Chapter 9

Common Case Studies of Marine Structural Failures

Goran Vukelić and Goran Vizentin

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72789

Abstract

Marine structures are designed with a requirement to have reasonably long and safe operational life with a risk of catastrophic failures reduced to the minimum. Still, in a constant wish for reduced weight structures that can withstand increased loads, failures occur due to one or several following causes: excessive force and/or temperature induced elastic deformation, yielding, fatigue, corrosion, creep, etc. Therefore, it is important to identify threats affecting the 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, probably the most suitable way would be reviewing case studies of common failures. Roughly, marine structural failures can be divided into structural failures of ships, propulsion system failures, offshore structural failure, and marine equipment failures. This book chapter will provide an overview of such failures taking into account failure mechanisms, tools used for failure analysis and critical review of possible improvements in failure analysis techniques.

Keywords: marine structures, failure analysis, fracture, fatigue, failure

1. Introduction

Marine structures must comply with such design requirements that the probability of failures or stability loss of parts and/or complete structures is reduced to minimum. Studies and analysis of marine structural 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.

Structural safety level is determined during design process by defining specific structural elements, material properties, and functional requirements based on the expected lifetime of the structure, ramifications of eventual failures and costs of failures. Time dependency of strength and loads has to be taken into account because the strength of a structure will decrease with time while the load is varying through the lifetime of the structure.

Successful material selection process implies reconciling requirements like suitable strength of material, sufficient level of rigidity, appropriate heat resistance, etc. Structures that are susceptible to crack growth need to be made of materials selected on the basis of fracture mechanics parameters. Fracture mechanics parameters that define material resistance to crack propagation are usually determined through experimental research, but nowadays some of the experiments can be successfully substituted with numerical analysis. Material fracture behavior is usually estimated using some of the well-established fracture parameters, like stress intensity factor (K), J-integral or crack tip opening displacement (CTOD). Besides that, fatigue limit has to be taken into account, also. It has become customary to perform an optimal fatigue design analysis as an integral part of design calculations. Such analyses are also largely based on data and procedures developed from experimental and empirical research.

Marine structural failures can be divided into three main groups: failures of ships, offshore structures, and marine equipment. This book chapter will provide an overview of most common case studies of such failures. Further, failure mechanisms will be emphasized and tools used for failure analysis outlined. Possible improvements in failure analysis techniques are discussed in the end of the chapter.

2. Common case studies

2.1. Ship structural failures

Maybe the most notable case of ship failures are failures of Liberty ships in the early 1940s. These failures gave a serious boost in the development of fracture mechanics. Ships, mass produced in assembly line style out of prefabricated sections as an all-welded construction, exhibited nearly 1500 cases of brittle fractures with 12 ships breaking in half. The results of failure investigation had shown that inadequate grade of steel allowed for brittle fracture at low temperatures. Further, rectangular hull openings, such as hatch square corners, that coincided with a welded seam acted as stress concentrations points and crack origins [1].

There has been a considerable amount of failures in recent times, also. For instance, structural failure of container ship MOL Comfort [2, 3] in 2013. A yearlong failure investigation concentrated on finding the possibility of fracture occurrence and structural safety level. Results had shown that the hull fracture originated from the bottom butt joint in the midship part. A possibility that the load's upper limit exceeded strength's lower limit was also estimated using probabilistic approach. Furthermore, safety inspections of the MOL Comfort sister ships have shown buckling deformations (concave and convex) of the bottom shell plating of up to 20 mm (4 mm allowable) in height observed near the center line. Finally, a numerical analysis of the ship hull taking the load history into account was done. After the investigation, it was concluded that the load of the vertical bending moment probably exceeded the hull girder ultimate strength when the deviations of the uncertainty factors are taken into account, which caused the bottom shell plates to buckle due to excessive load. The reduction of breadth of bottom shell plate between girders increased the stress in the girder which yielded in the lower part resulting in the collapse occurs in the middle part of the ship, at the bottom, near the center line.

Bilge keels structures are used to enhance the transverse stability of ships. Cracks have been noticed in various ships in the internal structure of the bilge keels and on the connecting points to the ship's hull. Failure analysis of the damage can identify the causes of failure and the analysis results serve as basis for design improvements. It has been shown, both theoretically and applying FEM analysis, that the failure locations in bilge keels structures occur in the stress concentration regions that are present due to the structure geometry commonly used, therefore new structural elements are proposed that significantly reduce the possibility of failure occurrence [4].

Corrosively aggressive cargo (acids, alkalis, etc.) can represent a danger to the integrity of ship structures. In the case of the "Stolt Rotterdam" freighter, which sank during the cargo loading in the port, the investigation (visual, macrofractographic, and chemical) following the sinking has shown that the residue valve has cracked due to a design-specific stress (stiffer main valve was missing), thus causing a leak of the acid that accelerated the corrosion process of the floor panels in the area of the leak. Also, the valve gaskets were made of a material not resistant to acid which also contributed to the speed of the leak [5].

Marine engines and propellers produce dynamic loads on their supportive structures which can lead to fatigue failures. One of the most stressed components of the engine structure is the bearing bushing foundation. A state-of-the-art design procedure for the bearing girders is comprised of essential procedures such as bearing loads determination, stresses calculation, and the bearing girder fatigue strength assessment [6]. The fatigue and structural durability analysis is conducted for multi-axial stresses and opens the possibility to construct lightweight engines.

2.2. Propulsion system failures

The propulsion system has a pivotal role on ships. A typical marine propulsion system is comprised of main engine, driving device, marine shaft, and propeller. Most of the failures occur on the propulsion shaft that is subjected to various types of loading during operation (torque moment, bending moment, axial thrust force, and transversal loads). The operating environment of the propulsion system is characterized by significant changes in temperatures and humidity, aggressive atmosphere, long-lasting interrupted operating time, and variations in load amplitudes. The risk of failures of the propulsion system additionally increases with the severity of sea and weather conditions as they have a direct effect on the dynamics of the load variation. All of the above has direct influence on fatigue behavior and life time of the propulsion shaft.

Shaft keys are recognized as a potential origin of growing cracks. The geometry of the ends of keyways represents a stress concentration factor in the cases of torque transmission through shaft keys for dynamic vibrational loads. Faulty machining of shaft key elements (key groove, keyway, and key) geometry, inadequate run out radii, or material imperfection can be root causes of torsional fatigue failure in shaft keys. The characteristic torsional failure indicator is the crack pattern that initiates at the end of the keyway and propagates in a 45° rotational direction in a helical shape. Also, interaction between engine body and hull must be taken into account, especially thermal loads that can affect the integrity of shafts and can be successfully solved numerically [7], **Figure 1**.

A case study [8] has shown that inadequate torsional vibration calculation parameters (shaft elements stiffness and damping, natural frequencies, safety factors) and a subsequent poor design of the shaft's keyway cause failures. In this case a root cause analysis was done by the analytical stress calculation process MIL G 17859D and VDI 3822 standards. A FEM model was used in order to verify the existing fracture characteristics and causes.

An alternative to shaft key joints are spline joints, which are press fitted to other shaft elements. Analysis of spline joint failure [9] shows that the press fitting of the joining elements can cause surface deformation which in turn causes surface cracks formation. Cracks usually start on the spline teeth at the shaft junction zone. Torsional fatigue caused by fluctuating stress promotes crack growth and propagation. Inhomogeneity of the shaft material can additionally assist crack propagation. In this case, visual and macroscopic inspection was performed, followed by material chemical analysis, hardness measurement, optical, and scanning electron microscope (SEM) microstructure analysis with X-ray dispersive analysis of particles under the SEM.

Bolted connections are used in collar coupling of shaft elements and in propeller blades connections. The changes of rotation direction of the shaft results in torque moment overloading

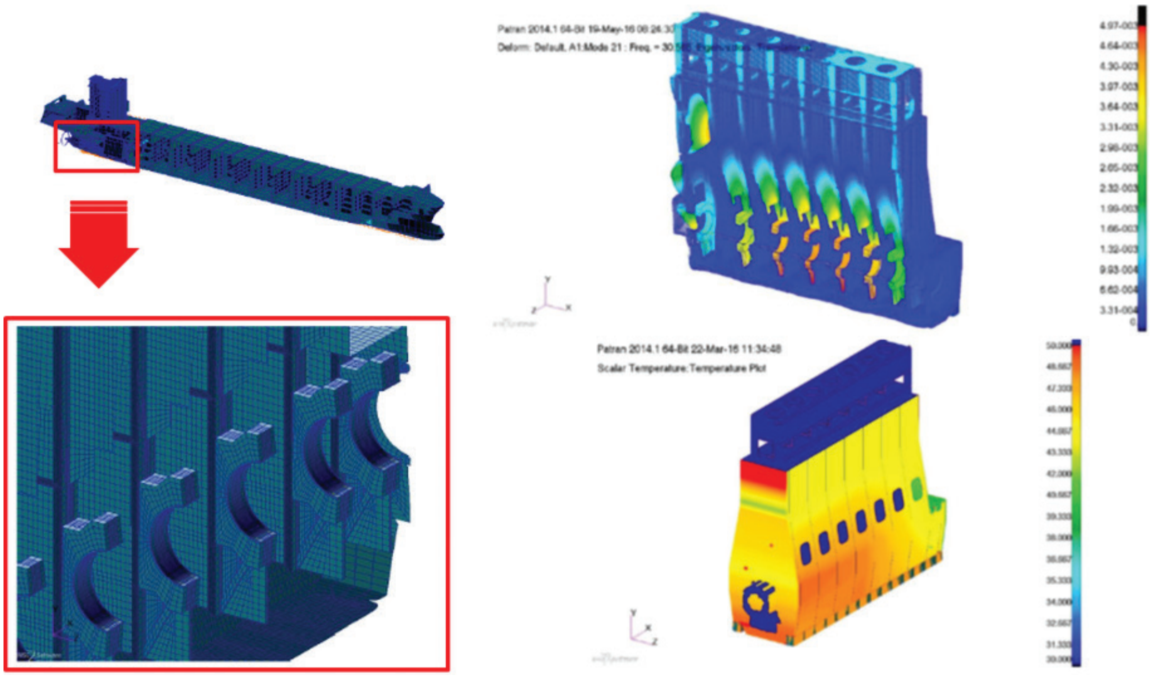

Figure 1. Engine body-ship hull interaction and thermal loads presenting a threat to structural integrity.

and direction change as well as thrust force direction change. The resulting effect is a dynamic load on collar coupling bolts in a longer operating time [10], which can result in fatigue failure. The fretting that occurs on adjacent connecting surfaces in these cases creates micronotches that develop into fatigue cracks with the direction of failure growth in planes angled from 35 to 60° which is not a characteristic of pure torsional fatigue failures. The analysis showed that the coupling bolts are subjected to an increasing bending moment which contributes to fatigue crack growth. The experimental research and numerical calculation done in this case study proved the hypothesis of variable bending stress in the coupling as the failure cause. Bolted connections of propeller blades and the shaft are often in a cathodic protection environment. Hydrogen inclusions in the material and variable stress conditions can cause crack nucleation and propagation, finally causing a failure [11]. Fractographic analysis, chemical analysis, microhardness tests, slow strain rate test, microstructure analysis, and finite element analysis were performed in this case.

Abnormal performance of the propeller by way of one non-performing malformed blade can generate a uniaxial force which fluctuates once per rotation in a consistent transverse direction across the shaft. The fluctuating force generates a couple which can cause fatigue failure of the propeller hub [12]. Uniaxial type of failure is characterized by a fatigue fracture with a single origination point that progresses across the shaft from the side where the force is being applied and results in the final overload failure occurring on the opposite side from the fluctuating force. Visual inspection, detail axis alignment measurements, microscopic metallurgical examination, hardness measurements, and ultrasonic scanning were used during the analysis.

2.3. Offshore structural failure

Offshore structures can be divided into three groups: fixed platforms (steel template and concrete gravity structures), compliant tower (compliant, guyed and articulated tower, and tension leg platform), and floating structures (floating production, storage and offloading systems).

The loads on offshore structures are gravity (self-weight, various equipment, fixed platform elements, and fluid loads), environmental (winds, waves, currents, and ice), exploitation loads, and seismic loads. Environmental loads play a major role in offshore structures design process.

In complex structures, such as offshore platforms, a fatigue failure of a single structural element may not result in a catastrophic failure of the entire structure, but it definitely changes the expected lifetime of the structure. The need for structural system failure probability estimation of typical marine structures in combination of fatigue and fracture arises. A proposed numerical and analytical method had been tested on real structures, like a Neka jack-up platform (Iran Khazar) [13], by applying various fatigue sequences that could lead to the collapse of the platform structure. This comparison has shown that the calculated system failure probability is higher for the case of combined fatigue and fracture scenarios than for only fatigue or fracture induced structure collapse which emphasizes the need for regular inspections of marine structures.

Offshore pipelines are usually damaged in the form of dents and gouges, which reduces its static and dynamic load bearing capacity as well as the fatigue life reduction in comparison to undamaged pipelines. The extent of the fatigue lifetime change depends on the type of the dent, and it can be analyzed and assessed analytically or numerically (FEM) [14]. Fatigue life analysis helps in the decision on the necessity of repairs and/or replacement of the damaged pipelines, i.e., planning of inspection and maintenance activities. Offshore pipelines segments are usually connected by welds which usually contain surface of embedded defects which exhibit large plastic strain characteristics if fracture occurs. In such cases, nonlinear elastic plastic fracture response should be modeled [15].

Subsea structures are subjected to significant external pressure loads which makes structural buckling a dominant failure mechanism. Ultra-deep water subsea separators are key equipment of subsea production in offshore petroleum industry. An experimental and numerical investigation on buckling and post-buckling of a 3000 m subsea separator has been done by Ge et al. [16]. The analysis has shown that the buckling behavior of deep sea structures can be assessed accurately applying numerical nonlinear global buckling analysis, proven by the comparison with experimental analysis results.

2.4. Marine equipment failure

This section deals with failures of marine equipment such as port or dock cranes, cables and ropes, pressure vessels-mounted onboard ships, and underwater pipelines.

Cranes can be subject to unexpected sudden events which can be divided into accidents and emergencies. Catastrophic failure of a dockside crane jib [17] occurred in the proximity of the standing tower, near the connection of the jib's three main tubes to the tower. Upon the visual inspection of the fracture surfaces, the presence of a large pre-existing crack was evident. The crack originated from a seam weld and propagated through one of the main pipes of the crane jib space frame. The failure occurred during maneuvering with no load attached. During the investigation crane material properties were obtained experimentally (tensile tests and Charpy impact tests) and the crane design was verified by FE analysis. Fatigue analysis was conducted, according to standards (FEM 1.001, Eurocode 3), for the welding joints and the pipes. Failure mode analysis was done from fracture mechanics and plastic collapse approaches. All of the analysis and investigations brought to the conclusion that the fatigue design of the jib structure was not done according to standards and that the final failure was determined by plastic collapse, after a long stable propagation period of a dominant crack which originated at the edge of a seam weld.

As for the pressure vessel failures, there are two main reasons for failures, i.e., pressure part failure (safety valves failures, corrosion, and low water level) or fuel/air explosions in the furnace (gas or liquid fuel leaks). Inadequate construction characteristics of high pressure tubes can cause failures. An investigation of a prematurely ruptured high-pressure oil tube has shown that inadequate pipe type (longitudinally welded instead of seamless) and material (design specified material replaced by a lower grade one) as well as inadequate installation procedures (not enough pipe clamps which allowed vibrations) resulted in vibration induced fatigue crack [18].

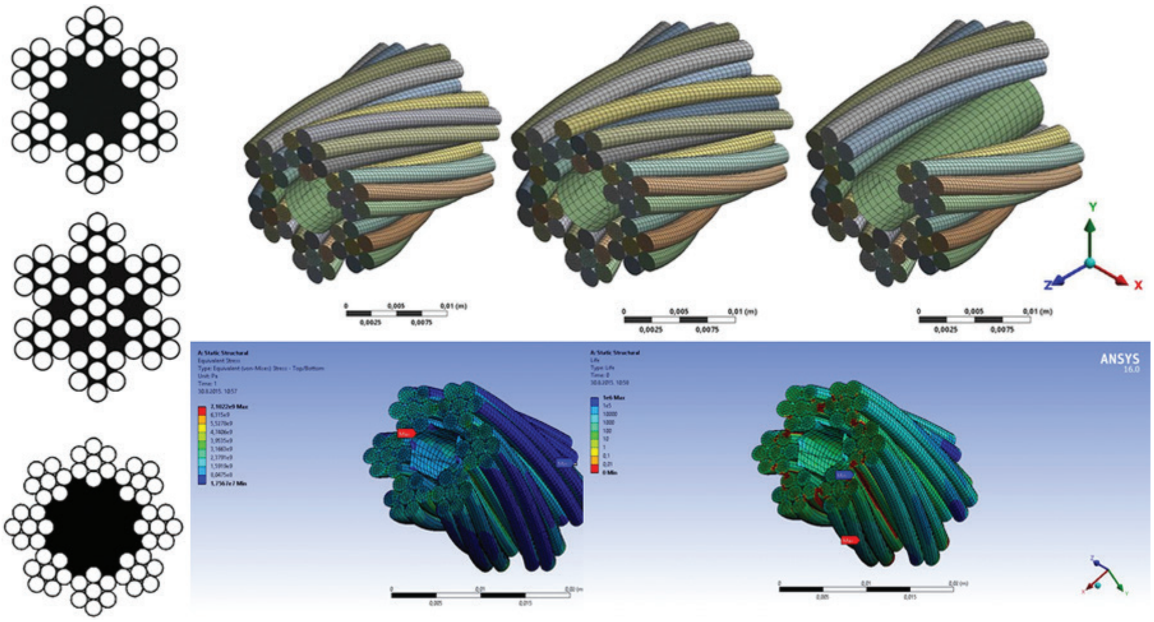

Figure 2. Numerical analysis of remaining fatigue life of a wire rope.

All equipment on marine structures is maintained and serviced continuously. In case of a malfunction, *in-situ* repairs are often performed. The quality of workmanship and material choice do have a great importance in such cases. Bending stresses in equipment elements that should be subjected only to tensile stress (ropes, wires, etc.) can cause failure of such elements. Numerical analysis of different wire rope cross section configurations is performed in order to determine remaining fatigue of operating wire ropes in dockside cranes [19], **Figure 2**.

Subsea umbilicals are composite cable and small diameter tubular bundles deployed on the seabed in conjunction with offshore installations for oil or gas exploitation. These tubes are loaded by alternating internal pressure and exposed to sea currents, i.e., dynamic loading [20]. Cracks in this type of equipment result in leaks and loss of load-carrying capacity. Umbilical tubes experience loss of circularity in shape (ovalization) and are subjected to re-rounding procedures by applying boost pressure prior to service which also translates in fatigue loading.

3. Failure causes and mechanisms

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 the 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.

The process of fatigue failure itself is highly complex in nature and it is dependent on a large number of parameters. The factors are numerous and perhaps the most significant are mean stress (distribution), residual stresses, loading characteristics and sequence, structural dimensions, corrosion parameters, environmental temperature, design criteria fabrication methods and quality.

Failure mechanisms that usually occur in marine structures can be progressive (excessive yielding, buckling, excessive deformations) or sudden (brittle and fatigue fractures). Excessive yielding and brittle fractures occur when the load exceeds critical strength, while buckling and fatigue fractures depend on time and specific load conditions.

4. 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).

Some authors [21] divide fatigue analysis methods in two groups: S-N approach based on fatigue tests and fracture mechanics approach. The first method is used for fatigue design purpose using simplified fatigue analysis, spectral fatigue analysis, or time domain fatigue analysis to determine fatigue loads. The second method is used for determination of acceptable flaw size, prediction of crack growth behavior, planning maintenance of the structure, and similar activities.

The latest trend in failure analysis development is the unification of analysis methods and procedures [22–24], 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.

4.1. Experimental tools

Nondestructive testing and examination (NDT and 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 100,000×) 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 analyses of marine structures and equipment have been conducted using SEM [25–28], one of them being analysis of speed boat steering wheel fracture, **Figure 3**.

As it is well known, 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 into electronic 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

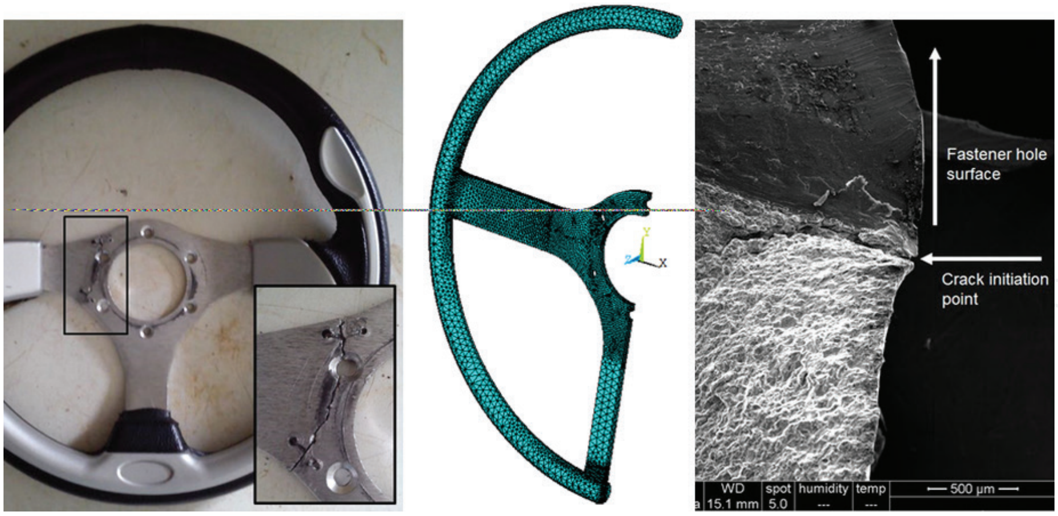

Figure 3. Experimental analysis of fractured speed boat steering wheel coupled with numerical analysis.

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 are that AE can be used in all stages of testing. Additionally, it is less sensitive to changes in geometry, the scanning is remote and it gives real-time evaluation [29]. 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.

4.2. 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 [30]. 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, the safest approach is to adopt an analysis that spans the entire range from linear elastic to fully plastic behavior. One of the methods that can be applied is the 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 [31, 32]. 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, J-based FAD, 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 [33], which 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 requires an elastic-plastic J analysis.

Marine structures are subjected to dynamic load that are characterized by exactly unpredictable, stochastic changes of value (environmental factors). Most fracture mechanics analyses are deterministic, therefore a need to view fracture probabilistically for real world conditions arise. The probabilistic fracture analysis overlaps the probability distributions of driving force in the structure and toughness distribution in the structure to obtain a finite probability of failure. Probabilistic methods can take into account time-dependent crack growth and stress corrosion cracking by applying appropriate distribution laws. Most practical situations exhibit randomness and uncertainty of the analysis variables so numerical algorithms for probabilistic analysis may be needed to apply. The well-known Mote Carlo method has been proven to be suited to accompany FAD models in cases of uncertainties.

Recently, normative institutions have been involved in projects and research, together with industry, in order to establish probabilistic methods for planning in-service inspection for fatigue cracks in offshore structures. DNV-issued recommendations on how to use probabilistic methods for jacket structures, semisubmersibles, and floating production ships [34]. Basically, the goal of probabilistic method is to replace inspection planning based on engineering assessment of fatigue and failure consequences with mathematical models for the influence of exploitation, fatigue causes, and crack propagation characteristics on the lifetime of the structure to obtain a more reliable and secure assessment methodology independent of the engineers' level of expertise.

Li and Chow [35] have developed a fatigue damage model by formulating a set of damage coupled constitutive and evolution equations in order to write a computer software that could predict the behavior of offshore structures under dynamic load. The fatigue damage model is based on sea wave's characteristics statistics. The model also includes historical damage data.

Cui [36] has focused his research on the requirement for accurate fracture growth predictions that preceding fatigue strength assessment methods, mainly based on cumulative fatigue damage theory using stress-endurance curves (S-N), have not taken into account. The effects of initial defects and load sequence are included in the prediction model. A fatigue crack propagation theory has been proposed as technically feasible and adoptable method for fatigue life prediction using commercial FEA/FEM software packages for the calculation processes. The need for a database of the size and distribution of initial defects for marine structures is emphasized.

Li et al. [37] have developed an improved procedure for creation of standardized load-time history for marine structures based on a short-term load measurement. The need for load-time history arises from the dependency fatigue crack growth behavior to load sequence effect.

It is known that small variations in the initial (basic) assumptions for a fatigue analysis can have significant influence for the predicted crack growth time. As mentioned above, the S-N based calculations are sensitive to input parameters values and definitions [38]. As the occurrence of a crack is not strictly deterministic, probabilistic methods for the prediction of crack behavior and sizes, based on fatigue crack propagation theory, can resolve accuracy problems. Probabilistic methods require extensive database of standardized load-time histories for marine structures, based on extensive experimental research, which can be used in analysis procedures.

4.3. 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 twentieth century. Various methods were used (finite difference method, collocation methods, and Fourier-transformations) but the finite element 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. Furthermore, numerical tools can be used to complement or even substitute experimental analyses, as in the material selection stage in design process [39], **Figure 4**.

As the extent of scientific material published on this matter is very ample, here recently developed methods will be briefly described and referenced.

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 problems. The method has been introduced in 1999 [40] 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 [40, 41]. The solution for the

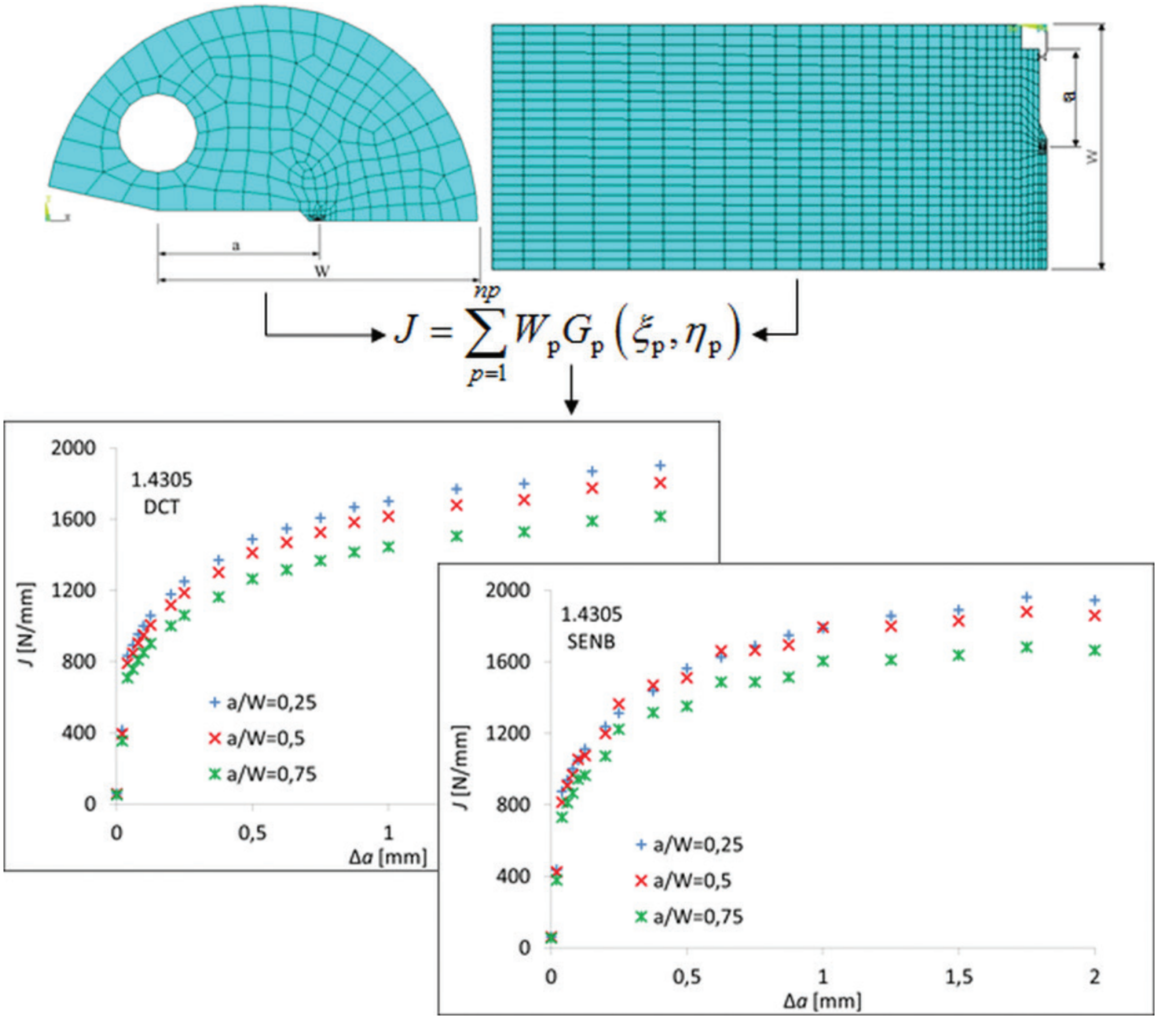

Figure 4. Numerical prediction of material fracture behavior using FE models of fracture mechanics standardized specimens in order to get dependence of J-integral to crack growth.

problem of modeling curved cracks was developed by forming higher order elements [42]. Improved XFEM methods are continuously being developed by various researchers as the method has been proven as very valuable.

Various computer software packages for fatigue crack growth analysis have been developed by NASA. FASTRAN is a life-prediction code based on the crack-closure concept and is used to predict crack length against cycles from a specified initial crack size to failure for many common crack configurations found in structural components. NASA FLAGRO v2 fatigue crack growth computer program developed as an aid in predicting the growth of pre-existing flaws and cracks in structural components using a two-dimensional model which predicts growth independently in two directions based on the calculation of stress intensity factors.

Recently, specific numerical automatic crack box technique (CBT) has been developed in order to enable to perform fine fracture mechanics calculations in various structures without global re-meshing [43]. The algorithm can be used for FEM calculations with ABAQUS code. The method represents an improvement as only the specific crack zone has to be re-meshed which results in simpler and time saving calculations. Also, the method allows the analysis of the influence of plastic material characteristics on the crack growth path.

5. Conclusions

This chapter provided an overview of common failures of marine structures taking into account failure mechanisms and tools used for failure analysis. As shown, the majority of employed failure analysis is comprised of visual, analytical, and mechanical inspection methods in the attempt to identify failure causes. The working conditions in which marine structures operate are often stochastic in nature and strongly dependent on weather conditions at sea as well on loading conditions of the structure. The complexity of failure analysis accentuates the need for numerical simulation of possible catastrophic scenarios during the entire lifetime span of the structure. If the marine structures coupled with the relevant data collected during maintenance procedures are numerically modeled than a tool for failure prediction can be developed. Therefore, complete analysis comprising analytical, experimental, and numerical research is desirable to obtain satisfying results.

Acknowledgements

The materials and data in this publication have been obtained through the support of the International Association of Maritime Universities (IAMU) and The Nippon Foundation in Japan.

Author details

Goran Vukelić* and Goran Vizentin

*Address all correspondence to: gvukelic@pfri.hr

Faculty of Maritime Studies Rijeka, University of Rijeka, Rijeka, Croatia

References

[1] Zhang W. Technical problem identification for the failures of the liberty ships. Challenges. 2016;7:20. DOI: 10.3390/challe7020020

[2] Class NK. Investigation Report on Structural Safety of Large Container Ships. Tokyo: Class NK; 2014.

[3] CLCSS. Final Report of Committee on Large Container Ship Safety (English Version) Tokyo: CLCSS; 2015. pp. 1-30

[4] Martins RF, Rodrigues H, Leal das Neves L, Pires da Silva P. Failure analysis of bilge keels and its design improvement. Engineering Failure Analysis. 2013;**27**:232-249. DOI: 10.1016/j.engfailanal.2012.06.002

[5] Zunkel A, Tiebe C, Schlischka J. "Stolt Rotterdam"—The sinking of an acid freighter. Engineering Failure Analysis. 2014;**43**:221-231. DOI: 10.1016/j.engfailanal.2014.03.002

[6] Grubišić V, Vulić N, Sönnichsen S. Structural durability validation of bearing girders in marine diesel engines. Engineering Failure Analysis. 2008;**15**:247-260. DOI: 10.1016/j.engfailanal.2007.01.014

[7] Murawski L. Thermal interaction between main engine body and ship hull. Ocean Engineering. 2018;**147**:107-120. DOI: 10.1016/j.oceaneng.2017.10.038

[8] Han HS, Lee KH, Park SH. Parametric study to identify the cause of high torsional vibration of the propulsion shaft in the ship. Engineering Failure Analysis. 2016;**59**:334-346. DOI: 10.1016/j.engfailanal.2015.10.018

[9] Arisoy CF, Başman G, Şeşen MK. Failure of a 17-4 PH stainless steel sailboat propeller shaft. Engineering Failure Analysis. 2003;**10**:711-717. DOI: 10.1016/S1350-6307(03)00041-4

[10] Dymarski C. Analysis of Ship Shaft Line Coupling Bolts Failure. Journal of Polish CIMAC. 2009;**4**(2):33-40

[11] Zhenqian Z, Zhiling T, Chun Y, Shuangping L. Failure analysis of vessel propeller bolts under fastening stress and cathode protection environment. Engineering Failure Analysis. 2015;**57**:129-136. DOI: 10.1016/j.engfailanal.2015.07.013

[12] Aurecon New Zealand Limited. Aratere Shaft Failure Investigation. Wellington: Aurecon New Zealand Limited; 2015

[13] Shabakhty N. System failure probability of offshore jack-up platforms in the combination of fatigue and fracture. Engineering Failure Analysis. 2011;**18**:223-243. DOI: 10.1016/j.engfailanal.2010.09.002

[14] Macdonald KA, Cosham A, Alexander CR, Hopkins P. Assessing mechanical damage in offshore pipelines—Two case studies. Engineering Failure Analysis. 2007;**14**:1667-1679. DOI: 10.1016/j.engfailanal.2006.11.074

[15] Zhang YM, Yi DK, Xiao ZM, Huang ZH. Engineering critical assessment for offshore pipelines with 3-D elliptical embedded cracks. Engineering Failure Analysis. 2015;**51**:37-54. DOI: 10.1016/j.engfailanal.2015.02.018

[16] Ge J, Li W, Chen G, Li X, Ruan C, Zhang S. Experimental and numerical investigation on buckling and post-buckling of a 3000 m subsea separator. Engineering Failure Analysis. 2017;**74**:107-118. DOI: 10.1016/j.engfailanal.2017.01.001

[17] Frendo F. Analysis of the catastrophic failure of a dockside crane jib. Engineering Failure Analysis. 2013;**31**:394-411. DOI: 10.1016/j.engfailanal.2013.02.026

[18] Pardal JM, de Souza GC, Leão EC, da Silva MR, Tavares SSM. Fatigue cracking of high pressure oil tube. Case Studies in Engineering Failure Analysis. 2013;**1**:171-178. DOI: 10.1016/j.csefa.2013.07.001

[19] Vukelic G, Vizentin G. Damage-induced stresses and remaining service life predictions of wire ropes. Applied Sciences. 2017;**7**:107-113. DOI: 10.3390/app7010107

[20] Zerbst U, Stadie-Frohbös G, Plonski T, Jury J. The problem of adequate yield load solutions in the context of proof tests on a damaged subsea umbilical. Engineering Failure Analysis. 2009;**16**:1062-1073. DOI: 10.1016/j.engfailanal.2008.05.013

[21] Bai Y. Marine Structural Design. 1st ed. Amsterdam: Elsevier; 2003

[22] Gutiérrez-Solana F, Cicero S. FITNET FFS procedure: A unified European procedure for structural integrity assessment. Engineering Failure Analysis. 2009;**16**:559-577. DOI: 10.1016/j.engfailanal.2008.02.007

[23] Cui W, Wang F, Huang X. A unified fatigue life prediction method for marine structures. Marine Structures. 2011;**24**:153-181. DOI: 10.1016/j.marstruc.2011.02.007

[24] Choung J. Comparative studies of fracture models for marine structural steels. Ocean Engineering. 2009;**36**:1164-1174. DOI: 10.1016/j.oceaneng.2009.08.003

[25] Vukelic G. Failure study of a cracked speed boat steering wheel. Case Studies in Engineering Failure Analysis. 2015;**4**:76-82. DOI: 10.1016/j.csefa.2015.09.002

[26] Peng C, Zhu W, Liu Z, Wei X. Perforated mechanism of a water line outlet tee pipe for an oil well drilling rig. Case Studies in Engineering Failure Analysis. 2015;**4**:39-49. DOI: 10.1016/j.csefa.2015.07.002

[27] Ilman MN, Kusmono. Analysis of internal corrosion in subsea oil pipeline. Case Studies in Engineering Failure Analysis. 2014;**2**:1-8. DOI: 10.1016/j.csefa.2013.12.003

[28] Harris W, Birkitt K. Analysis of the failure of an offshore compressor crankshaft. Case Studies in Engineering Failure Analysis. 2016;**7**:50-55. DOI: 10.1016/j.csefa.2016.07.001

[29] Hellier CJ. Handbook of Nondestructive Evaluation. 2nd ed. New York: McGraw-Hill Education; 2013

[30] Bardetsky A, Lee A. Analytical prediction of progressive structural failure of a damaged ship for rapid response damage assessment. In: Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering; 2016. pp. 1-9

[31] Dowling AR, Townley CHA. The effect of defects on structural failure: A two-criteria approach. International Journal of Pressure Vessels and Piping. 1975;**3**:77-107. DOI: 10.1016/0308-0161(75)90014-9

[32] Milne I, Ainsworth R, Dowling A, Stewart A. Assessment of the integrity of structures containing defects. International Journal of Pressure Vessels and Piping. 1988;**32**:3-104. DOI: 10.1016/0308-0161(88)90071-3

[33] Milne I, Ainsworth R, Dowling A, Stewart A. Background to and validation of CEGB report R/H/R6—Revision 3. International Journal of Pressure Vessels and Piping. 1988;**32**:105-196. DOI: 10.1016/0308-0161(88)90072-5

[34] Veritas DN. Probabilistic Methods for Planning of Inspection for Fatigue Cracks in Offshore Structures. 2015. p. 264

[35] Li DL, Chow CL. A damage mechanics approach to fatigue assessment in offshore structures. International Journal of Damage Mechanics. 1993;**2**:385-405. DOI: 10.1177/105678959300200405

[36] Cui W. A feasible study of fatigue life prediction for marine structures based on crack propagation analysis. Proceedings of the Institution of Mechanical Engineers, Part M. 2003;**217**:11-23. DOI: 10.1243/147509003321623112

[37] Li S, Cui W, Paik JK. An improved procedure for generating standardised load-time histories for marine structures. Proceedings of the Institution of Mechanical Engineers, Part M. 2016;**230**:281-296. DOI: 10.1177/1475090215569818

[38] Lotsber I, Sigurdsson G, Fjeldstad A, Torgeir M. Probabilistic Methods for Planning of Inspection for Fatigue Cracks in Offshore Structures. Marine Structures. 2016;**46**:167-192.

[39] Vukelic G, Brnic J. Numerical prediction of fracture behavior for austenitic and martensitic stainless steels. International Journal of Applied Mechanics. 2017;**9**:1750052-1-1750052-11. DOI: 10.1142/S1758825117500521

[40] Belytschko T, Black T. Elastic crack growth in finite elements with minimal remeshing. International Journal for Numerical Methods in Engineering. 1999;**45**:601-620. DOI: 10.1002/(SICI)1097-0207(19990620)45:5<601::AID-NME598>3.0.CO;2-S

[41] Moës N, Dolbow J, Belytschko T. A finite element method for crack growth without remeshing. International Journal for Numerical Methods in Engineering. 1999;**46**:131-150. DOI: 10.1002/(SICI)1097-0207(19990910)46:1<131::AID-NME726>3.0.CO;2-J

[42] Sonsino C. Fatigue testing under variable amplitude loading. International Journal of Fatigue. 2007;**29**:1080-1089. DOI: 10.1016/j.ijfatigue.2006.10.011

[43] Lebaillif D, Recho N. Brittle and ductile crack propagation using automatic finite element crack box technique. Engineering Fracture Mechanics. 2007;**74**:1810-1824. DOI: 10.1016/j.engfracmech.2006.08.029