary approaches to develop such evaluations are discussed. Sources of quantifications in performing probabilistic evaluations of human and organization factors are summarized.

An example is developed to illustrate application of qualitative and quantitative analyses to one portion of the design of a ship structures: Finite Element Analyses (FEA) of Critical Structural Details. Based on recent experience with FEA of CSD in ship structures, typical sources of errors in such analyses are defined and discussed. The effects of improvements in the human and organization aspects of FEA of CSD are discussed and illustrated.

APPROACHES

There are three alternative approaches that can be used to help develop evaluations of Human and Organization Factors (HOF) effects on the quality of marine structures: *1) qualitative, 2) quantitative, and 3) mixed qualitative - quantitative.*

It is important to stress that these three approaches are complimentary. They should be used in different stages and parts of the HOE evaluation process.

In this paper, quality is defined as an acceptable and desirable combination of serviceability, safety, durability, and compatibility; a system is the combination of the individuals (humans), organizations, procedures (software), environments (internal, external), and structure - equipment (hardware); failure is an unanticipated compromise in the desired or acceptable quality of a system; error is the unanticipated and undesired action or inaction that results in a compromise in quality; reliability is the probability that quality is equal to or greater than desired or acceptable (Bea, 1995).

At the outset, it is important to stress that the fundamental objective of evaluations of HOF effects is not the traditional engineering objective of "prediction." Rather, the objective is assessment of engineered systems to identify potential "critical flaws and situations" and identify how best to rectify the critical flaws and situations before they result in undesirable compromises in quality.

Qualitative - Subjective

The first approach can be identified as *subjective* or *qualitative*. Experience with evaluations of HOF in reliability of marine structures indicates that this approach should be the starting point for the evaluation and assessment processes (Bea, 1994a). In many cases, this approach can prove to be sufficient to achieve and assure the desired level of quality in a marine structure. This approach uses 'soft' linguistic variables to describe systems and procedures. Integration of the evaluations generally is subjective. This approach may or may not involve detailed structuring of systems and the related HOF EDA (Events, Decisions, Actions) that may influence the quality of these systems.

Quantitative - Objective

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. This approach generally examines in much greater detail the systems and the EDA that influence the quality of these systems.

This approach utilizes numerical models to provide quantitative indications of what the effects are of changes in the 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 quantitative approach has traditionally been identified as the PRA (Probabilistic Risk Analysis) or QRA (Quantified Risk Analysis) approach. It has been highly developed and applied to a wide variety of types of marine and non-marine systems.

Mixed Qualitative - Quantitative

The third approach is a mixed qualitative and quantitative process. Linguistic variables are translated to numerical variables. A mathematical process is provided to perform analytical integration of the effects and variables. In one form, this approach has been based on the mathematics of "Fuzzy Sets" (Zimmermann, 1991; Yager, Zadeh, 1994). Moore and Bea (1993) utilized such an approach in development of HESIM (Human Error Safety Index Method) to assist in the quantitative evaluations of HOF in operations of marine systems (ships, offshore platforms). Gale, et al. (1994) utilized a similar ranking - index method to evaluate the potentials for fires and explosions onboard offshore platforms. This method has been identified as FLAIM (Fire and Life safety Assessment Indexing Method). Xu and Bea (1992) applied traditional Fuzzy Set theory to the reassessment and requalification of offshore platforms.

This approach has been termed "soft computing" (Yager, Zadeh, 1994). The rigid structure of formal probability theory and analytical quantification are surrendered in favor of a "more flexible" structure. Expert systems (knowledge base systems) and neural networks have been combined with the theory of Fuzzy Sets to provide an evolving approach to the evaluation of systems in which there is either no need or it is not desirable to apply the analytically more demanding "hard computing" approaches. This approach is being applied to a wide variety of systems (Brown, et al., 1985). This approach is in a state of development and evolution in a wide variety of marine and non-marine sectors.

Fundamentally this third approach can be developed and applied in the context of the first two approaches (Moore, Bea, 1993b; Gale, et al., 1994]. Traditional reliability theory can accommodate this approach if analysts are willing to surrender rigid interpretations applied to probability numerical quantifications and analyses. Conventional probability theory and mathematics can be used to provide the necessary quantifications that provide links with qualitative expressions of likelihoods (Orisamolu, Bea, 1993).

QUANTIFICATIONS

Studies of the present databases on marine structures in which there has been unacceptable levels of quality indicates that they are very deficient in their ability to accurately define the key initiating, contributing, and compounding HOF that lead to compromises of quality (Moore, Bea, 1993; Nagendran, 1994; Mason, et al., 1994)

There has not been any common classification or definition of HOF related causes of marine accidents. There has been a dearth of well trained investigators. Investigations generally have focused on the immediate causes of quality problems, not the underlying factors that lead to these causes. Investigations have frequently been focused on placing blame rather than on determining the underlying, direct, and contributing factors. Organizational factors have largely been ignored. Due to legal action concerns, there is not a single generally available database that addresses violations or intentional circumvention related causes of low quality in marine structures.

There is not a single available database that addresses the very important near misses. Inclusion of such information in databases on the quality of marine systems could help indicate how design, construction, and operating personnel are able to interrupt potentially catastrophic compounding sequences of problems and bring the system back to a safe condition. If developed and employed on "real time" basis, such information could provide very important early warnings of developing problems with design, construction, and operating systems.

Given the requirement to improve the quality of marine structures and a desire to implement alternative Quality Assurance and Quality Control (QA / QC) strategies in design, construction, and operation of marine structures, there is a pressing need to begin gathering, archiving and analyzing high quality data on HOF error related incidences, causes, and effects. Some organizations have begun such developments. These efforts need to be encouraged and extended.

Information Sources

Given the dearth of reliable quantitative information that is presently available on HOF as they affect the quality of marine structures, analysts are left with four primary sources of information to perform evaluations: 1) judgment, 2) simulations, 3) field, laboratory, and office experiments, and 4) process reviews, accident and near-miss investigations. All of these sources represent viable means of providing quantitative evaluations. It is rare to find a structured and consistent use of these four approaches in HOF assessments.

Simulations in the laboratory, office, or field can provide significant insights into how and when errors are developed. The use of simulators is an important way to "train-out" error promoting tendencies. Simulations and simulators can not replicate the stresses and pressures of real situations because recovery is always possible.

Field and office experiments (examinations) are an important way to gather information on expertise and error tendencies. Such experiments represent samplings of the more general situation being studied. The experiments must be carefully designed to avoid bias in the results.

Process reviews, accident and near-miss investigations also are an important source of information. If carefully and insightfully done, such reviews and investigations can provide important data on errors in situations in which stresses and pressures are high. Legal and punitive threats often provide significant impediments to identifying the contributing, initiating, and compounding causes of these errors. Trained investigators are a "must" in performing such investigations. The use of anonymous accident and near-miss reporting systems have been reasonably successful in developing information on accidents and near-misses.

Judgment is perhaps one of the most important sources of quantitative information. Judgment should not be thought of as the opposite of rational thought. *Qualified* judgment is based upon both the accumulation of experience and a mental synthesis of factors which allow the evaluator to assess the situation and produce results. Judgment has a primary and rightful place in making quantitative evaluations because available data is always deficient for the evaluation of a particular situation.

Given the present situation regarding definitive quantitative information on which to base objective quantitative evaluations of HOF, one must rely primarily on judgment. As adequately structured databases are developed and implemented for HOF evaluations, then in the future, more reliance can be placed on objective data and evaluations based on a combination of data and judgment. It is not likely in the near-term, that sole reliance can be placed on objective data sources to provide quantitative evaluations. Adequately qualified and "unbiased" judgment will be essential to develop meaningful results.

Judgment can be influenced by a variety of types of "bias" (Bea, 1994). These biases distort one's perception of reality. These biases affect the way one interprets the past, predicts the future, and makes choices in the present. These biases or heuristics (rules of thumb) define an evaluator's cognitive structure and dictates the ways things are perceived. These biases must be taken into account as one attempts to quantify HOF.

Quantified Data on Task Reliability

Williams (1988), Swain (1978), Swain and Guttman (1983), and Dougherty and Fragola (1986) have published useful summaries that provide quantified information on task related human errors. This information has been developed primarily for evaluation of HOF effects in the operations of nuclear power plants. The information was developed primarily from experiments and simulations concerning general categories of human task reliability.

Results from the experiments performed by Swain and Guttman (1983) are summarized in Figure 1. Generic human error rates are assigned to general types of tasks performed under general types of influences and impediments. The range of error probabilities are intended to be associated with the potential ranges in the influences and impediments. If the influences and impediments are intense, then the error probabilities will be toward the upper portion of the range and vice versa.

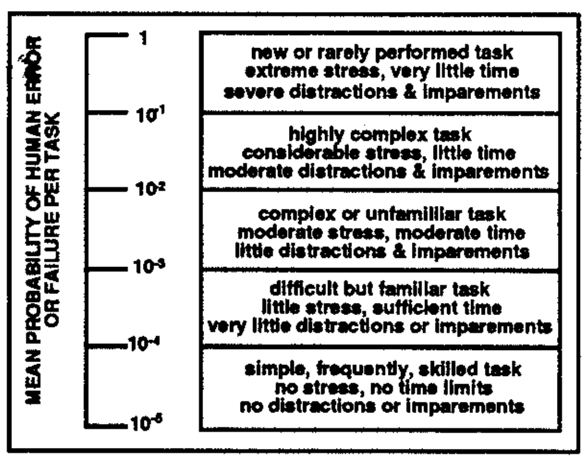

FIGURE 1 - GENERIC HUMAN TASK ERROR RATES

The ranges shown in Figure 1 are intended to define the mean probabilities of a significant or major human error per task performed by the human. The one Standard Deviation ranges associated with generic average rates of human errors have been developed by Williams (1988). The results are summarized in Figure 2. The ranges imply general task performance Coefficients of Variation in the range of 50 % to in excess of 100 %.

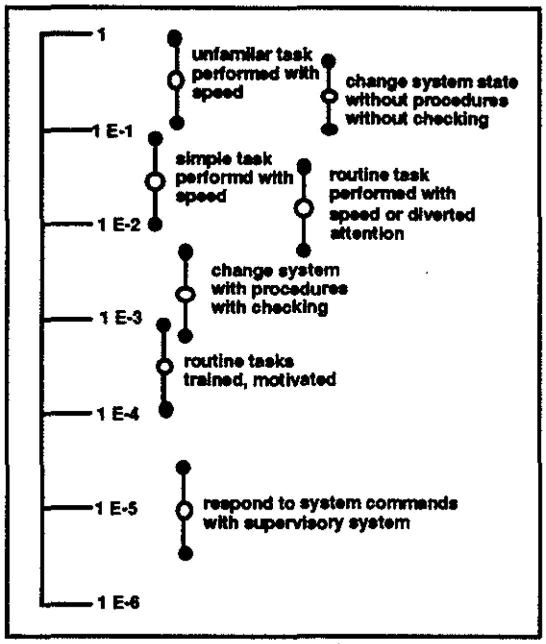

FIGURE 2 - NOMINAL HUMAN TASK PERFORMANCE UNRELIABILITY (O - MEAN; • - ONE STANDARD DEVIATION)

It is important to note that the severity or magnitude of the error is not captured in any of the available quantitative information. Errors are either major and significant or minor or not significant. It is has been noted that minor errors are generally caught by the individual or individuals and corrected; hence their lack of importance in the assessment of human reliability (Swain, Guttman, 1988; Dougherty, Frangola, 1988).

Information also has been developed on human error *performance shaping factors* (Williams, 1988; Swain, Guttman, 1983). These performance shaping factors are influences that can result in an increase or decrease in the mean rates of human errors. Simulations, experiments, and information gathered on plant operations provided this information (Dougherty, Frangola, 1988). The results are summarized in Table 1.

These performance shaping factors are useful in helping one develop quantification of the potential effects of changes in organization, hardware, procedures, and environments on the base rates of human errors.

TABLE 1 - PERFORMANCE SHAPING FACTORS

Error Producing Condition	Multiplier
Unfamiliarity	17
Time shortage	11
Low signal to noise ratio	10
Features over-ride allowed	9
Spatial / functional incompatibility	8
Design model mismatch	8
Irreversible action	8
Information overload	6
Technique unlearning	6
Knowledge transfer	5.5
Performance ambiguity	5
Misperception of risk	4
Poor feedback	4
Inexperience	3
Communication filtering	3
Inadequate checking	3
Objectives conflicts	3
Limited diversity	2.5
Educational mismatch	2
Dangerous incentives	2
Lack of exercise	1.8
Unreliable instruments	1.6
Absolute judgments required	1.6
Unclear allocation of functions	1.6
Lack of progress tracking	1.4
Limited physical capabilities	1.4
Emotional stress	1.3
Sleep cycle disruption	1.2

EVALUATIONS OF HOF

Experience in evaluating HOF in design, construction, and operation of marine systems (Moore, Bea, 1993; Bea, 1994) suggests a four-step approach.

Step #1 is to develop a comprehensive "picture" of the system; to define the system hardware, software, the environments (internal, external) in which it must operate, the organizations that can exert important influences on the system, and the individuals (teams, operators) that can interface with the system. This step should result in logical "diagrams" or layouts of the physical and organizational components of the system.

Step #2 is to develop an understanding of the processes and situations in which the system exists or could exist. The process analysis is intended to define how things work, how they might not work (latent causes of failures) the procedures, premises, and interfaces that can be important to the reliability of the system. It is critical to focus on situational relationships that can result in failures.

Step #3 is to perform evaluations of the system and its processes as they are presently configured. As previously discussed, these analyses can be qualitative, quantitative, and combined. The qualitative methods are intended to identify the most important scenarios that can lead to major compromises in quality. These scenarios then become the focus of the quantitative methods. The objective of these evaluations is to provide insights into the levels of quality that can be achieved and into the likelihood of achieving these levels. Defining potentially hazardous (to quality) situations and "latent" sources of potential failures are important aspects of this step.

Step #4 is to perform evaluations of the reconfigured system and its processes. A variety of practical and imaginative options and alternatives need to be defined. The objective of this step is to understand the potential effectiveness of improvements in the system and processes. This step entails evaluations of the costs and benefits of these options and alternatives and an assessment of the "best" alternative to achieve the desirable and acceptable level of quality in the system and its processes (Bea, et al., 1994; Bea, 1994b).

The most critical ingredient in these evaluations is extensive experience with the particular system. The objective of the evaluations should be to empower those that have the front-line responsibilities for the quality of the system; these are the people with the requisite experience. Expertise in reliability and decision analyses are means to an end, not an end in themselves. "Shallow" evaluations should not be expected to develop useful results; "bad attitudes" and diverted critical resources can be developed from such evaluations.

A second important aspect of the evaluations is to perform them in a progressive and recursive manner. The broad over-view of the system should be developed before one becomes immersed in the details of the system. If this is not done, one tends to become "lost in the weeds" and loose sight of the important aspects of the system. The recursive aspect regards updating the models and evaluations as more experience is gained with the system and with the effects of changes in the system. Such evaluations take significant time to perform.

Another important aspect regards "awareness of critical situations" as contrasted with awareness of the normal physical and procedural aspects of the system. Perverse imaginations and knowledge of how critical situations can arise are important ingredients in HOF evaluations.

EXAMPLE CASE HISTORY

The following example addresses the design of the *Critical Structural Details* (CSD) in a class of commercial tankers (Bea, 1993). The example is based on experiences that span five years in performing Finite Element Analyses (FEA) of CSD (Ma, Bea, 1994; Schulte-Strathaus, Bea, 1993) in these ships.

A CSD is a section of the structure which experiences very high stress concentrations in comparison with the rest of the structure, and therefore requires special attention in the design, construction, and operations phases.

The goal of this example is to illustrate in a simplified way how HOF in FEA and the quality of CSD might be evaluated (Salancy, 1994). The HOF classification system and analytical approach has been documented by Bea (1995).

Background

FEA is a numerical technique to determine the physical responses of a ship structure to imposed loads, moments, and stresses (Hughes, 1988). The use of the FEA techniques became feasible and economical with the advent of high-speed and storage capacity computers which could carry out the thousands of equilibrium calculations required of an FEA model in a reasonable amount of time.

FEA seeks to define a structure "as an assemblage of individual structural elements interconnected at a discrete number of nodes" (Hughes, 1988). In a continuous structure, such as a ship, the choice of what to model as an individual element can be difficult to determine, as continuous panels must be subdivided into separate finite elements for the modeling to work (Ziliotto, et al., 1991).

FEA proceeds through a series of analyses that are intended to *zoom-in* on a particular CSD to determine the local hot-spot stresses (Ziliotto, et al., 1991; Sumi, 1994). First a global analysis of the ship is performed to determine the distribution of loadings through the length of the ship. Next, a section of the ship is identified (e. g. one tank space either side of the area of interest) and the boundary conditions / loadings to be imposed on the ship section determined from the previous step. These boundary conditions are imposed on a coarse finite element model of the ship section of interest. The loadings and displacements are analyzed to determine the loadings and displacements close to the CSD of interest.

These local loadings and displacements are then imposed on a section that surrounds the CSD of interest and a gross finite element model developed of the CSD. Next, detailed fine-mesh FEA are performed on the CSD to determine the stresses (principal, crack opening) that are important to the strength and durability of the detail (Figure 3). The final step is associated with determination of the hot spot stresses associated with each of the important loading conditions (Figure 4).

At the local hot-spot level of the analyses, the choice of mesh size can lead to problems in compatibility which are difficult to detect (Ma, Bea, 1994). Another potential source of problems is the sheer complexity of FEA models (Stear, Paulling, 1992; Xu, et al., 1992). Even simple models of structural details tend to have thousands of individual elements, making a finite element model very complex and, in almost all cases, too large to check by hand calculations.

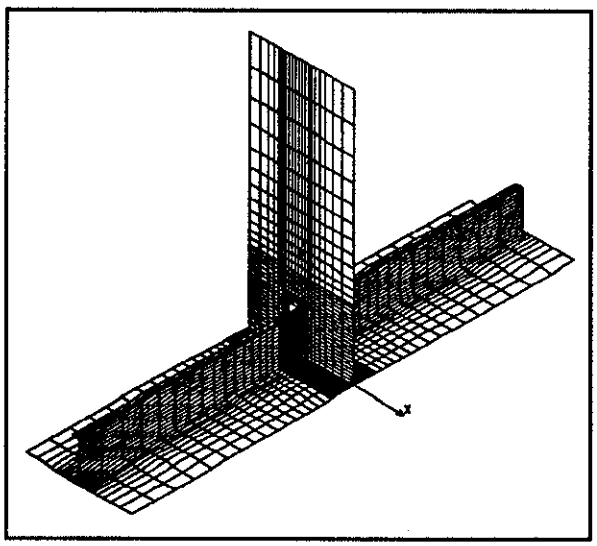

FIGURE 3 - DETAILED FEA OF CSD WITH BOUNDARY CONDITION LOADINGS AND RESTRAINTS

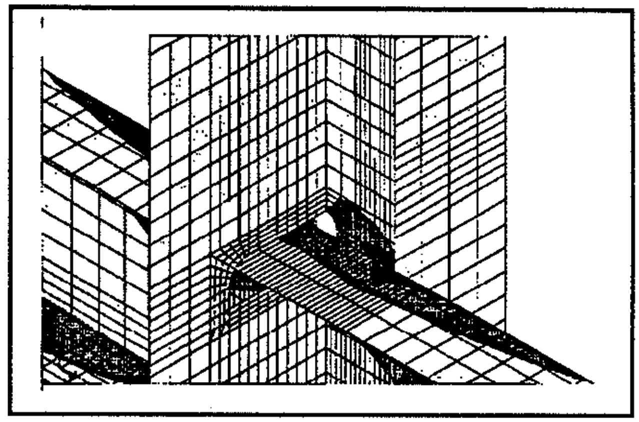

FIGURE 4 - LOCAL HOT SPOT STRESSES IN CSD

FEA is commonly used in the analysis of ship structures to determine the "hot spot" stress ranges in fatigue analysis of CSD (Schulte-Strathaus, Bea, 1993). These hot spots are the areas where the highest stress concentrations are expected to occur, and therefore where fatigue cracking is most likely to initiate. It is this level of FEA that will be addressed in this example.

Common FEA Errors

Mesh Incompatibility. For results to be accurate, the mesh of a finite element model must be compatible from element to element. Where discontinuities in the mesh exist, there are likely to be discontinuities in the stress distribution, which can affect an entire analysis, even when the incompatibility occurs in a low stress area, far away from the point of interest.

The problem in mesh compatibility arises because it is necessary to define "fine" mesh over the area of interest and "coarse" mesh elsewhere. Coarse mesh must be used to reduce computing time to reasonable levels, while fine mesh must be used to obtain a sufficiently detailed analysis of the hot spot area. The problems of mesh compatibility arise in the areas where coarse mesh and fine mesh border. An intermediate mesh is required in these areas. This intermediate mesh supplies connectivity between the fine and coarse mesh nodes so that the stresses and strains determined at these nodes are correctly interfaced. This concept is illustrated in Figure 5.

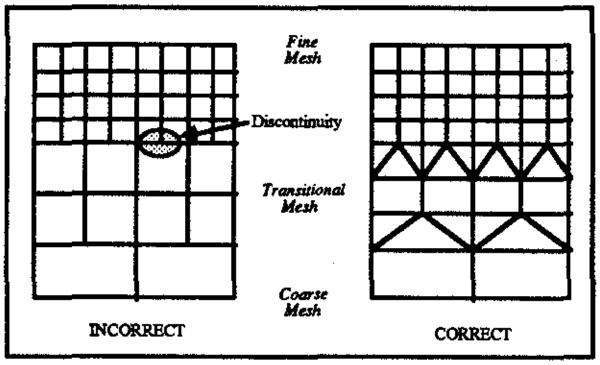

FIGURE 5 - AUTOMATED ADAPTIVE MESHING (INCORRECT) AND CORRECT MESH CONNECTIVITY

Incorrect mesh connectivity is very difficult to detect. Most programs do not have a feature which can detect this type of problem, so incorrect results are returned without warning. One program utilized by Ma and Bea (1994) incorporates "automated adaptive meshing" routines. These routines have hard-wired an incorrect meshing technique that was detected when some "intuitively incorrect" results were developed. Therefore, it is up to the user to visually examine the model for mesh incompatibility. This can be very difficult and time consuming in a complex three-dimensional model. Training, attention to detail, care, and provision of incentives to "be accurate" are critical in preventing errors of this type.

Realistic Modeling. Current FEA packages fall short of perfectly realistic modeling in several ways. FEA programs seek to model three dimensional structures with one and two dimensional elements. This is done because three dimensional elements would require enough nodes to slow down FEA applications to the point of being uneconomical. The use of one dimensional and two dimensional models has drawbacks and risks, however.

Using two dimensional elements can result in a model that accurately represents most aspects of a ship structure. However, some aspects cannot be accurately modeled. Elements which overlap other elements, for example, cannot be accurately modeled. This is a problem in modeling CSD, as "locks" are usually used. These locks are plates which overlap gaps in the CSD.

Another problem in the use of one and two dimensional analysis is the degree of accuracy obtained. It is very difficult to determine how well a non-three dimensional element models the behavior of a three dimensional element, as testing is not possible. It is also difficult for most engineers to anticipate how a one or two dimensional element will behave. This means that errors in the modeling are more difficult to detect.

The FEA models generally are elastic and are thus unable to recognize plastic strains and the accompanying stress redistribution effects. Residual stresses caused by welding and fabrication are generally ignored. Accurate modeling of details such as welds and the characteristics of their heat affected zones is beyond the capabilities of most FEA.

Element Sizing. The choice of relative element size can have an effect on the stresses obtained in analysis. This is due to the averaging effects of the finite element method, as illustrated in Figure 6. Smaller elements will tend to give higher stresses than larger elements in the same area in regions where stress increase with proximity to a discontinuity, such as a joint or angle. The average stress for an element is indicated by a dotted line. It can be seen that smaller elements will give higher stresses. Therefore, the engineer using FEA must be aware of this problem and have an intuitive feel for what a reasonable stress level in the given type of detail would be. An engineer not familiar with this effect may not realize that stress concentrations are high if large elements are used, and may believe stresses are deceptively high if small elements are used.

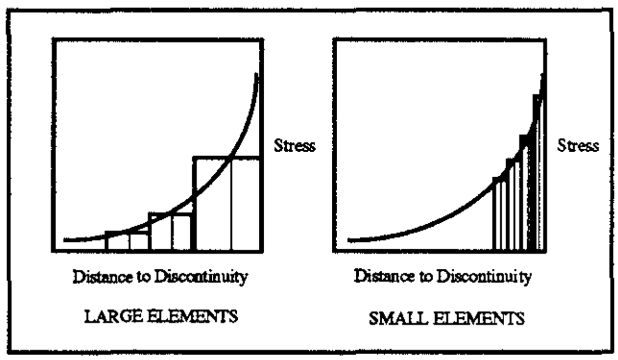

FIGURE 6 - HOT SPOT EXTRAPOLATION STRESS LEVELS AND ELEMENT SIZES

Qualitative Evaluation

Based on the foregoing evaluations of the FEA - CSD system, the next step is to develop a "quality profiling instrument" for the example FEA of CSD (Bea, 1994). This requires identifying the properties of an FEA process which indicate high or low quality and reliability. A FEA quality profiling instrument is shown in Figure 7 together with an evaluation of the FEA process utilized in the example CSD analyses.

Accuracy refers to how well the FEA tool represents the actual structure and its behavior. Correctness refers to the lack of faults or flaws in the procedures. Consistency refers to the repeatability of results for similar problems with different users.

Input Practicality refers to the ease of use of the tool and how difficult or simple it is to model a structure or process. It also refers to the availability of input data. Output refers to the clarity of the answers given by the tool and whether problems are made evident.

Compatibility refers to the ability of the design procedure to be readily integrated into common engineering and naval architecture procedures. Simplicity refers to the degree of complication, intricacy, and difficulty of understanding and using in the context of common engineering and naval architecture procedures.

Intuitive Verification refers to the ability of a user to tell whether answers appear reasonable or not by experience and general scientific knowledge. First Principles Verification refers to the ability of a user to check the accuracy of results by independent and / or "hand" calculations. Empirical Verification refers to the ability to check the results given by the tool by model or full-scale testing.

Procedures organization and documentation refer to the practicality and clarity of the written procedures, the detail and correctness of their documentation and the effectiveness of the information transmission contained in the written procedures.

A tool which has high marks for all of these attributes should give high quality results, as users will understand its workings and recognize any problems, as well as knowing how accurately the tool represents reality. A tool with an indicated low quality is likely to produce designs with undetected problems.

The example FEA process is given an average score for accuracy. Although FEA can be very accurate for plates and simple structures, it loses accuracy when welds and other important details must be included. The problems cited with the automated adaptive meshing routines can lead to significant degradation in accuracy.

Consistency is given a low score because of the high dependence on mesh sizing, which is a function of user experience and judgment and can vary widely with different users.

Input is given a low score because some important points in input are often glossed over in FEA packages, particularly mesh sizing, shortcomings of non-three dimensional elements and the effect of welds and other factors such as nonlinearity in material behavior and residual stresses. Output is given a low score because output is often too complex to check thoroughly, resulting in users "drowning in numbers". Problems can easily go unnoticed.

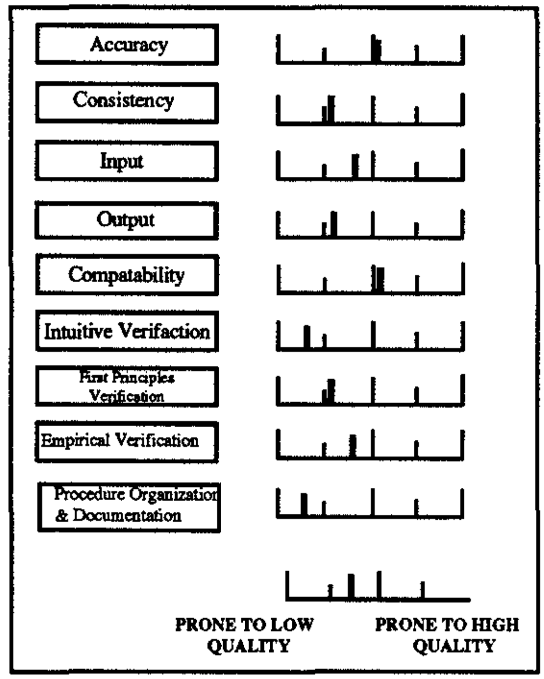

FIGURE 7 - QUALITY PROFILE FOR EXAMPLE FEA OF CSD

Compatibility / Simplicity is given an average score because the FEA can be merged reasonably well with common engineering procedures used to design ship structures.

Intuitive Verification is given a low score because the example users do not have a feel for how a one- or two-dimensional structure will behave. Users are also ignorant of exact stress values that should be expected in CSD.

First Principles Verification is given a low score because it is nearly impossible to check even a small section of a structure by hand, as boundary conditions are not known. Simple beam analysis is usually the best method of checking available, and this gives only an order of magnitude comparison.

Empirical Verification is given a low score because actual testing would require a full-scale model and a very large number of strain gauges. Such testing was not done, and in general, is a rarity in this industry [Schulte-Strathaus, Bea, 1993].

Documentation is given a low score because of the absence of definitive guidelines and procedures to perform FEA of CSD. The example FEA computer program documentation is a "nightmare." Unnecessary complexity, incompleteness, and errors in the documentation abound.

The overall quality profile of the example FEA of the example CSD is that it is prone to low quality, i.e., it is likely to result in designs with undetected quality problems.

The qualitative evaluation defined four major categories of the FEA process that were prone to HOF. These categories and their components are summarized in Table 2. The identification of human and organization errors follows the classification system developed in a companion paper (Bea, 1995).

TABLE 2 - HOE FACTORS IN EXAMPLE FEA OF CSD

I. MESH COMPATIBILITY
Human Error, Ignorance
Human Error, Slips
II. MODELING
Organizational Error, Ignorance
III. ELEMENT SIZING
Human Error, Ignorance
Human Error, Selection and Training
IV. ANALYSIS
Human Error, Ignorance
Human Error, Selection and Training

Errors in mesh compatibility are judged to be the product of ignorance (users who do not understand how to correctly form the mesh to pick up stress concentrations) and slips (users who accidentally define a mesh with discontinuities).

Modeling errors are expected to be due to organizational ignorance; organizations which do not realize the approximations and assumptions implicit in modern FEA, including dimensionality and welds, and promote it as a universally accurate and applicable tool for CSD design.

Element sizing errors are expected to be due to ignorant (users who do not understand how to properly size for relevant concentrations) and selection and training (users who can not recognize a reasonable or unreasonable stress result in FEA of CSD).

Errors due to analysis factors are also considered to be errors of ignorance (users who are unaware of the shortcomings of the specific FEA package in approximating the stress-strain relationship) and selection and training (users whose background does not give them a feel for what reasonable values are and what the implications of a linear approximation of the stress-strain relationship can be).

Quantitative Analysis - Original System

The quantitative analysis formulation developed by Bea (1995) was used in this example (HOF errors combined as unions and intersections of the events).

A baseline error rate must be established for each HOF in the example. All of the errors are ones that may be expected to occur under normal conditions. These errors fit the category of "Errors of commission such as operating the wrong button or reading the wrong display" (Williams, 1988). Based on this information, the base rate for individual (human) and organization induced FEA errors during the design phase were assigned a likelihood of 10^{-3} (Figures 1 and 2).

The probabilities of human and organization errors being present in the FEA in this segment of the analysis are summarized in Table 3.

Quantitative Analysis - Re-configured System

The reconfiguration of the system to reduce the likelihood of errors in FEA is based on two measures: increased QA / QC and organizational changes in management of FEA (Roberts, Bea, 1995). These measures are described for each factor in the following paragraphs.

Factor I can be improved chiefly by concentration on training in the proper usage of FEA. When users understand the issues involved in defining mesh -- the problems of discontinuities, the calculation time involved in coarse mesh, etc. -- they will be much less likely to create a model with mesh problems, as well as being more likely to catch errors in mesh in existing models. Defining a standard method for mesh creation would have a very good effect on consistency. It would also improve the effectiveness of checking, as all users would be basing their mesh on the same principles. Development of standard practices can be of great value in improving quality.

Changes in Factor II would rely on an organization-wide change in the engineering management of FEA. The shortcomings of FEA in modeling physical structures and behavior must be realized and incorporated into the use of FEA. Complete reliance on FEA is unreasonable, and the organization must communicate this attitude to the users of FEA. Making this change in the engineering management "culture" would be difficult.

Factor III would be improved by QA / QC focus on education of FEA users on the limitations of FEA in representing details, particularly the relation between element size and stress concentration values. Users would also benefit from a background on what are reasonable values and what are not. Standard guidelines would be very helpful in reducing this problem, as guidelines could detail how mesh should be handled in areas of importance where stress concentrations may be affected by element sizing.

Factor IV would be best handled in the same manner as Factor III; by a concentration on teaching users what the limitations are in linear analyses, how they can be recognized, avoided or circumvented.

Given these changes, the system is analyzed in its re-configured format. The probabilities of occurrence were changed based on the results summarized earlier (Figures 1 and 2, Table 1). The changes in the probabilities of occurrence and the final results are summarized in Table 3.

TABLE 3 - SUMMARY OF RESULTS FROM FEA OF CSD EXAMPLE

FACTOR I : MESH COMPATIBILITY		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Ignorance	*0.50*	*0.10*
P Slips	*0.50*	*0.25*
P Error - Ignorance	5.00E-04	1.00E-04
P Error - Slips	2.50E-04	2.50E-05
Total P Error	7.50E-04	1.25E-04
Net Change		**83%**
FACTOR II : MODELING		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Ignorance	*0.50*	*0.10*
P Error - Ignorance	5.00E-04	1.00E-04
Total P Error	5.00E-04	1.00E-04
Net Change		**80%**
FACTOR III : ELEMENT SIZING		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Ignorance	*0.50*	*0.10*
P Selection and Training	*0.50*	*0.25*
P Error - Ignorance	5.00E-04	1.00E-04
P Error - Selection	2.50E-04	2.50E-05
Total P Error	7.50E-04	1.25E-04
Net Change		**83%**
FACTOR IV : ANALYSIS		
Baseline Error Rate	*1.00E-03*	
	As Configured	As Re-configured
P Ignorance	*0.50*	*0.10*
P Selection and Training	*0.50*	*0.25*
P Error - Ignorance	5.00E-04	1.00E-04
P Error - Selection	2.50E-04	2.50E-05
Total P Error	7.50E-04	1.25E-04
Net Change		**83%**

Results

In the original system, the total probability of an significant error in the FEA during the design of the CSD was estimated to be 3 E-3.

After the design FEA system reconfiguration, the probability of a significant error in the FEA during the design of the CSD was estimated to be 5 E-4. The improvements in the FEA CSD design system resulted in about an 80 % reduction in the likelihood of a major error.

The next step in the evaluation process would be to evaluate the costs associated with the improved system and determine if they were warranted and could be justified to management (Bea, 1993b; 1994; Bea et al., 1994).

CONCLUSIONS

The objective of this paper has been to illustrate how HOF qualitative and quantitative evaluations can be performed to identify potential weak links and critical flaws in design processes. The purpose of these evaluations is to help produce insights into how quality in marine structures might best be improved and to promote communications among those responsible for the quality of such structures. The purpose of the analyses is to encourage a comprehensive evaluation of the "system" including its human, organization, hardware, procedure, and environmental aspects.

The purpose of these analyses is not to produce numbers. The purpose of these analyses is to help empower those who have front-line responsibilities for the quality of marine structures to improve the quality of such structures how, where, and when it is needed.

The research on which this paper has been based (Bea, 1989; 1994) indicates that the fundamental problem in improving the quality of marine structures is not knowing what to do. The fundamental problem is not doing what experience has shown we should not do. Qualitative and quantitative evaluations of marine systems should provide structured and disciplined frameworks to help evaluate when and how best to improve the quality of marine structures.

REFERENCES

Bea, R. G., 1989, "Human and Organizational Error in Reliability of Coastal and Ocean Structures," *Proceedings of the Civil College Eminent Overseas Speaker Program*, Institution of Engineers, Australia, Barton, ACT, December.

Bea, R. G., 1993, "Ship Structural Maintenance: Recent Research Results and Experience," *Transactions of The Institute of Marine Engineers*, Vol. 105, Part 5.

Bea, R. G., 1994a, "The Role of Human Error in Design, Construction, and Reliability of Marine Structures," *Report SSC - 378*, Ship Structure Committee, Washington, D. C.

Bea, R. G., 1994b, "Evaluation of Alternative Marine Structural Integrity Programs," *Marine Structures*, Vol. 7, Elsevier Science Limited, England.

Bea, R. G., et al., 1994, "Quality Assurance in Design, Construction, and Operation of Marine Structures," Report of Committee V.2, *Proceedings 12th International Ship & Offshore Structures Congress*, St. Johns, Newfoundland, Canada.

Bea, R. G., 1995, "Quality, Reliability, Human and Organization Factors in Design of Marine Systems," Proceedings of the 14th International Conference on Offshore Mechanics and Arctic Engineering, Paper OMAE 95 1232, Copenhagen, Denmark.

Brown, C. B, Chameau, J. L., Palmer, R. and Yao, J. P. T. (Editors), 1985, *Proceedings of National Science Foundation Workshop on Civil Engineering Applications of Fuzzy Sets*, Purdue University, West Lafayette, Ind.

Dougherty, E. M., Jr., and Fragola, J. R., 1986, *Human Reliability Analysis*, John Wiley & Sons, New York, 1986.

Gale, W. E., Jr., Bea, R. G., Williamson, R. B., 1994, "FLAIM, Fire and Life Safety Assessment and Indexing Methodology," *Final Report to U. S. Dept. of Interior, Minerals Management Service, Tech. Assessment and Research Branch*, Dept. of Civil Engineering, University of California, Berkeley, CA.

Hughes, O. F., 1988, *Ship Structural Design : A Rationally-Based, Computer-Aided Optimization Approach*, The Society of Naval Architects and Marine Engineers, Jersey City, NJ.

Ma, Kai-tung, and Bea, R. G., 1994, "Calibration and Verification of S-N Curves for Repaired Critical Structural Details," *Report to Joint Industry Sponsors, Report SMP III-1-1*, Dept. of Naval Architecture & Offshore Engineering, University of California, Berkeley, CA.

Mason, E., Roberts, K. H., and Bea, R. G., 1994, "Marine Human and Organizational Error: A Data Evaluation," *Report to Sea Grant Program on Project RO/E 28*, Haas School of Business, University of California, Berkeley, CA.

Nagendran, R., 1994, "Modeling the Assessment of Human Factors and Safety in the Marine Transportation System," *Thesis*, Dept. Of Civil Engineering, Virginia Polytechnic Institute and Sate University, Aug.

Moore, W. H., and Bea, R. G., 1993, "Management of Human Error in Operations of Marine Systems," *Report No. HOE-93-1, Final Joint Industry Project Report,* Dept. of Naval Arch. and Offshore Engrg., University. of California, Berkeley, Dec.

Orisamolu, I. R., and Bea, R. G., 1993, "Reliability of Offshore Structural Systems: Theory, Computation, and Guidelines for Application," *Report to Engineering Branch, Canadian National Energy Board,* Calgary, Alberta, Canada.

Roberts, K. H., and Bea, R. G., 1995, "Organization Factors in the Quality and Reliability of Marine Systems," *Proceedings of the 14th International Conference on Offshore Mechanics and Arctic Engineering,* Paper OMAE 95 1231, Copenhagen, Denmark.

Salancy, A., 1994, "The Roles of Human Errors in Design, Construction, and Reliability of Marine Structures," *Graduate Student Research Report (NAOE 299),* Dept. of Naval Architecture & Offshore Engineering, University of California, Berkeley, CA.

Schulte-Strathaus, R. and Bea, R. G., 1993, "Development of Calibrated S-N Curves and System for the Selection of S-N Curves," *Report to Joint Industry Project on Fatigue Classification of Critical Structural Details in Tankers, Report No. FACTS-1-1,* Dept. of Naval Architecture & Offshore Engineering, University of California, Berkeley, CA.

Stear, J., and Paulling, J. R., 1992, "Structural Analysis and Loadings," *Report to Joint Industry Project Structural Maintenance for New and Existing Ships,* Report No. SMP 3-1 (Vol. 1 and Vol. 2), Dept. of Naval Architecture and Offshore Engineering, University of California, Berkeley, CA.

Sumi, Y., et al., 1994, "Two-Phase Finite Element Comparative Study of a Side Structure of a Middle Size Tanker," *Report to ISSC by Committee II.*1, Yokohama, Japan.

Swain, A. D. & Guttman, H. E., 1983, "Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications", *NUREG/CR-1278,* U. S. Nuclear Regulatory Commission, Washington, D. C.

Swain, A. D., 1978, "Estimating Human Error Rates and their Effects on System Reliability," *Sandia Corporation Report SAND-1240,* Albuquerque, New Mexico.

Williams, J. C., 1988, "A Data-Based Method for Assessing and Reducing Human Error to Improve Operational Experience," *Proceedings of IEEE, 4th Conference on Human Factors in Power Plants,* Monterey, CA.

Xu, T., Paulling, J. R., and Bea, R. G., 1992, "Study of Critical Structural Details," Study 3 - Interaction of Details with Adjacent Structures," *Report to Joint Industry Project Structural Maintenance for New and Existing Ships, Report No. SMP-3-2,* Dept. of Naval Architecture & Offshore Eng., University of California, Berkeley, CA.

Xu, T., and Bea, R. G., 1992, "Reliability Evaluation of Existing Platforms Based on Fuzzy Set Theory," *Proceedings of the Second International Offshore and Polar Engineering Conference,* San Francisco, CA.

Yager, R. R. And Zadeh, L. A., 1994, *Fuzzy Sets, Neural Networks, and Soft Computing,* Van Nostrand Reinhold, New York, NY.

Ziliotto, F., et al., 1991, "Comparison of Different Finite Element Analyses of the Transverse Frame of a 350000 DWT Tanker," *Marine Structures,* Vol. 4, Elsevier Science Publishers, Ltd., England.

Zimmermann, H. J. (1991). *Fuzzy Set Theory and Its Applications,* Kluwer Academic Publishers, London.