

# Sources of structural failure in ship unloaders

G. Milana

*Lloyd's Register Global Technology Centre, Southampton, UK and UCD, Belfield, Dublin 4, Ireland*

K. Banisoleiman

*Lloyd's Register Global Technology Centre, Southampton, UK*

A. Gonzalez

*University College Dublin (UCD), Belfield, Dublin 4, Ireland*

**ABSTRACT:** This paper reviews the most common causes of failure in ship unloaders. The structural forms employed in the design of ship unloaders and the characteristics of the loads acting on these structures are introduced first. Then, typical failures including overloading, joint failure, cable breaking, corrosion and fatigue failure amongst others, are described. Fatigue failure is discussed in further detail. When assessing a ship unloader for fatigue, it is necessary to define the fatigue demand and the fatigue strength capacity of those structural details under investigation. The latter experiences stress cycles that accumulate over time until reaching a limit that leads to cracking. Loads and stresses need to be monitored to describe those cycles, and critical locations must be checked to prevent a catastrophic failure.

## 1 INTRODUCTION

Ship unloaders represent a crucial link in the maritime transport system. These structures are subject to alternating loadings due to both horizontal and vertical motions with additional exposure to an extremely aggressive environment. It is thus understandable that port cranes are subjected to a rapid rate of deterioration compared to other welded structures. Indeed, in addition to general wear, abrasion, fatigue and accidental damage, these structures experience a significant deterioration from environmental factors and mechanisms such as corrosion, physical and chemical attack and bio-deterioration. Loss of thickness due to corrosion and cracks due to fatigue can be identified as the most critical effects. Melchers (2003) discusses corrosion models for structural reliability assessment of steel in a marine environment and their calibration with field data.

Due to the significant operational impact from a possible failure of a ship unloader, it is vital to investigate their causes and thus, the applied loads. The consequences derived from fatigue cracking are critical, even in the case in which they do not lead to total failure. Usually, Palmgren Miner Rule is used to assess compliance. Cycles of stresses induced on the ship unloader and the total damage is the sum of the individual damages by all cycles to a given point in time. According to that rule, the structure fails if the whole damage is equal or superior to 1. There are three major aspects with associated uncertainties that need to be considered in the process of carrying out a fatigue analysis:

- The structural form: For example, results in areas of high stress concentration from finite element modelling of the structural details may differ substantially

depending on the type and size of the elements as a result of singularities.

- The loads: Operational loading history due to the movement of cargo and environmental due to wind. These are dynamic loads that can excite the ship unloader to a far greater extent than a static analysis could suggest. In the past, these loads have been assessed via the use of equivalent (or pseudo-) static loads, which do not address the influence of inertial forces or how a structure may be prone to a specific mode of vibration.

- The methodology for fatigue analysis: Miner's rule lies on the assumption that damage accumulates linearly, which may not always be true, and that critical damage occurs for a fixed value. These limitations can be addressed by a more sophisticated approach such as an inverse power law model allowing for the probabilistic nature of failure.

The following sections review these aspects playing a major role in fatigue calculations together with other main causes of failure found in ship unloaders.

## 2 THE STRUCTURAL FORM

Among the various types of cranes, this paper focuses mainly on the grab ship unloaders. These are a large scale type of port cranes, whose main aim is the unloading of bulk material and containers from ship to hopper. The common scheme of a generic grab ship unloader is shown in Figure 1. They are based on the quay, supported at the four corners by bogies (no. 1 in Fig. 1) rolling along a rail. The main steel structure can be seen as composed by two parts: a base and an upper structure.

The base is made of two portal legs connected by diagonal braces (no. 5 in Fig. 1) and lower tie bars. The upper structure is mainly composed of a double box girder construction that can be divided into lifting (no. 6 in Fig. 1) and rear boom (no. 7 in Fig. 1). The latter is a fixed track girder connected to the waterside portal (no. 2 in Fig. 1) and extends beyond the landside portal (no. 3 in Fig. 1). The lifting boom, pin-connected to the rear boom, is retractable and supported by the pylon (no. 10 in Fig. 1) through front ties (no. 8 in Fig. 1), which are pin-connected at both ends. During the lifting of the front boom, these ties are folded at central pins. The boom is equipped with a trolley, where the grab is travelling to move bulk materials from the vessel to the hopper (no. 4 in Fig. 1) connected with a conveyor belt. With the exception of the front ties that are I-shape, the other main members are constructed of box-type elements.

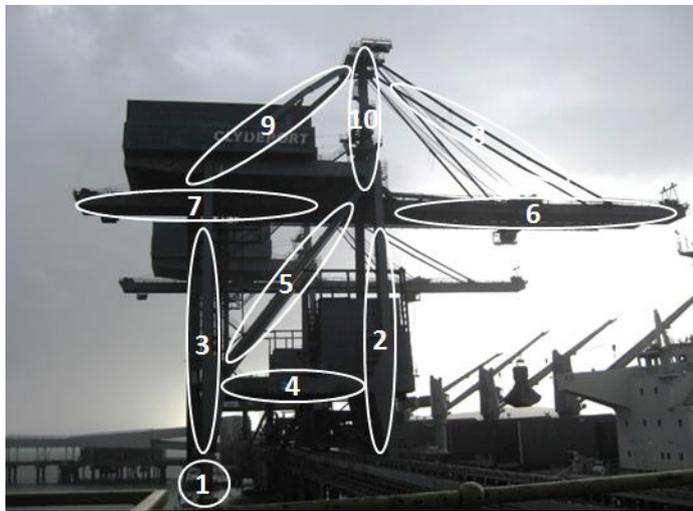


Figure 1: Ship unloader elements: 1Bogies; 2Waterside portals; 3Landside portals; 4Hopper; 5Diagonal brace; 6Lifting boom; 7Rear boom; 8Front tie members; 9Back tie members; 10Pylon (adapted from Lloyd's Register)

In conformity with the British Standard EN 13001 (2004), rigid kinetic models can be used to calculate the movements, inner forces and losses of the crane or its parts. Examples of rigid kinetic models can be found in Ghigliazza and Holmes (2002), Ju and Choo (2005) and Ju et al (2006). Combining this type of model with the loads models, it is possible to derive any variation of displacement, speed, acceleration and inner forces. It is also stated that the calculation of nominal stresses in any mechanical or structural components can be based on appropriate elasto-static models, consisting of beam or more sophisticated elements, such as plane stress, plate or shell elements.

### 3 THE LOADS

#### 3.1 Types of Loads

Following different codes, it is possible to identify different classification criteria for the loads. For example, FEM 1.001 (1987) (Table 1) divides the loads applied to these structures in four categories, according to their sources: *principal loads*; *loads due to vertical motions*; *loads due to horizontal motions* and *loads due to climatic effects*. Whereas, BS EN 13001 (2004) presents three categories depending upon their frequency of occurrence as: *regular*, *occasional* and *exceptional* loads. The 'Code for Lifting Appliances in a Marine Environment' by Lloyd's Register (1987) distinguishes the acting loads as '*in-service*' and '*stowage*' conditions.

Table 1 – Load Classification by the European Materials Handling Confederation (FEM 1.001 1987)

Type	Load
Principal loads:	due to dead weight of the components; due to the working loads;
Loads due to vertical motion:	from picking up the working loads; from accelerations of the hoisting motion; from vertical shock loadings due to travelling along rails tracks;
Loads due to horizontal motions:	inertia effects due to acceleration of the traverse, travel, slewing or luffing motions; effects of centrifugal forces; transverse horizontal reactions resulting from rolling action; buffer effect;
Loads due to climatic effects:	wind action; snow load; temperature variation.

#### 3.2 Loading Scenarios

As mentioned, the crane's structural members are subject to alternating loading that must be taken into account in the structural design or assessment. Different load combinations need to be considered. In order to take into account situations that are not expected during the design life of the structure, an accidental limit state design can be considered, with the aim of limiting accidental consequences such as structural damage and environmental pollution. According to Thayamballi and Paik (2003), design accidental scenarios and associated performance criteria must be decided upon the basis of risk assessment.

Wind load is the most crucial of the climatic effects (shown in Table 1). In the in-service condition, the wind loads are assumed to be applied in the least favorable direction in combination with the appropriate service loads, while out-of-service wind is the maximum wind load for which the crane is designed to remain stable in out of service conditions. It is

worth mentioning that, in general, the lifting structures do not have to be checked for seismic effects. Table 2 gives the most common loading scenarios considered in the structural analysis.

Table 2 – Loading Scenarios

Scenario	Load
I	crane in-service condition without wind;
II	crane in-service condition with limiting working wind;
III	crane out-of-service condition with wind and environmental actions;
IV	crane subjected to exceptional conditions such as buffer forces or failure of mechanisms in combination with in-service condition.

For each scenario, a maximum load must be determined as a basis for the calculations. In all four scenarios of Table 2, amplifying coefficients are included in order to allow for a certain probability of exceeding the calculated stress, as a result of method of approach of calculation and contingencies.

As suggested by the British Standard (2004) for the simulation of the time varying process of load actions on a crane or its parts, static equivalent loads shall be applied to elasto-static models. These static equivalent loads are considered as deterministic actions, which have been adjusted in such a way that they represent load actions during the operational conditions of the crane.

It has to be emphasized that, in the past, the dynamic loads due to operation and environment have been assessed via the use of equivalent (or pseudo-) static loads, introducing dynamic effects through amplifying coefficients. However, a more realistic picture of the structural response can be obtained via a full dynamic transient response analysis.

For example, FEM (1987) applies dynamic coefficients to represent the oscillations from operation and static loads for the constant wind speed reactions.

## 4 TYPES OF FAILURE

Catastrophic failures of cranes are potentially very dangerous events, and often have fatal consequences (Marquez et al. 2014). Indeed, as pointed out by Neitzel et al. (2011), cranes are involved in up to one third of all construction and maintenance fatalities. In addition, the economic impact caused by failure or malfunctioning of these structures is often critical since that implies an unscheduled interruption in construction and maintenance operations.

Table 3 lists four different motions of a port crane that can be identified from observation of the behavior of a ship unloader in operating condition.

Table 3 – Types of Motion

Motion	Description
Hoisting motion	Usually achieved by steel wire ropes attached to a crane hook or grab, used to lift or lower the load
Luffing motion	Movement of the boom in a vertical plane aimed to lift a load from the ship
Slewing motion	Imparted to the whole super structure of the crane so that it can turn about a central pivot shaft moving the load
Travel motion	It may be required when the whole structure has to be shifted along a rail track or a road

As consequence of these motions, the mechanisms of the structure under consideration can experience one of the following functions (FEM 1.001 1987):

- displacement of the center of gravity of the moving masses purely vertical (hoisting motions);
- displacement of the center of gravity of the moving masses purely horizontal (luffing, slewing, travel or counterbalanced luffing motions);
- combination of horizontal and vertical displacement of the center of gravity of the moving masses (non-counterbalanced luffing motion).

Due to these motions, the cranes and their components are subject to alternate stresses that can lead to failure.

### 4.1 Modes of Failure

In the last 35 years, many studies have been undertaken in order to assess the major causes of crane-related fatalities. A ship unloader crane can be considered as a subset of cranes and specific ship unloader crane case studies have been presented in Section 5. Over this period of time, the following list of failure modes by MacCollum (1980) has been widely accepted: overloading; side pull; outrigger failure; hoist limitations; two-blocking; killer hooks; boom buckling; upset/overturn; unintentional turntable turning; oversteer/crabbing; control confusion; access/egress and power-line contact.

### 4.2 Structural Causes of Failure

As pointed out by Ye et al (2014), understanding the fatigue mechanism is a prerequisite for considering various factors which affect fatigue life and fatigue crack growth. This knowledge is essential for the analysis of fatigue properties of an engineering structure.

The failure modes above can be due to a number of causes, among which human errors very often turn out to be one of the most significant. Focusing on structural causes, the British Standard 13001-1 (2004) gives the following list of hazardous events and situations that could lead to failure of the structure and its components:

- Rigid body instability of the crane or its parts (tilting, shifting);

- Elastic instability of the crane or its parts (buckling, bulging);
- Exceeding the limit of strength leading to failure of components or connections (static failure, failure by fatigue and formation of critical cracks)
- Plastic deformations from the effect of nominal stresses or sliding of frictional connections;
- Exceeding temperature limits of material or components.

From experience, three structural components have been identified as most prone to failure in ship unloaders: the *boom* (no. 6 and 7 in Fig. 1), the *tie rods* (no. 8 and 9 in Fig. 1) and the *joints*. Table 4 provides the most common causes that lead to failure of the boom.

Table 4 – Causes of Failure of the Boom

Failure	Description
Hoisting-rope failure	Rope connections usually fail due to improper clamping, sharp edges and corrosion;
Hoisting-overtopping	If boom hoisting continues after the boom has contacted the boom latch, loads greater than the design loads can develop in the ropes and the boom apex structures.;
Fatigue failure of boom support components	When the crane operates, the strays and struts experience fluctuating tensile stresses which initiate and propagate crack growth.;

In light of what has been noted, structural causes of failure can be grouped into four main categories:

- Overloading and wear;
- Material defects;
- Corrosion;
- Fatigue.

## 5 CASE STUDIES

A case study of a 23-year-old grab ship unloader by (Chang 2010) and (Chang & Wang 2012) and residual life assessments by Lloyd's Register of two 20-year-old ship unloaders in Israel (2001) and a 34-year-old ship unloader in Scotland (2013), have identified the main threats to the safety of these port cranes and the most critical members, that thus need to be subject to a more restricted maintenance plan. This section summarizes their findings.

In approaching the safety/risk assessment of ship unloaders, which sometimes, may be near the end of their lives, a proper condition survey is essential. For that purpose, all the aforementioned case studies start with a review of the historical information and analyses of available data from monitoring of the infrastructure under investigation. In the case of the 23-year-old ship unloader, 34 strain gages were installed, mainly on the structural members of retractable parts,

in order to obtain real stress responses of the structure. The strain histories, provided by the measured strain data, have been processed with a rainflow counting methods to provide the stress range histograms for fatigue assessment. In addition, static tests were performed under different operating conditions and long-term stress monitoring was carried out continuously for one year in order to collect dynamic data under real working conditions (Chang 2010). In the residual life assessments conducted by Lloyd's Register, after undertaking condition surveys, strength and fatigue assessments were carried out. The fatigue life assessment of structural details, assessed in accordance with BS 7608-1993, has been made for conventional cycles and for the measured spectra.

As shown in Figure 2, a three-dimensional finite element model was used for structural analysis, in which two loading conditions (in-service and stowage) and six loading cases for each loading condition are considered. The FEM was built using primary structural elements based on Timoshenko beam theory and four point masses modeled with element mass. For the main structural members equivalent beam sections had been calculated and used as input. Whereas, secondary structural members, such as the lift, the hopper and the machinery room were modeled as point masses.

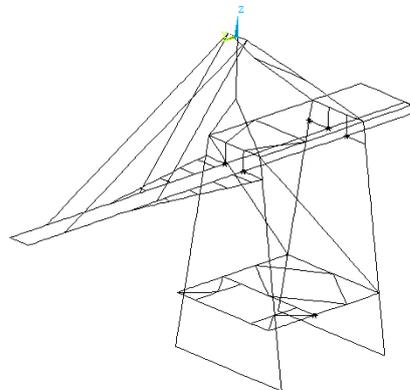


Figure 2: 3D Finite Element Model

In the mentioned case studies only static analyses have been carried out. These analyses are not always able to model a realistic behavior of the structure. Considering the ship unloader in Scotland, the bending stresses in the ties are not well predicted by the finite element analysis model, since the measured bending stresses are highly dynamic. Therefore, conducting dynamic analysis would be a more accurate assessment of the structure under consideration. In addition, a reconciled finite element model based on modal testing would be able to reduce the model uncertainty associated with the description used to approximate the physical behavior of the structure.

Results from the finite element structural analysis combined with data from the condition survey and monitoring system show that, in general, the boom and the ties exhibit significant tensile stresses, including both steady (static) and alternating (dynamic) components. In particular, it has been shown that the boom experiences reduction in thickness due to corrosion and cracks are more likely to develop in its main welds. Regarding the retractable members, pins and ties show signs of overloading, wear and fretting. It should, also, be mentioned that the front ties (no. 8 in Fig. 1) have certain safety problems mainly due to the fact that the end pins are not free to rotate, inducing unexpected moments that could be large enough to threaten safety.

Based on these case studies, the combination of both corrosion and fatigue of the steel structure emerge as a main structural safety risk for ship unloaders. Even in the case in which cracking does not lead to a complete failure, the cost of inspections and repairs and the level of environmental pollution turn out to be very high. Therefore, the following section reviews the most common methods employed in fatigue assessment and their limitations.

## 6 THE METHODOLOGY FOR FATIGUE ANALYSIS

Fatigue can be defined as a cumulative damage process in which the amplitude of cyclic loads applied is not high enough to cause sudden global failure, but the accumulation of fatigue damage can lead to failure after a certain number of load cycles that identify a limit state for the structure. Over the last decades growing importance has been given to fatigue assessment, leading to a number of methods applied to welded structures. Cracks are known to initiate at stress concentration transitions causing a local rise in stress intensity.

Fatigue assessment includes a process where the fatigue stress on a structural element is established and compared with the predicted fatigue strength of that element. The result of a fatigue assessment for a structural detail is expressed in terms of fatigue damage or expected fatigue life (Wang et al. 2004).

### 6.1 Classification of Methods

As underlined by Pountiainen & Marquis (2006), fatigue assessment methods are introduced to assess durability of metal structures under dynamic loads, and they have evolved with analysis methods becoming more sophisticated and with computers increasing in speed and memory capacity. These methods can be classified in global and local approaches depending on the kind of stresses used in the calculations. The nominal stress approach (S-N curve approach or classification method) is a global approach. The structural

stress approach (geometrical stress approach or Hot Spot Stress (HSS) method), the notch stress or strain approaches (local stress or strain approach) and fracture mechanics based approaches are local approaches. As pointed out by Aygul (2012), the first three methods consider the linear elastic theory or numerical methods (such as FEM or BEM) and are based on the S-N curve classification which refers to estimating the total life while the last method is based on the principles of fracture mechanics which covers crack growth, independent from any S-N curve.

Local approaches have often been shown to be more accurate than global approaches, especially when complex structural details are considered, although they are also more difficult to implement. Figure 3 summarizes the types of local approaches.

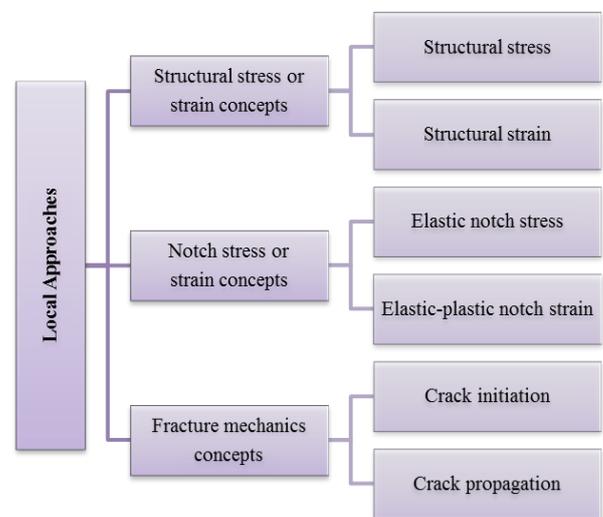


Figure 3: Classification of local concepts of fatigue assessment of welded joints (Adapted from Radaj et al. 2009)

#### 6.1.1 Types of Stresses

As mentioned before, these approaches are strongly related to the stress state at the crack tip.

The nominal stress,  $\sigma_n$ , is defined as the stress which can be derived from beam theory or from coarse mesh FEM models based on the applied loads and dimensions of the component. Increase in stresses due to discontinuities in structural geometry and presence of welds is disregarded when calculating nominal stresses.

The hot-spot stress,  $\sigma_{hs}$ , is defined as the local stress at the critical point (hot spot) in the structural detail where a fatigue crack may be initiated. In this case, increase of stress due to change in the geometry is taken into account, but the effects due to the presence of welds are excluded.

The notch stress,  $\sigma_p$ , is defined as the locally increased stress (peak stress) in a notch. The notch stress approach takes into account stress concentrations due to the presence of welds (Blagojevic & Domazet 2002). These stresses are shown in Figure 4.

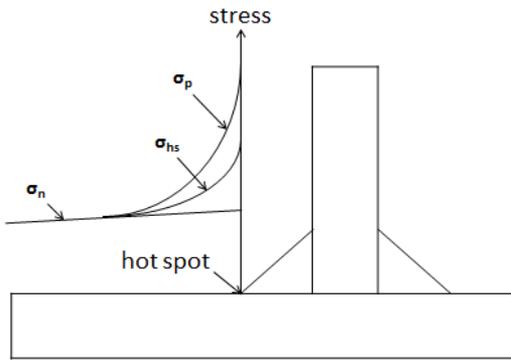


Figure 4: Types of stresses (Adapted from Blagojevic & Domazet 2002)

The subsections that follow review the approaches employed in fatigue assessment, and highlight their advantages and limitations.

## 6.2 Global Approach

### 6.2.1 Nominal Stress Approach

The nominal stress approach is the simplest and the most common method for estimating the fatigue life of steel structures. The stress distributions due to the presence of the weld and geometry discontinuities are implicitly considered in the nominal stress design S-N curves. These curves, determined experimentally, plot nominal stress ranges,  $S$ , versus number of load cycles to failure,  $N$ . In case of nominal stress, S-N curves are provided for each fatigue class that gathers welded joints with similar behavior and geometry.

According to Dong (2001), the selection of an appropriate S-N curve can be very subjective, since the weld classifications are also based on dominant loading mode. Dong identified another main issue within this method; nominal stresses,  $\sigma_n$ , cannot be readily calculated from finite element models due to their strong dependence on element size at weld discontinuities.

Therefore, this method turns out to be simple to use but quite difficult to apply, especially when dealing with complex joints and/or loadings. In these cases only local concepts can describe the local character of the fatigue process.

## 6.3 Local Approaches

### 6.3.1 Hot Spot Stress Approach

Even though this approach does not take into account the notch effect arising from the weld, it can be classified as local. The increases of stress arising from change in the geometry are considered in the calculation, reducing sensibly the number of S-N curves required. The S-N curves relate to the overall geometry

of the welded joints, hence, only one curve is associated to a type of weld. Stress concentrations due to the presence of weld are implicitly considered. Liu et al. (2014) discuss that the HSS approach is the most favorable option since it has higher precision and more extensive applicability, while avoiding the difficulty of determining the local geometry of the weld.

Probably for this reason different procedures and methods have been developed for the computation of the hot-spot stress,  $\sigma_{hs}$ , since 1960's when several researchers such as Radaj et al. (2009), Doerk et al. (2003) and Fricke & Kahl (2005) focused on relating the fatigue strength to a local stress or strain measured at a certain point close to the weld toe.

#### 6.3.1.1 Procedures to Compute the Hot-Spot Stress

The conventional way of evaluating the hot spot structural stress,  $\sigma_{hs}$ , is applying the linear or quadratic extrapolation of surface stresses evaluated at two or three reference points suggested by the International Institute of Welding (IIW 2007) recommendations. According to Liu et al. (2014), the problem of this approach is that only surface stresses are considered, even though it has been demonstrated that the stress gradient into the plate thickness also influences the fatigue life. In order to overcome this issue, many authors have proposed new extrapolation techniques.

Radaj (Radaj 1990) demonstrates that both extrapolation of stresses at specific point on the plate surface (Fig. 5(a)) and stress linearization over the plate thickness (Fig. 5(b)), lead to the exclusion of local non-linear stress peak caused by the weld toe, whose effect is considered in the S-N curves. This method appears to be mesh-sensitive.

Dong (Dong 2001), starting from the concept of internal linearization, provides a mesh-size insensitive structural stress definition that is consistent with elementary structural mechanics theory and provides an effective measure of stress in form of both membrane and bending components.

Since local stresses near a notch are mesh-size sensitive, they should be calculated at a distance  $\delta$  from the weld toe (Fig. 5(c)), imposing equilibrium condition in the context of elementary structural mechanics. As shown by Doerk et al. (2003), the method proposed by Dong turns out to be mesh-insensitive in the case of 2-D problems, but, when dealing with 3-D problems, results change slightly depending on the mesh density.

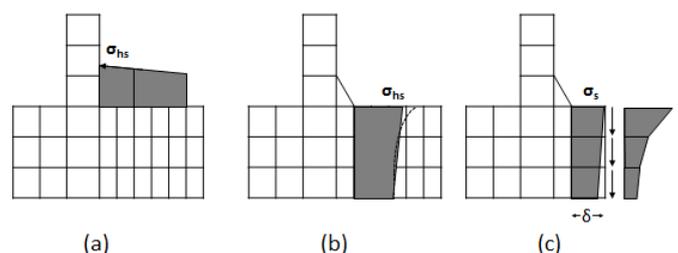


Figure 5: Structural stress at weld toe by (a) surface stress extrapolation, (b) linearization over plate thickness and (c) equilibrium with stresses at distance  $\delta$ . (From Fricke & Kahl 2005)

Xiao & Yamada (2004) introduce another approach for evaluating the structural stress in welded details. It considers the stress at a depth of 1 mm below the surface, in the direction of the expected crack path, as indicator of the fatigue strength of the structural detail. Fatigue tests carried out by the authors showed that the calculation is able to take into account size and thickness effect, being more suitable than the HSS evaluated by surface extrapolation. However, Fricke & Kahl (2005) argue that the applicability of this method still needs to be verified.

### 6.3.2 Notch Stress or Strain Approaches

It is possible to identify two concepts utilized to assess the fatigue strength: elastic notch stress and elasto-plastic notch strain. Radaj et al (2009) conducted a review of the various contributions and modifications of this approach. Stress discontinuities due to the presence of weld and geometry are included in the analysis. So, only one S-N curve is required for all details. Since it is more accurate than other approaches for fatigue life assessment, the effective notch stress method is one of the main methods recommended by the IIW (1996)..

In addition to the components of the stress identified for the HSS approach, a nonlinear stress peak component due to the notch effect of the weld is also considered. The main issue of implementation of this approach lays in the description of the geometry of the local notch at the weld.

### 6.3.3 Fracture Mechanics Based Approaches

Fracture mechanics based approaches can be divided in *stress intensity concepts* and *crack propagation concepts*. Within the stress intensity concepts, the elastic stress intensity factor at the weld toe is compared with endurable values represented by stress intensity K-N curves. Within the crack propagation concepts, analysis is performed integrating the Paris equation (Eq. 1) starting with an assumed or actually initiated short-crack (Radaj et al 2009). The Paris law is one of the most common relationships between crack growth rate ( $da/dN$ ) and stress intensity factor ( $\Delta K$ ).

$$\frac{da}{dN} = C \Delta K^m \quad (1)$$

where  $C$  and  $m$  are two parameters that can be easily fitted when two data points are known.

### 6.4 Comparison

Fricke & Kahl (2005) and Blagojevic & Domazet (2002) compare fatigue approaches and conclude that

uncertainties in fatigue strength evaluations and predicted fatigue lives are mainly due to material properties, geometry of structural components, weld modeling, stress approach applied and definition of fatigue loads.

Thus, fatigue assessment could benefit enormously by incorporating probabilistic reliability theory. If the aleatory variability of materials, loads and failures modes can be statistically modeled, then, some of the uncertainties included in the evaluation of fatigue demand and strength will be reduced, increasing accuracy on safety assessment. As a result, considerable savings will be achieved, if a ship unloader was deemed to be structurally safe, avoiding possible unnecessary replacement of the structure.

Probabilistic fatigue analysis and calculation of the probability of failure and reliability of critical joints during the service life of the ship loader improves the situation, Keprat (2015). This type of reliability information can be coupled with Optimised Inspection Planning resulting in improved inspection strategies and reduced cost.

### 6.5 Fatigue damage

The most largely employed approach to assess the cumulative fatigue damage is Miner's Rule. It evaluates the total damage as the sum of individual damages by all load cycles to a given point in time. Fluctuating stresses are divided into  $k$  steps of constant stress and equivalent length. The cumulative damage,  $D$ , is then given by Equation 2.

$$D = \sum_{i=1}^k \frac{n_i}{N_i} \quad (2)$$

where  $n_i$  is the number of cycles of stress range  $\Delta S_i$ , and  $N_i$  is the number of cycles to failure at constant stress range  $\Delta S_i$ .

Miner's Rule states that damage accumulates linearly and that the structure fails once the whole damage is equal or superior to 1. In addition, the fluctuating stresses are divided into mutually independent steps of constant stress. The above assumptions may lead to scatter between prediction and tests that could be reduced by introducing a probabilistic approach. For example, considering the loads as random variables would allow taking into account the fluctuations in the load cycles and eventually dependencies among these variables. Furthermore, it would be worthy to define a failure limit state based on reliability theory.

## 7 CONCLUSIONS

This paper has presented an overview of the main modes of failure, and their causes, for welded structures in the context of ship unloaders. Fatigue failure has been covered in more detail. A fatigue analysis is

going to require a model of the structural form, a definition of the loads and a selection of a fatigue methodology, considering their advantages and limitations.

Through the reliability theory, it would be possible to reduce some of the uncertainties included in the fatigue assessment. In addition, taking into account the variability of materials, loads and failure modes, the safety of the structure can be assessed more accurately, compared to the more traditional deterministic approach.

This reliability information coupled with Optimised Inspection Planning, could be the key benefit for decision makers by allowing them to strike a balance between structural reliability and inspection cost in determining in-service inspection strategies.

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## REFERENCES

- Aygun M. *Fatigue Analysis of Welded Structures Using the Finite Element Method*. 2012.
- Blagojevic, B. & Domazet, Z. 2002. Simplified procedures for fatigue assessment of ship structures. *10<sup>th</sup> International Congress of the International Maritime Association of the Mediterranean (IMAM 2002)*. Rethymnon, Crete 13-17 May 2002.
- British Standard Document 7608-1993. Code of practice for fatigue design and assessment of steel structures.
- British Standard Document 13001-1:2004. Cranes-General design. Part 1: General principles and requirements.
- British Standard Document 13001-2:2004. Crane safety-General design. Part 2: Load effects.
- Chang, Y.F. 2010. Fatigue life evaluation of a grab ship unloader. *China Steel Technical Report* 23:36-41.
- Chang, Y.F. & Wang, T.Y. 2012. The evaluation of fatigue crack propagation on a grab unloader. *Australasian Structural Engineering Conference (ASEC 2012)*. Perth, Western Australia 11-13 July 2012.
- Doerk, O. Fricke, W. & Weissenborn, C. 2003. Comparison of different calculation methods for structural stresses at welded joints. *Int. J. Fatigue* 25:359-369.
- Dong, P. 2001. A structural stress definition and numerical implementation for fatigue analysis of welded joints. *Int. J. Fatigue* 23:867-876.
- Federation Europeenne de la Manutention (FEM). Revised 1987.10.01. Rules for the design of hoisting appliances. 3<sup>rd</sup> Edition.
- Fricke, W. & Kahl, A. 2005. Comparison of different structural stress approaches for fatigue assessment of welded ship structures. *Marine Structures* 18:473-488.
- Ghigliazza, R.M. & Holmes, P. 2002. On the dynamics of cranes, or spherical pendula with moving supports. *Int. J. of Non-Linear Mechanics* 37:1211-1221.
- Hobbacher, A. 1996. Fatigue design of welded joints and components. IIV doc. XIII-1539-96/XV-845-96. *Int. Inst. Welding*.
- Hobbacher, A. 2007. Recommendations for fatigue design of welded joints and components. IIV doc. XIII-2151r1-07/XV-1254r1-07. *Int. Inst. Welding*.
- Keprat A. & Ratnayake C.R.M. 2015. Fatigue and fracture degradation inspection of offshore structures and mechanical items: The state of the art. *ASME 34<sup>th</sup> Int. Conf. Ocean, Offshore & Arctic Engineering OMAE2015*.
- Ju, F. & Choo, Y.S. 2005. Dynamic analysis of tower cranes. *J. of Engineering Mechanics* 131(1):88-96.
- Ju, F., Choo, Y.S. & Cui, F.S. 2006. Dynamic response of tower crane induced by the pendulum motion of the payload. *Int. J. of Solids and Structures* 43:376-389.
- Liu, G., Liu, Y. & Huang, Y. 2014. A novel structural stress approach for multiaxial fatigue strength assessment of welded joints. *Int. J. Fatigue* 63:171-182.
- Lloyd's Register Code for Lifting Appliances in a Marine Environment. 1987.
- MacCollum, D.V. 1980. Critical hazard analysis of crane design. *Professional Safety* 24:31-36.
- Marquez, A.A. Venturino, P. & Otegui, J.L. 2014. *Engineering Failure Analysis* 39:55-64.
- Melchers, R. 2003. Probabilistic Model for Marine Corrosion of Steel for Structural Reliability Assessment. *J. Struct. Eng* 129(11):1484-1493.
- Neitzel, R.L. Seixas, N.S. & Ren, K.K. 2011. A review of crane safety in the construction industry. *Appl. Occup. Environ. Hyg.* 16(12):1106-1117.
- Paik, J.K. & Thayamballi, A.K. 2003. *Ultimate limit state design of steel-plated structures*. Chichester: John Wiley & Sons.
- Pountianinen, I. & Marquis, G. 2006. A fatigue assessment method based on weld stresses. *Int. J. Fatigue* 28:1037-1046.
- Radaj, D. 1990. *Design and analysis of fatigue resistant welded structures*. Cambridge: Abington Publishing.
- Radaj, D. Sonsino, C.M. & Fricke, W. 2009. Recent developments in local concepts of fatigue assessment of welded joints. *Int. J. Fatigue* 31:2-11.
- Soderberg, E. 2011. Container crane boom collapse: cause and prevention Port Technology International. [www.porttechnology.org](http://www.porttechnology.org)
- Ye, X.W. Su, Y.H. & Han, J.P. 2014. A State-of-Art Review on Fatigue Life Assessment of Steel Bridges. *Mathematical Problems in Engineering*. Article ID 956473.
- Wang, X. Sun, Z. & Cheng, Z. 2004. Methods for fatigue assessment of critical ship details, *23<sup>rd</sup> International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2004)*. Vancouver, Canada 20-25 June 2004.
- Xiao, Z.G. & Yamada, K. 2004. A method of determining geometric stress for fatigue strength evaluation of steel welded joints. *Int. J. Fatigue* 26:1277-1293.