MARINE STRUCTURAL FAILURES: CAUSES AND ANALYSIS TOOLS

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Abstract. One of major design requirements for any marine structure (ship or offshore facility) is to have reasonably long and safe operational life cycle without any catastrophic failure. However, failures still occur causing financial losses and threating human lives, especially in modern structures with reduced weight but increased load carrying capacity. Engineering practice distinguishes usually one or few causes of failure: excessive force and/or temperature induced elastic deformation, yielding, fatigue, corrosion, creep, etc. Therefore, as a first step, it is important to identify potential threats that can affect integrity of marine structures. In order to understand the causes of failures, structure's load response, failure process, possible consequences and methods to cope with and prevent failures, it is important to educate marine engineers about such problems. Probably the most suitable way of transferring knowledge would be learning from actual examples from engineering practice.

Research on this topic includes: identifying potential threats affecting marine structural integrity, analyzing various cases of failures using experimental and numerical approach, assessing structural critical points that could serve as a root of failure, formation of a database comprised of elaborated case studies that can be used in the education worldwide, disseminating results and promoting open access to the database. This paper serves as a progress report of the first part of the ongoing IAMU research project for 2017 where the causes of typical failures in marine structures are determined and critical review of previously conducted researches on similar topics is outlined. Further, results of experimental and numerical failure analysis of typical failures in maritime structures are presented along with directions for future use and database forming.

Keywords: failure analysis, marine structures, education database, case studies

1. Introduction

In order to limit the occurrence of fatalities, environmental and economic damage marine structures are to be designed, built and operated in such manner that the probabilities of overall structural rigid body stability and failures of parts and/or complete structure are reduced to minimum. Extensive study of catastrophic accidents serves as a knowledge base source for future design procedures that will make marine structures safer and longer lasting.

Fatigue is regarded as a critical limit state that has to be taken into account during the design phase of a marine structure. It has become customary to perform an optimal fatigue design analysis as an integral part of design calculations. Nowadays, the theoretical basis for such an analysis is largely based on data and procedures developed from experimental and empirical research. As fatigue damage (cracks) phenomena imply nonlinear material damage in microscopic scale as well as continuous separation of the material, continuum mechanics principles and fundamentals are basically violated. Therefore, various fatigue assessment methods were developed for marine structures details.

Studies and analysis of marine structures failures had shown that a significant percentage of failures were a consequence of inadequate design due to lack of operational considerations, incomplete structural elements evaluations and incorrect use of calculation methods.

During the design phase of a specific marine structure, a level of structural safety is chosen by defining individual structural elements, used materials and functional requirements based on the expected lifetime of the structure, the ramifications of eventual failures (higher safety factors) and the costs of failures. An important factor that has to be taken into account is the time dependency of the strength and loads. The strength of a structure decreases with time and strongly depends on inspection and maintenance procedures, while the load itself is very variable through the lifetime of the structure [1].

2. Structural failure causes

The strength of a structure represents a limit state of loading conditions above which the structure loses ability to achieve its specified required function. As long as the actual strength of the structure is kept higher than the actual loading demands, a given marine structure can be deemed safe. Otherwise, structural failures will occur.

Structural failure can be defined as loss of the load-carrying capacity of a component or member within a structure or of the structure itself (including global failure modes like capsizing, sinking, positioning system failures etc.). The failure can result in catastrophic damage (i.e. complete loss of the structure itself) or partial structure damage when the structure can be repaired or recovered. Global failures can more often result in fatal casualties while smaller and localized structural damage may result in pollution and recoverable structural damage.

Structural failure is initiated when the material in a structure is stressed to its strength limit, thus causing fracture or excessive deformations. The structural integrity of a marine structure depends on load conditions, the strength of the structure itself, manufacturing and materials quality level, severity of service conditions, design quality as well as various human elements that have effects during exploitation of the structure.

There are two distinctive groups of failure causes. The first group is comprised of unforeseeable external or environmental effects which exert additional loading on the structure resulting in over-load. Such effects are extreme weather (overloads), accidental loads (collisions, explosions, fire, etc.) and operational errors. The second group comprises causes for failures that occur either during the design and construction phase (dimensioning errors, poor construction workmanship, material imperfections) or due to phenomena growing in time (fatigue), both resulting in reduced actual strength in respect to the design value. All of the listed causes can partially or completely be a result of human factor.

3. Failure analysis tools

The analysis methods can be grouped into methods that use nominal stresses (typical for standard codes) acting to a structure or part of a structure and then compare the stress amplitude to nominal S-N curves. This approach is appropriate for structures that are standardized and therefore well backed up with statistical experimental data that can be used as initial assumptions for fatigue analysis. The alternative is the evaluation of local stresses influence to fatigue (notch stress factors, N-SIF).

The latest trend in failure analysis development is the unification of analysis methods and procedures [3], [4], [5] in order to obtain a comprehensive procedure of structural failure analysis that would cover main failure modes and enable a safer and more efficient design, manufacture and maintenance processes.

3.1.Experimental tools

Nondestructive testing and examination (NDT, NDE), as well as structural health monitoring (SHM), of structures play a significant role in fracture analysis and control procedures. Any method used must not alter, change or modify the failed condition but must survey the failure in a nondestructive mode so as to not impact, change or further degrade the failure zone. This kind of examination provides input values for fracture analysis which yields results that define inspection and maintenance intervals for the structure and represent input values for life prediction estimates. Structures are inspected at the beginning of their service life in order to document initial flaws which determine the starting point of the structure fatigue life prediction. The most commonly used procedures for marine structures are optical microscopy, scanning electron microscopy (SEM), GDS and acoustic emission (AE) testing.

Optical microscopy is a common and most widely used NDT analysis method which enables rapid location and identification of most external material defects. This technique is often used in conjunction with micro-sectioning to broaden the application. One of the main disadvantages is the narrow depth-of-field, especially at higher magnifications.

Scanning electron microscopy is an extension of optical microscopy in failure analysis. The use of electrons instead of a light source provides much higher magnification (up to 100,000x) and much better depth of field, unique imaging, and the opportunity to perform elemental analysis and phase identification. The examined item is placed in a vacuum enclosure and exposed with a finely focused electron beam. The main advantage of this method is minimal specimen preparation activity due to the fact that the thickness of the specimen does not pose any influence to the analysis, ultra-high resolution and 3D resulting appearance of the test object. Various analysis of marine structures and equipment have been conducted using SEM [6], [7], [8], [9].

Structural supporting members emit sounds prior to their collapse i.e. failure. This fact has been the basis of the development of scientific methods of monitoring and analysis of these sounds with the goal to detect and locate faults in mechanically loaded structures and components. AE provides comprehensive information on the origin of a discontinuity (flaw) in a stressed component and also provides information about the development of flaws in structures under dynamic loading. Discontinuities in stressed components release energy which travels in the form of high-frequency stress waves. Ultrasonic sensors (20 kHz – 1 MHz) receive these waves or oscillations and turn them in electronical signals which are in turn processed on a computer yielding data about the source location, intensity frequency spectrum and other parameters that are of interest for the analysis. This method is passive, i.e. no active source of energy is applied in order to create observable effects as in other NDT methods (ultrasonic, radiography etc.). Three sources of acoustic emissions are recognized, namely primary, secondary and noise. The primary sources have the greatest structural significance and originate in permanent defects in the material that manifest as local stresses, either on microstructural or macrostructural level. The amount of acoustic emission energy released, and the amplitude of the resulting wave, depends on the size and the speed of the source event. The main advantages of AE compared to other NDT methods that AE can be used in all stages of testing, lesser geometry sensitivity, the method is stress related, less intrusive method, it can be used for global monitoring, the scanning is remote and it gives a real-time evaluation [10]. The disadvantages are the sensitivity to signal attenuation in the structure, less repeatability do to the uniqueness of emissions for a specific stress/loading conditions and external noise influence on accuracy.

3.2.Analytical tools

Although various analytical models have been proposed by a number of authors no comprehensive model exists. Analytical methods have been developed for prediction of progressive structural failures of marine structures [11]. The finite element modeling approach for prediction of the development of failures is accurate, but can be time consuming. Analytical procedures, based on spectral fatigue analysis, beam theory, fracture mechanics and structural factors, can provide solutions in considerably less time when needed.

The goal is to define approaches for computing the fracture driving force in structural components that contain cracks. The most appropriate analytical methodology for a given situation depends on geometry, loading, and material properties. The decisive choice factor is the character of stress. If the structure behavior is predominantly elastic, linear elastic fracture mechanics can yield acceptable results. On the other hand, when significant yielding precedes fracture, elastic-plastic methods such as referent stress approach (RSA) and failure assessment diagram (FAD) need to be used. Since a purely linear elastic fracture analysis can yield invalid and inaccurate results [12], the safest approach is to adopt an analysis that spans the entire range from linear elastic to fully plastic behavior. One of the methodology that can be applied is the failure assessment diagram (FAD) approach.

The FAD approach has first been developed from the strip-yield model and it uses two parameters which are linearly dependent to the applied load. This method can be applied to analyze and model brittle fracture (from linear elastic to ductile overload), welded components fatigue behavior or ductile tearing. The stress intensity factors are defined on the basis of the structure collapse stress and the geometry dependence of the strip-yield model is eliminated [13], [14]. The result is a curve that represents a set of points of predicted failure points, hence the name failure assessment diagram. The failure assessment diagram is basically an alternative method for graphically representing the fracture driving force.

Depending on the type of the equation used to model the effective stress intensity factors the FAD approach can be sub-divided into the strip-yield based FAD (described above and also known as the R6 approach), J-based FAD [15], [16], [17] and approximated FAD. The J-based FAD includes the effects of hardening of the material, while the simplified approximations of the FAD curve are used to reduce the calculation times of the analysis. When stress-strain data are not available for the material of interest generic FAD expressions may be used [138], [139] that assume that the FAD is independent of both geometry and material properties. The simplified curves proved adequate for most practical applications due to the fact that design stresses are usually below yield point. Fracture analysis in fully plastic regime require an elastic-plastic J analysis.

3.3.Numerical tools

The effective application of numerical methods in fracture mechanics and fatigue analysis begun with the development of computer science in the second half of the 20th century. Various methods were used (finite difference method, collocation methods, Fourier-transformations) but the finite elements method (FEM) has been established as a standard due to its universality and efficiency. FEM enables complicated crack configuration analysis under complex loads and non-linear material behavior.

Recent years have brought a significant development and increase in accessibility of commercial computational software and hardware for finite element analysis applications, marine structures included. This enables more advanced and detailed fatigue and fracture analysis even for more complex large scale structures.

Extended FEM (X-FEM) is the most recent finite element method developed and is used mainly for fracture mechanics applications. Based on the finite element method and fracture mechanics theory, X-FEM can be applied to solve complicated discontinuity issues including fracture, interface, and damage problems with great potential for use in multi-scale computation and multi-phase coupling problem. The method has been introduced in 1999. [18], and since then further developed by various authors. The basic idea of the method is to reduce the re-meshing around the crack to a minimum. The improvements enabled the crack to be represented in the FE model independently from the mesh itself [19]. Further development has enabled modeling of arbitrary discontinuities by [20], [21]. Other researchers have extended this method for three-dimensional applications 22], [23], [24], [25]. The solution for the problem of modeling curved cracks was developed by forming higher order elements [26]. Improved XFEM methods are continuously being developed by various researchers as the method has been proven as very valuable.

4. Discussion

Safety of sea navigation requires that ship structure systems have to be free from excessive stress and vibration levels (which can result in fatigue damage). Two main types of marine systems can be distinguished: a ship hull (with a superstructure and a main engine body) and a power transmission system (a crankshaft, a shaft line, a propeller). The operation of ships occurs often in extremely bad weather conditions. Marine structures are operating in more aggressive conditions than land-based constructions and even aerospace structures. Proper assessment of the ship technical condition in the critical environmental conditions is crucial from the perspective of safety of maritime navigation. Limitation of maritime disasters is of great economic importance and, more importantly, will reduce the negative environmental impact and human injuries and life losses.

Especially the propulsion system of the ship should be subject to important assessment, because like in aviation, inoperative propulsion results in a very high probability of disaster in a storm weather conditions.

International law states that each sea going ship has to fulfill regulations of one of the classification institutions. More important, classification society’s rules are based on wide knowledge collected over hundreds of years. Classification society's rules are based on simplified, empirical equations, but not all problems can be solved by empirical rules or even differential equations. Most problems with ship failure mechanisms have to be analyzed by applying numerical calculations procedures and afterwards verified by tests and measurements.

The Finite Element Method (FEM) is one of the best available approaches to the numerical analysis of continuum. It is currently the most popular technique, and numerous commercial software packages are now available for its implementation. All classification societies admit alternatives to their calculation methods, especially FEM. These, more detailed, analyses are usually more expensive but optimization is possible. The FEM consists of modelling the physical structure by a discrete mathematical model.

5. Conclusion

Engineers and scientists, when researching, designing or manufacturing devices and systems have to model complex natural and technical phenomena. It is important to model such phenomena with physical models and then convert them into simple mathematical models. Model or idealization of technical issues will be easier to calculate, test and predict the working conditions of the equipment. In order to do so, engineers and scientists must be able to describe and analyze objects, and devices to predict their behavior to see if they are consistent with the behaviors that the engineers, scientists desire. A mathematical model that describes a system in a form that uses appropriate mathematical and language concepts to facilitate the process of solving technical and natural science problems. A model may help to explain a system and to study the effects of different components, and to make predictions about behavior.

All engineers should be knowledgeable with numerical methods. There are engineers specialized in numerical analyses but also designers can have ability to supports their drafts by calculations. Strengths vibrations and fatigue analyses are a special part of numerical calculations. But also, engineers working with machine exploitation should have knowledge about numerical calculations. Usually they received several documents with applied procedures as well as with numerical analyses with practical conclusions (e.g. barred speed range for marine propulsion system caused by torsional vibration). They should have a basic knowledge about modern analyses and failure mechanisms.

The engineer should remember that all presented analysis methods are only a modelling method of abundant real life - real physical behavior. Each model has got limitations. For instance, if we use linear strain-stress theory for modelling vibrations of the machine placed on rubber pads in hot temperature (strong nonlinear material) we get proper results from numerical point of view but these results are completely wrong from practical point of view. Basic knowledge about failure mechanisms is crucial for modern engineers.

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