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Fatigue Life Assessment Methods: the Case of Ship Unloaders

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ABSTRACT

This paper reviews methodologies for fatigue analysis with emphasis on ship unloaders. Maintaining the performance of ship unloaders at a satisfactory level is essential for any port's operation in order to comply with the global demand of shipping and trading. Ship unloaders are subject to alternating operational loadings and to adverse environmental conditions, and as a result, they show a rapid rate of deterioration that makes them susceptible to failure by cumulative damage processes such as corrosion and fatigue. The purpose of this paper is to review key features of the most common methodologies for fatigue analysis and to underline the limitations and uncertainties involved. Finally, developments in reliability-based approaches are suggested for a more accurate fatigue assessment of ship unloaders.

Keywords: Fatigue, Ship unloader, Failure, Reliability.

INTRODUCTION

Ship unloaders are a key element of port's infrastructure subject to aggressive environment and operational loadings that accelerate their deterioration. In general, this deterioration is associated with two cumulative damage processes: fatigue and corrosion. Here, fatigue refers to the deterioration of steel strength under cyclic loads, which may ultimately cause cracking and lead to failure of the structure or costly inspections and repairs. Towards the end of their lives, maintenance becomes more expensive and the impact on their productive capacity more serious. For this reason, the definition of a detailed maintenance program assessing the remaining life of existing (old) ship unloaders can lead to a significant reduction of risk and cost associated with/to unexpected failures.

When carrying out a fatigue design assessment, the fatigue demand on a structural detail is defined first and then compared to the fatigue strength capacity of the material. Fatigue strength of a structural component can be defined as the number of cycles that it can withstand a stress range oscillating at a constant amplitude. However, the estimation of the remaining fatigue life is not a simple task. First, inspection for fatigue cracks

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is difficult as they remain very small and hardly detectable for most of their existence. Second, a calculation of fatigue life is very sensitive to the stress range, but the determination of the range that a structural component has experienced in the past and that will experience in the foreseeable future has often associated a large degree of uncertainty. For convenience, histograms where loads are divided into ranges with number of times that each range takes place are employed in fatigue calculations. Ship unloaders are therefore slender structures with relatively low frequencies, which makes them prone to dynamic excitation. The latter can considerably shorten their fatigue life.

An appropriate design of structural details, located in that areas identified as the most critical, is the most efficient method for prevention of fatigue cracks. Therefore, fatigue design assessment has become of increasing importance over the last decades, aiming to ensure and maintain a satisfactory fatigue performance. The most efficient method to attain and maintain a satisfactory fatigue performance, throughout the lifetime of the structure, is to introduce the fatigue assessment at the design stage.

This paper reviews the most common methodologies in fatigue assessment of welded structures, their potential and limitations. Case studies on ship unloaders reveal the most common causes of failure of a crane or its part and the most critical areas in which it is necessary to carry out a fatigue design assessment. Modern reliability approaches to the fatigue problem are also presented.

SHIP UNLOADER

Structural Members

Among all the different kinds of crane employed in the construction sector, maintenance works and recovery operations, grab ship unloaders (Fig. 1) are taken as reference here. The main aim of these large scale port cranes is unloading ships and barges, moving enormous bulk cargos (materials) from ships to the hopper, from where they are then taken to the storage yard (through a conveyor belt). Fig.1 shows the two substructures composing a grab ship unloader:

- A lower substructure: A waterside and a landside portal, connected each other by diagonal braces and platforms, form the main scheme of the lower structure. The entire unloader is supported by bogies, placed at the four corners of the portal, allowing the structure to move along a rail installed on the quay.
- An upper substructure: The main structural members of the upper substructure, leant against the lower one, are the boom and the tie members. The boom, a double box girder structure, can be divided in the lifting boom that extends beyond the waterside legs and the rear boom on the landside legs. The lifting boom, unlikely the rear one, is retractable. It is supported by the front tie members, pin-connected at both ends, which lead to the pylon. Similarly the rear boom is connected to the pylon through the back tie members.

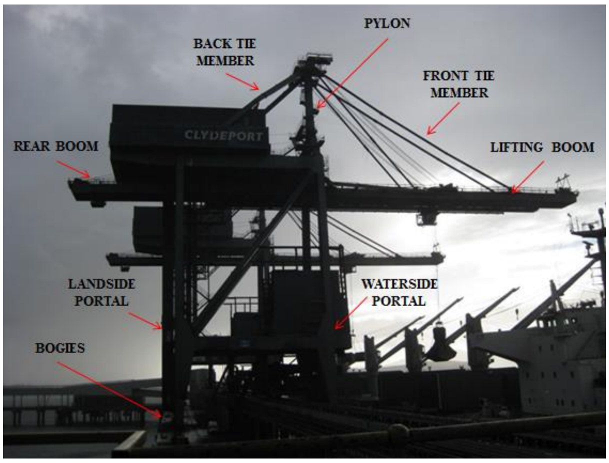

Figure 1. Ship unloader elements: Lower (Bogies, waterside portal, landside portal, hopper and diagonal brace) and Upper Substructures (Lifting boom, rear boom, front tie member, back tie member and pylon)

Failures Modes

Marquez et al (2014) and Neitzel et al (2011) warn that failure of a crane or its part can have catastrophic consequences in terms of both fatalities and economic impact caused by interruption in service and maintenance operations. MacCollum (1980) suggest a list of 13 failure modes that is still the most largely accepted, and that has been further expanded by Suruda et al. (1999) who identified other causes of fatal injuries.

Based on the list of hazardous events that could lead to failure of a crane or its components provided by the British Standard 13001 (2004), and on case studies of crane failures carried out over the last 35 years, it is possible to conclude that the most critical structural members of a ship unloader are: the boom, the tie rods and the joints. Furthermore, four main groups can be identified as the head causes of failures at a macro level: overloading, material defects, corrosion and fatigue. Overloading appears as the major cause of structural failure (around 80%) in all crane statistics. In most of cases, the latter can be attributed to human error when the operator inadvertently exceeds the crane's capacity causing irreversible damage. Morgan et al (2005) analyzed failures of over sixty materials handling crane-type machines finding that about 10% of failures can be attributed to fatigue failure, which is most of the times unexpected and of catastrophic consequences.

Loading Scenarios

Fatigue cracks will propagate when subject to cyclic (dynamic) loads. In the case of a building frame, the stress cycles generally are not sufficiently large to cause fatigue problems, however, this is not the case of ship unloaders, where dynamic loads (i.e., due to moving loads and/or wind) are very significant. During the loading and unloading operations, the structural members of a ship unloader are subject to alternating loading conditions. Identifying the stress response of these elements turns out to be essential in the framework of structural design and assessment. In order to do that, structural analyses have to be performed under different operating conditions. A description of the most relevant loading scenarios can be found in the British Standard EN 13001 (2004), FEM 1.001 (1987) and the Code for lifting appliances in a marine environment (1987), and they are summarized in Table 1.

Table 1. Loading Scenarios

Scenario	Operating Conditions
I	Crane under normal operating condition without wind
II	Crane under operating condition with wind
III	Crane in stowed condition
IV	Crane subjected to exceptional loadings

FATIGUE ASSESSMENT METHODS

Unlike other causes of failure, fatigue is considered a cumulative damage process. Fatigue occurs when an element is subjected constantly to repeated stresses that may be even much less than the strength of the material. For example, the maximum load associated to the static design of the structural components of a ship unloader, generally only represents one cycle, and it is not that relevant for fatigue analysis. A ship unloader can experience millions of cycles of uplifting and moving loads through their lives. Indeed, the loads applied are generally not high enough to cause overloading and a sudden global failure, but during each cycle of stress, the element under consideration is progressively damaged and the damage accumulates until leading to material failure.

Within the cumulative damage process, it is usually possible to identify three main phases (Violette, 1997), as follows:

- I-Fatigue initiation: it is linked to the microscopic material behavior, and may be defined as a process of cumulative plastic strain. In general it is a surface phenomenon and it is usually provoked by shear stresses.
- II-Fatigue crack growth: the crack direction becomes perpendicular to direction of the largest principal stress, and the fatigue crack driving force changes from the shear stress to the maximum principal stress.
- III-Unstable fracture: the progressive fatigue failure leads to an unstable state where the structure will fail by basically three mechanisms (brittle fracture, ductile tearing or plastic collapse). Final failure is usually characterized by a maximum tolerable or critical crack size.

Since fatigue cracks are known to initiate at stress concentration points, such as weld toes, over the last decades different methods have been developed to evaluate the fatigue strength of welded structures. These methods can be classified according to the:

- model employed: physical model or numerical analyses;
- parameter used in the calculations: approaches based on stress, strain or energy;
- character of the process: 'global' or 'local' approaches;
- type of stress employed in the analysis: nominal stress method, Hot Spot Stress (HSS) method or notch stress method.

A brief evolution of the methods under the last and most widely used criterion above is presented next.

Nominal stress method

This method, also called S-N curve (or Wohler curve) approach, takes the name from the nominal stress used in the calculation. The nominal stress can be defined as a general stress in a structural component calculated by beam theory based on the applied loads and the sectional properties of the component (Violette 1997). S-N curve are determined experimentally by testing small-scale specimens, with similar characteristics, at different stress range at a given stress ratio, and plotting the mean of the data obtained on log-log or semi-logarithmic scale. Equation 1 gives the relationship between the applied nominal stress range (S) and the number of load cycles to failure (N).

$$S^m \cdot N = C \qquad (1)$$

where *m* and *C* are constants depending on material and weld type of loading, geometrical configuration and environmental conditions (Blagojevic and Domazet, 2002).

Pountiainen and Marquis (2006) categorize this approach as 'global', given that the local geometric properties of a weld are included in the corresponding detail class and corresponding S-N curves. Indeed, the stress concentrations due to discontinuities in structural geometry and the effects caused by the presence of the welded are disregarded in the fatigue stress calculation but they are embedded in the S-N curves.
The classes of weld for which the S-N are derived are based on the geometry of the weld, the direction of the stress and the manufacture of the detail. Therefore, the choice of the more appropriate S-N curve is not so immediate, especially if dealing with complex structural details. Another issue within this method pointed out by Dong (2001), is that it is not easy to derive the nominal stress directly from the finite element model due to its mesh sensitivity at weld discontinuities.

Since very often the structural details under consideration are more complex than the test specimens, both in terms of geometry and applied loads, 'local' approaches should be employed in order to include the local character of the fatigue damage process. Nevertheless, the nominal stress method is comparatively easier to apply than 'local' approaches and still widely applied in fatigue strength evaluation.

Hot Spot Stress Method

The HSS method has been developed to enable an accurate estimation of the load effects for the fatigue strength of welded steel structures, in case where the nominal stress is hard to estimate because of geometric and loading complexities or in case where there is no classified detail with an S-N curve that is suitable to be compared with (Aygul 2012).

This method also referred to as structural or geometrical stress approach is based on the HSS that can be defined as a local stress at the critical point in a structural detail where a fatigue crack is expected to initiate. The HSS includes stress concentrations due to structural discontinuities and the presence of attachments, but excludes the effect of welds (Violette 1997).

The relationship between the nominal stress, $\sigma_{nominal}$, and the HSS, $\sigma_{hotspot}$, is given by Equation 2:

$$\sigma_{hotspot} = K_g \cdot \sigma_{nominal} \tag{2}$$

where K_g is the stress concentration factor due to the geometrical configuration of the connection.

Unlikely the nominal stress method, the HSS method can be classified as a 'local' approach since it takes into account the increase of stress due to discontinuities in structural geometry in the calculations, whereas the local stress concentrations due to the presence of the weld are still implicitly considered in the S-N curves. In this way, the number of S-N curves needed for fatigue life assessment is drastically reduced, leading to a more extensive applicability. Indeed, all kind of welded detail with a similar geometry are related to the same hot spot S-N curve.

The main issues affecting this method can be resumed in the mesh-sensitivity of the hot spot stress and the fact that this method can be applied only for weld toes where cracks start from the surface. Since it is not possible to derive the HSS directly from the finite element analysis results, it is necessary to adopt stress evaluation methods able to obtain a relevant stress that can be related to the fatigue strength of the detail. According to Liu et al (2014), the traditional approach to derive the HSS is using linear or quadratic extrapolation of surface stresses measured at two or three reference points in front of the weld toe. These reference points are suggested by the International Institute of Welding (IIW 2007) recommendations. Since the first investigations in 1960's, a number of methods have been developed in order to address these issues, among which the most significant are presented below.

Stress evaluation methods

First investigations to relate the fatigue strength to a local stress or strain measured at a certain point close to the weld toe are performed in the 1960's by several researchers, including Peterson, Manson and Haibach, (Doerk et al. 2003). Since these methods provide stress that is dependent on local notch geometry, the traditional HSS approach is developed in the 1970's. This method uses reference points for the stress evaluation and extrapolation, which are located at distances from the hot spot depending on the plate thickness; allowing the definition of HSS concentration factors in relation to dimensionless geometry parameters (Fricke and Kahl, 2005).

Following on the work by his predecessors, Radaj (1990) defines the structural stress at the weld toe as the surface stress which can be calculated following elementary structural mechanics theory. He demonstrates that local stress concentrations due to the weld toe can be kept out, and that the structural stress can be defined carrying out both extrapolation of stresses at specific points on the plate surface (Fig. 2a) and stress linearization over the plate thickness (Fig. 2b). The effects of this local non-linear stress peak are included in the S-N curves. Doerk et al. (2003) shows that this approach is still affected by mesh-size and element properties. Consequently, recommendations regarding the HSS evaluation from finite element model results have been given by Hunther et al. (1999) and Fricke (2002).

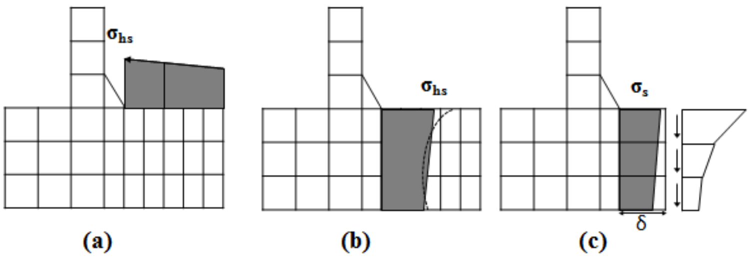

Figure 2. Evaluation of structural stress at weld toe by (a) surface stress extrapolation; (b) linearization over plate thickness and (c) equilibrium with stresses at distance δ. (Adapted from Fricke and Kahl 2005)

In order to overcome the mesh-sensitivity issue that still affects this method, Dong (2001) modifies the concept of internal linearization, for the definition of structural stress from finite element models, in order to obtain a mesh-insensitive procedure. His definition of structural stress follows some simple considerations that are summarized as follows:

- for a distribution over plate thickness derived from finite element model it is possible to define an equivalent simple stress distribution given in the form of a membrane component and bending component;
- the equivalent stress distribution has to satisfy equilibrium conditions at both the hypothetical crack plane and a reference plane where the local stress distribution are known a priori;
- while local stresses near a notch are mesh-sensitive, the imposition of the equilibrium conditions in the context of elementary structural mechanics should minimize the mesh-sensitivity in the structural stress calculation.

Therefore, Dong concludes that the structural stress should be evaluated at a distance δ, as shown in Fig.3c, from the weld toe, imposing equilibrium condition between the section at the weld toe and that at distance δ from it. As noted by Radaj et al. (2009), this procedure ignores the shear stresses at the flank sides of the element, leading to inaccuracies in the case of pronounced structural stress concentrations. In addition, the mesh-insensitivity of this approach remains questionable since the structural stress directly evaluated at the weld toe turns out to be mesh-size insensitive for 2D problems, but shows some scatter when comparing different mesh densities in a 3D problem (Doerk et al. 2003).

A variation of the structural stress approach has been proposed by Xiao and Yamada (2004), who evaluate the geometric stress 1 mm below the surface, following the direction of the expected crack path. The total stress along this path is given in the form of a geometric stress and a non-linear local stress. The latter is considered to be equivalent to the whole stress of small sized cruciform joints. According to Fricke and Kahl (2005), the depth of 1 mm is due to the faster decrease of the structural stress over the thickness than along the surface. Indeed, the local stress increase along the surface disappears at a distance of 2.5 mm, whereas at a depth of 1 mm the nominal stress is reached, regardless the shape of the weld. Even though positive results have been obtained experimentally, especially in terms of thickness effect, this approach has to be verified for other welded joints and load cases.

Notch Stress or Strain Method

Another method classifiable as 'local' approach is the notch stress or strain method, also referred to as local stress or strain approach. Within this process, the stress used in the calculations is the notch stress that can be defined as a peak stress at the root of a weld or notch taking into account stress concentrations due to the effects of structural geometry as well as the presence of welds. Equation 3 gives the relationship between the notch stress and the nominal stress.

$$\sigma_{hotspot} = K_G K_W \sigma_{nominal} \tag{3}$$

where K_W is the weld stress concentration factor.

Here, the effects due to the weld are removed from the S-N curve and explicitly taken into account in the fatigue stress calculations. Hence, the notch stress S-N curve is shifted toward higher values of the stress range. For calculating the notch stresses, an extremely fine mesh is needed in order to account for the weld profile. However, the actual weld profile is not always available, and in such cases recommendations provided by IIW (2007) have to be applied (Violette 1997).

These approaches use the maximum elastic notch stresses (notch stress method) and the maximum elastic-plastic notch strains (notch strain method) to assess the fatigue strength. The elastic notch stress concepts were originally restricted to the high-cycle fatigue range. The elastic-plastic notch strain concepts apply to the medium-cycle and low-cycle fatigue range. Successive contributions and modifications have been provided by different authors. It is worth to note the effective notch stress approach developed by Radaj et al. (2009) that introduces fictitious effective notches of radius 1 mm to weld toes or weld roots. Further studies have been performed and this notch stress approach has been included in the IIW (Hobbacher 2009) fatigue design recommendations (Rubanenco et al 2012).

Although it is acknowledged that this approach is more accurate than others described before, it can be difficult to define the exact geometry of the weld joint.

Fracture Mechanics Based Approaches

Keprate and Ratnayake (2015) point out, that large uncertainties are associated with fatigue life assessment based on the S-N approach. The uncertainties are mainly due to S-N curves, applied loads and Miner's rule. Unlike S-N approaches, the fracture mechanics approach assumes that a crack exists in the structure and thereby employing a deterministic crack growth model predicts the remaining useful life estimation of the structure. Indeed, all the approaches previously introduced are based on an S-N curve classification which refers to the estimation of the total life while these approaches are based on the principles of fracture mechanics which covers crack growth, independently from any S-N curve (Mustafa 2012).

Fracture mechanics develops in various directions since 1921, when Griffith carries out significant experimental studies, being the first to give importance to imperfections and already existing cracks (Schreurs 2012). The prediction of crack growth can be mainly based on an energy balance or on the stress rate at the crack tip.

- Based on an energy balance: It considers energy release rate as main parameter and leads to a crack growth criterion that can be considered as a 'global' one due to the large volume of material considered. Within the crack growth criterion, analyses are performed integrating crack growth law. To predict the fatigue life of structure, different crack growth models have been developed, relating the crack growth rate da/dN to load amplitude or maximum load that are usually expressed in term of stress intensity factor K. In the linear elastic fracture mechanics this relation is usually expressed by the well-known Paris law, given by Equation 4:

$$\frac{da}{dN} = C(\Delta K)^m \tag{4}$$

  where ΔK is the range of the stress intensity factor, and C and m are two parameters that can be fitted once two points are known (Schreurs 2012).

- Based on the stress rate at the crack tip: It is characterized by the stress intensity factor, K, which results in a criterion referred to as 'local' since a small material volume is investigated at the crack tip. Within the stress rate concept, the stress intensity factor, K, is determined and compared to a critical value K_c, which is evaluated through experimental procedure and considered to be a material constant. Based on the assumption that the distribution of the elastic stress field in the vicinity of the crack tip is invariant, the magnitude of the elastic stress at the crack tip can be described by the stress intensity factor (Violette 1997).

Compared to the other approaches based on the S-N curves, fracture mechanics provides a quantitative assessment of crack growth. On the other hand, it is relatively complex and requires an initial boundary condition in terms of the initial crack size to assess the fatigue life, which is subject to a large uncertainty (Violette 1997).

Miner's Rule

Since 1945, a number of damage accumulation models have been proposed to assess the fatigue damage of a structure. Among them, Miner's Rule (1945) is still the most popular due its ease of implementation and the difficulty in calibrating more sophisticated models. Schreurs (2012) states that the fatigue life for the whole load spectrum considered is independent from the sequence of the individual loadings and, thus, the individual harmonic loadings do not influence the damage growth in the following stages.

The measure of damage is defined as cycle ratio constant work absorption per cycle and characteristic amount of work absorbed at failure. Therefore, the energy accumulation leads to a linear summation of cycle ratio or damage (Fatemi and Yang 1998).
The cumulative damage, *D*, is given by Equation 5. The final life is considered to be reached once the cumulative damage *D* equalizes the value of 1.

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{5}$$

where n_i is the number of cycles characterized by a stress range ΔS_i and N_i is the number of cycled that lead to failure for a constant stress range ΔS_i.

Some of the uncertainties within the fatigue life assessment are related to Miner's rule and its limitations, including (Keprate and Ratnayake 2015):

- it does not take into account the influence of the mean value;
- experimental tests have shown that the damage threshold of 1 is not accurate;
- it is not able to take into account load interaction effects that have been observed to influence the cumulative damage.

FATIGUE RELIABILITY EVALUATION

Design against fatigue

Schreus (2012) identifies three design strategies in order to avoid failure due to fatigue:

- 'Infinite life design': It is the most conservative approach and considers a fatigue threshold below which all the highest stresses, in the most critical sections of the structures, have to be kept.
- 'Safe life design': This approach is based on data from specimens fatigue testing. Knowing the load applied to the component, the number of cycles to failure is derived from the S-N curve; once this number is reached, the component is replaced. Usually for a safer design, a much lower number of cycles are considered.
- 'Damage tolerant design': This approach is based on the monitoring of crack length. It considers a critical crack length (often a smaller value), that when reached, leads to replacements of the structural component. In this case, periodic inspections are required in order to check that the predicted crack lengths are correct.

Following the application of the 'infinite life design' the fatigue crack growth will be nearly zero, but at the same time the dimension of the structure will be so larger, that this approach is usually disregarded. Within the 'safe life design', structural components are often replaced when they still have significant remaining lives, thus it involves economic penalty (Kulkarni et al. 2006). If the rate of damage is well understood and can be periodically monitored, the 'damage tolerant design' can avoid this penalty. In particular, if monitored pre-crack and crack formation can be related by analytical fatigue damage procedure, cost reduction and safe improvements can be achieved.

Deterministic versus reliability-based approaches

Due to the stochastic nature of the fatigue cumulative damage process, the fatigue life assessment is affected by a number of uncertainties that usually arise mainly from external loadings, material properties and environmental effects. According to Xiong and Shenoi (2011), these uncertainties can be divided in three groups:

- physical uncertainty, related to the natural randomness of a quantity or imperfect measurements;
- statistical uncertainty, that arises due to limited sample sizes of observed quantities;
- model uncertainty, associated with the idealized mathematical model used to approximate the actual physical behaviour of the structure.

Within traditional deterministic fatigue life assessment, safety factors are introduced to take into account these uncertainties, leading to a qualitative assessment. When using large safety factor the structure is forced to be certified to a much longer design life than it is intended to withstand in operation incurring in enormous costs (Torng 2006).

Introducing reliability concepts at the design criterion of fatigue life can improve the prevention of failure due to fatigue of structural and mechanical elements subject to alternating service loads, achieving a reliable fatigue condition assessment. Furthermore, these concepts can also be applied at the design optimization, life extension of existing structure and assessment of in-service fatigue failures (Pountiainen and Marquis 2006).

Reliability approaches

The probabilistic procedures for reliability-based design can be categorized in the levels summarized in the chart in Figure 3. Here, higher order levels correspond to deeper calculations as described below:

- Level 1: Random variables are represented by their nominal values and the uncertainties of the variables are covered by introducing safety factors.
- Level 2: A mean value and standard deviation are used to describe each random variable, along with a measurement of any correlation between the variables in case one exists
- Level 3: A full probabilistic approach is applied. Each variable is described by a complete probability distribution function. Based on these functions, a failure probability can be calculated for each load and failure mode in order to result to a combination of failure probability for the entire structure.
- Level 4: For specific cases of severe failure effects, a combination of failure probabilities and the associated benefits and costs can be applied.

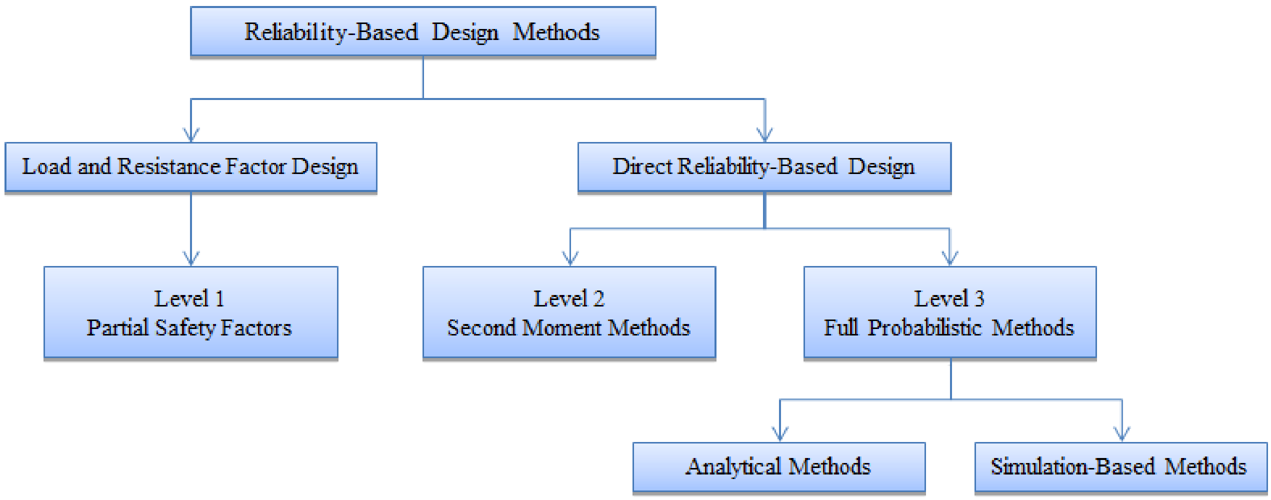

Figure 3. Levels of probability procedures for reliability-based design

Ayyub and Assakkaf (2000) distinguishe between Direct Reliability-Based Design (Level 2 and higher order levels) and Load and Resistance Factor Design (Level 1). The first method requires probability and statistical analysis, while the latter does not and is based on the use of Partial Safety Factors (PSF) resulting from reliability analysis. Within the Direct Reliability-Based Design category, there are:

- Full Probabilistic Methods (can be found as Probabilistic Feasibility Formulations), which are based on input parameter distribution leading to distributional results. For this Level 3 method, it is crucial to have a full set of the probabilistic characteristics of the parameters, making this method hard to apply. Xiang and Liu (2011) further divide the Probabilistic Feasibility Formulation into Analytical approaches and Simulation-Based approaches. The main Analytical are the First Order Reliability Method (FORM) and Second Order Reliability Method (SORM). From the Simulation-Based group, the Monte Carlo simulation method is the most commonly used for the calculation of failure probability.
- Second Moment Methods (can be found as Moment Matching Formulations), which are based on the moments (mean and variance) of the parameters (random variables). This is a more simplified Level 2 method reducing the computational effort, and thus often applies a linearization of non-linear

states. The Second Moment methods rely on utilization of reliability safety indexes in order to have a simplified process of determining the failure probability. The two most common indexes are Cornell and the Hasofer & Lind Reliability Index. The latter is an evolution of the former.

Reliability-Based Design

Since 1945 - when a paper entitled 'The safety of structures' was published - increasing attention has been given to structural reliability (Ye et al 2014). Because of the stochastic character of the fatigue damage process, reliability has been widely applied in this field, producing two main categories of fatigue reliability assessment: fatigue reliability assessment using *fracture mechanics approach* and fatigue reliability assessment using *stress-life method*. A brief overview of the developments within each of these categories is presented in the following sub-sections.

Probabilistic fracture mechanics

The probabilistic fracture mechanics are based on crack propagation data, on a more detailed approach combining fracture mechanics with stochastic methods, and on allowing for uncertainties resulting from external loads, geometry and material properties Liu et al. (1996). Contributions to the field include a linear elastic fracture mechanics-based reliability model proposed by Zhao and Haldar (1996), based on information from non-destructive tests and updating it after every inspection, and a combination of the crack propagation model, as expressed by the Paris law, by Lukic and Cremona (2001) based on the criteria of fracture toughness and plastic yield, allowing a better evaluation of the risk of fatigue damage.

Almost all kinds of reliability methods have been examined and employed in fatigue reliability analyses, including FORM, Monte Carlo, Markov process, response surface method and random finite element method (Xu 2015). For example, Oh (1978) approaches crack tip position as a state variable and calculates the probability of a fatigue crack reaching a critical size by solving the diffusion equation. Liu et al (1996) compare FORM, Monte Carlo simulation and Lagrange multiplier formulation concluding that the latter is the most efficient method for the general fatigue crack growth reliability problems. In more recent studies, Xiang and Liu (2011) propose a general probabilistic life prediction methodology, based on an inverse first order reliability method (IFORM), in order to predict the fatigue life at an arbitrary reliability level. Leonel et al (2010) use a coupling of reliability analysis with boundary element method. More specifically, they consider two coupling procedures: direct coupling of reliability and mechanical solvers and indirect coupling by the response surface method.

Probabilistic stress-life

The probabilistic stress-life approach is based on the S-N curves representing fatigue test data, so fatigue loads and resistance are the main variables that have to be measured and then defined. Constant-cycle fatigue tests are usually used in order to provide the data for the fatigue behaviour of the structure. Distributions are applied for defining the variables. Some investigations have been conducted to define the best representative distribution. It is the case of the work by Murty et al (1995) who derive the fatigue strength distribution as a function of number of cycles to failure. This distribution is based on S-N curves derived from fatigue test for two stress levels and their number of cycles to failure following a log-normal distribution. Whereas, Zhao and Wang (2000) develop an approach aiming to identify the appropriate distribution among four possible ones. It includes contest of checking the total fit effects, investigating the consistency with the fatigue physics and checking the tail fit effects.

Load-Strength technique

For the calculation of fatigue reliability, usually a load-strength model is used. It can be summarized in the estimation of the probability that the load applied to the structure (L) remains at a lower level than the one of its strength (R). Both the load and the strength are modeled by random variables. In order to carry out the reliability analysis, the nature of these variables has to be defined. Doing so, it is possible to define the probability of failure as shown in Equation 6:

$$P_f = P(L > R) \tag{6}$$

As can be seen from the graph shown in Figure 4, the probability of failure is highly dependent on the probability distributions used to describe the load and strength random variables. In particular, the upper tail of the load distribution and the lower tail of the strength one affect the final result.

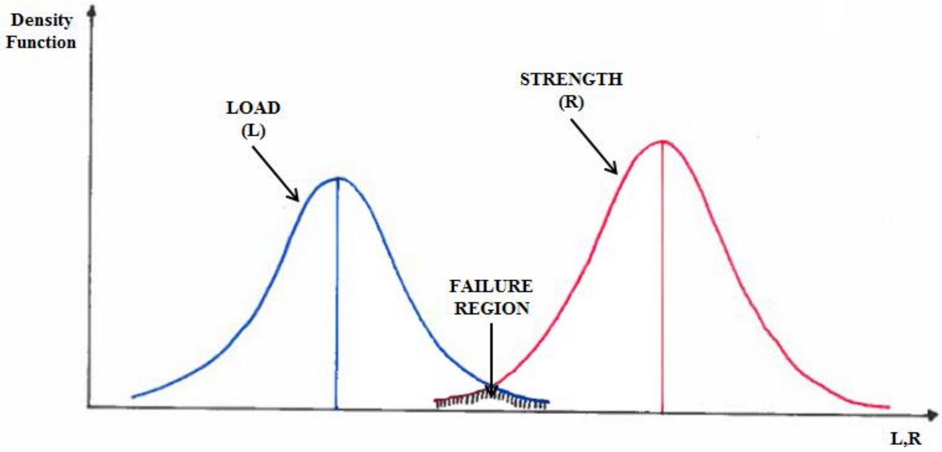

Figure 4. Frequency distribution of strength R and Loads L (Adapted from Ayyub and Assakkaf 2000)

Torstensson (2004) indicates that this approach can be applied for assessing the life of a structural element, applying a threshold to the probability of failure or at a design optimization process, finding a function that minimizes the life cycle cost of the structural element, given by the sum of the manufacturing and operation cost.

Defining Load and Strength

As stated before, an evaluation of the structural reliability requires input load and strength as a set of basic random variables, the statistical characteristics of which must be estimated. Since uncertainties can arise from a wide range of conditions, a great number of basic random variables can be detected. In order to reduce the dimension of the space of random variables, sensitivity factors can be calculated identifying the variables that can be well treated as deterministic ones.

Frequency distributions are used for the description of load and strength. Usually, normal, log-normal and Weibull distributions are employed. The design and application of these distributions depends on a variety of parameters of the aforementioned random variables. Different methods are employed in order these parameters to be estimated. According to Faber (2000), two main groups of estimation methods are *the methods of point estimate* and *the methods of interval estimate*. While the former is based on data to estimate a single value, the latter leads to a definition of an interval of possible values. Among the methods of point estimate, the most commonly employed are: method of moment (MM) and method of maximum likelihood (ML).

Defining Limit-State

The aim of reliability analysis is to define a limit-state function, thus evaluate the probability of exceeding it under certain loading conditions. Calling $G(x)$ the arbitrary function that defines the limit-state, the parameter space can be divided in safe domain, failure domain and limit-state surface as in Equation 7.

$$G(x) \begin{cases} > 0 \text{ safe domain} \\ = 0 \text{ limit-state surface} \\ < 0 \text{ failure domain} \end{cases} \tag{7}$$

When considering the capacity of a structure to not exceed a global limit-state, the ability of structural members to satisfy the member limit-state must be considered. In addition, also the way in which the structural members interact and the way in which they influence the performance of the entire structure has to be taken into account. In order to do that, it is important to define all the possible modes that lead the structure to failure and associate to each of them a limit-state function.

Probability of Failure

If the design parameters considered are random, $G(x)$ results to be a random variable. Because of that, the aforementioned probability of failure can be expressed by Equation 8.

$$P_f = P[G \leq 0] = F_G(0) \tag{8}$$

where F_G is the cumulative distribution function of the limit-state function.

Since for real world application it is usually not possible to derive the cumulative distribution function F_G, Equation (8) is more commonly expressed as Equation 9.

$$P_f = P(\mathrm{x} \in \mathcal{F}) = \int_{\mathcal{F}} f_X(\mathrm{x}) d\mathrm{x} \tag{9}$$

where $f_X(\mathrm{x})$ is the joint probability density function and $\mathcal{F}$ is the failure domain.

Apart from few particular cases, the accurate definition of the probability of failure is a complex task. For this reason, the reliability approaches described in the previous section 'reliability approaches' are preferred to carry out a structural reliability analysis.

PAST EXPERIENCE AND FUTURE RECOMMENDATIONS

This section summarizes the findings of fatigue life assessments for a 23-year-old grab ship unloader studied by Chang (2010) and then by Chang et al. (2012); two 20-year-old ship unloaders in Israel (2001) and a 34-year-old ship unloader in Scotland (2013), both carried out by Lloyd's Register.

The typical procedure in all of these fatigue life evaluations starts by an initial condition survey that reviews both historical information and data from monitoring systems. From the latter, strain histories are obtained which enable the determination of stress range histograms for fatigue assessment (by employing the rainflow counting method). Static analyses are then conducted using finite element models. Looking at the results provided by the finite element analyses and condition surveys, it is possible to identify the most critical areas to be selected for a detailed fatigue life assessment. The structural elements that require more attention are subject to significant tensile stresses and located at:

- the boom, more prone to crack propagations due to also corrosion;
- the tie rods, which exhibit overloading due to also pin ends not free to rotate.

Analyzing the results from the finite element structural analyses and the condition surveys of these case studies, it turns out that many uncertainties are related to the analyses conducted, the applied loads and the way in which the physical behavior of the structure has been approximated. Considering the unloader in Scotland, for example, the bending stresses in the ties are not well predicted by the static analyses, since they are not able to take into account the highly dynamic behavior of the elements under consideration. A full dynamic analysis would allow the reduction of scatter between the real stresses and that provided by a static analysis of the finite element model.

Other uncertainties, related to the model, could be reduced considering a reconciled model based on modal test conducted on the real structure, allowing a more accurate prediction of the structural behavior and more accurate stresses to be used in the fatigue design assessment. In addition, more than one unloader has shown some safety problems in the ties due to unexpected moments induced from the pin end not free to rotate. Therefore, it would be worth to study in detail these pin ends and to model this reduction in the rotation capacity in the finite element model, enabling a better representation of the real behavior of the structure over its life.

Regarding the applied loads, when Miner's rule is applied, the random loads applied to the structure are transferred into load spectrum, using rain flow counting techniques and successively divided into steps of constant stress range considered mutually independent. This assessment of fatigue life can be improved through modeling of the loads as random variables and through introduction of structural reliability concepts.

C ONCLUSIONS

This paper has reviewed the main structural features of a ship unloader and mechanisms of failure. Then, focus has been placed upon the most common approaches employed for estimating fatigue life, their limitations and strengths. Due to the increasing attention given to reliability-based assessment over the last decades, a brief overview of the most common methods and significant developments has been provided. The specifics of the ship unloader have been discussed in more detail, based on current fatigue assessment practice. It has become clear that large uncertainties are involved in fatigue assessment derived from the fatigue strength, the structural model, the stochastic and dynamic nature of the applied loads and the method employed for estimating fatigue life. A better knowledge of these parameters is needed for a more accurate fatigue assessment. However, the decision on the method to be applied and on the accuracy level being sought will depend on the applicability, resources (mainly cost and time) and the location, geometry and operation of the structure.

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