A JIP Proposal (Final Draft 2-5)

MOORING CONNECTORS ASSESSMENT

Background

Recent field failures of mooring components have raised concerns over the current design criteria and material property requirements (e.g., Charpy toughness) as well as their implications on the structural integrity of already installed components like shackles, H-links, tri-plates, cable sockets, etc. Subsequent testing of spare components from separate installations by various organizations has shown that Charpy toughness can vary from values well below to above the required toughness specification (e.g., 50J at -20°C), depending upon sampling location etc. A recent review of the existing data available to date suggests that the problem appears to be more wide-spread than originally thought. Since mooring line components can be subjected to extreme loading conditions such as those induced by hurricanes, e.g., in Gulf of Mexico and typhoons in Asia, their structural integrity must be assured by demonstrating adequate fracture toughness to prevent pre-mature brittle fracture and sufficient fatigue resistance to typical operating conditions.

Through a series of recent meetings and discussions with interested parties, it has become clear that there is a strong interest in establishing a JIP to address the structural integrity of mooring components through an Engineering Critical Assessment (ECA) methodology. In doing so, well-established fracture mechanics principles can be adopted to quantitatively demonstrate if mooring connectors already installed are “fit for service”, and if or when preventive measures should be put in place to avoid any potential for a major failure.
The present JIP is proposed following the initiative of TOTAL, BATELLE, and BUREAU VERITAS.

The Need for a JIP

Although general ECA (or fitness-for-service) procedures have been available from various Recommended Practices and Standards, such as those in BS 7910 (1999, 2005), API 579-1/ASME FFS-1 (2000, 2007) etc., they have been developed and validated primarily for much simpler and extensively used for many decades components such as pressure vessel and piping systems rather than mooring connectors. A direct adoption of these existing ECA procedures for mooring connectors will undoubtedly introduce various uncertainties that typically require the demonstration of a large margin of conservatism through extensive sensitivity studies. To avoid un-necessary conservatism, the ECA procedure must adequately address a series of issues unique to mooring components, including:

(a) Appropriate fracture toughness definition and its transferability to hot spot locations in mooring connectors during service, recognizing that existing data tends to show significant variability from location to location and from part to part
(b) An industry-wide consensus on interpretation of NDT results provided anonymously by JIP participants, which can then be used as a basis for performing ECA to establish an upper bound on fracture propability

(c) Reliable methods for fatigue and fracture driving force determination, particularly for short-crack regime

(d) Validation and calibration of ECA procedures using actual mooring component testing

(e) An industry-wide consensus to ensure that the resulting ECA procedure is not only technologically consistent with the state of the art, but also offers an acceptable margin of safety from a regulatory point of view as well as the economic benefits from an operator's point of view.

A joint industry project (JIP) provides the most effective forum to address the ECA-related issues associated with mooring components.

Objective

The objective of this proposed JIP is to develop and validate an effective ECA procedure specifically suited for evaluating with industry-wide consensus mooring components / connectors, in the first place for existing mooring systems. The findings from this project should also provide a technical basis for updating the Rules of the participating Classification Societies and the specifications of new designs in terms of forging, Q/T, and toughness sampling procedures, etc. . . Such an ECA procedure should also allow assessment results for a given application to be presented as much as possible in a simple form for decision makers, e.g., if possible in the form of the calculated safety factor and perceived probability of failure in relation to the required 50J Charpy at -20°C toughness and other appropriate design requirements.

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Scope of Work

The scope of work envisioned will consist of the following major tasks, subject to JIP participants' approval:

1. Review and assess JIP participants' experiences with mooring connectors: This task is designed to establish (on a voluntary and anonymous basis), a computerized repository of:

    - any problem areas of concerns and case histories including design and manufacturing procedures, operating conditions, as well as engineering evaluations or test reports
    - available toughness data and testing procedures
    - NDE results on mooring connectors
    - Review and assess the existing design and fabrication practices
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A data collection/documentation protocol will be developed and issued to facilitate the information collection process. In addition, the current class rules, e.g., the 50J at minus 20°C and UTS/SMYS requirements and their implementation at shop floors of mooring component manufacturers will be assessed. The knowledge gathered in this task will provide a basis for executing the later tasks within this JIP

2. <u>Review and recommend FEA procedures for ECA applications</u>: FEA is required to perform ECA in order to adequately resolve local stress gradient effects which dominate small crack behaviors that could have important implications on both the fatigue and fracture capacity of these mooring components.

   At present, FEA procedures are used for strength check (e.g., MBL, Proof Load) of mooring connectors by evaluating peak surface stresses or plastic strains. These FEA procedures will be reassessed.

   To facilitate ECA analysis, FEA-based stress analysis should to take into account a given form of the fatigue and fracture driving force expressions, e.g., in terms of stress intensity factor K. Depending upon the specific form of a K solution, there are certain requirements in terms of both accuracy and form of the stress solutions which will impact how a FEA analysis should be performed. The recommended FEA stress analysis and post-processing may include the following:

   - load and loading mode definitions
   - corrosion allowance considerations
   - misalignment considerations
   - element refinement requirements at hot spot locations
   - a consistent procedure for determining the minimum breaking load or limit load (overloading) which will be used to construct the FAD in performing ECA in later tasks
   - stress decomposition into membrane and bending with respect to a hypothetical crack plane, etc.

3 <u>Review and validate existing K solutions for mooring connectors</u>: Relevant K solutions for potential applications in mooring connectors will be reviewed by conducting a comprehensive literature search, including those in BS 7910, API 579-1/ASME FFS-1, and other fitness for service Codes and Standards. Emphasis will be placed upon the validity of surface crack K solutions in small crack regime. Detailed finite element cracked body solution procedures capable of resolving small surface crack effects such as 3D finite element alternating method (FEAM) will be used as a validation. Depending upon the findings from this validation effort, either recommendations on using existing K solutions will be given, or a new set of K solutions based on the finite element computation will be developed during this investigation.

4 Determination of material fracture toughness: Existing fracture toughness data and their testing procedures reviewed in Task 1 will be used to identify issues associated with the determination of toughness for ECA applications in mooring components. These may include recommended fracture toughness testing method (Charpy, CTOD, or K), sampling location, representative constraint effects, and data interpretation/qualification procedures, etc. Through data analysis coupled with FEA based fracture mechanics analysis such as FEAM of these specimens, a set of recommended procedures substantiated by the validation tests will be proposed for performing fracture toughness testing and data interpretation for ECA applications. These testing procedures will be used on selected mooring connectors made available from the JIP participants for generating additional fracture toughness data. For mooring installations which do not have spare components for sampling fracture toughness, a conservative scheme for estimating toughness value using comparable components in terms of material and manufacturing processes will be established. An empirical Charpy toughness/CTOD relationship may also be established using the data collected and tested in the JIP for performing a conservative estimate of CTOD if CTOD tests cannot be carried out since spare components may no longer available for some applications.

5 Procedure for critical crack size determination: A conventional failure assessment diagram (FAD) approach, incorporating the findings from Tasks 1-4 above, may be adopted. However, additional investigation is needed with the emphasis on a sufficient resolution for identifying propensity for pre-mature brittle fracture in view of the possibility of low toughness in installed mooring components as suggested by some of the preliminary testing results. As such, an equivalent Level 2A procedure similar to that in BS 7910 (2005) will be established for performing ECA for mooring connectors. The treatment of residual stresses due to quenching and tempering will be examined to eliminate the excessive conservatisms built in BS 7910, based on the most recent developments incorporated in API 579-1/ASME FFS-1 (2007).

6 Procedure for fatigue life determination: Based on cursory examination of recent experience with mooring components, short crack phenomena could be important in determining fatigue growth limit before attaining its critical size. Therefore, alternative Paris type crack growth models such as the two stage growth model incorporating short crack anomalous growth effects will be examined. Relevant crack growth data for relevant material such as 34CrNiMo6 (4340) covering the short crack regime will be collected and correlated to support the use of the most appropriate Paris type growth model. Depending upon these findings, selected crack growth rate testing on forging material taken from some of the representative mooring connectors may be needed to supplement the data collected from literature. Recommendations on initial crack size will be developed based on detailed examination of available NDE records. Proof loading effects will also be quantitatively addressed by performing detailed finite element simulation to estimate typical residual stress distributions after specified proof loading conditions. Available residual stress measurement data will be reviewed and documented for both validation and ECA assessment purpose.

7 Establish a risk-based ECA procedure for mooring components: Based on the analysis results of fracture toughness data, available NDT data, and mooring line loading conditions, a risk-based ECA procedure for estimating an upper-bound failure probability will be proposed

8 <u>Validation and calibration of the ECA procedure with large scale testing:</u> A series of spare mooring connectors from existing installations, depending upon the test machine capacity required, will be identified for consideration for testing in this task. The validation tests will be divided into fracture tests and fatigue tests. Detailed test plans and test matrix will be developed at the end of Year 1 with input from the JIP participants. Each testing conditions will be simulated using FEA and the ECA procedure developed, with test sample designs and manufacturing conditions fully documented. Spare samples under identical conditions to the large scale test samples will be used to perform fracture toughness testing according to procedures established in Task 4. A minimum of two tests under identical manufacturing conditions will be performed and fully documented. The test results will also be used to calibrate the ECA procedures developed. Additionally, available S-N data of mooring connectors and notched specimens of the same material types will be collected and analyzed to support the validation efforts on fatigue.

9 <u>Documentation of recommended ECA procedure for mooring components</u>: Upon completion of the validation and calibration in Task 7, a detailed step-by-step ECA procedure for evaluating shackles, H-links, tri-plates, and cable sockets will be prepared and reviewed by the JIP participants as a preliminary ECA procedure for further evaluation in the next task. The ECA procedure developed will allow a simple presentation of acceptance criteria with respect to the original 50J Charpy toughness requirements:

- Against fatigue crack growth approaching to critical crack size and its associated safety factor

- Against unstable fracture and overload in a form similar to the conventional failure assessment diagram (FAD) and associated safety factors.

10 <u>ECA Round Robin</u>: With the draft ECA procedure from Task 8, a series of two to three mooring components under a set of hypothetical service conditions will be identified by working closely with the JIP participants. A Round Robin protocol will be developed and issued to JIP participants to perform independent ECA evaluation of these components according to the draft ECA procedure proposed. The Round Robin results will be used to refine the proposed ECA procedure. A final ECA procedure will be developed as the JIP deliverable for further review and comment by Class Societies participating in the JIP for final adoption.

11 <u>Technical Documentation and Technology Transfer</u>: Throughout the JIP, the technical developments and findings will be documented as a topical report to serve as background documentation supporting the ECA procedure developed. In addition, a JIP workshop will be conducted near the end of JIP to illustrate the use of the ECA procedure with a series of worked examples.

Project Time Line and Sponsorship

As soon as four major organizations (with an initial Year 1 funding of $200K) are committed to join the JIP, the JIP will officially start, following a JIP kick off meeting. At the project kick off meeting, a prioritized task list and associated details will be developed and approved by the JIP participants. The JIP is planed to have a two-year duration with a participation fee of $50K/year for two years. The fee for Class Societies will be $25K/year for two years. Mooring component manufacturers may participate with a contribution of $25K/year To execute the full JIP program, particularly Task 7, a minimum of 10 major companies will be sought. If less than 10 companies are participating by the end of Year 1, Task 7 will be scaled down according to the available funding. This would however adversely affect the pertinence of the theoretical work validation

Deliverables

The JIP deliverables consists of following:

- Topical reports documenting all detailed technical developments and major findings at completion of in each task
- Final documentation of the recommended ECA procedure developed
- A technology transfer workshop focused on how to effectively use the ECA procedure developed for evaluating mooring shackle components with worked examples.

JIP Management

Mr. Jean-Pierre Sauvage of Bureau Veritas (based in Paris, France) will serve as the JIP Manager, overseeing all JIP activities, including contracts administration. Dr. Pingsha Dong of Battelle Memorial Institute (based in Columbus, USA) will serve as Principal Investigator leading the ECA methodology development with testing support from CETIM (based in Paris, France) and other organizations to be identified. Mr. Jean-Michel Aubert of TOTAL (based in Paris, France) will serve as the JIP Industrial Steering Committee Chair, to ensure that the JIP participants' interests are addressed.

Contacts

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