Probability calculation applied to potential failure zones of the bridge girder of metallurgical crane

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Abstract. This article addresses the examination of potential failure zones of metallurgical casting crane with 300 ton lifting capacity. Complex system of static loading applied to a 24-meter long and 3-meter high girder was regarded as the object of examination. Girder components were manufactured from steel Bcr3en5. Calculation was first performed using the “LIRA-SAPR” automatic design system to obtain the actual stresses and displacements. Probability density for limit and safe actual stresses was then built based on previously conducted research and simulation. It was established that further operation under such loads could result in a failure. After analyzing the level of loading applied to the crane girder components and assemblies, the decision was made to reinforce them with a truss bar. The recalculation demonstrated that such decision was adequate and that the crane could be further operated without failure. The presented information can be used in the technology related to extending the service life of metallurgical cranes most of which are operated after the expiry of their warranty period.

1. Introduction
The identification of potential failure zones represents one of the main phases of structure risk analysis. Considering that the examined structures can operate for quite a long time – moreover, many of them can operate after the expiry of their warranty period - and under the influence of multiple factors, such calculation must certainly make allowance for probability. We shall regard a girder – the load-bearing structure of metallurgical casting crane with 300 ton lifting capacity - as the structures. Therefore, the proposed article represents importance.

2. Research goal
Articles [1-3, 6-9] describe simulation of reliability, safety and risk indicators related to metallurgical equipment components. However, there are not so many calculations today that link real equipment with the resulting operating loads and the indicators.

The goal of this article is to perform calculation on the structural girder of a casting crane with 300 ton lifting capacity, to establish the link between such calculation and the probabilistic characteristics of loading and to set out measures on mitigating the risks of failures.

3. Research materials and methods
We shall examine the girder of metallurgical crane with 300 ton lifting capacity. The calculation is carried out using the “LIRA-SAPR” software package and based on the finite element displacement
method [4, 5]. The following displacements of assemblies are taken as the key unknown values: x – linear displacement along the X-axis and z – linear displacement along the Z-axis. Static loads were calculated using a plane system consisting of swivel bar elements.

Universal solid bar finite element of type 10 was examined.

The following types of forces are applied to the finite element:

- N – axial force; positive sign corresponds to expansion.
- MK – torque in relation to the X1-axis; positive sign corresponds to the torque effect in anti-clockwise direction when observed from the end of the X1-axis, which is produced on the cross-section of the bar end.
- MY – bending torque in relation to the Y1-axis; positive sign corresponds to the torque effect in anti-clockwise direction when observed from the end of the Y1-axis, which is produced on the cross-section of the bar end.
- MZ - bending torque in relation to the Z1-axis; positive sign corresponds to the torque effect in anti-clockwise direction when observed from the end of the Z1-axis, which is produced on the cross-section of the bar end.
- QY – shearing force along the Y1-axis; positive sign corresponds to the matching force direction and the Y1-axis for the cross-section of the bar end.
- QZ - shearing force along the Z1-axis; positive sign corresponds to the matching force direction and the Z1-axis for the cross-section of the bar end.

The original diagram indicating the numbers of assemblies and components of the 24-meter long and 3-meter high crane girder is presented in figure 1.

![Figure 1. Original diagram indicating the numbers of assemblies and components.](image1)

The deformed diagram of the bridge structure girder with a clearly visible potential failure zone was obtained based on calculations – figure 2.

![Figure 2. Original and deformed diagrams.](image2)

### 4. Research findings and their discussion

The following data were obtained after the conducted examination: internal forces inside structural components (table 1) and displacement of assemblies (table 2).
**Table 1.** Internal forces inside structural components.

| Component No. | Forces                  |
|---------------|-------------------------|
|               | N (ton)                 |
|               | Mk (ton*meter)          |
|               | My (ton*meter)          |
|               | Qz (ton)                |
|               | Mz (ton*meter)          |
|               | Qy (ton)                |
| 1             | - 0.048                 |
| 2             | - 261.682               |
| 3             | - 0.048                 |
| 4             | - 314.134               |
| 5             | 0.000                   |
| 6             | 522.220                 |
| 7             | 522.220                 |
| 8             | 1041.399                |
| 9             | 1041.399                |
| 10            | 627.220                 |
| 11            | 627.220                 |
| 12            | 0.000                   |
| 13            | 0.000                   |
| 14            | - 261.430               |
| 15            | - 782.223               |
| 16            | - 782.223               |
| 17            | - 939.723               |
| 18            | - 939.723               |
| 19            | - 313.930               |
| 20            | 0.000                   |
| 21            | 130.520                 |
| 22            | - 368.921               |
| 23            | 0.187                   |
| 24            | 367.807                 |
| 25            | - 0.311                 |
| 26            | - 366.638               |
| 27            | - 143.684               |
| 28            | 441.838                 |
| 29            | - 442.953               |
| 30            | 156.673                 |
| 31            | 0.283                   |
| 32            | - 0.311                 |
| 33            | 360.333                 |
| 34            | - 350.960               |
| 35            | 351.008                 |
| 36            | - 292.263               |
| 37            | 292.311                 |
Table 2. Displacement of assemblies.

| Assembl No. | X (millimeter) | Y (millimeter) | Z (millimeter) | UX (radian*1000) | UY (radian*1000) | UZ (radian*1000) |
|-------------|----------------|----------------|----------------|------------------|------------------|------------------|
| 1           | -74.571        | 0.000          | 0.000          | 0.000            | 0.000            | 0.000            |
| 2           | 0.000          | 0.000          | 0.000          | 0.000            | 0.000            | 0.000            |
| 3           | -13.394        | 0.000          | -4.798         | 0.000            | 0.000            | 0.000            |
| 4           | -64.462        | 0.000          | -5.761         | 0.000            | 0.000            | 0.000            |
| 5           | -33.668        | 0.000          | -5.759         | 0.000            | 0.000            | 0.000            |
| 6           | -42.786        | 0.000          | -4.797         | 0.000            | 0.000            | 0.000            |
| 7           | -74.571        | 0.000          | -95.159        | 0.000            | 0.000            | 0.000            |
| 8           | -64.693        | 0.000          | -163.505       | 0.000            | 0.000            | 0.000            |
| 9           | -54.815        | 0.000          | -219.291       | 0.000            | 0.000            | 0.000            |
| 10          | -39.272        | 0.000          | -269.980       | 0.000            | 0.000            | 0.000            |
| 11          | -23.728        | 0.000          | -236.350       | 0.000            | 0.000            | 0.000            |
| 12          | -11.864        | 0.000          | -178.343       | 0.000            | 0.000            | 0.000            |
| 13          | 0.000          | 0.000          | -105.268       | 0.000            | 0.000            | 0.000            |
| 14          | -13.394        | 0.000          | -90.375        | 0.000            | 0.000            | 0.000            |
| 15          | -18.339        | 0.000          | -163.496       | 0.000            | 0.000            | 0.000            |
| 16          | -27.466        | 0.000          | -219.301       | 0.000            | 0.000            | 0.000            |
| 17          | -36.594        | 0.000          | -256.770       | 0.000            | 0.000            | 0.000            |
| 18          | -47.559        | 0.000          | -236.359       | 0.000            | 0.000            | 0.000            |
| 19          | -58.524        | 0.000          | -178.334       | 0.000            | 0.000            | 0.000            |
| 20          | -64.462        | 0.000          | -99.521        | 0.000            | 0.000            | 0.000            |

Calculated data allowed to obtain multiple representations of actual stresses for the girder, one of which was presented in figure 3.

![Figure 3. Representation of actual stresses for the 24-meter long and 3-meter high girder of the crane bridge.](image-url)
Stress calculations and verification were carried out using the first and the second limit states [4, 5]. Based on the approaches described in [9-20], we shall build the distribution of probability density for actual stresses - figure 4.

The probability distribution density in this case is subject to the normal law of distribution:

\[ f(\sigma_i) = \frac{1}{\sqrt{2\pi \sigma_i^2}} e^{-\frac{(\sigma_i - \langle \sigma_i \rangle)^2}{2\sigma_i^2}}. \]  

(1)

Figure 4. Probability distribution density for limit and safe actual stresses for the bridge girder.

Figure 4 shows that the operation under such limit loads can result in a failure. From this perspective, a number of measures must be developed. Reinforcing the component cross-sections with truss bars was suggested in our case – figure 5.

When recalculating all the data taking into account the reinforcement with a truss bar, we discovered that the probability distribution density for limit actual stresses was significantly reduced, which indicated the perspective of such calculations and the applicability of this technology in production.

5. Conclusions
Risk analysis of structures is currently gaining momentum. All the existing methods are primarily focused on obtaining quantitative evaluation of safety and risk relating to structures.

The combination of calculated and probabilistic data allow to draw a conclusion on the perspective of this subject.
Calculations and verifications were carried out using the first and the second limit states. The probability distribution density for limit and safe actual stresses was built based on the calculated data and probabilistic representations of loading applied to potential failure zones.

It is suggested to reinforce the bridge girder components with a truss bar in order to minimize negative implications. Such technology will allow to reduce the failure risk indicators significantly and to improve the safe operation not only for metallurgical cranes but also for other complex structures.

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