A Method of Calculus of Residual Lifetime for Lifting Installation

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Received April 21, 2015; Revised July 08, 2015; Accepted July 20, 2015

Abstract In this paper a method of calculus is presented step-by-step in order to establishing the residual lifetime of a lifting crane, using non-destructive methods of study. First it must be establish the actual state of machine and also areas subject to study, and then by applying the method it can be drawn the conclusion that at 2/3 of initial load can be reached an extension up to 5 times of actual residual lifetime.

Keywords: methodology, lifetime, lifting installation, non-destructive methods


1. Introduction

Metal fatigue is a process that produces premature breakage or damage of parts subjected to repeated loads. As defined in ASTM E 1150-93 [1], fatigue is “the process of structural permanent change, localized and gradual, occurring in a material subjected to conditions that produce fluctuating stresses and deformations specific to one or more points, which may culminate in cracks or complete break after a sufficient number of fluctuations”. For loads with tensions above the fatigue, but remaining in the elastic domain, is calculated limited sustainability, i.e. is calculated the number of cycles to failure. This way, one can develop analytical methods to quantify fatigue damage for structures subject to repeated dynamic loads [2].

Two phases are crucial for determining the remaining duration of life on some machines operating in dynamic mode [3]:

a. Technical inspection phases: visual inspection and non-destructive control (US, PL)

b. Expertise phases: static and dynamic calculations, and estimation of remaining duration of life.

After the expiry of the normalized lifetime of lifting equipment (overhead cranes, cranes, etc.). appears the problem of determination of residual lifetime, under normal safety conditions, meaning to function at a normal operating capacity or diminished, but not more than 25-30%.

2. Technical Inspection and Examination

Necessity and opportunity of this procedure is in accordance with HG 2139/30.11.2004, regarding the classification and the useful life of equipment and in accordance with L64/21.03.2008 regarding the safe operation of pressure vessels, installations and high fuel consuming equipment.

For exemplification, the investigation of a high gantry crane is considered, crane type MPT 20/5 – with 2 consoles and mobile cab with the following characteristics:

- hook load: main mechanism rated load = 20 t;
- rated load auxiliary mechanism = 5 t
- gauge (bridge crane) = 20 m
- wheelbase (bridge crane) = 9 m
- opening bracket = 4 + 4 m
- main lift mechanism height = 8 m
- auxiliary lift mechanism height = 8.75 m
- speed of the crane (bridge) = 31.5 m/h
- the trolley speed = 25 m / min.

This crane has a total effective work duration of 23 years and it’s wanted to establish remaining duration of life in full security and normal working conditions.

Figure 1. MPT 20/5 gantry crane

Two phases are completed in assessing the duration of lifetime remaining to lifting machines or to any type of machine:
2.1. Equipment Inspection in Situ

Equipment inspection in situ: which consists of:

- Analysis of the technical data provided by the owner/user of lifting equipment on history of operation in accordance with ISCIR technical book (Table 1)

<table>
<thead>
<tr>
<th>No.</th>
<th>Date of record</th>
<th>Date of expiry</th>
<th>Duration of operation [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>07.04.1984</td>
<td>03.1992</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>20.05.1992</td>
<td>04.1995</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>11.07.1995</td>
<td>07.1998</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>18.01.1999</td>
<td>12.2001</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>NOT working between 2001 - 2004</td>
</tr>
<tr>
<td>6</td>
<td>11.06.2004</td>
<td>30.05.2007</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>06.06.2007</td>
<td>Stopped</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>08.11.2007</td>
<td>03.2010</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>17.03.2010</td>
<td>31.03.2011</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total duration of operation $D_{ISCIR}$ = 23</td>
</tr>
</tbody>
</table>

b. Checking lifting equipment technical documentation, from which is determined the loads for calculation on each wheel of lifting mechanism, R1 ... R5, according to charging scheme, Figure 2;

c. Estimation of mass loading of cabinets with electric appliances $Q_{elec}$ [KN];

d. non-destructive examination, which is performed by:
   - visual inspection of the entire structure and on parts, Figure 3;
   - PL (Penetrating Liquids) control;
   - US (Ultrasound) or magnetic powders control.

2.2. Technical Expertise

Technical expertise which consists in analysis of data collected in situ and calculation of remaining lifetime depending on:

- Analysis of model for computation and of disposed loads;
- Establishing number of functioning cycles, depending on total duration of operation $D_{ISCIR}$ and working program per working day/year;
- Calculation of $Q_e$ - equivalent loads of fatigue damage, according to SR EN 1991-3/2007;
- Establishing welding detail, according to SR CEN/TS 13001/2005, typical for studied structure;
- Establishing distribution surface for loads on rolling track [3].

3. Structural Analysis of Load-Bearing Structure

To optimize non-destructive investigation and the establishment of control areas, and for determining maximum equivalent stress in welding and the load-bearing structure is used finite element method (FEM), applied to a simplified calculation model of lifting machine.

Analysis on models using MEF impose preprocessing and postprocessing stages.

3.1. Preprocessing

Preprocessing – starts with the achievement of geometric model of structure, Figure 4.

where:
1 - beam supporting pillars, are considered encased support so $dx = dy = dz = rx = ry = rz = 0$;
2 - loading surfaces for cabinets with electric appliances $Q_{elec}$ [KN];
3 - loading areas for loads R1...R5. Size of these areas is determined according to [3].

It continues with the choice of finite element type used in meshing the structure, in this case elements type tetrahedral grade 2, because there are also circular surfaces (the main beam pillars), Figure 5. Such a
structure has been meshed into a number of 1508119 elements with 493 830 nodes.

Next must assigning material for the structure, respectively the steel used in load-bearing structure of the crane portal. The material is known from the quality certificates of materials and technical documentation. The steel used shall have the following characteristics:

<table>
<thead>
<tr>
<th>Table 2. Characteristics of structural steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Description</td>
</tr>
<tr>
<td>Mass Density</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
</tr>
</tbody>
</table>

The load used for fatigue calculation, Qe, for each running wheel, according to SREN 1991-3/2007 is:

\[ Q_{e,i} = \phi_{fat,i} \cdot \lambda_i \cdot Q_{max,i} \]  

\( Q_{max,i} \) – maximum load on wheel i, respectively R1...R5 from technical documentation; 
\( \lambda_i \) – equivalent coefficient of damage 
\( \phi_{fat,i} \) – dynamic equivalent coefficient of damage 

For establishing equivalent coefficient \( \lambda_i \), next steps are done: 
It results HC2 / S4-S5; 
- From tab. 2.12 [12]: \( \lambda_i = (0.5 - 0.63) \); 
- It’s established a medium value: \( \lambda_i = 0.57 \); 
- It’s established the dynamic equivalent coefficient of damage:

\[ \phi_{fat,1} = \frac{1 + \varphi_1}{2} \]  
\( \varphi_1 = 1.1 \) – tab.2.4, SREN 1991-3/2007;  
\[ \phi_{fat,1} = \frac{1 + 1.1}{2} = 1.05 \]  
\[ \phi_{fat,2} = \frac{1 + \varphi_2}{2} \]  
\( \varphi_2 \) – dynamic effects when lifting the load from the ground,

\[ \varphi_2 = \varphi_2_{min} + \beta_2 \cdot v_h \]  
\( \varphi_2_{min} \), \( \beta_2 \) - depending on the lifting class, tab. 2.5 
For lifting class HC2, values for the 2 coefficients are: 
\( \beta_2 = 0.34; \varphi_2_{min} = 1.10 \)  
\( v_h = 25 \text{ m/min} = 0.41 \text{ m/s} \)  
\( \varphi_2 = 0.34 + 1.1 \cdot 0.41 = 0.79 \)  
\[ \phi_{fat,2} = \frac{1 + 0.79}{2} = 0.90 \]  
\[ \phi_{fat} = 1.05 + 0.90 = 1.95 \]

The load used for fatigue calculation, Qe, for each running wheel will be: 
Wheel _1- R1 = 19.7 KN 
\[ Q_{e,1} = 1.95 \cdot 0.57 \cdot 19.7 = 21.87 \text{ KN} \]  
Wheel _2- R2 = 20.2 KN 
\[ Q_{e,2} = 1.95 \cdot 0.57 \cdot 20.2 = 22.42 \text{ KN} \]  
Wheel _3 - R3 = 26.4 KN 
\[ Q_{e,3} = 1.95 \cdot 0.57 \cdot 26.4 = 29.30 \text{ KN} \]  
Wheel _4 - R3 = 26.7 KN 
\[ Q_{e,4} = 1.95 \cdot 0.57 \cdot 26.7 = 29.64 \text{ KN} \]  
Wheel _5- cabin- R5 = 12.36 KN 
\[ Q_{e,5} = 1.95 \cdot 0.57 \cdot 12.36 = 13.74 \text{ KN} \]

This last load is evenly distributed on all 4 wheels of the cabin. 
Thus: \( Q_{e,5.1} = Q_{e,5.2} = Q_{e,5.3} = Q_{e,5.4} = 3.45 \text{ KN/wheel} \) 
Load for cabinets with electric appliances is: 
\[ Q_{elec.} = 16.4 \times 1.1 = 18.4 \text{ KN} \]

Calculated loads will be disposed on geometric model, Figure 4.

3.2. Postprocessing

Postprocessing - It includes running the program and results interpretation.

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Postprocessing - It includes running the program and results interpretation.
There are three important objectives: a) determining the maximum equivalent stress in the weld; b) distribution map of tensions in the whole structure; c) the deformed shape of the structure under the action of loads determined previously.

a) determination of the maximum equivalent stress in the weld, as sum of loads considered for fatigue calculus, \( \sigma = 74 \text{[N/mm}^2] \), Figure 6.

b) distribution map of tensions in the whole structure, Figure 7

From structural analysis it can be drawn two conclusions:
- Value of equivalent tension in compressed area is \( \sigma = 74.5 \text{[N/mm}^2] \), being the tension value in HAZ (Heat Affected Zone).
- Non-destructive investigation US/PL will be done in the central zone of bearing beam, but also in pillars – beam connection zone, Figure 6 and Figure 8.

Following visual control (VC) in pillars – beam connection zone (zone detected by FEA, Figure 8), crack was found in the HAZ of weld of pillar-bearing beam, as shown in Figure 10.

4. Calculation to Estimate the Remaining Duration of Life, according to [6,7] – Technical Expertise

Loads used to verify the fatigue may be determined according to EN 13001, SR CENT_TS 13001-3-1, SR EN 13001-2 + A3, EN 1993-1-9-2006.

Working time - According to the ISCIIR (State Inspection for Control of Boilers, Pressure Vessels and
Elevation Installations) operating book and the machine's history operation is established the lifetime $D_{ISCIR}$ time [years] $= 23$ years.

4.1. Calculus of Average Number of Working Cycles [8]

The average number of machine cycles per year is calculated for 250 working days, 8 hours daily.

**Notations:**
- $H_{med}$ - lifting height $= 8$ m
- $L_{c,med}$ - displacement of trolley $= 28$ (m)
- $L_{p,mp}$ - crane displacement on tracks $= 100$ (m)
- $V_r$ - lifting speed $= 4.25$ m/min
- $V_{dc}$ - trolley speed $= 25$ m/min
- $V_{dp}$ - crane speed $= 31.5$ m/min
- $t_{r,1}$ - rest time between cycles, for shift I
- $t_{r,II}$ - rest time between cycles, for shift II, $t_{r,1} = t_{r,II} = 600$ [s]

Is made the calculus of average working times, considering that the crane the trolley don’t travel the whole displacement.

- Lifting respectively lowering the load $t_1$ (s)
  
  $$t_1 = 60 \cdot \frac{H_{med}}{V_r} = 113 \text{ s} \quad (17)$$

- Time of trolley displacement $t_2$ (s)
  
  $$t_2 = 60 \cdot \frac{L_{c,med}}{V_{dc}} = 67 \text{ s} \quad (18)$$

- Time of crane displacement on tracks $t_3$ (s)
  
  $$t_3 = 60 \cdot \frac{L_{p,mp}}{V_{dp}} = 190 \quad (19)$$

- The duration of a complete cycle:
  
  $$t_c = 4 \cdot t_1 + 2 \cdot t_2 + 2 \cdot t_3 = 967 \text{ s} \quad (20)$$

- Maximum number of cycles per hour:
  
  $$n_{c,max} = \frac{3600}{t_c} = 3.72 \quad (21)$$

- Rest time during one cycle and between consecutive cycles:
  
  $$t_{r,1} = t_{r,II} = 600 \text{ [s]} \quad (22)$$

- The degree of utilization $q_1; q_2$:
  
  $$q_1 = q_2 = \frac{t_c}{t_c + t_{r,1}} = 0.617 \quad (23)$$

- Average number of daily cycles $- n_z$ [cycles]:
  
  $$n_z = 8 \cdot n_{c,max} \cdot (q_1 + q_2) = 36.75 \quad (24)$$

- Average number of cycles per year, $n_{year}$ [cycles]:
  
  $$n_{year} = n_z \cdot n_{working,days} = 9.189 \cdot 10^3 \text{ cycles} \quad (25)$$

- Total number of cycles during functioning time according to ISCIR book, $D_{ISCIR} = 23$ years:
  
  $$n_{max,ISCIR} = n_{year} \cdot D_{ISCIR} = 2.11 \cdot 10^5 \quad (26)$$

With total number of cycles determined it can be found the class of loading spectrum, according to Table 2.11-SR EN 1991-3/2007, resulting class U4.

With data from technical inspection in situ have been determined:
- The load used for fatigue calculation, $Q_e$
- Lifting class HC2 / S4-S5;
- Total number of cycles during functioning time.

4.2. Establishing Stressed Welding Detail

1. The detail category it’s established according to SR CEN/TS 13001/2005 [9].

The detail category $\Delta \sigma_c$ (N/mm²) of the weld joint shape it’s established regarding the potential cracks between the basics elements and welding material, and the most heavily stressed elements of machine during work cycles.

For the portal crane MPT 20/5, with suspended trolley, the most stressed item is welded joint between wall and bottom flange of the caisson beam on which acts running wheel trolley with lifting-lowering mechanism, Figure 13 and Figure 14.

![Figure 13. Welding detail](image-url)
Fatigue curves are established in accordance with SR EN 1993 [10] and ENV 1993 [11], respectively diagram in Figure 15:

2. There are determined values for welding detail, that under the EV 1993/2006 are:
- ∆σ_c = 63 N/mm² - reference value of the fatigue strength
- ∆σ_d = 46 N/mm² - fatigue limit for the stress at a constant amplitude of a number of cycles N_D.
- ∆σ_L = 26 N/mm² - tier limit for the areas of tension in N_L cycles.

4.3 Calculation of the Number of Variable Amplitude Cycles for Primary Estimation of Remaining Life at Baseline Workloads

1. Estimation of primary residual life
   Using a constant slope m = 3, determined according to EN 1993/2006, the number of cycles Ni(Δσ_j) of solicitation of considered welding detail can be calculated according to ENV 1993 correlated with SR CEN / TS 13001.

2. Values of variables
   \[ \gamma_F = 1.0; \gamma_M = 1.35 \]
   It’s considered the condition, according to SR EN 1993/2006 (ENV 1993/1992):
   \[ \gamma_F \Delta \sigma_i \leq \frac{\Delta \sigma_D}{\gamma_M} \]
   In accordance with SR EN 1993-1-9-2006 (ENV 1993-1-1:1992), can be calculated the number of cycles of solicitation of considered welding detail:
   \[ N_i(\Delta \sigma_j) = \left( \frac{\Delta \sigma_D}{\gamma_M \Delta \sigma_D} \right)^3 \]

3. Number of cycles for welding detail under load forces
   \[ N_i(\Delta \sigma_i) = 4.794 \times 10^8 \text{ cycles} \] These are cycles of use, at real loads during work.

4. Dd20 degradation number
   This number (index 20 is used for portal crane of 20 t) is determined based on lifetime of work under operating history, which occurred in the intervals of work under the influence of Δσ_i efforts:
   \[ D_{d20} = \Sigma (n_{cycles} / N_{20.to}) < 1 \]
   \[ D_{d20} = n_{max.ISCIR} / N_i(\Delta \sigma_i) = 0.441 \]
   It is considered that by performing the n_{max.ISCIR} cycles it’s consumed a part of total lifetime, considered 100%. So the theoretical left period of lifetime is:
   \[ C_D = 100\% - D_{d20} = 0.559 \]
   This period can be consumed under certain conditions.

5. Time to consume reserve after performing the n_{max.ISCIR} cycles
   Residual length of life remaining for considered detail, under the action of normal load and time worked, denoted by T_{RLF.ISCIR} [years] is:
6. Recalculation of estimate residual life length of the machine, for a lowered load

In previous calculations residual life length for lifting crane was set at about 1.5 years, approximate running time for the maximum initial parameters of the equipment.


Initial kinematics parameters, dimensional and dynamic calculation coefficients \( \phi_1, \phi_2, \ldots \) will be retained and considered prior welding detail, for which will be reevaluate the remaining time.

Next is recalculated the number of cycles for variable amplitude.

Using a constant slope \( m = 3 \), slope determined according to SR EN 1993/2006, the number of cycles recalculated \( N_{\text{REL}}(\Delta\sigma_i) \), which loads the considered detail can be calculated according to ENV 1993 correlated with SR CEN/TS 13001.

\[
N_{\text{REL}}(\Delta\sigma_i) = 4.794 \times 10^5 \text{ cycles} \quad (35)
\]

7. Residual duration of life for considered detail

Based on recalculated number of cycles for variable amplitude, it can be recomputed \( T_{\text{RLF RE}} \) [years], which is the approximate residual use of machine on recalculated parameters, where rated load is reduced to about 2/3 of the nominal to main hook. So \( T_{\text{RLF RE}} \) [years] recomputed is:

\[
T_{\text{RLF RE}} = \text{approx. 7.696 [years]} \quad (36)
\]

5. Conclusions

By following the steps described in this paper, based on metal fatigue theory and practice, one can perform a full study of an equipment (here the lifting crane MPT 20/5). Therefore, it is stated that following presented methodology it can be done the estimation of remaining duration of life of studied equipment, according to recommendation of STAS 11694-83 and SR EN ISO 13920.

By using FEM analysis, can be detailed 3 aspects:
- establishing areas of maximum stresses, where the non-destructive investigation/examination will be made;
- lowering the costs and expertise time, by checking only interest areas;
- calculus of tension in local welding, considered as a sum of the loads used for fatigue calculation.

By applying all those steps, it was established that the studied equipment can operate with kinematics parameters set initially, but at reduced nominal load of 133 kN, i.e. approx. 13.2 t, and thus leading to an extended lifetime up to 5 times, leading to approx. 7.5 years.

References

[8] PT R 1-2010 - Machines for hoisting (cranes, lifting mechanisms, forklifts, elevating work platform erecting and platforms for persons with disabilities, vehicle lifts and special type machine high) - ISCIR 2010.