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Selection of Bridge Crane Beam Optimization Parameters

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Abstract: This paper is focused on the suitability of the selection of the parameters of the supporting structure of the bridge crane for the needs of cross-section optimization. The cross section of the beam is analysed in terms of its rigidity and dimensions with respect to the span of the crane. When optimizing to reduce overall weight, recommendations are given to address the issue of cross-sectional stability. An iterative procedure for the design of the cross-section of the beam at the specified load capacity of the crane and its span is proposed. In the article, only a theoretical analysis of the issue for the selection of suitable cross-section parameters of the crane girder for optimization needs is made, with the indication of another possible procedure for the optimization process itself aimed at minimizing the weight of the bridge crane girder.

Keywords: Crane Bridge; Girder Cross Section; Load

1. Introduction

When designing the construction of a specific product or device, some parameters of the construction are always fixed and some can be changed by the designer. In the case of load-bearing structures of handling equipment (cranes), the load-bearing capacity of the structure, the span, the lifting height and the travel and lifting speed are fixed. The design of the concept of construction, materials and dimensions remains at the choice of the designer. After designing a conceptual solution of the structure, the procedure is usually iterative to the final form of the solution. The initial design is often based on a similar, already implemented solution, which is modified until it meets all the requirements. From a structural point of view, it is necessary to design the structure so that it meets all strength, legislative, technological and functional requirements. The competitive environment forces manufacturers to offer the customer something extra. Most often, it is a question of economic evaluation, which means for the designer the minimum weight of the structure, simplicity, commonly available materials and purchased components. However, there are several questions associated with weight minimization, the answer to which requires the deployment of complex approaches that can simultaneously take into account all requirements and generate the final solution. The authors in [2], [3] point out the fact how the operation of the equipment is affected by an incorrectly manufactured crane structure and what changes need to be made to the crane structure when changing the operating parameters. Many authors verify their computational insights in the design of beam structures using FEM analysis [8], [10], [14] to [16], calculations and experiments [12], [17], or the whole design is the result of optimization procedures [7], [11], [13], [15].

Primarily, this contribution is intended to serve as a summary of theoretical assumptions for a successful procedure for optimizing the dimensions (minimum four dimensions) of the cross-section of the bridge crane beam. From the point of view of the scope of the whole issue, we considered it more practical to divide it this way,

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with the fact that the next article, which will be just a continuation of the mentioned issue, will include the optimization results themselves - FEM analysis after the previous dimensional optimization in the Matlab program for various optimization procedures (e.g. linear programming, quadratic programming, genetic algorithms, etc.).

2. Crane Bridge

The bridge is an essential construction part of the bridge crane. It consists of one or two main beams connected by crossbeams into a rigid frame. The main girder of the bridge transfers to the crossbeam the weight of the crane trolley with the load, as well as its own weight with the accessories. The basic requirements for a crane bridge are closely related to the requirements for a crane, i.e. the highest operational reliability with the lowest production and operating costs. The bridge must be sufficiently rigid so that the crane does not skewing during operation. On the other hand, the unnecessarily large weight of the bridge increases the production cost of the crane, the operating costs and the stress on the crane track. The concept of bridge construction should maintain an optimal ratio between production, operating and maintenance costs.

In terms of stress, the crane bridge is bent in a vertical and horizontal plane, twisted and, in addition, bent as a closed frame. Vertical bending is predominant. The main dimensions of the bridge, its design, construction, production and safety are relatively closely linked to the relevant standards. Due to their dimensions, crane bridges are usually divided into crossbeams for transport reasons, and at large spans also in main and secondary girders. Special requirements for crane operation are also imposed by special bridge designs (e.g. crane trolley for main and auxiliary lift, requirement for abnormal lift height).

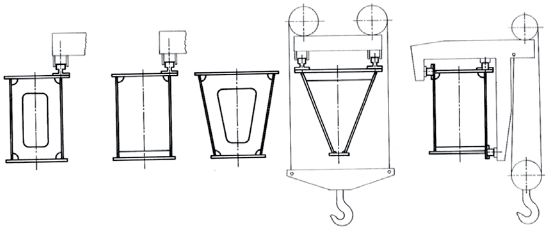

Figure 1: Cross sections of box girders of single girder cranes [1].

The design of the crane bridge is subject to the expected workload of the crane. The choice of the cross-section of the bridge depends on the type of operating load of the crane and on the dimensional parameters. These requirements are related to the choice of the type of main beams, which depends mainly on the load capacity of the crane, its span and on the location indoors or outdoors. For large loads, plane and box girders are preferred. With large spans, there is a tendency to use lattice beams with a closed cross-section of the bridge. The height of the main girders of the bridge is given by a compromise between the functional, strength, deformation, structural requirements and the requirement for the optimal weight of the girder. The height of the main beam is determined by the necessary moment of bending resistance during the strength check (ultimate limit state), or the necessary axial moment of inertia during the deformation check for deflection (serviceability limit state). The height of the cross beam is approximately one third to half the height of the main beam.

If a rolled profile is used as the main girder (most often of cross-section I, it is used up to a span of 15 m), a footbridge with a lattice wind is often connected to the upper flange, which reinforces it against deflection during vertical bending. If a weathered footbridge is not used, two L-profiles, a U-profile or only flat horizontal strips, are used to be symmetrically welded to the pressed flange (see Fig.2). One approach to solving such beams is given in [9].

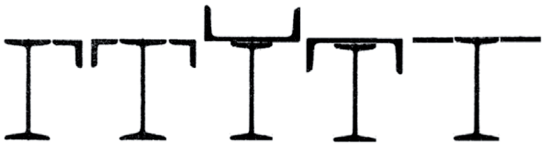

Figure 2: Increasing the stiffness of beams in the horizontal direction.

A typical representative of bridge cranes with a box structure of the supporting frame is a foundry crane, Fig.3. The main beam of the box structure has a rectangular cross-section according to Fig.4. The webs are thin-walled; local stability of the wall is achieved by reinforcements. In the case of plane beams, local wall stability is achieved by increasing the wall thickness, exceptionally by welding reinforcements. The flanges are thicker.

Flanges extend across the webs on both sides for better welding. The cross-section, in order to withstand especially twisting, is reinforced inside with transverse partitions – diaphragms.

The diaphragms are spaced 100 to 125% of the height of the main beam. Disruption of the stability of the webs most often occurs in the upper fifth to a quarter of the height of the beam, which is solved by welding longitudinal reinforcement angles. The width of the protruding part of the reinforcement should not be less than 1/15 of the width of the protruding part of the structure. The height of the box girder is selected in the range of 1/15 to 1/20 of the span. The ratio of the height to the width of the rectangular cross-section shall not exceed 3,5. The thickness of the web should be at least 5 mm and increases with respect to the stability of the wall.

The bent beams have a part of the cross section loaded with pressure, which means the risk of loss of shape stability.

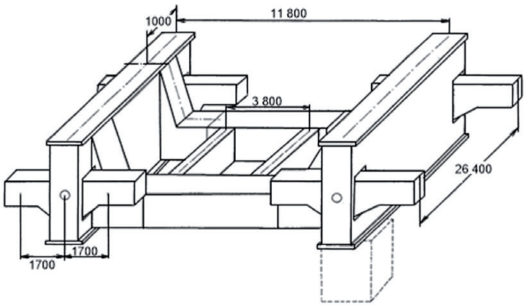

Figure 3: Support structure of a 250 t foundry crane (without wheels and trolleys of the main and auxiliary lift).

3. Stability Problems

The issue of loss of shape stability is therefore relevant for the structures we are trying to lighten (weight reduction - the most common approach from optimization methods), because weight reduction leads to the use of thin-walled structures. Compound bent beams can lose shape stability in two basic cases depending on the type of load, the cross-sectional arrangement and the boundary conditions. In the first case it is a lateral torsional buckling of the beam (global case), the second possibility is a local buckling of flanges and/or webs, Fig.5. Therefore, when optimizing the design, the loss of stability must be taken into account in the form of restrictive conditions.

Under the term stability in the field of steel structures of transport and handling equipment, we understand two basic meanings. Position stability - e.g. tilting of the crane around the tilting edge and shape stability - the phenomenon of thin-walled structures loaded with pressure.

The loss of shape stability occurs in the pressed areas of the structure when the compressive stress reaches the limit values, after which the structure (or part of it) begins to deform excessively and with further increasing load it quickly loses its original shape and thus load-bearing capacity [16], [18], [19]. From the energy point of view, it is a rapid redistribution of stress energy from compressive (membrane) to bending stress, which results in a substantial increase in deformations. From the point of view of idealization and modelling, we distinguish between the loss of shape stability when the balance is bifurcated and when the limit load is reached [16,

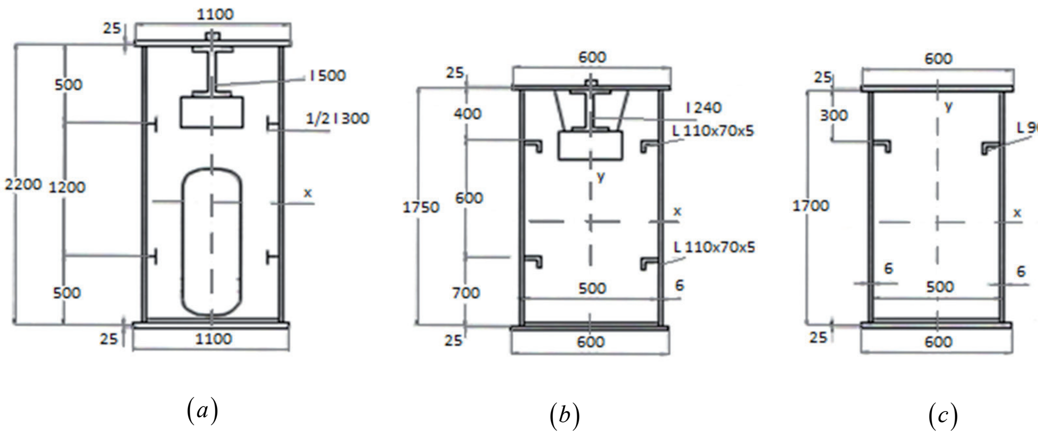

Figure 4: Cross-sections of beams foundry 250 t crane; (a) – cross-section of the main lift beam, (b) – cross-section of the auxiliary lift beam, (c) – cross-section of the cross beam.

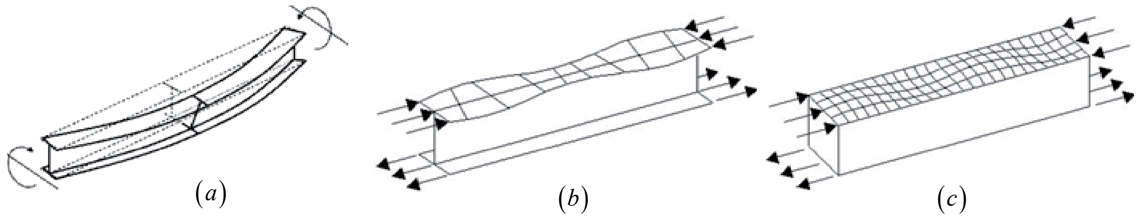

Figure 5: Loss of beam stability; a – lateral torsional buckling of the beam, b, c - local buckling of the flanges of the beams.

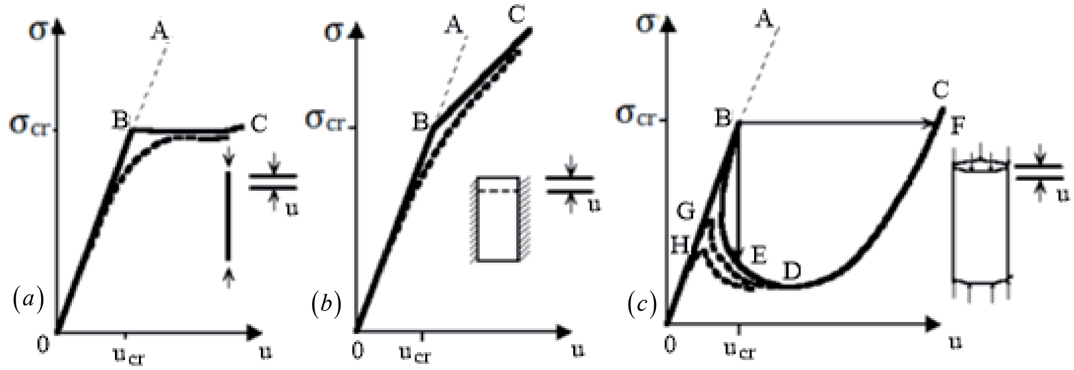

Figure 6: Loss of stability of basic idealized and real elements of the structure [4]. (a) - straight slender thick-walled bar under pressure, (b) - straight wall under pressure, (c) – thin cylindrical columns under pressure.

17]. Bifurcation is a theoretical computational state, which is determined by achieving the so-called critical load of ideally straight, planar or cylindrical structural elements, which are loaded so that a simple pressure or compressive membrane stress is created in them in the linear-elastic behaviour of the material. This state has a sharp transition on the load diagram (point B Fig. 6), after which it is divided into a stable and unstable branch.

The stable branch represents a new deformation of the structure in some characteristic mode, the unstable branch continues in the original deformation. The calculation of critical loads and the corresponding post critical deformation modes has fundamental practical importance, because we obtain an estimate of the maximum load of the structure from the point of view of the loss of dimensional stability by a simple and fast procedure. The accuracy of this estimate is given by the accuracy of the model, the slenderness and the type of structure, which determines the sensitivity of the value of the critical force to deviations from the ideal state, which we call imperfections. Every real structure has imperfections, because the structures are made with a certain dimensional and geometric accuracy, tolerances in material composition, material inhomogeneity, anisotropy, residual stress after technological operations and are often stored in imperfect bonds. The course of loading of a real and ideal structural element is different, because the real element bends from the beginning of the load due to imperfections, which results in the creation of additional bending stresses leading to a gradual decrease in stiffness. Load diagrams of real structures are more or less close to bifurcation behaviour. Fig. 6 shows for comparison the behaviour of ideal (thick line) and real (dashed line) basic elementary body types under compressive loading.

On the size of the load at which the structure loses its shape stability has also significantly affect taking into account the imperfections of the structure. Computational approaches also differ in taking into account imperfections. The imperfections are by the simplest model ignored. However, the load calculated in this way may be a non-conservative estimate of the actual load causing the unstable behaviour [5], [6].

More sophisticated methods of imperfection take into account and provide much more accurate results, but at the cost of higher computational complexity. In general, we can divide the methods into analytical, analytical-empirical and numerical. Analytical methods are based on strongly simplified assumptions and are relatively complex even for simple beams. Numerical approaches can also handle the construction of more complex shapes and boundary conditions. Analytical-empirical methods usually use an analytically calculated critical load to determine the slenderness for reading from the appropriate cut-off curve.

Due to the fact that in weight-optimized constructions we work with thin-walled elements that move at the boundary of limit states, it is necessary to include in the optimization process the prediction of the load causing the loss of shape stability.

4. Results and Discussion

The procedure of the proposed optimization methodology is shown on the example of the design of the parameters of the weight-optimized cross-section of the box girder of the double-girder bridge crane. The goal is to design the lightest possible variant of the welded beam, which, however, meets the strength requirements given by valid standards. The optimization problem solves only basic parameters. The effectiveness function will be the volume of material used to construct the crane girder. The value is directly loaded from the parametric model in the program, e.g. SolidWorks, NX, Catia, etc. Limiting conditions are formulated with regard to the selection of beam cross-section parameters, strength and stability conditions. The main beam of the box structure has a rectangular cross-section according to Fig.7. The parameters L, L_1, h_1 and d are given in advance (they do not represent design variables). The height of the beam h will change depending on the width in the ratio h = 3.5d.

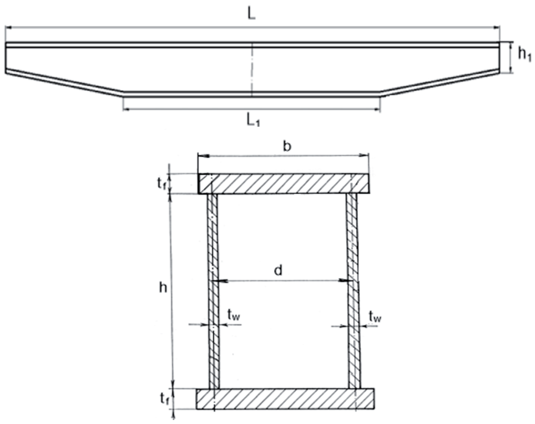

Figure 7: Design of beam cross-section parameters.

The webs are thin-walled. In the case of full-wall beams, the local stability of the wall is achieved by increasing the thickness of the wall, exceptionally by welding reinforcements. The flanges are thicker. For better welding, the flanges on both sides extend over the webs. The cross-section, in order to resist twisting, is reinforced inside with transverse partitions – diaphragms, in our case they should be spaced at 100% of the height of the beam, i.e. at a distance h, and they will have the same thickness as the webs. The subject of the optimization will be the search for optimal values of the dimensions of the cross-section at the minimum weight of the beam. In general, it is possible to choose seven design variables describing the box cross-section, if we were to consider different thickness and width of the flanges in the upper and lower part of the beam. This number is reduced to four design variables for practical reasons. We will set the stand spacing d to the largest possible value in order to maximize the torsional stiffness and thus the resistance to tipping. The width of the flanges b is derived from the parameter d so that there is enough space for the weld on the edges. It is not advisable to choose the ranges of individual design variables unnecessarily large, because large ranges of design variables generally lead to lower quality metamodels due to the creation of an approximation over a larger design space. If we do not know the approximate position of the optimum, it is possible to perform the optimization in two or more steps, where in each subsequent step we reduce the design space depending on the indicated position of the optimum.

Formulation of limiting conditions:

The reduced tension in the webs and flanges of the loaded beam must not exceed the yield strength of the material (legislative requirement).

$$\sigma_{red} \leq f_y \quad [\mathrm{MPa}]; \tag{1}$$

where σ_{red} – reduced stress [MPa], f_y – yield strength of the material used [MPa].

The beam must not show global or local shape instability under the load condition (legislative requirement).

$$k_B = min\left(k_{B,L}; k_{B,N}\right) \leq 1 \quad [-];$$

$$k_{B,L} = \frac{F_{cr}}{F_{Norm}} \quad [-]; \tag{2}$$

$$k_{B,N} = \frac{F_{L1}}{F_{Norm}} \quad [-];$$

where k_B – the resulting coefficient of stability safety with respect to the normative load F_{Norm} [-], $k_{B,L}$ – stability safety factor determined from the bifurcation load F_{cr} due to the normative load F_{Norm} [-], $k_{B,N}$ – stability safety factor determined from the limit load F_{LI} due to the normative load F_{Norm} [-].

The beam must be sufficiently rigid in bending. This requirement is quantified by the maximum amount of deflection when loaded with a nominal load (contractual requirement).

$$\delta \le \delta_{\max}; \tag{3}$$

where δ – beam deflection [mm], $\delta_{\max}$ – permissible beam deflection [mm].

The web thickness t_w is limited by the interval

$$t_w \in \langle t_{w,\min}, t_{w,\max} \rangle; \tag{4}$$

where t_w – web thickness [mm], $t_{w,\min}$ – minimum possible web thickness [mm], $t_{w,\max}$ – maximum possible web thickness [mm].

The thickness of the flanges t_f is limited by the interval

$$t_f \in \langle t_{f,\min}, t_{f,\max} \rangle; \tag{5}$$

where t_f – flange thickness [mm], $t_{f,\min}$ – minimum possible flange thickness [mm], $t_{f,\max}$ – maximum possible flange thickness [mm].

The center pitch of the flanges d is limited by the interval

$$d \in \langle d_{\min}, d_{\max} \rangle; \tag{6}$$

where d – centre spacing of webs [mm], $d_{\min}$ – the minimum possible centre spacing of webs [mm], $d_{\max}$ – the maximum possible centre spacing of webs [mm].

The width of the flanges a is limited by the interval

$$b \in \langle b_{\min}, b_{\max} \rangle; \tag{7}$$

where b – flange width [mm], $b_{\min}$ – minimum possible flange width [mm], $b_{\max}$ – maximum possible flange width [mm].

From a mathematical point of view, optimization is the process of finding the extremum of an effectiveness function while observing given limiting conditions. The effectiveness function is a suitably formulated dependence of the optimized quantity on design variables. In our case, the effectiveness function is the weight of the beam. Since a continuous beam metamodel is used for the optimization, it is of course clear that only the mathematical solution method with continuous functions can be used. According to the type of algorithm, it can be analytical methods of mathematical analysis, numerical gradient methods or heuristic algorithms. When considering limiting conditions in the form of inequalities, our radius of action is narrowed to only methods that can work with such conditions. It is advantageous to use the functions in our conditions of the frequently used Matlab software. For criteria constructed in this way, they can be used in the Matlab program from the gradient tasks of the linear programming method, sequential quadratic programming and from heuristic methods, e.g. genetic algorithm.

5. Conclusions

There are many restrictions and criteria that a crane's construction must meet in order to comply with normative regulations and ordinances. Historically, the use of bridge cranes has resulted in several structural arrangements that have proven themselves over time and did not need to be changed. The most used ones are often reflected in standards, and some, like an unwritten law, serve as a first estimate of the shape of a new design. The requirements associated with proving the competence of the supporting structure of the handling equipment are given by legislation and contract. Fulfilment of legislative requirements will be achieved e.g. using the so-called harmonized standards, which describe in detail the individual criteria of the selected parameters. However, meeting all the normative requirements for construction does not generally guarantee their optimal arrangement. The design team usually has a certain possibility to further change the structure so that the optimal arrangement is achieved with respect to a certain criterion (most often it is the weight of the structure).

The difference in the solution of this problem described in the article compared to the authors who are mentioned in the review of the used literature and who were as an inspiration for writing this article is that most methods optimize a maximum of two dimensions of the cross-section of the crane beam from the point of view of optimization aimed at minimizing weight and then additionally checking for example, the vibration of the beam. While they do not take into account the loss of stability of the cross-section of the beam. Or a check is made for the limit state of bearing capacity, but there is no check for the limit state of serviceability. Many optimization methods are not even optimization in the true sense of the word, because they work on the principle of trial and error until they arrive at a solution that shows signs of being optimal.

For the selection of the parameters of the crane bridge girder, which are usable for the optimization procedure, according to the previous analysis, the following findings result when entering the load capacity of the crane and its span. As a first iteration use the design of the cross-section of the beam from the deformation condition for deflection, while as a first limitation we use the condition that the web of the cross-section cannot be thinner than 5mm, choose the height of the beam in the range 1/15 to 1/20 of the span. Maintain approximately a beam height / beam width ratio of 3.5. For single-girder cranes with a span of up to 15 m, we will use as a first iteration a rolled profile with a cross-section that has a cross-sectional characteristic "J" in the more stressed plane at least 50% higher than calculated. At this point, the serviceability limit state check will definitely be fulfilled; therefore, it is necessary to further check the designed cross section and the beam for the ultimate limit state and at the same time perform the shape stability check. For higher cross-sections (larger loads and spans), we recommend supplementing the cross-section with transverse reinforcements spaced 1.0 to 1.25 times the height of the beam. According to the chosen optimization procedure (using a criterion function or, for example, a very frequently used trial-and-error procedure) and according to the time available for the design of the structure, a control strength calculation is performed. Depending on the results of the calculation, the individual cross-sectional parameters (sheet thickness, cross-sectional height and width) can then be corrected if necessary. It should be noted that the magnitudes of the loading forces of the calculation model are increased by combinations of dynamic effects according to the selected loading conditions and the magnitude of individual dynamic coefficients is prescribed by the standard according to the category and type of crane.

A theoretical analysis of the issue with the possibilities of further use is in this article. The practical procedure, which will refer to this theoretical procedure, will be the content of a free continuation of the solved problem and presented in one of the following issues of this journal.

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References and Notes

1. Kuľka,J., Mantič, M., Puškár, M. (2017). Žeriavy mostového typu. 1. vyd. – TU Košice, pages 220, ISBN 978-80-553-2908-6.
2. Kuľka,J., Mantič, Fedorko, G., Molnár, V. (2020). Failure analysis concerning causes of wear for bridge crane rails and wheels. Engineering Failure Analysis, No. 110, pages 1-14, ISSN 1350-6307.
3. Kuľka,J., Mantič, Faltinová, E., Molnár, V., Fedorko, G. (2018). Failure analysis of the foundry crane to increase its working parameters. Engineering Failure Analysis, No. 88, pages. 25-34, ISSN 1350-6307.
4. Design of beams in composite bridges. Steel Construction. Info (Online) Tata Steel, BCSA and the SCI.
5. ESDEP, (1993). The European Steel Design Education Program. London: SCI.
6. Šťastný, A. (2015). Modeling of load impacts acting on transport and handling equipment with the aim of their optimization. Doctoral thesis, VUT Brno.
7. Maláková, S. et al. (2019). Design of constructional optimisation determined for mixed truck gearbox. AD ALTA : journal of interdisciplinary research : recenzovaný mezioborový vědecký časopis. - Hradec Králové (Česko): Magnanimitas akademické sdružení Roč. 9, č. 2, s. 414-417, ISSN 1804-7890.
8. Maláková, S., et al., (2021). Design of Geometrical Parameters and Kinematical Characteristics of a Non-circular Gear Transmission for Given Parameters. Applied Sciences, volume. 11, No. 3, pages 1-23.
9. Trahair, N.S. (2021). Limit states design of crane runway girders. Engineering Structures, Volume 240, ISSN 0141-0296, doi.org/10.1016/j.engstruct.2021.112395.
10. Alkin, C., Imrak, C. E., Kocabas, H. (2005). Solid Modeling and Finite Element Analysis of an Overhead Crane Bridge. Acta Polytechnica, Vol. 45, No. 3, ISSN 1805–2363, doi.org/10.14311/712.
11. Fan, X., Xu, G., Yang, R., (2010). The GA to the optimal design for crane girder and research on its optimization performances. 8th World Congress on Intelligent Control and Automation, pages 3220-3224, doi: 10.1109/WCICA.2010.5555060.

12. Delić, M., Pervan, N., Čolić, M., Mešić, E., (2019). Theoretical and experimental analysis of the main girder double girder bridge cranes. International Journal of Advanced and Applied Sciences, vol.6, No. 4, pages 75-80, doi.org/10.21833/ijaas.2019.04.009.
13. Jármai, K., (1990). Decision support system on IBM PC for design of economic steel structures applied to crane girders. Thin-Walled Structures, Volume 10, Issue 2, pages 143-159, ISSN 0263-8231, doi.org/10.1016/0263-8231(90)90060-C.
14. Tong, Y., Ye, W., Yang, Z., Li, D., Li, X., (2013). Research on Multidisciplinary Optimization Design of Bridge Crane. Mathematical Problems in Engineering, vol. 2013, Article ID 763545, 10 pages, 2013. doi.org/10.1155/2013/763545.
15. Liu, P.F., Xing, L.J., Liu, Y.L. et al. (2014). Strength Analysis and Optimal Design for Main Girder of Double-Trolley Overhead Traveling Crane Using Finite Element Method. Fail. Anal. and Preven. Vol. 14, pages 76–86, doi.org/10.1007/s11668-013-9767-1.
16. Lee, D. H., Kim, S. J., Lee, M. S., Paik, J. K., (2019). Ultimate limit state based design versus allowable working stress based design for box girder crane structures. Thin-Walled Structures, Volume 134, pages 491-507, ISSN 0263-8231, doi.org/10.1016/j.tws.2018.10.029.
17. Kettler, M., Derler, Ch., Schörghofer, A., Macho, Ch., Unterweger, H., (2019). Laboratory and numerical tests on real crane runway girder with box section. Journal of Constructional Steel Research, Volume 160, pages 540-558, ISSN 0143-974X, doi.org/10.1016/j.jcsr.2019.06.002.
18. Wang, C. M., Wang, C. Y. and Reddy, J. N., (2004). Exact solutions for buckling of structural members. Boca Raton, Florida: CRC Press LLC, p. 207, ISBN 0849322227.
19. Trahair, N.S., (1993). Flexural –Torsional Buckling of Structures. 1st Edition, Boca Raton, Florida, CRC Press Inc. 1993. ISBN 0419171105.