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Assuring Quality and Reliability of Ship Structure Finite Element Analysis

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Abstract

The finite element method is widely used in the analysis of ship structures and, in common with any powerful tool, the opportunity exists for misuse. As a result the quality of finite element analyses (FEA) can be quite variable. This paper addresses the issue of assuring the quality of FEA of ship structures. Aspects relating to quality assurance (QA) of FEA are reviewed, including the procedures used in conducting FEA, software, and the human element.

The primary contribution of this paper is an assessment methodology for FEAs. While the primary audience are those responsible for evaluating FEAs conducted by others, the methodology can equally be used by analysts. The methodology is systematic and flexible, and can accommodate a wide range of size of FEAs. In addition, the methodology can be used by personnel with varying levels of skill in FEA.

Software quality is a broad issue and only a particular aspect is addressed in this paper. A series of benchmarks are proposed for assisting in establishing the engineering validity of the software. Such benchmark problems can be used for assessing new, or significantly modified, software.

1. Introduction

The finite element method is fast becoming the tool of choice for analyzing ship structures. While FEA has been used for analyzing special problems for perhaps a generation, it is only within the last decade that it has entered the mainstream design environment and been utilized routinely. There are several reasons for this trend. Principal among these is the move towards modern design methods based on first principles. This requires, among other things, a more explicit expression of the ships structural capability.

Finite element analysis is used at various levels in ship structural analysis and design. At the most global level finite element models, of vary degrees of sophistication and detail, are used to compute the response of the hull girder to wave loads. At the intermediate level, FEA is employed to determine stresses in stiffened plate assemblies, frames, beams and girder systems. Local FEA is used to compute peak stresses for fatigue and fracture analysis. Hence, the scale at which FEA is applied varies enormously.

In parallel with the trends outlined above computer technology has become less expensive and therefore more accessible. While great advances have taken place in computer software and hardware, certain aspects of FEA have lagged. Two of the most important of these aspects are:

1. Lack of standards and guidelines for FEA,

2. Lack of design criteria appropriate to FEA.

The latter is a subject of research in its own right, and is not discussed here.

Well established design methods are normally supported by standards, guidelines and conventions. These ensure a certain uniformity in application. In the case of newer design methods, or design methods that rely on new analysis techniques, such standards, guidelines and conventions are generally absent. Where they are available they are scattered, rarely complete or comprehensive, and there is a lack of consensus on the application of the method concerned.

Superficially FEA is a numerically precise technique. However, for the method to be applied cost effectively several compromises have to be made, the consequence of which is a less than ideal, although potentially acceptable, result. The quality of the FEA depends critically on the skill of the analyst. This is perhaps less the case when applying the simplified formulae used in traditional design approaches.

The deficiencies and difficulties outlined above have led to a high degree of variability in the quality of FEA in the marine and, indeed, in other industries. The elements that determine the quality of a FEA are many and varied. While this paper addresses the broad question of quality of FEAs the primary purpose of the paper is to present a methodology developed for assessing the quality of FEAs and FEA software. The methodology was developed as part of a project, sponsored by the Ship Structure Committee (1), on guidelines for evaluating ship structure finite element analysis.

Several valuable contributions have been made by other organizations and industries in the broad area of guidelines for the application of the finite element method. Examples include guidelines published by the National Agency for Finite Element Methods and Standards (2) and the American Society of Civil Engineers (3), and application-oriented texts by Brauer (4) and Steele (5). In the context of marine structures a useful review on the subject was published by the International Ship and Offshore Structures Congress (6).

2. Problems in Assuring the Quality of FEA

Several factors are responsible for the overall quality of a FEA. In broad terms these can be categorized as follows:

- Information,
- Technique,
- Tools,
- Personnel.

Figure 1 summarizes the interaction of these processes.

The information upon which an analysis is based needs to be complete and accurate. This includes a clear understanding of the objectives of the analysis, the data required to build the engineering model and the finite element model.

The techniques used to build the engineering and the finite element models need to be consistent with the objectives of the analysis, and cognizant of the limitations of the finite element method and of the software employed. This also applies to the exercising of the model and interpretation of the results. The degree to which appropriate techniques are applied depends largely on the training and experience of the analyst.

The right tools for the job are required. The primary concern in this category is the software employed. FEA software packages are complex systems which can never be guaranteed to be free of errors. Reputable vendors go to considerable lengths to verify and validate their products but there is a limit to what can practicably be achieved. Modern computer hardware is generally very reliable and rarely, if at all, of concern for FEA quality.

The personnel who conduct, and check, FEAs need to be appropriately trained and experienced. Only an experienced analyst can identify the information required for an analysis, assess its quality, and use it to undertake an analysis in a cost effective manner. The present state-of-the-art of ship structural analysis is such that a considerable measure of judgment is required of the analyst in striking a balance between accuracy and cost.

Each of the above elements are discussed in more detail below.

2.1 The Process of FEA

There are several phases in a FEA:

- Planning and Preparation,
- Development of the Engineering Model,
- Construction of the Finite Element Model,
- Exercising the Finite Element Model,
- Interpreting the Results.

The overall quality of the analysis depends upon the proficiency with which each phase is conducted.

A characteristic of the FEA process in that errors tend to be cumulative. Poor decisions made early in the process have far reaching consequences on the results. Furthermore, it is not always apparent that a poor modeling decision has been made. Therefore fundamental to any approach to assure the quality of a FEA is that all the decisions are made proficiently. Since numerous such decisions are made and since, except for a few cases, guidance cannot be numerically precise, a thorough systematic methodology is required. In certain cases the guidelines can be quantitative even if not precise. In other cases the guidelines can be in a form that encourage certain thought experiments which, when followed, should lead to sound decisions. In some cases the influence of varying selected modeling parameters on the result can be presented concisely as these can be useful guides.

There are several tasks that need to be undertaken in preparation for a FEA. The job specification needs to be clear and comprehensive such that there is no uncertainty in regard to the objectives and scope of the analysis. This must be supported by the appropriate documentation in the form of drawings, reports, standards etc. The tools, in terms of hardware and software, need to be adequate for the job. It is essential that the analysis, and its checking, be performed by personnel that are suitably trained and experienced.

While development of the engineering model is common to all structural analysis techniques it is a more explicit process as a precursor to a FEA. Several far reaching decisions are made at this stage. Errors at this stage can rarely be recovered at a later stage. The key decisions made concern the following:

Performance assumptions (e.g.. static, dynamic)

- Purpose of analysis,
- Extent of model,
- Level of detail,
- Material behavior (e.g.. linear, elastic etc.),
- Load modeling.

The construction of the finite element model comprises numerous decisions and typically belong in the following categories:

- Element types,
- Mesh design,
- Loads and boundary conditions,
- Solution options and procedures.

A primary requirement for this phase of the analysis is a complete understanding of the limitations of the finite element method in general, and the finite element formulations and assumptions in the finite element software in particular. Again, as in the development of the engineering model, the quality of this phase of the analysis is best achieved by applying guidelines which can range from quantitative recommendations to more general qualitative advice. Where possible these guidelines should be supported by examples that illustrate the effect on the quality of results of varying various modeling parameters. Prime examples include mesh density, element shape and element size transitions.

Once the finite element model has been built it is necessary to exercise it to obtain the required results. While the solution process is an automated process there are several decisions to be made in this phase which affect quality. FEA software often have default options that may be overlooked with unknown influence on the results. When alternative solution techniques are available, particularly in dynamic analysis, it is important to ensure that the solution technique selected is consistent with the modeling assumptions made.

The summary of the FEA process shows that a large number of factors have to be considered in undertaking a FEA. Unlike traditional methods of structural analysis certain elements of the FEA process are transparent to the analyst.

Guidelines can provide a systematic approach to assessing the many aspects of FEA that contribute to quality. At their simplest, guidelines can act as reminders which is an important feature in view of the large number of factors to be considered.

2.2 Software Quality

There are potentially several sources of uncertainty in the results of FEA that can be attributed to software. Software QA is a broad subject all aspects of which cannot be adequately treated in this paper. Hence, the question of software design, testing and maintenance are not covered here, although these are important subjects within the domain of software QA. The subject of primary interest here is the question of the engineering validity of the software.

Engineering validation concerns the ability of the FEA software to deliver results of an acceptable accuracy with reasonable effort. There are several elements in the validation of FEA software including :

- Element performance,
- Mesh design,
- Solution methods,
- Stress averaging and extrapolation.

A common method for assuring the validity of FEA software is to run a large number of tests for simple structures and components. Most such tests are for configurations for which closed form solutions are available. Therefore the configurations tested are necessarily simple and regularly shaped. The finite element models for these configurations are similarly uncomplicated. Such models usually have regular geometry, elements that do not deviate too much from the ideal, simple loading conditions etc. This is not to say that such tests are not valuable. They are essential as one element in the validation process.

Another component of the validation process are tests at the element level. Elements, which perform perfectly well when ideally shaped, can behave quite poorly when irregularly shaped. Again, while this is an important part of the validation process, it is outside the scope of this paper.

The type of tests outlined above are generally not representative of typical usage for ship structures. Ideally, the testing of the validity of FEA software would involve comparisons of results from a large number of full-scale experiments on typical ship structures and results from FEAs of these structures. Apart from being prohibitively expensive there are many practical problems. Actual physical structures deviate from the ideal. In general plates are not flat, thicknesses are variable, stiffeners may have significant degrees of twist, etc. These, and other deviations from the ideal, could have an influence on the response complicating comparisons. For these reasons there would always be a degree of uncertainty associated with the results. Despite these remarks such tests are useful if the uncertainty in the process is recognized.

An alternative validation approach is to develop benchmark analyses that fall somewhere in between the two extremes described above. Models representing typical structural assemblies in ships, loaded and supported in an appropriate manner could be used as benchmarks. The approach would be to analyze these benchmark models using a number of well established commercial FEA programs. Ideally the displacement and stress results would be identical. Where they are not the differences would have to be rationalized.

This approach is appealing for the following reasons:

1. Benchmark problems more closely represent the way FEA would be used in ship structural analysis. The problems would, in general, include:
   - Different element types in the same model,
   - Element shapes that deviate from the ideal,
   - Multiple load cases and mixed load types,
   - Mixed boundary conditions,
   - Special features such as multi-point constraints.

These features are often absent in typical verification examples.

2. The benchmark problems need not be large and the basic input data could be made available in a convenient form such that new, or significantly modified, FEA programs can be easily assessed.

2.3 The Human Element

In common with most powerful tools the opportunity to abuse and misuse FEA is great. The power of FEA has been enhanced with the provision of pre- and post-processors in FEA software, both of which greatly ease the work of the analyst. However, this convenience is accompanied by several dangers. While the analyst can be warned against some of these dangers, for example by consulting guidelines or by heeding warning messages generated by the software, the overall quality of the analysis is ultimately dependent on decisions made by the analyst.

The first commercial FEA software packages were cumbersome to use. The preparation of input data was tedious and error prone as was the interpretation of the results which usually came in the form of reams of numbers. The graphics capability of FEA software was rudimentary if it existed at all.

This aspect of FEA has improved tremendously with the development of very capable pre- and post-processors with extensive use of graphics. These are now used routinely in FEA. The building of finite element models is now automated to a significant degree. Meshes are generated, and loads and boundary conditions assigned with a minimum of human intervention. Similarly, the results from a FEA are processed to ease interpretation. This typically involves the presentation of stresses averaged in some fashion. Most FEA software contains facilities to warn the user if good practice has been violated. These improvements have certainly made the job of the analyst easier.

In contrast to the early days of FEA when the analyst was regarded as a specialist, the ease with which FEA software can now be used has allowed analysts without the appropriate levels of training and experience to be employed on FEA projects. Post-processed results can be misleading for an inexperienced analyst. Stress results are averaged in some fashion and presented as smooth contours. These can conceal large differences in stress from element to element.

When tools, such as modern FEA, become easy to use the human element becomes even more important. The role of human error in activities such as FEA does not appear to have been investigated. However, as part of research into structural failures, the role of human error in structural design has. There are several similarities in the structural design process and the FEA process, which often is an element of structural design, that suggest the lessons from the research are relevant to FEA QA.

Based on surveys by several researchers Melchers (7) notes that human error is involved in the majority of recorded structural failures. Some researchers have attempted to categorize the factors involved in the failures. One such example quoted by (7) and adapted from work by Matousek and Schneider (8) is presented in Table 1. The data shows that the human factors most prevalent in failures concern lack of knowledge, negligence and carelessness. When the data is considered together with other similar data it is clear that the dominant factors are related to deficiencies in training and experience.

Human error is, of course, a fact of life. In recognizing this several strategies are applied to reduce the incidence of errors. Table 2 taken from (7) identifies the main strategies in the structural design environment. Again, there is good reason to assume they apply equally to FEA. Melchers notes that by far the most successful strategy in reducing human error is by external checking and inspection. In order to minimize errors occurring in the first place, investment is best directed at education and training of analysts. In order to mitigate errors that are committed, checking is the most cost effective strategy.

3. Methodology for Quality Assurance of FEAs

The previous discussion outlined the requirements for a methodology to assure the quality of ship structure FEAs. To be practical and effective, the methodology should exhibit the following characteristics :

- Systematic,
- Easy to use and allow rapid assessment,
- Flexible to accommodate the range of analysis procedures, types of elements, model sizes, boundary conditions, loads, etc. encountered,
- Provide check lists, or the equivalent, to ensure all appropriate aspects have been evaluated,
- Use quantitative criteria wherever possible,
- Provide additional details or guidance that the evaluator can refer to when required.

In response to this requirement, a FEA QA methodology consisting of two main parts has been developed:

1. Assessment Methodology for Evaluating FEAs,
2. Benchmark Problems for Evaluating FEA Software.

The following sections describe the FEA assessment methodology and benchmark problems for ship structures.

3.1 A Proposed Assessment Methodology

The methodology developed for assessing FEAs of ship structures is summarized in Figure 2. The primary audience for this methodology is evaluators of FEAs, however it is structured such that it could also be used by analysts to guide the process for FEA modeling, results interpretation and documentation. The guidelines assume that the evaluator is trained in ship structural analysis and design, but is not necessarily expert in FEA.

The assessment methodology is organized in three levels:

1. Level 1 comprises a flowchart with high level check lists of attributes of the FEA that need to be evaluated as part of the quality assessment process. The flowchart guides the evaluator through the various steps involved.
2. Level 2 comprises detailed check lists for each of the high level attributes identified in the Level 1 flowchart. The Level 1 flowchart can be regarded as a summary of the Level 2 assessment.
3. Level 3 contains guidelines on recommended or acceptable finite element modeling practice. The guidelines are cross referenced with the Level 2 check lists. During the assessment process the evaluator may, if required, refer to Level 3 guidelines for advice.

The highest level (Level 1) addresses general attributes of the FEA broken down into five main areas as identified in each of the five main boxes shown in Figure 3. They include :

1. Preliminary Checks : These checks are to ensure that the analysis documentation is complete, the requirements of job specification (statement of work, etc.) have been properly addressed, the FEA software used is properly qualified or validated for the application, and that the contractor / analyst is appropriately trained and qualified for FEA and is sufficiently experienced with the FEA software.

2. Engineering Model Checks : These checks are to ensure that the assumptions used to develop the engineering model (idealization of the physical problem) are reasonable. They include checks of the type of analysis (e.g.. linear, static, dynamic, etc.), assumptions of the geometry, material properties, stiffness and mass properties, choice of dynamic degrees of freedom, loads and boundary conditions.

3. Finite Element Model Checks : These checks are to ensure that the finite element model is an adequate interpretation of the engineering model. They include checks of the types of elements employed to model the structure, the design of the finite element mesh, the use of substructures or submodels, the loads and boundary conditions applied in the FE model, and the software options used to solve the model.

4. Finite Element Results Checks : These checks are to ensure the finite element results are calculated, post processed and presented in a manner consistent with the analysis requirements. They include checks of solution warnings and error messages, calculated mass and reaction forces, post processing methods (including calculation of stresses, safety factors, results smoothing or extrapolation procedures, etc.), and checks of displacement, stress and frequency results.

5. Conclusions Checks : These checks are to ensure that adequate consideration of the various criteria are included in arriving at the conclusions from the FEA. They include considerations of the accuracy of the applied loads, the strength or resistance of the structure, the acceptance

criteria, the accuracy of the FE model and results, and the overall conclusions and recommendations of the analysis.

As indicated above, each of the five highest level attributes are divided into four to six Level 2 sub-attributes to be checked. The Level 2 sub-attributes are presented in detail in separate tables that form the core of the evaluation process. The Level 2 tables contain many detailed questions regarding specific aspects of the FEA. An example Level 2 table is shown in Figure 4.

The Level 2 tables include spaces for the evaluator to enter comments regarding specific and overall aspects of the FEA. At the end of the evaluation process, these comments will provide the evaluator with reminders of aspects of the FEA that were not acceptable, or not explained well. The evaluator may refer to these comments to seek further explanation or clarification from the contractor / analyst before deciding on the final acceptability of the FEA.

Each question in the Level 2 tables includes a reference to a specific section in the guidelines (Level 3) should further explanation or guidance be necessary. The guidelines include a comprehensive description of good FEA practice. As a further aid to the assessment methodology, several example FEAs, typical of ship structures, are included to illustrate the influence of various model parameters on the results.

Specific use of the assessment methodology begins with the *"1 - Preliminary Checks"* contained in Box 1 of Figure 3. The evaluator proceeds by completing each Level 2 table referred to in this box (i.e.. *1.1 Documentation Requirements, 1.2 Job Specification, 1.3 FEA Software,* and *1.4 Contractor/Analyst Qualifications).* As each Level 2 table is completed, the evaluator enters the results in the corresponding box in the Level 1 flowchart. After completing all of the Level 2 tables for "*1 - Preliminary Checks*", the flowchart asks the evaluator if "*Preliminary checks are acceptable?*". The evaluator should check the "*Yes*" or "*No*" box below this question based on the results of the corresponding Level 2 checks. If the answer is *"No"*, then the FEA is very likely not acceptable since it does not meet certain basic requirements. The evaluator may therefore choose to terminate the evaluation at this point. Otherwise, the answer is "*Yes*" and the FEA has passed the preliminary checks and the evaluator is instructed to proceed to the next major aspect of the evaluation, entitled *"2 - Engineering Model Checks*".

The evaluation process continues as described above for each of the five main areas identified in Figure 3. At the end of this process, the evaluator will check either the oval box entitled *"FE analysis is Acceptable"*, or the one entitled *"FE analysis is Not Acceptable"* depending on the outcome of the checks.

The methodology is structured to allow the evaluator to apply the methodology at the appropriate level of detail. For simple FEAs, an experienced evaluator can probably perform the assessment without having to refer to all of the Level 2 check lists.

Ideally the assessment methodology and guidelines would be provided as part of the job specification to the analysts. The Level 1 and 2 check lists could then be viewed as acceptance criteria for the work. This will encourage self-checking and ensure that the data provided by the contractor to the customer is complete.

3.2 Ship Structure Benchmarks for Assuring FEA Software Quality

The assessment methodology presented in the previous section includes a requirement that FEA software be qualified as suitable for ship structure analysis. To this end, several benchmark problems that test the ability of software to provide accurate solutions for assemblies typical of ship structures have been developed.

The benchmarks problems involve simple configurations of a number of representative ship structures, but are detailed enough to retain the key characteristics of the structural assembly or detail. The ship structure FEA benchmarks include the following:

1. Reinforced Deck Opening,
2. Stiffened Panel,
3. Vibration Isolation System,
4. Mast,
5. Bracket Detail.

Figure 5 summarizes the main modeling and analysis features that the benchmarks are intended to test. The problems typically require that several types of elements, materials, and loads be used in combination. The benchmark FEA models are limited in size to 200 nodes or elements (1200 degrees of freedom). An attempt has been made to design the benchmarks such that, collectively, most key features that determine the validity of FEA packages for ship structural analysis are tested.

The benchmarks do not have closed form theoretical solutions. Instead, the results from analyzing the benchmark problems obtained using three well known commercial FEA software programs have been used to establish the reference benchmark results. The three programs used were ANSYS, MSC/NASTRAN, and ALGOR.

New, or significantly modified, FEA software can be evaluated by exercising the software with the benchmark problems and comparing the results obtained with the reference benchmark results. FEA software that has been thoroughly tested by the vendor at the verification example level, will, by successfully yielding solutions for the ship structure benchmark problems, provide another level of assurance that the software is fit for performing ship structure FEA.

The following sections describe the ship structure benchmark problems together with a sample of the results for BM-1.

3.2.1 BM-1 Reinforced Deck Opening

Openings and penetrations are among the most commonly encountered sources of high stress levels in surface ship structures. FEA is often required to evaluate the stress levels and the effectiveness of reinforcement technique. The benchmark problem is shown in Figure 6a. The benchmark tests the FEA programs capability to analyze a plane stress concentration problem using either 4-node or 8-node plate elements. However, it goes beyond the classical hole-in-a-plate problem by including two plate thicknesses for the deck and the reinforcement insert plate, and by including stiffeners in the plane of the deck.

Table 3 lists the maximum von Mises stress results for this benchmark. The "converged solution" for this benchmark was obtained using a very refined model of the same problem consisting of 8 node shell elements with ANSYS 5.1, and is used as a reference for the coarser mesh benchmark models.

The stress results listed for the plate elements are the nodal averaged stresses which are obtained by extrapolating stresses at the element integration points to the node locations, and then averaging the values at each node. Different FEA software use different extrapolation and averaging methods which can lead to significant differences in the nodal stress results. For example, the ANSYS and ALGOR programs extrapolate nodal stresses from the element Gauss points, whereas MSC/NASTRAN extrapolates from the element centroidal stresses. The difference in the maximum nodal stress due to the extrapolation and averaging techniques for this benchmark is approximately 5% for the three FEA programs used. It should be noted that extrapolation errors become more pronounced in regions of high stress gradient, such as at the corner of the opening in this benchmark problem.

To get around the problem of stress extrapolation techniques used by different programs, the benchmark FE models also include "dummy" truss elements of small arbitrary area (1 mm^2) which are used to obtain stresses around the free edge of the opening. The maximum axial stress reported in the line elements corresponds to the maximum von Mises stress at the edge of the opening, irrespective of the stress extrapolation method used for the plate elements. As indicated in Table 3, the maximum stresses in the "dummy" truss elements obtained by the three different FEA programs are within 0.5%, and are also closer to the "converged solution" than the plate element results.

3.2.2 BM-2 Stiffened Panel

Stiffened panels are the most common structural component in ships. The appropriate modeling approach for stiffened panels depends on both the scale of the response (i.e.. local or global response) and the main structural actions of interest. Two main structural actions typically modeled are 1) bending action due to loading normal to the panel surface, and 2) membrane action due to loading in the plane of the panel. This benchmark, shown in Figure 6b, tests the capability of FEA packages to analyze bending action due to normal loading using various plate and stiffener element modeling techniques. These include :

a) In-plane beam elements for stiffeners and 4-node shell elements for plate,

b) Off-set beam elements for stiffeners and 4-node shell elements for plate,

c) 4-node shell elements for stiffeners and plate,

d) 8-node shell elements for stiffeners and plate.

Both static and modal analyses are conducted for each model. The static analysis involves surface pressure loading causing out-of-plane panel bending under symmetric boundary conditions (i.e. quarter model). The modal analysis tests the programs capability for calculating natural frequencies and mode shapes under symmetric and antisymmetric boundary conditions.

3.2.3 BM-3 Vibration Isolation System

Vibration isolation systems are often required for ships' equipment and machinery. FEA analyses may be used to optimize the isolation system and ensure that vibration and shock design criteria are achieved. This benchmark considers a 12 degree of freedom system consisting of a generator which is mounted and isolated on a raft structure which is, in turn, isolated from the foundation structure. The problem is summarized in Figure 6c. Some of the key testing features of this benchmark include:

- Modal analysis,
- Point mass with rotational inertia for the generator,
- Spring elements with stiffness in three directions,
- "Rigid" beam elements connecting generator mass and isolator springs to raft.

3.2.4 BM-4 Mast Structure

Mast structures on ships must be designed to withstand environmental loads (wind and ship motions). Masts on naval ships usually have additional requirements for resisting shock and blast loading. This problem is shown in Figure 6d and the key modeling and testing features include :

- Beam elements (with axial and bending stiffness) for main legs and polemast,
- Truss elements (with axial stiffness only) for braces,
- Point mass elements for equipment "payloads,"
- Inertial loading combined with nodal force loading,
- Two materials (steel and aluminum),
- Static and Modal analysis.

While the benchmark problem is that of a lattice mast structure, it can be used to assess the FEA programs capabilities for modeling similar frame or truss like structures such as booms and derricks, especially where beam and truss elements are used in combination.

3.2.5 BM-5 Bracket Connection Detail

Welded connection details on ships are subject to fatigue loading. Poorly designed or constructed details can lead to premature fatigue failure. Finite element methods are frequently used to calculate fatigue stresses and to aid in the development of improved detail geometry and configurations. This benchmark problem is summarized in Figure 6e. Some of the key modeling and testing features of this benchmark include :

- 3-D geometry with shell elements of varying thicknesses and with transverse shear capability,
- Line elements for bulkheads, deck and flange of bracket,
- Transition from coarse to fine mesh at the bracket weld,
- Prescribed non-zero displacement boundary conditions.

The latter feature was included since in many cases the boundary conditions for a detail FEA are obtained from displacements and loads derived from a global FEA.

Further details of the ship structure benchmark problems and the FEA assessment methodology are presented in Reference (1).

4. Conclusions

Several aspects of the QA of FEA have been discussed. The key elements, upon which overall quality is dependent, were identified as the techniques applied, the tools used and the human element.

The paper summarizes an assessment methodology which seeks to provide guidance to those faced with the problem of evaluating the FEA work performed by others, although it could equally used by analysts performing the work. The assessment methodology is comprehensive and systematic, and is designed to be flexible in terms of the level of skill expected of the evaluator, and in terms of the size and complexity of the FEA.

FEA codes are large and complex and hence can never be guaranteed to be free of errors. However, it is suggested that FEA software that has been thoroughly tested by the vendor at the verification example level, will, by successfully yielding solutions for the benchmark problems, provide another level of assurance that the software is fit for performing ship structure FEA.

5. References

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Table 1 Error factors in observed failure cases

Factor	%
Ignorance, carelessness, negligence	35
Forgetfulness, errors, mistakes	9
Reliance upon others without sufficient control	6
Underestimation of influences	13
Insufficient knowledge	25
Objectively unknown situations(unimaginable?)	4
Remaining	8

adapted from (8)

Table 2 Human intervention strategies

Facilitative measures	Control measures
Education	Self-checking
Work environment	External checking and inspection
Complexity reduction	Legal (or other) sanctions
Personnel selection	

source: (7)

Table 3 Results for BM-1 Reinforced Opening

Result	ANSYS 5.1	MSC/NASTRAN Windows 1	ALGOR 3.14	"Converged Solution"
Max Stress in Plate Elements (MPa)	198.3	189.2	199.3	206.3
Max Stress in Line Elements (MPa)	204.4	203.3	204.4	209

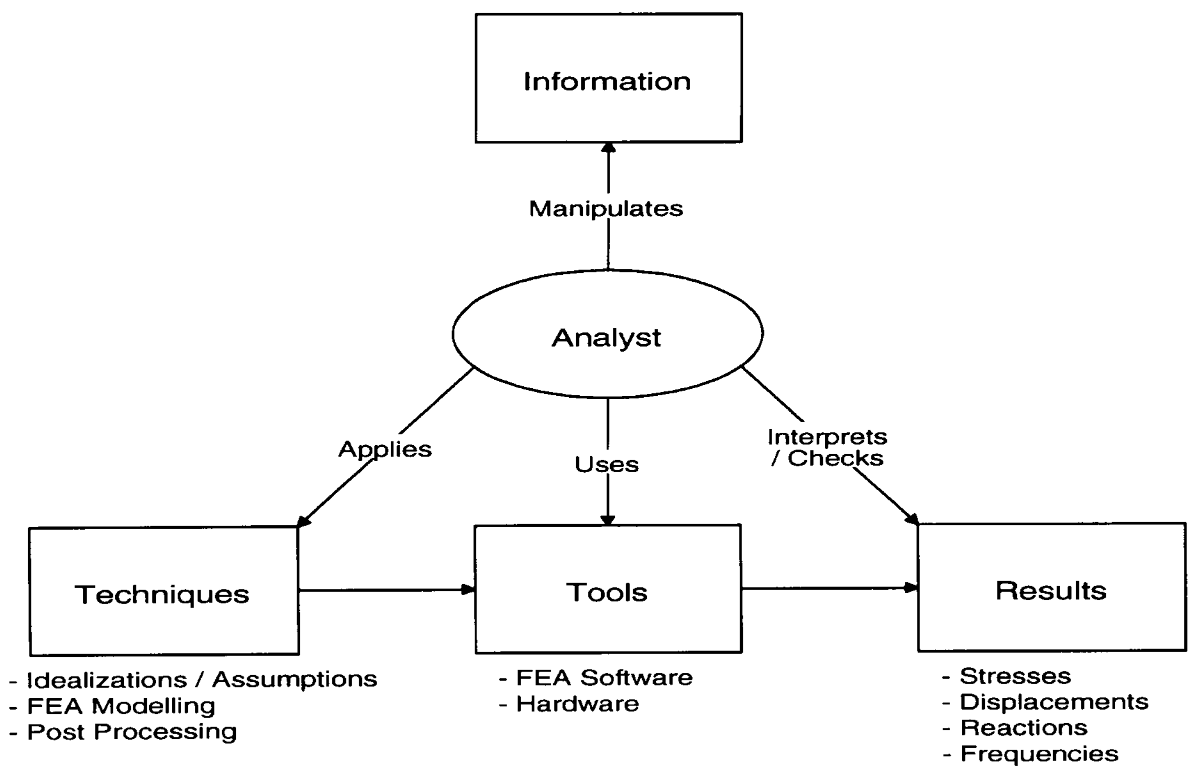

Figure 1
Quality Assurance Aspects of FEA

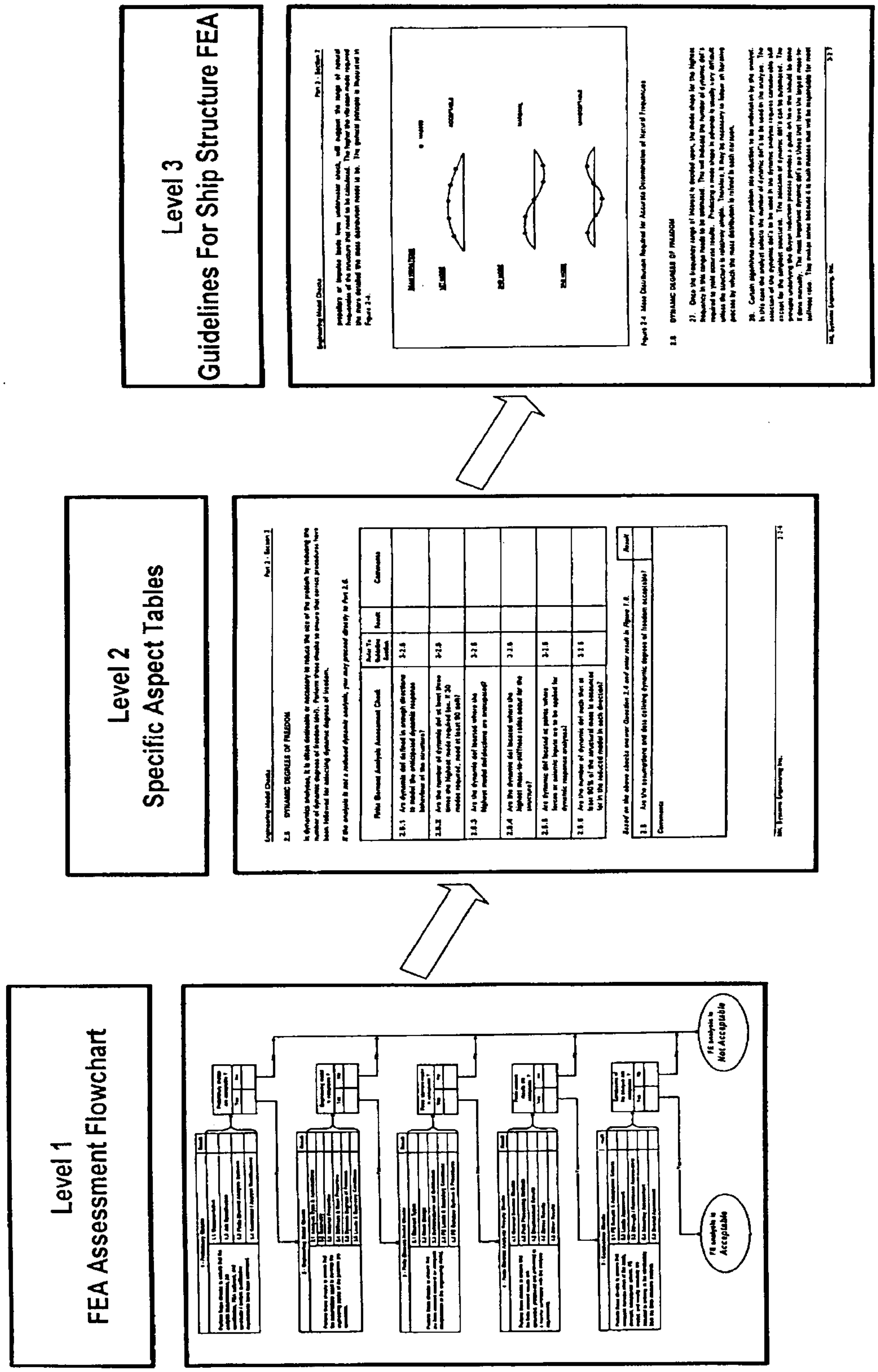

Figure 2
Assessment Methodology for Ship Structure FEA

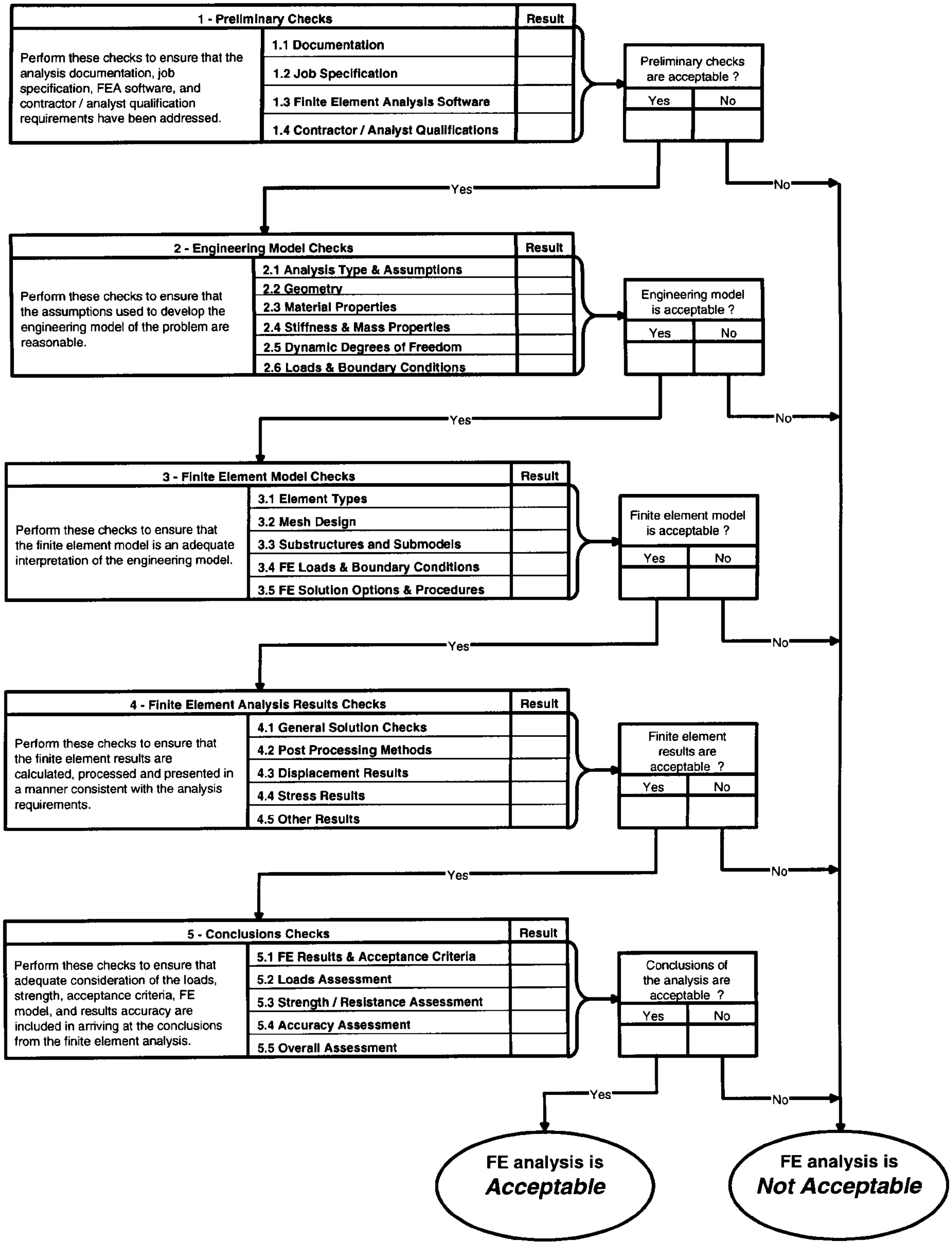

Figure 3
Assessment Methodology Level 1 Flowchart

FINITE ELEMENT ANALYSIS ASSESSMENT			**FINITE ELEMENT MODEL CHECKS**
Project No.	***Project Title :***		
Contractor Name:			***Date :***
Analyst :		***Checker :***	

Finite Element Analysis Assessment Check	**Refer To Guideline Section**	**Result**	**Comments**
3.1.1 Are all of the different types of elements used in the FEA model identified and referenced in the analysis documentation?	3-3.1		
3.1.2 Are the element types available in the FEA software used appropriate to ship structural analysis?	3-3.1		
3.1.3 Do the element types support the kind of analysis, geometry, materials, and loads that are of importance for this problem?	3-3.1		
3.1.4 If required, do the selected beam element types include capabilities to model transverse shear and / or torsional flexibility behaviour?	3-3.1		
3.1.5 If required, do the selected beam element types include capabilities to model tapered, off-set or unsymmetric section properties?	3-3.1		
3.1.6 If required, do the selected beam element types include capabilities for nodal dof end releases (eg. to model partial pinned joints)?	3-3.1		
3.1.7 If required, do the selected plate element types include capabilities to model out-of-plane loads and bending behaviour?	3-3.1		
3.1.8 If required, do the selected plate element types include capabilities to model transverse shear behaviour (ie. thick plate behaviour)?	3-3.1		
3.1.9 If the model is 2-D, are the selected element types (or options) correct for plane stress or plane strain (whichever case applies)?	3-3.1		

Based on the above checks answer Question 3.1 and enter result in Figure 1.0.	***Result***
3.1 Are the types of elements used in the FEA model acceptable?	
Comments	

Figure 4
Example of Level 2 Check list Table

Features		Benchmark Problem				
		BM-1 Reinforced Opening	**BM-2 Stiffened Panel**	**BM-3 Isolation System**	**BM-4 Mast**	**BM-5 Bracket Detail**
Analysis Types	2D	●				
	3D		●	●	●	●
	Static	●	●		●	●
	Modal		●	●	●	
Element Types	Mass			●	●	
	Spring			●		
	Truss	●			●	●
	Beam		●	●	●	
	Membrane	●				
	Shell		●			●
	Brick					
Load Types	Force	●			●	
	Pressure		●			
	Accel.				●	
	Displ.					●
Boundary Conditions	Displ.	●	●	●	●	●
	Symmetry	●	●			
Results	Displ.	●	●		●	●
	Reactions				●	●
	Stress	●	●		●	●
	Frequency		●	●	●	

Figure 5
Summary of Ship Structure FEA Benchmark Problems

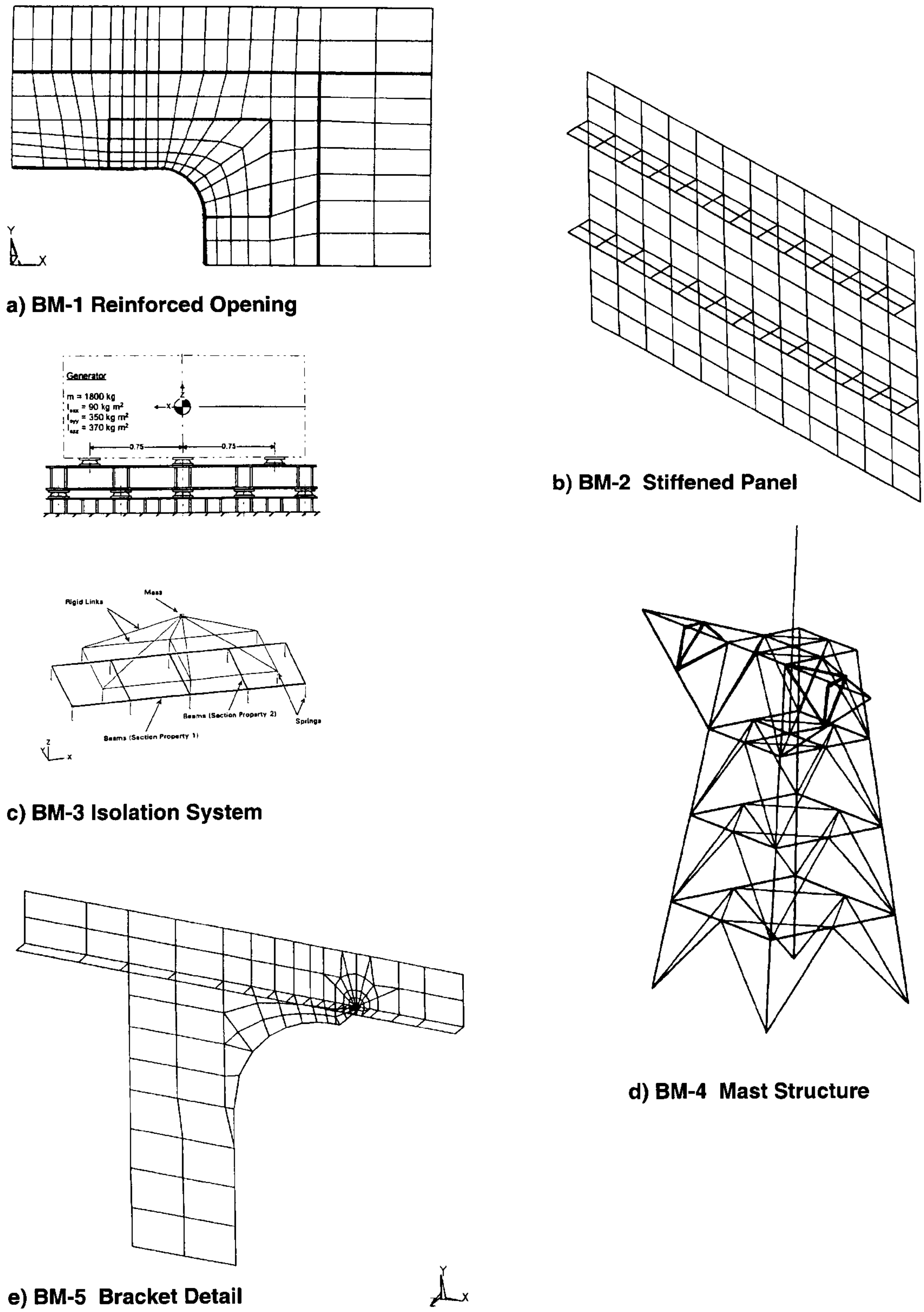

Figure 6
Overview of Ship Structure Benchmark Problems

Discussion

by Robert A. Sielski
Marine Board, National Academy of Science

The paper presented by the authors is the result of work that has continued over several years to develop specific standards for finite element analysis of ship structures. The adequacy of a particular finite element analysis to adequately reflect a physical situation is a problem that has existed since the method was first used in the mid-1960s, and I believe will always exist as long as the method is used. This is not a unique situation in structural analysis; there have always been degrees of approximation between analysis and reality. For example, in some situations, such as computing the stress at mid-span of a uniformly loaded beam over multiple supports of equal spacing and rigidity, computation by the old FEM (Fixed End Moments) is nearly an exact solution. However in most cases, there is a question of end fixicity, shear lag, effect of openings, reinforcements, local buckling, actual scantlings and many others that the analyst had to deal with. In many cases the inexperienced engineer would use some cook book approach that generally incorporated healthy factors of safety, thinking that the standard computational method represented reality.

Things have not really changed with the introduction of the finite element method. Careful consideration may show that an apparently exhaustive analysis does not represent reality, but many will continue to think so. The human factor here is a willingness to accept numbers because they are generated by a method that seems to have authority. Knowledge of fundamental principles is necessary, but that knowledge needs to be supplemented by verification. Years of experience are meaningless; continually doing the same thing wrong does not make it right.

The authors have developed a method to help ensure that a finite element analysis has been properly performed and a check list for the reviewer. The analyst will know that the analysis will be reviewed using this check list, and will ensure that all requirements are met prior to submitting the work. This seems to be a bureaucratic approach to a technical problem. Many are the individuals and organizations skilled in getting results through a government inspection system without really meeting the requirements. At best, such a lengthy check-off process can only add to administrative burdens. Do the authors view the check lists as being the primary means of ensuring adequacy of computation, and of reducing human and organizational errors that will influence the process?

If the primary goal is to ensure that the analysis is properly performed, then emphasis must be on ensuring that the proper information on the geometry of the structure and the nature of the loads are available to the analyst, that the model used has been sufficiently exercised to understand its sensitivity to variation in parameters, and that the analysis is free of internal difficulties. All of these are formidable tasks and are demanding of time and resources. Isn't the adding of check lists to the process just adding another function that diverts from the primary goal?

Although an extensive analysis performed in a parametric way, including all of the checks and converging mesh density may appear to provide accurate results, comparison with experimental data or a similar analysis done by other individuals typically shows great differences in results. There is a great need within the marine industry to have available analyses of typical structures to provide analysts examples of successful use of finite element analysis methods that have been verified through comparison. However, there appear to be significant organizational barriers to providing such examples in open literature. Panel HS-3 of the Society of Naval Architects and Marine Engineers has struggled with this issue for several years, and although good verified comparative analyses have been identified, there has been a reluctance by organizations to release such analyses, even in a sanitized form that removes authorship. Likewise, in the conduct of their study, the authors asked representatives of the Ship Structure Committee to provide such analyses from their organizations, but such examples were not forthcoming, and the authors had to produce examples of their own. Unless such organizational barriers can be broken, there is little chance for real progress. How do the authors think this problem of sample computations should be solved?

Author's Reply

We thank Bob Sielski for raising a number of interesting questions and issues. Our response is presented below in four parts. The first part provides background to the subject and the remaining parts address the following three topics:

- Use of check lists as the primary means of ensuring adequacy of FEA
- Check lists as an additional burden diverting effort from the primary goal
- The use of experiments and other analyses as a means of providing benchmarks

Background

Finite element analysis (FEA) is based upon the same principles of classical mechanics as those underlying hand calculation methods. In application FEA suffers from most of the limitations associated with the application of classical methods of structural analysis. In the working world FEA models typically do not include initial distortions or residual stresses, and the model is based on nominal, rather than actual, geometric and material properties, etc. In this sense the FEA model is very much a surrogate of the "real" thing. However, despite these limitations, analysis methods, both classical methods for simple configurations and FEA for complex configurations, have served the structural design community well.

FEA represents a real advance over hand-calculation methods allowing the competent analyst to rapidly analyze quite complex structures and components that could not be analyzed any other way. A key feature of FEA is its ability to analyze arbitrarily-shaped structures and components. This versatility, which is absent in hand-calculation methods, is one of the main reasons for its popularity. The alternative of experiment is expensive and slow.

The primary reason that FEA results can be so variable has much less to do with the inherent limitations of the method, which a competent analyst should be aware of, than with the misapplication of the method. The beguiling nature of modern commercial FEA software systems, which are apparently so easy to use, conceal the complexities and intricacies of the method. It is suggested that FEA, when properly applied, is a powerful and flexible analysis tool.

Use of check lists as the primary means of ensuring adequacy of FEA

While the evaluation methodology may seem overly bureaucratic we believe it is flexible enough to allow the methodology to be applied at an appropriate level. The three-tier approach allows the evaluator to apply the methodology at the required level. The evaluation of a large complex FEA by an evaluator with limited experience in the method may well require reference to substantial parts of all three levels. At the other extreme simple FEAs being evaluated by an evaluator with substantial experience in FEA will rarely require to use the methodology below Level 1.

The experience of the authors suggests that the effort required in applying the methodology should not amount to more than about 5-8% of the effort required for the analysis itself. This does not appear excessive.

Virtually all systems designed to assure quality rely on the goodwill of those concerned. No quality system can be effective if staff wish to circumvent the system, or worse, if staff have malicious intent.

Assuring the quality of a FEA requires each of the following four elements to be addressed:

- Information
- Technique
- Tools
- Personnel

The assessment methodology addresses all these elements to some extent, but the emphasis is on the second. The benchmark problems described in outline in the paper, and in detail in the referenced report, address "Tools". The human element is addressed in the report to a limited extent.

While the assessment process, as described in the report, cannot be regarded as the "primary means of ensuring adequacy of computation,...", it is of comparable importance to the other elements listed above. All elements are important, and requirements associated with each must be satisfied to ensure proficient FEA.

The paper notes that human error, a major theme of this conference, is a major contributor to structural failures. Many of these failures are associated with factors such as lack of knowledge, negligence and carelessness. Assuming that this applies equally to the structural analysis and design process, it is suggested these potential shortcomings are best addressed by requiring that analysts and checkers have the appropriate training and experience, and that the best strategy for limiting errors is by (external) checking.

Check lists as an additional burden diverting effort from the primary goal

In his discussion Bob Sielski notes that for the analysis to be "...properly performed, then emphasis must be on ensuring that the proper information on the geometry of the structure and the nature of the loads are available to the analyst, ...", etc.

Ensuring that the information used is appropriate, the loads are correct, etc. is precisely what the check lists are designed to do. The purpose of the check lists is to, at the very least, act as reminders of what must be considered by the analyst, and checked by an evaluator or checker. The check lists are, of course, supported by guidelines and, in some cases, by illustrative examples as well.

The assessment methodology is designed to be used primarily by those who have the responsibility of ensuring that a FEA has been undertaken proficiently. Thus the methodology can be used in performing an independent check within the performing organization, or by a customer to ensure the adequacy of a FEA performed by a second party.

Check lists, which are at the heart of the assessment methodology, should not be regarded as "an additional burden" but more as an essential element of the quality assurance process. External checking, which the check lists are designed to facilitate, is recognized as perhaps the most powerful strategies to control human error in this context.

The use of experiments and other analyses as a means of providing benchmarks

The final point is the most difficult to address.

Bob Sieslki notes that the results of FEAs typically differ greatly from those generated by experiments and other analyses. It is suggested that the differences are more apparent than real. The authors' experiences are instructive in this regard.

The work upon which this paper is based includes several benchmark problems which were modeled and exercised using three different FEA software systems. In some cases initial results from the analyses differed significantly. However, after investigation, in all cases the differences were reconciled to within a few percent. The most dramatic illustration of apparent differences are the stresses calculated in plates/shells by the different FEA software systems. Two, and in some cases three, analyses of the identical structure would yield essentially identical displacements and reactions yet quite different stresses. This was attributed to the different algorithms used by the software to extrapolate stresses within each element. Typically these algorithms would yield identical stresses for simple structural configurations.

Similarly the authors have had the good fortune in working on a project in which it was possible to compare FEA results with those obtained from physical tests. The comparison were generally good. Where the differences between analysis and experiment were significant the reasons became apparent after investigation. Where liberties where taken in modeling the results were poor, and vice versa. This limited experience suggests that FEA is easy to misapply. As with all powerful methods, FEA must be applied with discipline and maturity which are characteristics that can only be found in appropriately trained and experienced analysts.

The authors agree that a compilation of successful FEAs and reports of experiments would be useful. There do not appear to be easy answers to this question. Each industry has made some attempt in this direction but the results appear to be quite variable. However there have been some successes. For example the National Agency of Finite Element Methods and Standards in East Kilbride, Glasgow, UK have developed several documents addressing subjects such as guidelines, standards, comparative studies, and several benchmark problems.

In terms of the marine industry voluntary efforts do not appear to have been successful. It is suggested that a funded effort with the sole purpose of compiling successful FEAs and experimental results should be productive. In this effort it will likely be necessary to undertake a limited number of FEAs to compare with experiments.

by Rickard Anderson
Military Sealift Command

Whether we like it or not, it seems that more and more of reality consists of computer generated output. I suspect that this layman's conception of reality also makes the incorrect assumption that what the computer generates is correct. Even the technically knowledgeable must realize that FEA is nothing more than a very sophisticated type of numerical analysis where cost must be balanced against the degree of accuracy. Another concern I have and one which is addressed in the paper is the knowledge and the experience of the analyst. With the increasing user friendliness and CAD related modeling commands of today's software, you don't need a structural engineer to model structure and estimate stresses. Although I don't review as many FEA's as a regulatory body, I do get to review four or five analyses a year from various engineering contractors and shipyards. The quality still runs the gamut from very poor to very good. Some analyses still cross my desk that consist of reams of computer paper, twenty year old software, and reports devoid of graphics, and little or no description of model geometry, element types, materials, boundary conditions, and loading. Because of this wide variation in quality, I welcome this paper and the companion SSC Report SSC 1387, *Guidelines for Evaluation of Ship Structural Finite Element Analysis* and view it as a step in the right direction to improve the quality of the FEA's we receive. Since the publication of SSC 1387, we have required all engineering contractors doing FEA's for us comply with these guidelines as well as our in-house use of them in reviewing the results.