The Analysis of the State of Stress and Strain of a loaded Portal Crane, using FEM, with respect to the Strength, Stiffness and Stability

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Abstract: - The paper’s subject is highly topical, is very interesting from scientific point of view but also very complex. The authors propose to study the elastic structures of the cranes on basis of the similarity criteria, for this purpose the two basis criteria are shortly presented: Hooke and Cauchy. One underlines that the gantry and the half gantry cranes work outside, being subjected to actions as time changing loads; under these circumstances one needs a special check of the crane’s stability. The basic study is that one based on the analysis with finite elements, using ABAQUS software – advanced software with highly efficient possibilities of modelling. By graphical post processing are presented the equivalent fields of stresses von Mises and of deformations.

The sensitive zones where the failure of the crane may occur are:
- the main beam of profile I, where the support beam is welded (fig. 1 and fig. 1/part. II), Si1;
- the main beam, the longitudinal tube, straight in the zone where the support stand is welded, Si2;
- the support stand, in the welding zone to the straight longitudinal tube;
- the main beam, the longitudinal tube at left, in the zone where the support stand is welded, fig. 1/part II, Si4;
- the support stand, where the left longitudinal tube is welded, Si5.

Key-Words: - Gantry crane, stress, deformation, similarity, ABAQUS, windbracing, graphical post processing.

1 Introduction
The practical utility of the portal cranes is demonstrated by their large spread as destination and work conditions. One requires a theoretical and modern experimental study, using advanced software. The subject is very complex but also very interesting from scientific point of view. In a modern acceptation the cranes are lifting equipments, having a complex structure composed of a metallic frame, of changing shape, construction and dimensions; the structure upholds more mechanisms which serve to the lifting and to the moving of loads.
A very important finding is that the gantry cranes and half gantry cranes work “outside”; they are subjected to some actions as time changing loads, so that it needs a special verification of the stability. Based on the existing theoretical studies, on the operative normative, on the experts recommendation, on the restrictive indications used in designing, one establishes that the problems regarding the vibratory state of the cranes are not taken into account.

We specify the fact that the first signs regarding a bad work or the first obvious changes in the evolution of the technical state appear in their “vibrating stamp”. In order to increase the work safety of the gantry cranes, one proposes a theoretical study by elaborating of some modern methods of structural check, using the numerical analysis software ABAQUS.

2 The Study of the Elastic Structures Based on the Similarity Criteria [3], [6]
In order to establish a calculus methodology for the big structures two similarity criteria (theoretically) have been used: HOOKE and CAUCHY. The calculus relations are from paper [3], mentioned at the references. One sets out from the explanation that $K_\sigma = K_E$ which represents the stress scale written on basis of HOOKE’s law in normal stresses $\sigma = E \cdot \varepsilon$; $\varepsilon$ being the deformation.
per unit length – a nondimensional unit. The relations above lead to the similarity criterion HOOKE written between the real structure and the model attached to it:

\[ \varepsilon_r = \varepsilon_m = ct. \quad \text{or} \quad \frac{F_r}{A_r \cdot E_r} = \frac{F_m}{A_m \cdot E_m} = H \]  

(1)

Equation (1) express the static similarity; \( F \) is the traction internal force, \( A \) – the cross sectional area; \( E \) – the longitudinal modulus of elasticity.

The similarity criterion CAUCHY refers to the dynamic strains due to the vibrations. One refers to elastic systems. If one refers to the prismatic beams of changing section, it results relation:

\[ E \frac{\partial^2}{\partial x^2} \left( I \cdot \frac{\partial^2 v}{\partial x^2} \right) + \rho \cdot A \cdot \frac{\partial^2 y}{\partial t^2} = 0 \]  

(2)

where: \( \rho \) is the material density of the beam; \( \rho \cdot A \) is the mass per unit length; \( \rho \cdot A \cdot \frac{\partial^2 y}{\partial t^2} \) is the force of inertia per unit length; \( I \) is the axial moment of inertia of the cross section \( A \); \( v \) is the deflection measured from the static equilibrium position of the beam; \( x \) is the distance to the cross section, measured from the origin; \( t \) is the time.

Based on the transformations and by introducing nondimensional units, one gets the similarity criterion Cauchy under the form:

\[ \frac{\ell_0}{t_0} \sqrt{\frac{E_0}{\rho_0}} = \frac{\nu}{c} = C_a \]  

(3)

where: \( \nu \) is the velocity of the oscillation motion of the beam’s point; \( c \) is the propagation velocity of the longitudinal waves.

Likewise one writes the scale of the time \( T \) and of the velocities, \( K_v \).

The resulted conclusions from the beam may be extended to the elastic structures. We can specify the following conclusions (these may have a general rank):

- if the Cauchy’s criterion has the same value both of the real structure and on the model, the studied phenomenon on the model is similar to that on the real structure;
- the studied model must be achieved from the same material as the real structure;
- from the geometrical point of view both must respect a certain scale;

one grants a special attention to the elastic constants of the material.

The structure of the gantry crane is very complex, both from constructive point of view and from the point of view concerning the behaviour under load.

This is the reason why the concise theoretical considerations concerning a study by similarity between the pattern – model and the real model will be in this way understood: the study methodology which will be performed on a model at scale (“pattern”) may be spread to any other structure, inclusively to the real one.

### 3 The Analysis with Finite Elements of a Gantry Crane (Abaqus), [3], [4]

One achieved a functional pattern, using 1/10 scale, of a real structure, Fig. 1.

![Fig. 1 Pattern of a gantry crane](image)

The pattern shown in Fig. 1 consists mainly of a central beam, achieved from an I section, with 42 x 80 x 2660 mm dimensions, reinforced by a truss. On the main beam of I profile are marked the points P1, P2, …, P4, …, P7 (equal distances between two successive points) where are applies an external load (for lifting; descent).

The structure contains also: 4 tubes of \( \phi \) 25 and the thickness of the wall \( t = 2 \) mm, called also windbracings, as well as bars with the dimensions: \( \phi \) 14 mm, \( t = 2 \) mm; carriage, electric hoist, marked weights etc.

Two constructive type are studied: crane with windbracings and crane without windbracings.

The load of 1444 N is successively applied in points P1, P3 and P4. One extends the results by the symmetry of the structure.
4 Theoretical Results Based on the Analysis with FEM – Abaqus, [1], [2]

The use of the ABAQUS software - an advanced software, is applied to the pattern from fig. 1. One emphasizes the fact that one used Beam 3D elements, in a number of 2818.

By graphical working, the fields of the equivalent stress von Mises and of deformations are shown. In figures, the state of stress and strain is coloured represented; the numerical identification is made by framing the colour of the element of interest in the conventional signs of colours represented in the figure.

![Image 1](image1.png)

**Fig. 2** The state of stresses for the crane loaded with 1444 N in point P4

![Image 2](image2.png)

**Fig. 3**. The state of strains for the crane loaded with 1444 N in point P4

A centralization of the stresses denoted by $S_i$ and defined in [MPa] and of the strains (deflections) $S$ in [mm] established in the points P1 … P4 … P7, when the forces are applied in the points P1, P3 and P4 is reproduced in Table 1. [3]

| Points of load application | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $S_7$ | $S_8$ | $S_9$ | $S_{10}$ | $S_{11}$ | $S_{12}$ | $S_{13}$ | $S_{14}$ | $S_{15}$ | $S_{16}$ | $S_{17}$ | $S_{18}$ | $S_{19}$ | $S_{20}$ | $S_{21}$ | $S_{22}$ | $S_{23}$ | $S_{24}$ | $S_{25}$ | $S_{26}$ | $S_{27}$ | $S_{28}$ | $S_{29}$ | $S_{30}$ | $S_{31}$ | $S_{32}$ | $S_{33}$ | $S_{34}$ | $S_{35}$ | $S_{36}$ | $S_{37}$ | $S_{38}$ | $S_{39}$ | $S_{40}$ | $S_{41}$ | $S_{42}$ | $S_{43}$ | $S_{44}$ | $S_{45}$ | $S_{46}$ | $S_{47}$ | $S_{48}$ | $S_{49}$ | $S_{50}$ | $S_{51}$ | $S_{52}$ | $S_{53}$ | $S_{54}$ | $S_{55}$ | $S_{56}$ | $S_{57}$ | $S_{58}$ | $S_{59}$ | $S_{60}$ | $S_{61}$ | $S_{62}$ | $S_{63}$ | $S_{64}$ | $S_{65}$ | $S_{66}$ | $S_{67}$ | $S_{68}$ | $S_{69}$ | $S_{70}$ | $S_{71}$ | $S_{72}$ | $S_{73}$ | $S_{74}$ | $S_{75}$ | $S_{76}$ | $S_{77}$ | $S_{78}$ | $S_{79}$ | $S_{80}$ | $S_{81}$ | $S_{82}$ | $S_{83}$ | $S_{84}$ | $S_{85}$ | $S_{86}$ | $S_{87}$ | $S_{88}$ | $S_{89}$ | $S_{90}$ | $S_{91}$ | $S_{92}$ | $S_{93}$ | $S_{94}$ | $S_{95}$ | $S_{96}$ | $S_{97}$ | $S_{98}$ | $S_{99}$ | $S_{100}$ |
|---------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|---
One resumes the calculation with FEM, using the ABAQUS software, in the case of the cranes without windbracings. In order to apply the load of 1444 N in the point P4, one presents the field of stresses and strains in figures 5 and 6.

A comparative presentation of the results of stresses and strains for the two cases of the crane with windbracings and without windbracings, is made in Table 2. One presents only the case when the load is symmetrical (force in P4). [4], [5].

Table 2

<table>
<thead>
<tr>
<th>Type of cranes</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windbracings</td>
<td>0.019</td>
<td>0.017</td>
<td>0.056</td>
<td>1.5</td>
<td>0.127</td>
<td>4.5</td>
<td>0.121</td>
</tr>
<tr>
<td>Without</td>
<td>0.011</td>
<td>0.048</td>
<td>0.22</td>
<td>0.16</td>
<td>4.2</td>
<td>0.121</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Fig. 7 Comparative presentation of the constructive solutions for a crane with windbracings and for a crane without windbracings, when the force is applied in the middle, in P4 [3]

Figure 7 shows a graphical presentation of the state of strain included in Table 2. From the analysis of the content of Table 2 and of the representation from fig. 7, one establishes that:

- from the stresses point of view, the two constructive solutions don’t present major differences;
- from the analysis of the strains, the constructive solution with windbracings is more favourable, being a safer and a stiffer solution.

The state of deformation of the main beam is represented. The main beam has the profile I of dimensions 42 x 80 x 2660 mm, reinforced in a truss. The load is applied in point P4 (a symmetric structure symmetrically loaded; one gets an axis-symmetrical state of deformation); the records of the deformations are made in points P1, P2, ..., P4, ..., P7. The authors make a theoretical study of the main beam in two cases of end support – double supported and double fixed supported and in two cases of loading: concentrated load in points P1, P3 and P4 and uniformly distributed load on the whole span. One established theoretically the sectional stresses (axial stresses) in the members of the truss. The structure was statically loaded, and the determinations were made with the help of the node isolation method. One checked the results using FEM. For the node displacements calculation of the structure one used specialized software – FTOOL. After this theoretical study one established the sensitive zones of the crane, zones where maximum load may occur, zones where the danger of the crane’s failure exists.

These zones have been emphasized in the abstract of the present paper.

5 Conclusion

The validation of the used mathematical model, the validation of the state of stress and strain included in these two papers, one will be made partially in the next paper – Part II.

The established theoretical analysis refers to a special structure, to a 3D structure, prevalent of beams, statically and dynamically loaded. These structures requires special needs; first of all one notices the problems of the working safety.

At the basis of the working safety is the accurate knowledge by adequate techniques and technologies of the state of strain of the whole structure, but also of its components; one requires a precisely knowledge of the answer of the structure, in static and dynamic regime, expressed mainly by the values of the field of strains and stresses. The studied subject appeared as a necessity. The checks required by ISCIIR in order to license the cranes are necessary but not enough to ensure their working safety.
References: