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Applying of Stress Collectives in the Design of Structural Elements of Heavy Load-Bearing Structures

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Abstract The article deals with the analytical-experimental means of determining the rate, respectively, the degree of fatigue damage for the analysis of limit state of main supporting structural element of the main beam on the twin beam of the bridge crane. Taken into account it is the dynamic effect of load hoisting and the application of load collectives and the position of the crane crab obtained experimentally for the development of stress collectives. In this analysis, the expression of the link between random load process and fatigue properties of material the Palmgren-Miner linear theory on fatigue damage accumulation was applied.

Keywords: *stress collective, bridge crane, fatigue damage*

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1. Introduction

All types of hoisting devices such as tower cranes, bridge cranes (Figure 1 with marked profile) and gantry cranes are exposed to an elevated risk of fatigue damage.

It especially concerns overhead travelling and gantry cranes operating in landfills. Also concerns metallurgic industrial halls with a heavy operating regime with above average rotating wheel pressure. Even great static and dynamic loading effects. Specific for this type of equipment is the unevenness of the crane track, unevenness of the crane crab, transverse forces of the crane or crab. Particularly vulnerable to fatigue damage are the main beams and crane rails [1,2,3].

Adverse effect can also result from aggressive handling during operations and strong winds combined with high temperatures which can lead to limit state.

The whole solution adheres to the relevant part of the algorithm used for calculating the random load process via characteristic parameter frequency method.

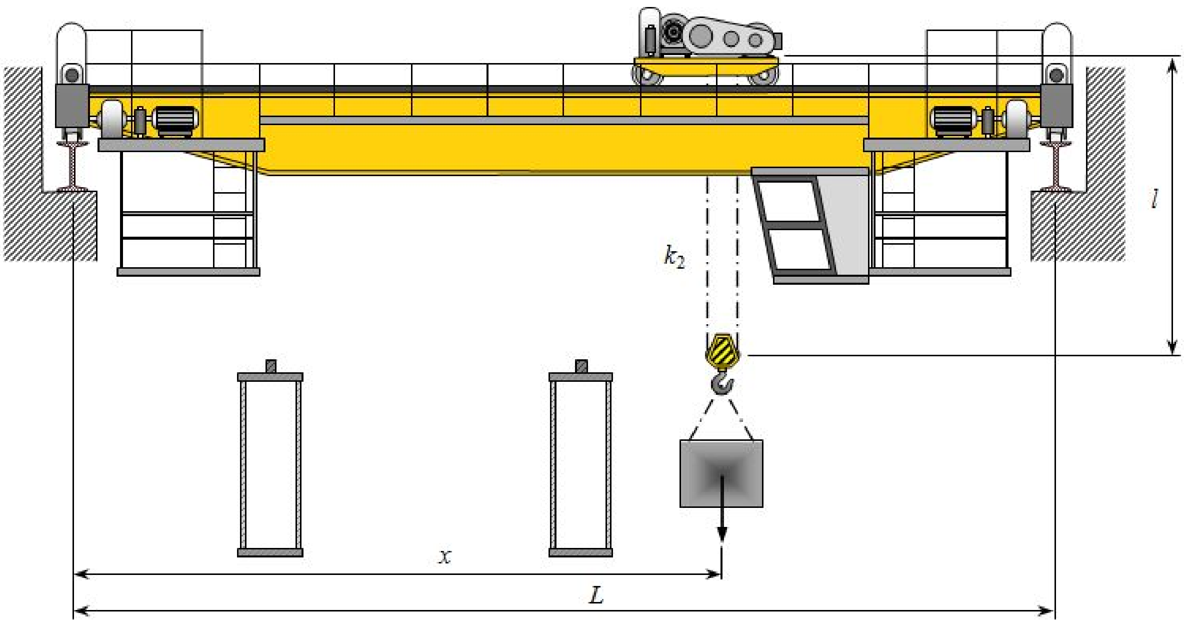

Figure 1. Scheme of traveling crane

2. Collective (Spectrum) of Observed Variables

In connection with the assessment of existing structural elements and whole structures, particularly in the field of hoisting equipment, the impact on the limit state of fatigue failure from fatigue fractures should be understood based on the historical operation of the particular equipment. As such, numerous parameters or variables enter or may enter the current analysis. For example, in regards to the limit state analysis of hoisting equipment fatigue such as an overhead bridge crane. Overhead bridge crane is a type of structure particularly vulnerable to fatigue failure. Important historic information includes the size of the load handled by the hook, the position of the crane crab, the length of the extracted carrier rope. This in turn corresponds to the history of stress, expressed as the occurrence of certain levels of normal or shear stress at a critical point or the design node of a critical structural element. Simply, it concerns the number of occurrences of certain variables. More precisely the level of characteristic parameters of certain variables. Statistically, it is possible to express such a quantity. In other words, a collective or spectrum in the histogram (distribution function) (Figure 2).

Based on the collective or spectrum of a specific variable. We will understand the statistical distribution of absolute (n_j) or relative (h_j) frequency levels of the characteristic parameter value. How much the value, represented by the character - sorting interval, occurs in the respective sorting interval for a given period – duration value. The graph can represent the data in a stepped or continuous form. Subsequently, following the history of the overhead travelling cranes construction, it is possible to talk about a collective or a load spectrum (the load on the hook). Collectives of the crane crabs position, collectives of the unwound length of the carrying cable, collectives of stress or stress collectives.

3. Collectives Used for Problem Solving

For the purpose of this analysis, a portion of the input data, variables and parameters were obtained experimentally – experimental measurements on real experimental objects. The missing part was obtained analytically – the calculation using the relevant theory. Particular data of the position of the crane crab x on the bridge of the bridge crane and the size (weight) of the load Q on the hook. Representing the actual operating load was obtained via experimental measurements on an actual overhead travelling crane with a nominal load capacity $Q_{nom} = 12{,}5$ t in actual metallurgic operating conditions. This data then entered the analysis in the form of two collectives. Devised to calculate the total number of cycles $n_c = 2{,}5 \cdot 10^6$. The first set revealed the relative frequency of the occurrence of p_{xi} relative position x_i/l of the crane crab on the crane bridge for $i = 1, \ldots I = 6$ (Figure 3). The second load bearing collective, revealed the relative frequency of the occurrence of p_{Qr} relative load weight Q_r/Q_{nom} pre $r = 1, \ldots R = 7$ (Figure 4).

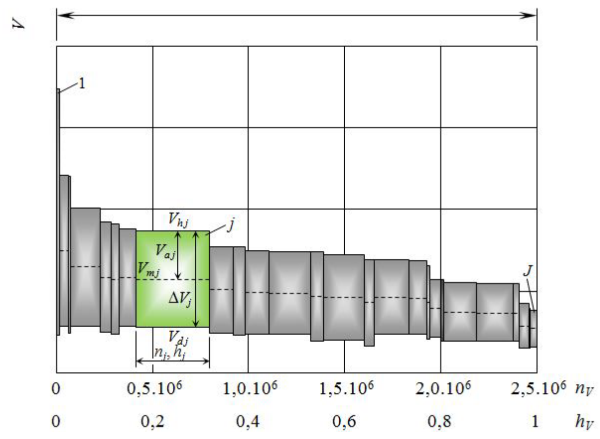

Figure 2. The collective history of the occurrence of observed variable V

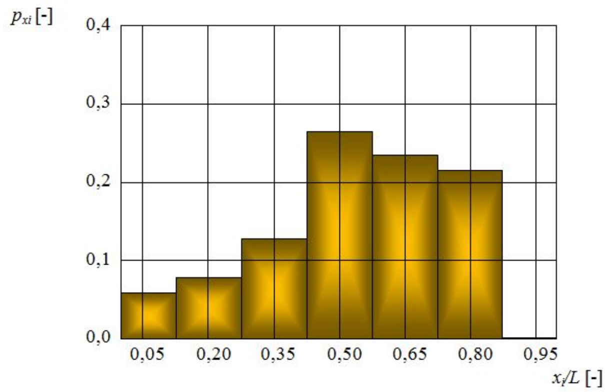

Figure 3. The collective of relative position of the crane crab

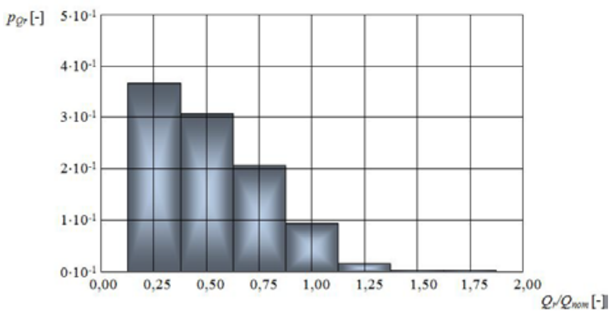

Figure 4. The collective of relative load weight

4. Application of the Bridge Crane Dynamic Model

The processing of the random load process is one of the node input parameters obtained from the experimental course of random load process. In our case, this was absent. For the analysis of missing dynamic effects of an bridge crane, we used analytical solutions in combination with a suitable dynamic model. It was developed in a way as to take into account above all else, those parameters which the engineer could influence or change. Parameters substantially affect the dynamic actions of a structure. Particularly, it concerns individual weights, stiffness, dampening, torque, speed. Given the number of mutually independent movements associated with the computational model, the number of motion equations, natural frequencies and unique shape oscillations, a compromised selection of a dual mass model with two degrees of variance was made (Figure 5) [5]. The search for a solution, among other things, lead to the formulation of dynamic coefficients. Particularly for the crane bridge and for the lifting cable.

The following values were entered into the calculation:

L [m] range of the main beam;

v [ms^{-1}] hoisting speed;

m_m [kg] weight of the crane crab;

m_M [kg] weight of both main beams;

m_2 ,Q [kg] weight of load on hook;

E [Pa] modulus of elasticity of material pull of the main beam;

E_L [Pa] modulus of elasticity of material pull of the lifting rope;

A [m^2] content cross-sectional surface area of rope;

J_y [m^4] the sum of the variable torque rotations of the cross-sectional area of the main beam's largest cross-sectional point;

W_{oy} [m^3] cross-sectional modulus for flexing of the main beam's largest cross-sectional area;

x [m] distance expressing the position of the crane crab with load;

l [m] length of rope unwound;

ϑ [-] factor reducing the mass of the main beam to the point of current position of the crane crab loads, also dependent on the position of crab x, with values according to Figure 6.

Other symbols in the image (Figure 5) present:

k_1 [Nm^{-1}] stiffness of the main beams during flexing, also dependent on the position crab x;

k_2 [Nm^{-1}] stiffness mast rope during hoisting, also dependent on length of unwound rope l;

y_1, y_2 [m] vertical axis of crab and load along path;

m_1 [kg] sum of the masses of the crane crab and reduced weight of the main beams.

5. Acquisition – Creation of Stress Collectives for the Crane's Main Beams

The next stage of the analysis involved the creation of stress collectives. From several acquired collectives, consistently for a particular discrete length of unwound carrying cable are found in Figure 7 and Figure 8, only some samples shown in illustrations. It concerns stress collectives for values of normal stresses in the extreme (upper or lower) fibers enclosed box shaped cross-section in the middle of the main span beams. Exactly these structural elements and their concrete points have been identified above as the most stressed components of dynamically loaded structure of a twin beam of bridge crane. The creation of individual blocks of stress collectives for static and dynamic components of stress was always a function of variables entering into the calculation. Partially formulated with the applied dynamic model:

$$\sigma_{stat} = \mathrm{f}\left(L, m_m, m_M, W_{oy}\right),$$

$$\sigma_{dyn} = \mathrm{f}(L, v, m_m, m_M, m_2, E, E_L, A, J_y, W_{oy}, x, l, \vartheta).$$

Collectives are comprised of $J = I \times R = 42$ discrete blocks (macroblock) as separate files with a sinusoidal cycle. The upper edge of the j block ($j = 1, ...J$) corresponds to the upper - dynamic (σ_{dyn}) stress value σ_{hj}, the lower edge corresponds to the lower - static (σ_{stat}) stress value σ_{dj} and the width of the block corresponds to an absolute or occurrences of relative frequency (n_j, h_j) of appropriate stress levels. The blocks are not arranged in order of occurrence because the respective parameter of this order was unknown, respectively, wasn't researched. Individual blocks are artificially arranged and in the descending order. Extensive research shows that the order of blocks in a macroblock, set of stress blocks. In this case with a variable constant amplitude, affects the resulting life. In particular, exertion during the descending operation of blocks accounting for the size of the amplitude of stress based fatigue life is shorter than ascending operation.

The main reason for this phenomenon is the fact that the first cycle of each block of the macroblock broadband random load process most likely causes melting (decomposition) in the material of the exposed structural elements and results in a change in the internal stress in the crystal lattice. Effect of the first cycles of stress, and any consecutive and therefore especially the first block of stress grade is the primary course of fatigue. Compared to the impact of cycles of subsequent stress changes. Since current existing theories on fatigue damage accumulation in the calculation of damage accumulation obviously do not consider the order in which vibrations of different size are applied. Therefore their effect on the calculated value of fatigue damage is not considered. That is, in this case, using Palmgren-Miner of theory on fatigue damage accumulation.

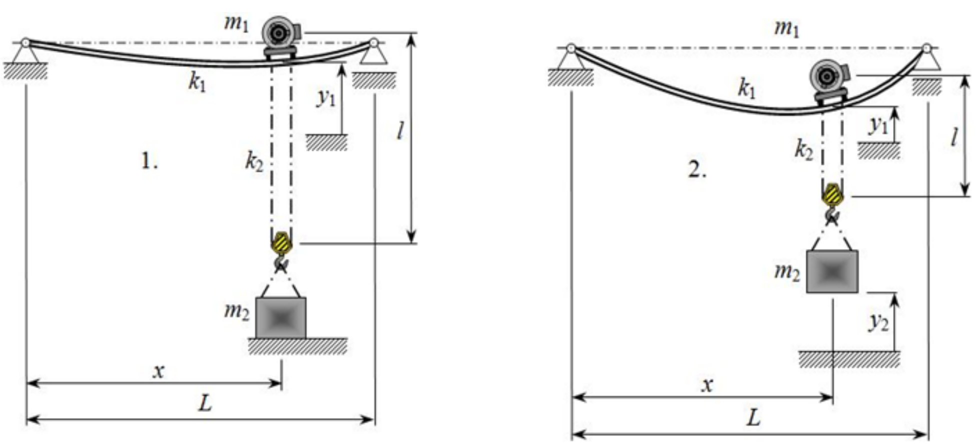

Figure 5. Dual mass dynamic model of bridge cranes

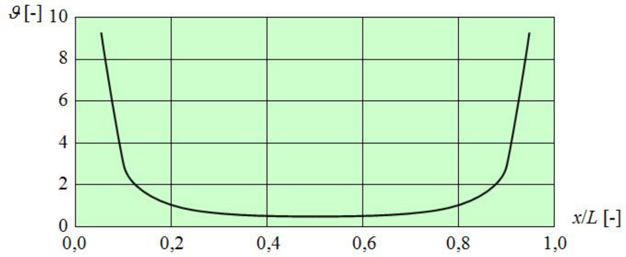

Figure 6. Factor reducing the mass of the main beam to the point of current position of the crane crab loads

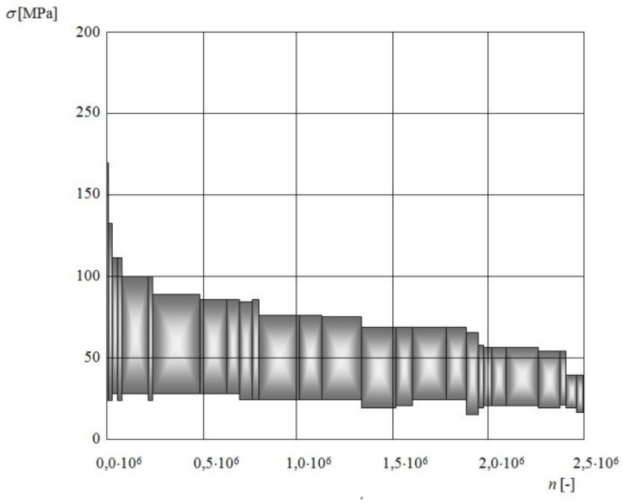

Figure 7. Stress collective various lengths of unwound cables l_1

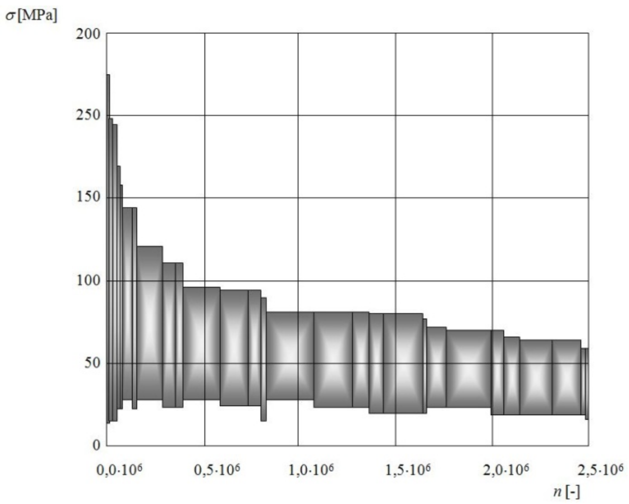

Figure 8. Stress collective various lengths of unwound cables l_6

Stress collectives in Figure 7 and Figure 8 comprise various lengths of unwound cables in descending order of length *l*. The shortening of the cable length results in its increased rigidity. With it grows the dynamic response and stress, which is obviously connected with the increase of the maximum levels of stress. This difference can be noticed in particular when comparing the first collective of the longest cable length and the last collective of the shortest cable length. There is a noticeable increase in dynamic stress values throughout the entire activity. The largest increase can be observed on the left side with the highest stress values. However, these were observed to have a low frequency of occurrence. In some blocks, such small values of occurrence frequency were observed, that they are not identifiable in the collective images.

In practice, it is possible to effectively obtain normal stress values required for the creation of stress collectives directly via experimental measuring. This is the representative sample random load process for the given operational conditions applied with electrical resistance strain gages.

6. Estimates of the Resulting Degree of Fatigue Damage for the Development of Limit State Fatigue

For the calculation, or more precisely the estimate of the cumulative resulting degree of fatigue damage in connection with the possible emergence of limit state fatigue one must apply one of the theories (hypotheses) on fatigue damage accumulation. It is a key link that presents the relation of random load process with fatigue properties of materials. More likely, with a concrete structural element [4,6]. Random load process is presented with appropriate characteristics organized in the form of a matrix or collective. Fatigue properties are represented by fatigue curves (i.e. based on Wöhler or Manson-Coffin). These are described by their respective material characteristics. The result of such a connection should be the relation between limit state fatigue and seeking the fatigue lifespan determined by the estimated degree of accumulative damage. It needs to be emphasized that the use of the stress collective, in other words, set of harmony cycle blocks (macroblocks) during the calculation of the lifespan, is a kind of a compromise between the considered completely unsuitable equivalent harmonious process and the considered individual cycles. Currently, an estimated several dozen diverse linear and non-linear, one or multi-parameter theories on fatigue damage accumulation, either brand new or modifications of existing ones have been created. Most have been developed and designed for specific load bearing, material and structural conditions and to a certain extent, influenced by philosophical concepts of fatigue processes, and equally the focus and practical experience of the respective author. Individual theories on fatigue damage accumulation can be distinguished by their required parameters.

In this analysis, the expression of the link between random load process (represented by the obtained stress collectives) and fatigue properties of material (represented by a respective Wöhler curve), the Palmgren-Miner (P-M) theory on fatigue damage accumulation was applied. The linear P-M theory is among the most well-known and used theories and its linearity leads to an equally linear fatigue damage accumulation. The basic presumption of the theory is that varying stress to material causes damage. This damage accumulates into a critical state during operation. It results in a fatigue crack. Damage increase per stress cycle is constant and revealed by the reciprocal value of the number of cycles to reaching failure with constant stress level. Therefore, it is possible to directly specify fatigue from, for example, the Wöhler-curve or

Manson-Coffin curve. The general popularity of this theory is clear, in its simplicity and the fact that it provides results that are generally on the safe side, overestimating the impact of individual cycles in the macroblock. On the other hand, it does not consider the stress fatigue strength and the corresponding damage. P-M theory is based on the standard median Wöhler curve with a likely breach of P =50 %. The description of the Wöhler curve uses the following dependence

$$\sigma_a^m N = \sigma_C^m N_C = konšt \qquad (1)$$

by which the reference point is the selected point RB[N_C,σ_C] (Figure 9).

For j = 1,2,3,…k …, J is the corresponding number of cycles

$$N_j = N_C \left(\sigma_C / \sigma_{aj} \right)^m , \qquad (2)$$

for $\sigma_{aj} \geq \sigma_C$ and $j = 1, 2, 3, ..., k$

$$N_j = \infty \text{ for } \sigma_{aj} < \sigma_C \text{ a } j = k+1, ..., J. \qquad (1)$$

For number of cycles n_j and one stress level σ_{aj} is relative damage

$$D_j = n_j / N_j . \qquad (2)$$

Critical level of fatigue damage accumulation is

$$D = \sum_{j=1}^{J} D_j , \qquad (3)$$

and lifetime (number of cycles)

$$\bar{N}_{PM} = \sum_{j=1}^{J} n_j \left[\left(\sum_{j=1}^{k} n_j \sigma_{aj}^m \right) \Big/ \left(N_C \sigma_C^m \right) \right]^{-1} . \qquad (4)$$

If the law of linear fatigue damage accumulation is applicable, then a fatigue fracture on a design element should always occur at $D = 1$. Experiments, or more precisely, practical experience shows that fatigue failure occurs when the values of $D \neq 1$. Sometimes, even greater deviations of value D can be realistically explained where the process of degradation is basically more complex. In other words, less linear than presented by the applied model. It is assumed that particular displays of damage are non-linear. During relatively prolonged periods of stress, materials are going through latent changes, whereby the durability of the materials are being reduced to eventual cracks that eventually spread throughout. Another potential source of deviation from linearity is from its own violation process. The crack spreads via material which is locally disintegrated resulting from a large concentration of stress at its source. The disintegrated area again depends on the stress load. Despite of this, this law is the basis of most theories on fatigue damage accumulation developed by other authors, who have paradoxically attempted to reach a better model match which better corresponds to reality. Even though the P-M theory is rejected by a number of professionals, on the other hand, the majority of existing norms, calculation codes and proven experiments still continue to demand the use of the linear P-M fatigue damage accumulation theory.

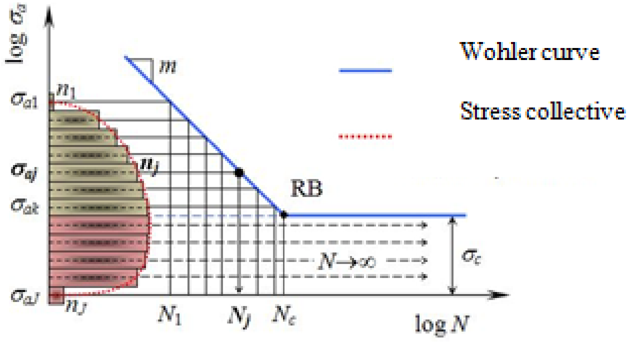

Figure 9. Connection between stress collectives and Wöhler curve

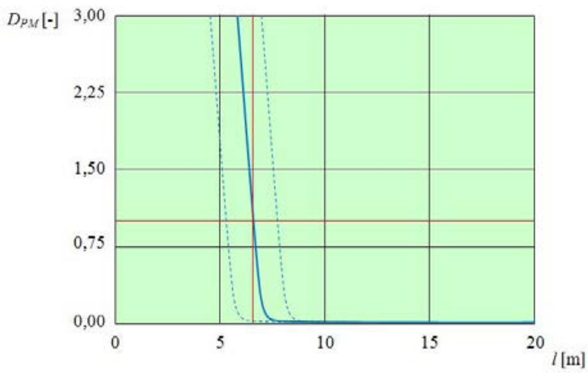

Figure 10. Estimate of the degree of fatigue damage D depending on the length l of the unwound cable

The obtained estimates of the degree of fatigue damage D under hypothesis P - M, depending on the length l of the unwound cable are graphically demonstrated in Figure 10 with the amended scale and extent of the vertical axis D. Also, indicated in Figure 10, is the level of permanent length of cable for fatigue damage $D = 1$ and simultaneously shifted progressions such as condition estimates of the altered flex rigidity of the main beams. Here, a shorter cable means greater rigidity, increased dynamic stress, greater level of damage, shorter lifespan and therefore shorter period to limit state. It is necessary to interpret the results such that the degree of degradation for a certain length of cable corresponds to the premises that hoisting equipment throughout its entire period of operation would operate with only such a length.

7. Conclusion

The complicated nature of the outcome, reflecting the behavior (response) of the structure is caused by several parameters entering the calculation and the described properties of the construction and their impacts on the construction. At the same time, among the many parameters or their collectives during calculation, were not correlated to their mutual dependence because of the absence and unavailability of pertinent information. For example, the unknown interdependency of the frequency of changes to crab positions, size of the load, the length of unwound cable. Said combined, analytical and experimental means of problem solving presented a compromise between analytical and experimental solutions. Accounting for actual geometric material parameters of a construction would result in replacing the use of a dynamic model of experimental measurements on real constructions, under real conditions. Geometric material parameters are any imperfections, categories of individual details, especially welded joints, specific types of loads and actual dynamic effects, impacts of actual operating conditions.

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