Influence of the sheet metal quality over the characteristics for the main girder at bridge crane applications

***Lachezar N. Lazov*[1], *Petko N. Nedyalkov*[2] *and Dragomir Ts. Vrazhilski*[1]**

1) Technical University of Sofia, 8 Kliment Ohridski Blvd., Sofia, Bulgaria

2) "St. Ivan Rilski" University of Mining and Geology, 1 prof. Boyan Kamenov str., Sofia, Bulgaria

Corresponding author: petko.nedyalkov@mgu.bg

Original scientific article

Abstract: The presented paper deals with simulation research of the probability density function of geometrical characteristics for main girder of one bridge crane. The bridge crane is represented through idealized calculation model of main girder witch is sheet material thickness relevant. The quality characteristics for the main girder is developed with material sheet thickness probability density function, cumulative density function and its inverse function. The functional dependence between parameters are revealed with triangular probability density function. Relevance between sheet metal thickness and cumulative density function for sectional inertial moment and girder stiffness is done with Monte-Carlo simulations.

Keywords: *bridge crane; girder; sheet thickness; simulation; triangular distribution*

1. Introduction

The main component of the hoisting bridge cranes is their steel construction which ensures reliable exploration. Reliability and exploration assurance are in the straight subjection to the main girder characteristics represented with its stiffness and sectional inertial moment values. Constructional design of the main girder and steel construction is valuated at the crane weight and price cost. At the engineering parameters it is valuated at required dynamical deformation, stiffness to frequency dependence, statically and fatigue strength. In the cases for small and middle class hoisting applications the main girder is formed by the steel profiles from standard or unified constructional catalogues. In the most usual case at heavy hoisting applications main girder is composed by the steel sheet weldment in a spatial box forming with respect to the mass and the price optimization.

The weldment construction is direct reflected to the mechanical characteristics of the main girder but also there is a dependence between mechanical parameters from the sheet metal quality and the main girder stiffness and sectional inertia moment. The quality property of the sheet metal have two main factors – the material compositional characteristics and the thickness value.

Previous researches [1], [2] shown that the typical sheet thickness values compared to nominal shown as histogram at Figure 1. The thickness value reflects over the strength amount for the weldment construction but also can be subjected as a fatigue and notch coefficient [3], [4], [5] factor with dual impact over the geometrical characteristics and material properties. Other researchers investigate [6], [7], [8] connection and dependence between carrying capacity, geometrical properties of main girder section ant its influence over proof of competence, reliability and durability.

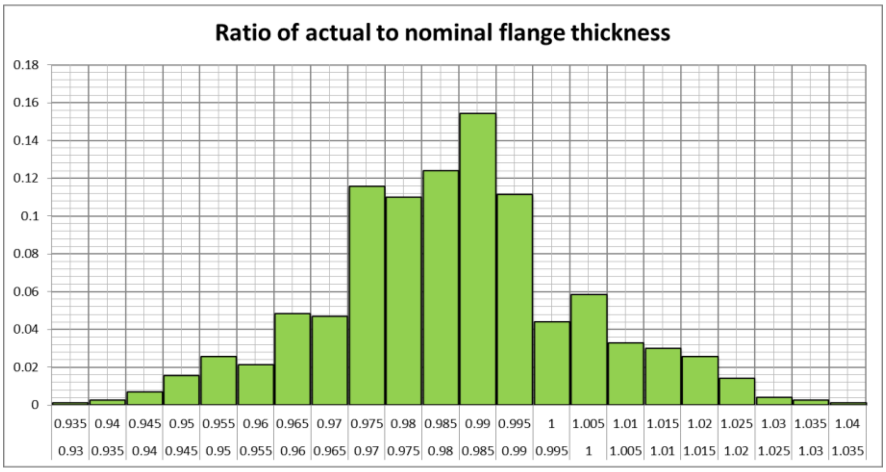

Figure 1. *Experimental density [1] for the sheet metal thickness*

2. Theoretical background

In a simulation study of the sectional inertia moment and stiffness characteristics the typical probability density function for variable values have to be represented with substitution theoretical density function. The substitution density function has to fulfill the requirements of any broadly-used non-parametrical criteria, non-parametrical Pearson's density type test or Kolmogorov-Smirnov's test. According to those criteria one can choose the triangular probability density function /Triangular(*a,m,b*)/ with parameters: - '*a*' is lower limit; - '*m*' is mode; - '*b*' is upper limit. Comparison between the experimental density from Figure 1 and triangular density function is presented at Figure 2, where: - '*Oi*' is the observed empirical density sample graph representation; - '*Ei*' is expected density from triangular pdf graph representation.

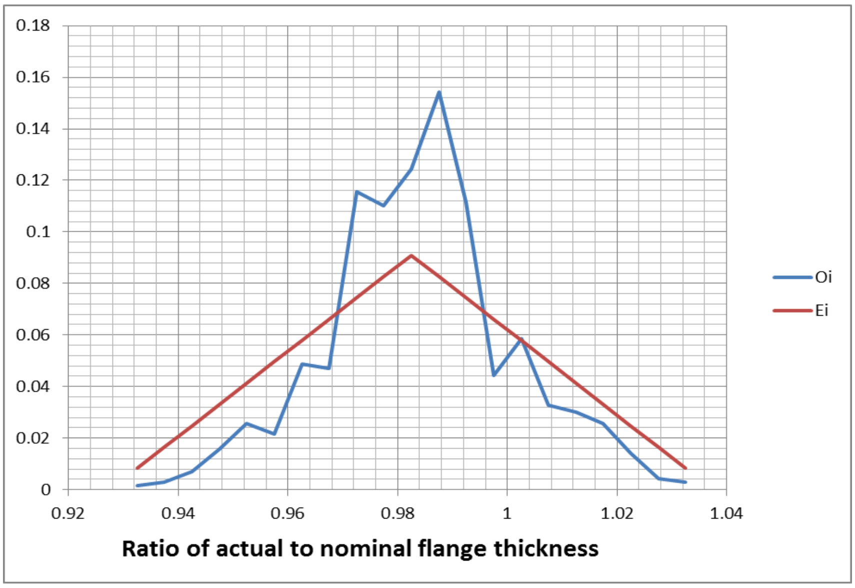

Figure 2. *Comparison between observed 'Oi' density and expected 'Ei' theoretical density functions*

The triangular density function is split at two continuity intervals according to the following formulas:

$$f_1(x) = \frac{2\ \cdot (x-a)}{(a-m)\cdot(a-b)}, \qquad x \in [a,m] \tag{1}$$

$$f_2(x) = \frac{2\ \cdot (x-b)}{(b-m)\cdot(a-b)}, \qquad x \in [m,b] \tag{2}$$

where the 'x' is the variable; 'f_1' is the density at first continuity interval; and 'f_2' is the density at second continuity interval for triangular probability density function. The artificial history generation [9] for the input factor can be processed by different methods. One can choose the inverse function method which need cumulative distribution function (CDF), and for chosen triangular density function its CDF is presented by the following formulas and graph (Figure 3).

$$F_1(x) = \frac{(x-a)^2}{(a-m)\cdot(a-b)}, \qquad x \in [a, m] \tag{3}$$

$$F_2(x) = \frac{(x-b)^2}{(b-m)\cdot(a-b)} + 1\,, \qquad x \in [m, b] \tag{4}$$

where the 'x' is the variable; 'F_1' is the cumulative distribution at the first continuity interval; and 'F_2' is the cumulative distribution at the second continuity interval for triangular probability density function.

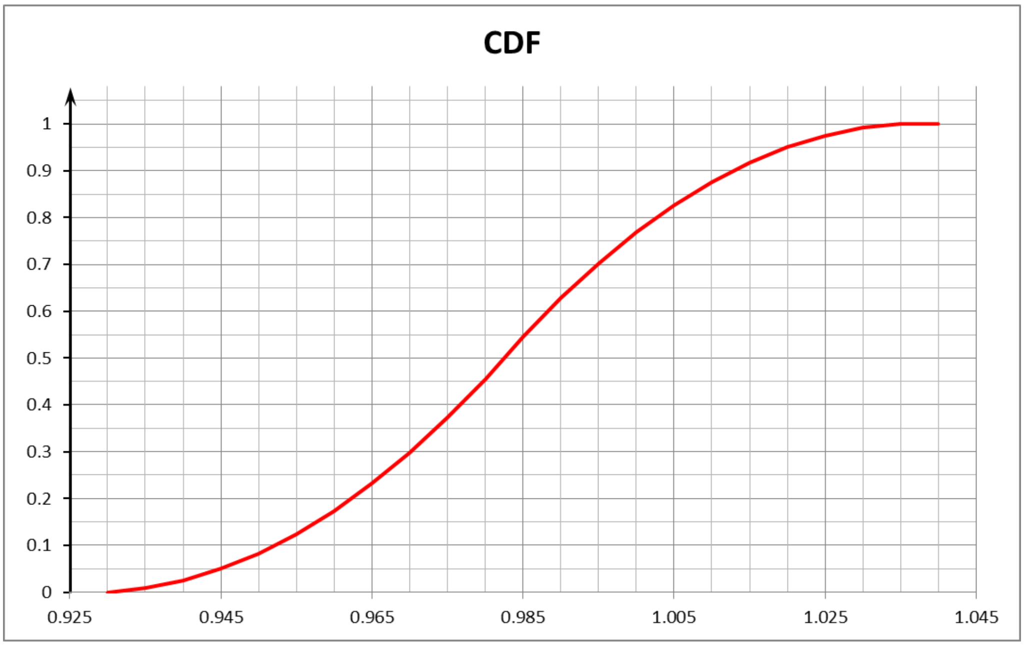

Figure 3. *Theoretical CDF for sheet thickness from triangular density*

The core of the Monte Carlo simulation calculation is a random number generation with suitable prepositional distribution. Usual case at the random number generator is by using random numbers from the uniform distribution whereafter had to be placed in the inverse function to calculate the variable random value at the chosen functional interval. The inverse cumulative distribution function is square root function for triangular probability density, represented by the following formulas:

$$x_1(F_1) = a + \sqrt{F_1 \cdot (a-m)\cdot(a-b)}, \qquad F_1 \in \left[0, \frac{m-a}{b-a}\right] \tag{5}$$

$$x_2(F_2) = b - \sqrt{(F_2-1)\cdot(b-m)\cdot(a-b)}, \qquad F_2 \in \left[\frac{m-a}{b-a}, 1\right] \tag{6}$$

where the 'x_1' and 'x_2' are the random variables; 'F_1' and 'F_2' are the values for random variables from the uniform distribution '*U[0, 1]*' sitting at the continuity interval for triangular probability density function. Those random values (represented with 'F') generate the randomized values for sheet thickness, which randomized values are used in the Monte Carlo simulation.

3. Calculation and Simulation model

3.1. Section Inertia calculation

Sectional inertia moment for rectangular scheme, with typical form shown at Figure 4, is well known formula for box main girder, as presented below:¸

$$J = \frac{h^3 \cdot t_w}{6} + \frac{B \cdot t_f{}^3}{6} + 2 \cdot \left(\frac{h+t_f}{2}\right)^2 \cdot B \cdot t_f \ , \ m^4 \tag{7}$$

where the - 'h' is girder height; - 'B' is girder width; - 't_w' is web thickness; - 't_f' is flange thickness.

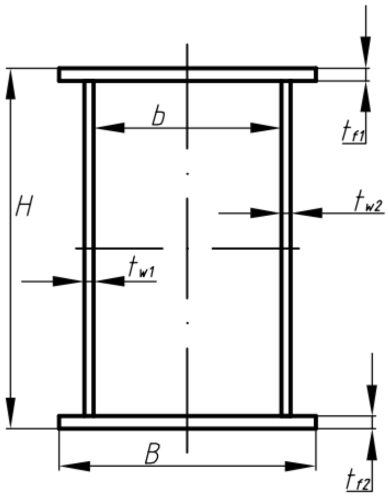

Figure 4. *Scheme of main girder dimensions*

Model for idealized bridge crane [10], [11] with parameters: - load capacity Q = 8 t; - bridge length L = 28,5 m; and with main girder section dimensions: - girder height H = 936 mm; - girder width B = 328 mm; - nominal flange thickness t_{fn} = 8 mm; - nominal wall thickness t_{wn} = 6 mm. Theoretical nominal value for sectional inertial moment, calculated according equation (7) is as follows:

$$J_n = \frac{h^3 \cdot t_w}{6} + \frac{B \cdot t_f{}^3}{6} + 2 \cdot \left(\frac{h+t_f}{2}\right)^2 \cdot B \cdot t_f \ = 19.087 \cdot 10^{-4} \ m^4 \tag{8}$$

3.2. Section Inertia for simulation model

The simulation model for sectional inertial moment have to use the formula without simplifications as follows:

$$J(t_{f1}, t_{f2}, t_{w1}, t_{w2}) = \frac{h^3 \cdot (t_{w1} + t_{w2})}{12} + \frac{B \cdot (t_{f1} + t_{f2})^3}{12} + \cdots$$
$$+ \left(\frac{h+t_{f1}}{2}\right)^2 \cdot B \cdot t_{f1} + \left(\frac{h+t_{f2}}{2}\right)^2 \cdot B \cdot t_{f2} \ , \ m^4 \tag{9}$$

where according to Figure 4: - t_{f1}, mm is upper flange thickness; - t_{f2}, mm is bottom flange thickness; - t_{w1}, mm is left web thickness; - t_{w2}, mm is the right web thickness.

The values for wall and flange thickness have to be taken as a random quantity with probability densities obtained from inverse transformation models from equations (5) and (6). Simulated thickness values are taken from computer software generated pseudo randomized real numbers from following intervals:

- ✓ flange thickness – $t_{fi}(F) = Triangular(0.93 \cdot t_{fn}, 0.975 \cdot t_{fn}, 1.04 \cdot t_{fn})$;
- ✓ wall thickness - $t_{wi}(F) = Triangular(0.93 \cdot t_{wn}, 0.975 \cdot t_{wn}, 1.04 \cdot t_{wn})$;

3.3. Results from simulation model

The result from simulation model represent particular realization for section inertial moment value. The control of the influence of the sheet metal quality over the main girder characteristics and specifically over the studied section inertial moment it is developed the diagram shown at Figure 5. That particular diagram is representation of estimated cumulative distribution function for relative frequencies of ten interval bins resulted from Monte Carlo simulation model.

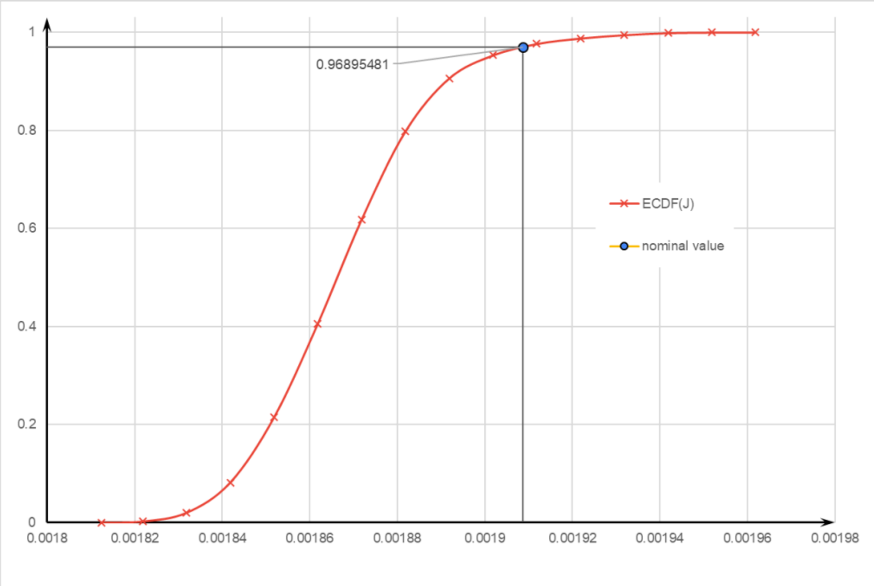

Figure 5. *Estimated cumulative distribution for section inertia moment value*

The diagram of estimated cumulative distribution function is pointing the nominal value towards the realizations of sectional inertial moment values from simulation model. The comparison between them shows that in 96.89 % of cases achieved moment value is smaller than the nominal.

3.4. Assessment for simulation results

The simulation model has to be assessed in some statistical criteria for stability of results values and statistical comparison. One can easy use the following two statistical indicators:

- ✓ Size effect /SE/ estimator:

$$efSd = \frac{\mu - \mu_0}{sd} \tag{10}$$

where: - $\mu = \mu(z) = mean(z_i)$ is the sample mean for the estimated variable; - $sd = sd(z) = stdev(z_i)$ is the sample standard deviation for the estimated variable; - $\mu_0 = z_n$ is the nominal value for the estimated variable;

- ✓ standard error of the sample mean:

$$sdSqn = \frac{sd}{\sqrt{n_s}} \tag{11}$$

where: - $sd = sd(z) = stdev(z_i)$ is the sample standard deviation for estimated variable; - $n_s = length(z_i)$ is the number of sample length in the estimated sample.

Usually [9], [12] the simulations using Monte Carlo method are recommended to be done with ‘as much as could be calculated’ number of calculations. The Figure 6 presented the algorithm one can use to achieve a software programmable procedure in calculation the simulated values and some estimators and assessors.

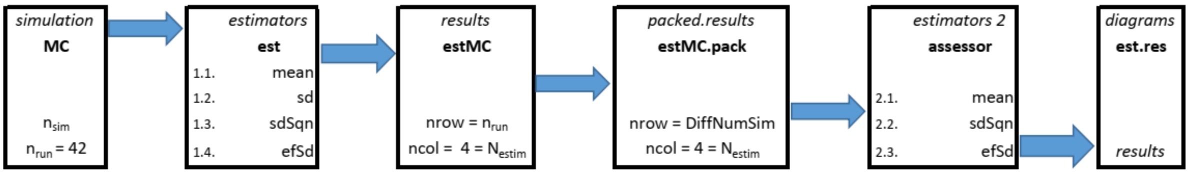

Figure 6. *Block scheme for estimation algorithm for Monte Carlo simulation.*

The secondary estimators algorithm was used to calculate an optimized 'n_{sim}' – number of simulations with randomized variables in particular spreadsheet which forms the resulting Monte Carlo simulated results. In purpose to estimate the stability of that particular result there were done a multiple runs 'n_{run}' at same conditions and same number of simulations. The results are stored at arrays and used in the calculation of second estimators.
The secondary estimator shown on Figure 7, size effect (SE) over the mean from different runs 'n_{run}' shows a table decreasing curve when rising the number of simulation. That curve is informative but there it is lacking with explicit inflex points. It is possible to use the change of drop angle between $20 \cdot 10^3$ and $200 \cdot 10^3$ number of simulations but not in definitive criteria because the changes in the slope can be influenced in particular complicatedness calculations.

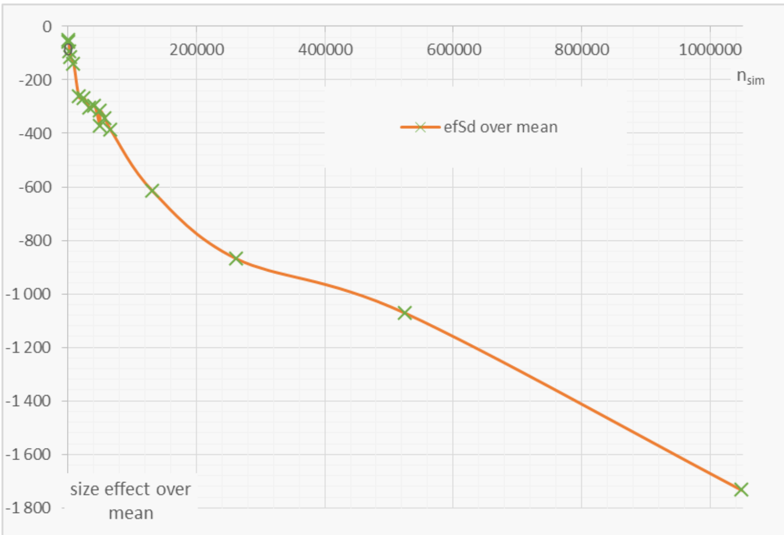

Figure 7. *Assessment diagram for the size effect over the mean.*

The secondary estimators shown on Figure 8, standard error of sample mean and mean over the size effect show different behavior. There is a definitive inflex of the slope (or drop down angle) and it is possible to be defined a minimum threshold level, for example $2.63 \cdot 10^{-10}$ for 'mean over SE' at near $10 \cdot 10^3$ simulations, and $1.68 \cdot 10^{-7}$ for '*sdSqn*' over SE at near $17 \cdot 10^3$ simulations. At Figure 9 is presented the interval of particular interest for number of simulations for Monte Carlo method between $1 \cdot 10^3$ and $100 \cdot 10^{3}$ simulations.

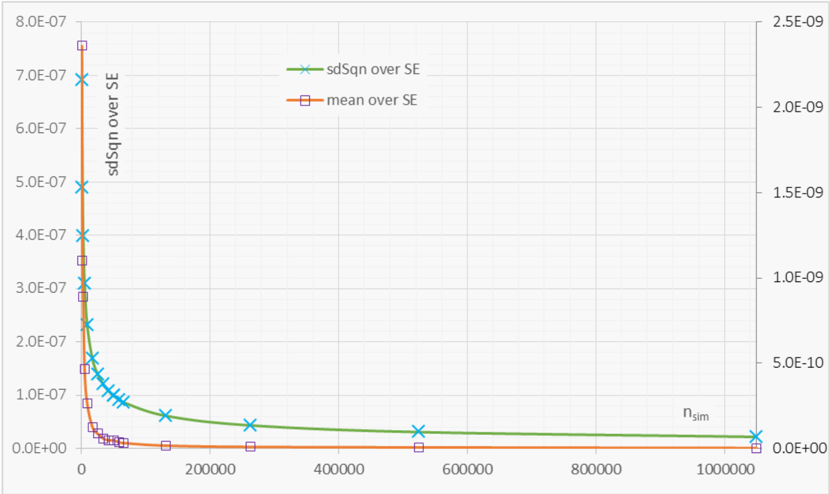

Figure 8. *Assessment diagram for the standard error of sample mean over the size effect and mean over the size effect.*

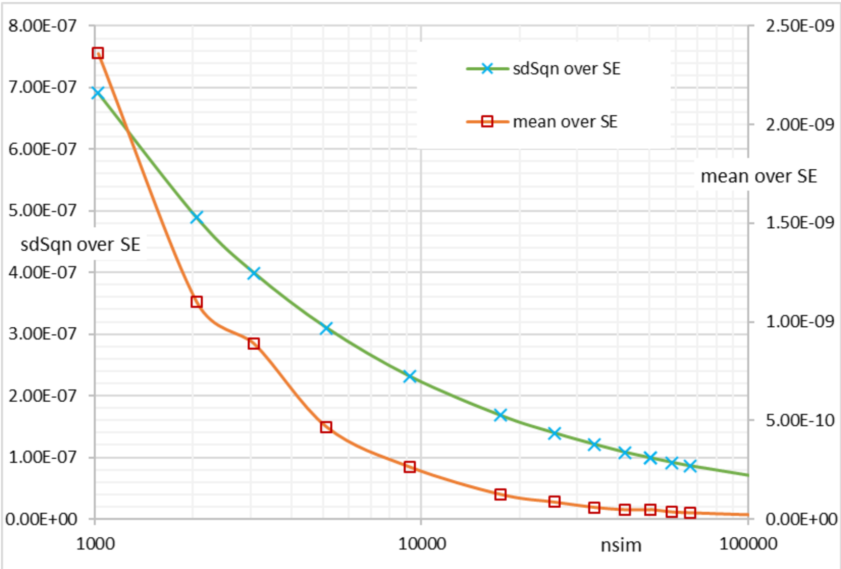

Figure 9. *Assessment diagram for the standard error of sample mean over the size effect and mean over the size effect with logarithmic horizontal axis.*

The total number of nearly twenty different samples with forty two (42) runs in a row and starting with thousand to more than one million ($1.0496 \cdot 10^6$) simulations were lead and results in global scale (Figures 7 and 8) shown that the stability of assessors was achieved over the one hundred thousands ($100 \cdot 10^3$) simulations where the curve of the assessor is asymptotiate to horizontal.

4. Conclusions

Deterministic approaches are at the heart of engineering education and engineering design. On the other hand, in operation, reliability, maintenance and testing, deviations are accounted for and realized, which are the basis for the development of probabilistic methods. The considered models and algorithms allow to reveal the relationship between deterministic and probabilistic approaches in a trivial engineering problem - calculation of geometrical characteristics of a main girder for a bridge crane. The presented comparative results show that ~97% physical performance of the structure cannot reach the design or nominal values.

The conducted multi length numerically-simulated experiment shows that number of simulations must exceed twenty thousands ($20 \cdot 10^3$) in order to ensure stability of numerical results at proposed model. The concluding remarks are summarized as follows:

✓ the presented model and algorithm is allowing to determine the influence of sheet metal quality over the main girder sectional inertia momentum and stiffness for bridge crane;

✓ the presented model is allowing to determine the limits for cumulative distribution function for sectional inertia moment value $J \in [J_{min}, J_{max}]$;

✓ it is possible to settle the type and parameters for the distribution of the sectional inertia moment;

✓ it is possible to conduct experimental ultrasonic thickness measurement and import data for the assessment of the section inertial moment characteristics about physical steel construction;

✓ algorithm is developed with criterial assessment values and steps for admission and estimation of minimal simulations in row for Monte Carlo method.

References

[1] Kirke Br., Al-Jamel I.H., 2011. Steel Structures Design Manual To AS 4100 1-st edition, Berkeley, USA.

[2] Byfield, M.P. and Nethercot, D.A., 1997. Material and geometric properties of structural steel for use in design - random variation in measured properties of nominally identical steel specimens, The Structural Engineer, Vol. 75, No. 21, 363-367

[3] Bright G. W. et. al., 2011. Variability in the mechanical properties and processing conditions of a High Strength Low Alloy steel, ISSN:1877-7058, doi:10.1016/j.proeng.2011.04.020, Procedia Engineering 10 (2011) 106–111.

[4] Motra, H.B., Hildebrand J. and Dimmig-Osburg A., 2014. Assessment of strain measurement techniques to characterize mechanical properties of structural steel, ISSN:2215-0986, http://dx.doi.org/10.1016/j.jestch.2014.07.006, Engineering Science and Technology, an International Journal 17 (2014) 260-269.

[5] MIhalikova M. and Janek J., 2007. Influence of the loading and strain rates on the strength properties and formability of higher-strength sheet, ISSN: 0543-5846(1334-2576), Metalurgija 46 (2007) 2, 107-110, Croatia

[6] Slavchev Ya., 2008. A Research on the Stressed State of Overhead Bridge Cranes Structure During the Steady-State Traverse of the Trolley, ISBN:978-954-580-248-5, Challenges in Higher Education and Research in the 21-st Century, vol. 6, part II, 393-396, Sozopol, Bulgaria

[7] Slavchev Ya., 2010. Research on Carrying Metal Structure of Overhead Bridge Cranes, ISBN: 978-3-8433-5644-2, Lambert Academic Publishing

[8] Radlov K., Mitrev R. and Rinkova, Ev. 2012. Statistical analysis methodics for hoisting crane failures. ISSN:1313-7530, Bulgarian Journal for Engineering Design, issue 12(2012), Sofia, Bulgaria

[9] Rubinstein R. Y. and Kroese D. P., 2017. Simulation and the monte carlo method, 3-rd Edition, ISBN: 978-111-8632-208, John Wiley & Sons, New Jersey, USA

[10] Lazov L., 2015. About the Influence of Camber Over Selection of the Main Girder Cross Sections of Bridge Cranes, ISSN:1314-9628, CAx Technologies, issue 3, 110-114, Sofia, Bulgaria

[11] Kotzev N., Lazov L., Dimitrov L., 2015. About numerical methods for strength calculations of steel crane structures, ISSN:1313-955X, BulTrans-2015, 46-50, Sozopol, Bulgaria

[12] Oberle W., 2015. Monte Carlo Simulations: Number of Iterations and Accuracy, ARL-TN-0684, July 2015