applied sciences

MDPI

Article

Optimisation of Box Girder Design of Overhead Cranes

Jozef Kulka *, Martin Mantič, Robert Grega, Marián Siman, Melichar Kopas and Silvia Maláková

Faculty of Mechanical Engineering, Technical University of Košice, Letná 1/9, 04200 Košice, Slovakia; martin.mantic@tuke.sk (M.M.); robert.grega@tuke.sk (R.G.); marian.siman@tuke.sk (M.S.); melichar.kopas@tuke.sk (M.K.); silvia.malakova@tuke.sk (S.M.)

* Correspondence: jozef.kulka@tuke.sk; Tel.: +421-55-602-2503

Abstract: The subject of the research presented in this article is the dimensional optimisation of the box structure of the main girder for overhead cranes, with the aim to reduce the main girder's own weight. Described are the applied optimisation methods and also the problems arising during the optimisation process. Loss of shape stability is analysed in more detail, as well as the methods determined for a constructional proposal of the girder cross-section. The developed optimisation procedure is a combination of the calculations, performed in the MS Excel environment, with the simulation of a parametrically modelled girder realised using Dassault Systèmes SolidWorks software v. 2023. Using the example of optimisation of an overhead crane girder with a lifting capacity of 50 tons, the effectiveness of the proposed optimisation procedure is declared, where the existing overhead crane box girder is compared with the optimised cross-section of the box girder.

Keywords: overhead crane; FEM; thin-walled structures; metamodel; optimisation

check for updates

Citation: Kulka, J.; Mantič, M.; Grega, R.; Siman, M.; Kopas, M.; Maláková, S. Optimisation of Box Girder Design of Overhead Cranes. *Appl. Sci.* **2024**, *14*, 9926. https://doi.org/10.3390/app14219926

Academic Editors: Mengchuang Zhang and Shaohua Liu

Received: 20 August 2024
Revised: 22 October 2024
Accepted: 23 October 2024
Published: 30 October 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

In the design of any structure, some parameters are fixed, while others can be changed at will by the designer. In the field of load-bearing structures of material handling equipment, the maximum load capacity of the structure, the working temperature of the machine, the service life of the structure, the maximum weight of the structure itself, the production price, and the operating costs are often specified. The task of the designer is then to design the concept of the structure, the choice of suitable materials, and the dimensions of the structure itself. The chosen configuration is often similar to a structure that has already been constructed. This is modified until the resulting structure meets all of the technological, strength, functional, and legislative requirements.

The impacts of various additional loads are often introduced into the structure [1], or due to incorrect manufacture technology (repair) [2], this structure is devalued or worn out [3].

However, the modification of a structure is now also understood to include a certain degree of optimisation of the structure's parameters.

The most common optimisation criterion in the design of overhead cranes is the weight of the entire structure. The weight of the structure is related to the purchase price of the necessary material, the production costs, and the costs of operating the machine.

Some authors have mathematically described the optimisation of welded beams of bridge cranes. Pavlovic and team [4] describe in detail analytically and using standards the methodology of optimisation of the box girder of bridge cranes. This optimisation is performed analytically for the two most important variables (beam height and width) using the Lagrange multipliers method, with consideration of the constraints on wall buckling and buckling.

A methodology focusing on the mass optimisation of a bridge crane girder considering stiffness and strain constraints is described in detail by a team of Chinese authors from Shenyang University [5]. In their work, the optimisation is solved numerically using simple

nonlinear programming. However, the stability of the beam itself is not considered at all in the constraints. Both the objective functions and the constraint conditions are formulated using analytical equations in their work.

The mass optimisation of a bridge crane girder using point cloud is described by Sun et al. [6]. Ten constraint conditions and six design variables are included. These are quantified and formulated analytically. A total of 400,040 variations of the constraint conditions and the objective function are required to find a solution. The relatively high number of enumerations is characteristic of all heuristic optimisation methods. A direct link to the finite element method is practically impossible due to the high number of analyses performed.

The mass optimisation of box girders (bridge cranes) is also described by a team of authors [7]. The optimisation is solved using MS Excel software. Verification is provided by ANSYS software using direct optimisation solvers. This is because the stability constraint is not solved using FEM, only the deflections and stresses are solved. The resulting optimisation is solved for 11 design variables. The stability of the beam is investigated analytically using the conditions of the "Crane Manufacturers Association Recommendations" in the USA.

Another method of mass optimisation of beams is presented in [8]. During structural design of the bridge crane, it is necessary to choose parameters of beams such as weight and span and various parameters of the cross-section according to their importance. The optimal design of the bridge crane structure is performed using the Bees algorithm. The bridge crane is numerically compared before and after optimisation with regard to design parameters.

Mathematical optimisation methods are rarely used in the design of steel structures. In the actual design and construction, an empirical approach including experience, trial-and-error, or comparing several analysed scenarios prevails. Although this procedure is called optimisation, it is not optimisation in the mathematical sense. A prime example is the optimisation of the web and stator thicknesses of a bridge crane girder [9].

The above works use either an analytical form of function description and constraint conditions or a direct link between the optimisation solution and the finite-element system. None of the above approaches address the stability constraints using the finite element method and a significant deviation from the optimum solution can also be caused by rounding to the available sheet thicknesses. None of the above work takes into account material fatigue. Published reports define the sheet thickness to decimal integers. However, it should be pointed out that rounding to integers can cause significant deviation [5,7]. When dealing with the stability of steel structures, standards are always used, which contain rules that take into account the influence of imperfections.

Many optimisation procedures are inspired by nature. Such techniques include generative design and topological optimisation. Using generative design, which involves some automation and process autonomy, several designs are created. The design process mimics the evolutionary process in nature by starting with one or more different designs and changing them over time into solutions that are more suitable for the requirements constrained by specific conditions. Solutions to design criteria that are not satisfied or constraints that are not satisfiable are discarded, and the search (evolution) process moves in a different/new direction [10–12].

Topological optimisation minimises the amount of material required while maximising the structural performance or efficiency of the design, given specific load and boundary conditions. Conceptually, shape and/or size optimisation is easy to define, considering its scope, limited to variables such as cross-sectional properties, element types and geometry, and tightly constrained by predefined configurations. Simply put, the topology cannot be changed and therefore this concept is considered an improvement on the existing design, which depends heavily on approaching the optimum [13]. Genetic algorithms [14] are a robust method suitable for solving various optimisation problems. They investigate a large area of design variables to find the best solution. From the user's point of view, the algorithm requires encoding the design variables into chains, and the optimisation

procedure uses them for optimisation. Here, it is key for the designer to find the form of the objective function, including the limitations of the task, as well as to avoid critical states in the solution of structural responses.

It is often used in the initial design phase to study and assess different design options in accordance with predefined criteria, such as weight reduction, stiffness increase, stress reduction, and strain reduction, among others [15]. In contrast to topological optimisation, in dimensional optimisation, the values of the design parameters related to the cross-sectional areas of the elements are adjusted in order to obtain the best solution in terms of weight, stress, strain, and other factors. These methods only allow changing the values of their parameters, not adding or removing new elements or cavities in the design of the elements [16].

The most effective method of reducing the weight of the crane structure is the use of suitable thin-walled structures. The disadvantage of this method is the high susceptibility of the supporting structure to loss of dimensional stability, which can lead to the crane itself crashing. The above-mentioned loss of shape stability can be determined by different approaches, e.g., by manual calculation or mostly by using FEM simulation analysis.

2. Loss of Dimensional Stability

Loss of dimensional stability is the limit state at which the compressive stress is rapidly converted to a bending stress. This process is accompanied by a rapid increase in local deformation, which causes another limit state to develop. This limit state often leads to the collapse of the entire structure.

In terms of material cross-section utilisation, bent members of load-bearing structures are much worse off than pushed or pulled members. The bending stress is not the same throughout the section, but varies not only throughout the length of the beam but also throughout the entire cross-section. In the middle of the beam, on the so-called neutral axis, there is no stress, which means minimum material utilisation [17]. The beam is essentially a thick-walled or thin-walled member with a predominant bending stress. There is also shear stress, but this is negligible.

The cross-section consists of crawlers and uprights. The flanges mainly transmit the bending moment, and the racks mainly transmit the shear stresses. The dimensioning of the flanges and racks is based on the transmission of these stresses. The cross-sections of beams (bridges) can be open or closed [18]. Open sections are prone to buckling or twisting, which is a major disadvantage for the purpose of use as a load-bearing element of the structure (Figure 1). However, they are cheaper and can be easier to manufacture. From a technological point of view, these cross-sections are most often produced by welding or direct rolling and rarely by riveting. Closed sections are more difficult to manufacture but can withstand greater stresses and are often suitable for the construction of heavy-duty overhead cranes. They are most often produced by welding.

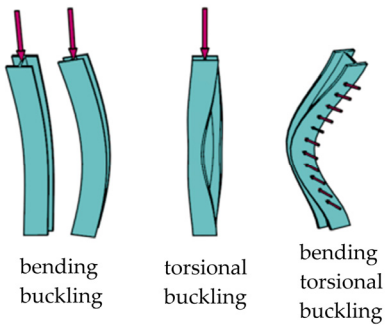


Figure 1. Types of beam buckling under simple compression loading.

The main girders of an overhead crane have the upper part of the cross-section subjected to compressive stresses [19]. This means an increased risk of loss of dimensional stability (Figure 2). The figure is illustrative and represents the mechanism of loss of stability

due to tilting of beam. This condition can arise in two cases, depending on the type of boundary conditions, the magnitude of the load, and the arrangement of the cross-section:

- Local buckling of racks or flanges,
- Local buckling of the beam.

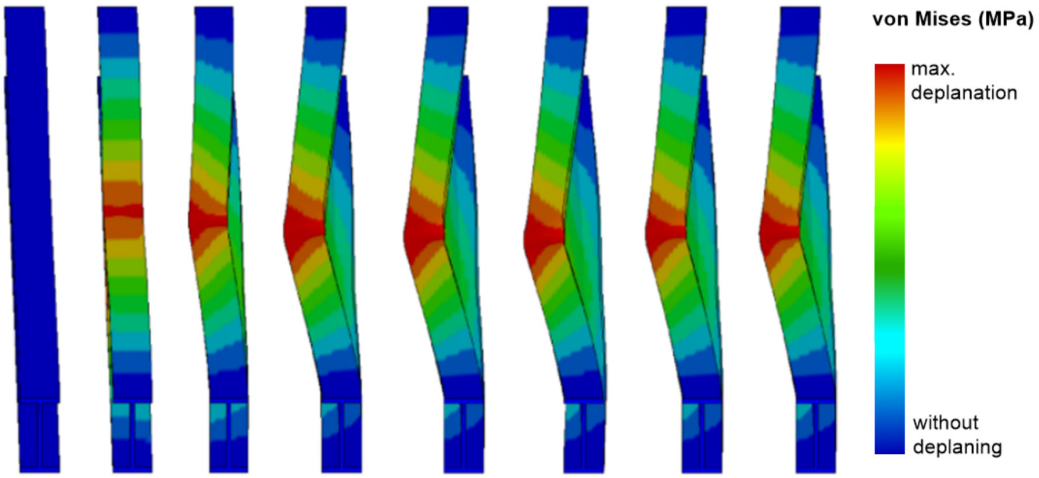


Figure 2. Load capacity loss of a real member.

Loss of dimensional stability is minimised by the appropriate choice of constraint conditions. In practice, there are several approaches with varying degrees of computational complexity and accuracy. Designing beams from composite cross-sections is possible in several ways. The aim is to choose the dimensions so that a given load is carried by the crane at minimum dead weight but, at the same time, the inherent stiffness of the structure must be maintained.

2.1. Methods of Designing Cross-Sections

- Numerical methods are suitable for designing structures of complicated shapes.
- Analytical-empirical methods use the analytically calculated critical load of the beam to determine the degree of slenderness. This is used in comparison with the limit curve of the shape stability limit state or elastic limit state.
- Analytical methods are complex even for simpler beams because they are based on strongly simplifying assumptions.

Description of the proposed optimisation methodology (Figure 3):

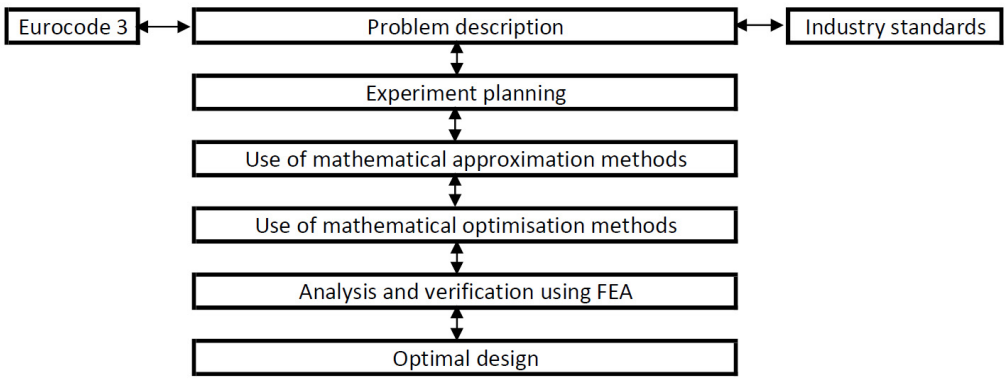


Figure 3. Simplified view of the proposed methodology.

The proposed optimisation methodology is focused on the design optimisation of the load-bearing nodes of steel structures of bridge cranes (girders). Mathematical optimisation

methods (gradient and heuristic based [20–22]), structural analysis (FEM), and mathematical approximation methods are applied in the methodology. The generated imperfections for FEA (shape and size) are developed according to Eurocode EC3 [23].

The methodology thus developed represents a systematic interconnection of various sub-methods into a single coherent procedure that leads to an optimum solution of the structure (Figure 4).

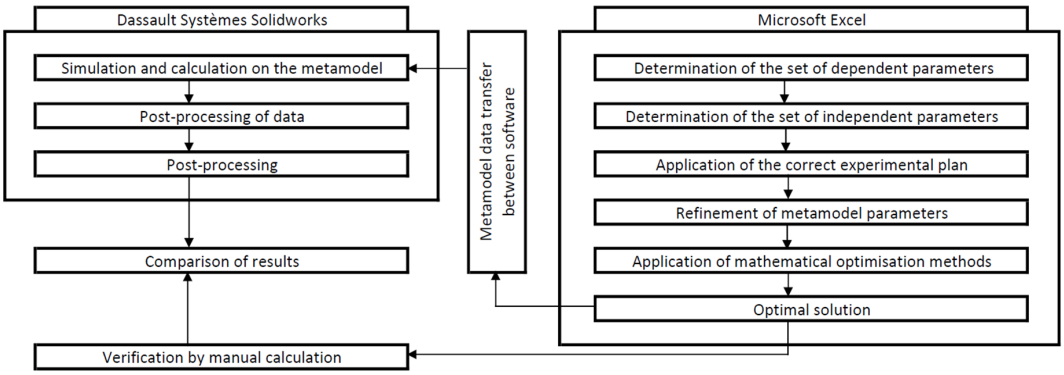


Figure 4. Schematic diagram of the methodology from the point of view of use of the software.

2.2. Methods of Computational Prediction of Loss of Shape Stability

The methods are used to formulate a boundary condition that accurately describes the limit of safe (stable) behaviour of the structure. To introduce geometric imperfections and nonlinear stability analysis performed in Dassault Systèmes SolidWorks, a codified approach using Annex "C" of STN EN 1993-1-5 [23] is used in the calculations. Since no permanent deformations of the structure are allowed when loading the bridge crane superstructures, the maximum allowable load is determined by reaching the yield strength (under continuous loading of the structure with the influence of geometric nonlinearity).

2.3. Approximation Methods (Mathematical)

They are used to identify the parameters of the metamodel under study in order to obtain bounding conditions and a description of the objective function in the design space. Artificial neural networks, radial basis functions, and linear regression metamodels can be simulated in Microsoft Excel (Microsoft Office Professional Plus 2010 v. MSO:14.0.7268.5000 (32-bit.)).

2.4. Optimisation Methods (Mathematical)

They are applied to the generated metamodels in order to find the optimal configuration of the investigated node structure (given the constraint conditions and the objective function). Heuristic and gradient-based principles are commonly used. The optimisation methods can be applied in Microsoft Excel.

2.5. Structural Analysis Using FEM

Since the finite element method allows solving common structural problems on three-dimensional solids, a parametric form of the model is crucial for this methodology, allowing a simple and fast change of the model of the solved node. This guarantees the automatic execution of the calculations in all configurations that have been determined by the experimental plan. Dassault Systèmes SolidWorks software v. 2023 allows the creation of parametric computational models. The program also allows the automatic evaluation (summation) of the necessary variables. The resulting values are calculated by including the limit loads of the structure determined by geometric nonlinear analysis, taking into account the influence of possible imperfections of the structure (Figure 5).

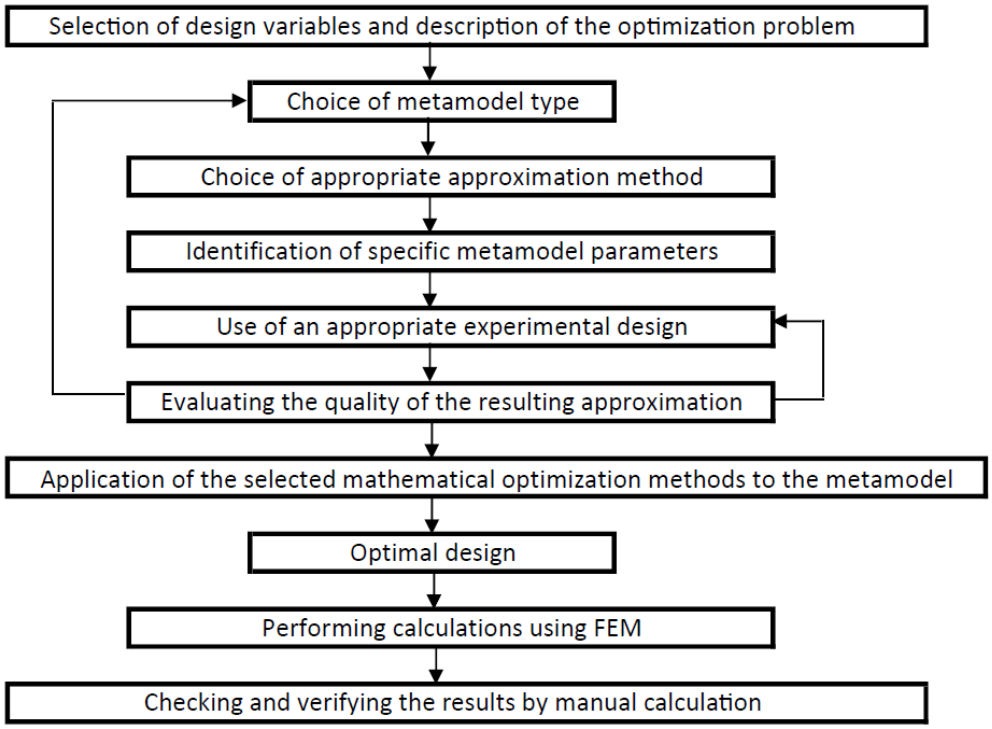


Figure 5. Procedure for finding the optimal solution.

3. Application of the Developed Methodology and Parameterisation of the Bridge Crane Cross-Section

Based on the given input parameters (boundary conditions), the objective of this chapter will be to use the developed optimisation methodology to design and parameterise the box section of the overhead crane. The optimisation is solved for a closed box girder cross-section with longitudinal and transverse stiffeners.

In any structural design, some structural parameters are given, and some can be changed at will by the designer. In the case of gantry crane structures, the capacity of the structure is specified, as well as the speed of travel and stroke, height of travel, and span of the bridge. The choice of the type of structure, the choice of materials, and the dimensions of the load-bearing parts remain the task of the designer, and the design is usually based on an already implemented solution.

Normally, the choice of the cross-section of the girder (bridge) depends on the dimensional parameters and on the type of crane service load expected. The height of the bridge girders is determined by the optimum between structural, functional, deformation, and strength requirements. The crane bridge itself must be sufficiently rigid so that it does not deform under loading. However, an unnecessarily large weight of the crane bridge increases not only the production cost of the crane but also the operating costs and, at the same time, the stresses on the crane runway. Thus, great emphasis is also placed on the weight of the girder itself, and the height of the main girder is always influenced by the bending moment in the strength check with regard to the ultimate limit state. Emphasis is also placed on the serviceability limit state, which is defined as the quadratic moment of the cross-section in the deflection check.

In terms of structural stresses, the crane bridge is bent as a closed frame, bent in the horizontal and vertical planes and, in addition, twisted. Therefore, the main girder often takes the form of a box structure with a rectangular cross-section (Figures 6 and 7). In such cases, the flanges are of greater thickness and the uprights are thin-walled; local stability of the wall is achieved by reinforcement at regular intervals (transverse reinforcement). In order to make the cross-section better able to withstand torsional stresses, the walls are reinforced internally with transverse baffles (diaphragms) [24].

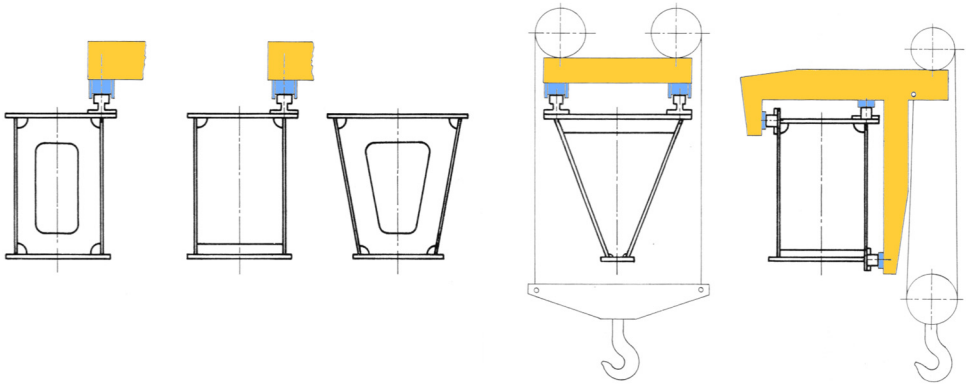


Figure 6. Single crane box girder cross-sections.

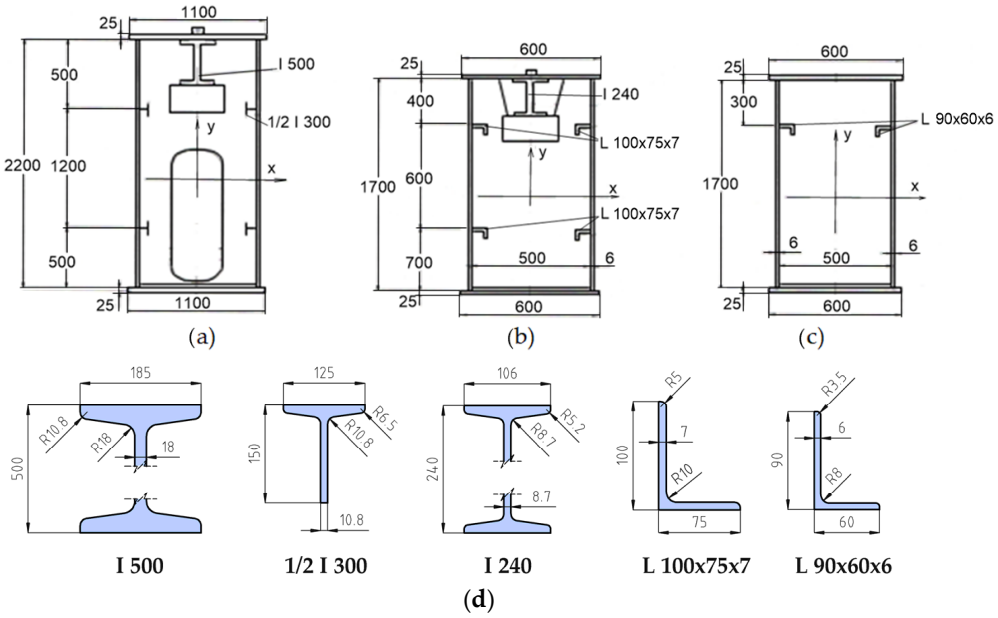


Figure 7. Cross-sections of box girders with reinforcements of a 250 t capacity casting crane. (**a**) cross-section of main lift beam (250 t capacity), (**b**) cross-section of auxiliary lift beam (50 t capacity), (**c**) cross-section of crosspiece, (**d**) dimension parameters of the used profiles.

As the stability failure of uprights usually occurs in the upper fifth to quarter of the beam height, the risk of buckling can be reduced by welding in longitudinal reinforcing angles. The transverse stiffeners are spaced 100 to 125% of the height of the main beam. Normally, the width of the projecting part of the bracing should not be less than 1/15 of the width of the projecting part of the structure. The height of the box girder shall be 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 should not be greater than 3.5 times. The thickness of the rack shall be at least 5 mm and shall be increased with regard to the stability of the wall.

All bent beams shall have part of the cross-section loaded in compression. For this reason, there is an increased risk of loss of shape stability in these beams and therefore the loss of stability must be taken into account in the form of constraining conditions when optimising the design. Using the example of a steel structure of an existing 50 t capacity crane with box girder beams as shown in Figure 8, we will show the dimensional optimisation procedure and its results, where the main optimisation criterion was the weight of the beams.

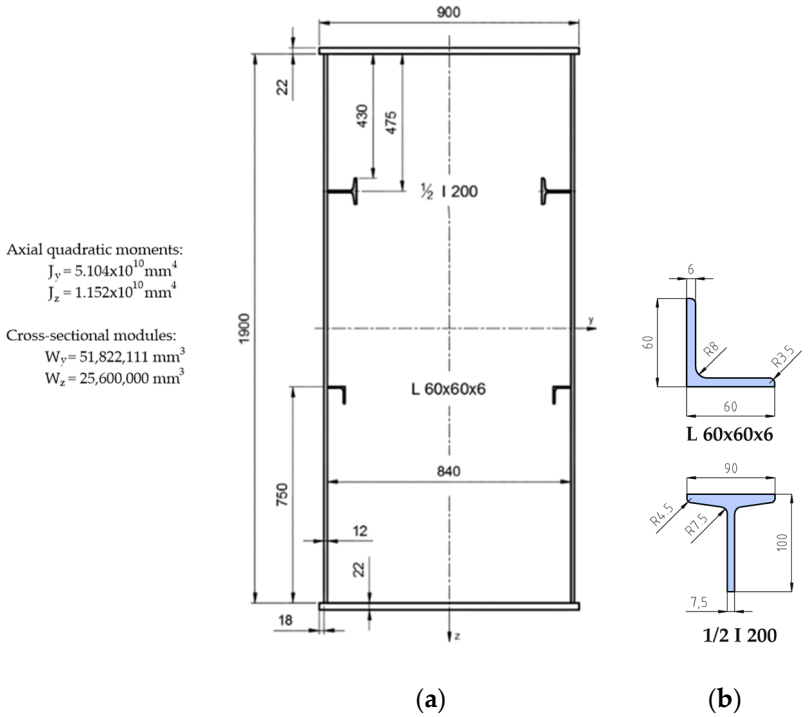


Figure 8. Beam cross-section: (**a**) cross section of the examined girder, (**b**) dimension parameters of the used profiles.

3.1. Definition of Boundary Conditions

The aim is to design an optimal solution of a reinforced welded girder of a bridge crane with the girder meeting all of the strength, legislative, technological, and functional requirements given by the valid legislation. Only those parameters that are relevant to its design are included in the optimisation. The optimisation will address the design of the optimal geometric configuration of the girder of the overhead crane without including local type details (e.g., local stress concentrators). Beam buckling (global case) and local buckling of flanges and/or stands will be taken into account.

The new beam must meet the following parameters:

Material: S355JR + N (f_y = 355 MPa)
Beam length: L = 31.8 m
Load capacity: 50,000 kg
Maximum vertical deflection: δ_{max} = L/700 = 45 mm
The cross-section stand cannot be thinner than 5 mm.
Beam height to be chosen in the range of 1/15 to 1/20 of span.
Beam height/beam width ratio at 3.5.
Cross bracings are spaced 120% of the height of the main beam.

A simple linear regression is used in the developed program in the MS Excel environment (Figure 9). Using this, the minimum and maximum heights of the box girder cross-section are created based on the input data bounding the resulting girder height between 1/15 and 1/20 of the crane span.

boundary conditions	min	max			
The cross-section stand cannot be thinner than 5mm	5	50			
Beam height to be selected in the range of 1/15 to 1/20 of span	20	15	1590	2120	min/max height
Maintain beam height/beam width ratio at 3.5		3.5	454.2857143	605.7142857	min/max width
Cross bracing spaced 100 to 125% of main beam height.	1	1.25	1.2	enter the selected value by hand	

Figure 9. Entry conditions to the program in the MS Excel environment. —fixed variable boundaries, —manually entered value of variables.

This range of heights is then divided into 100 equal parts and rounded to whole numbers. The set of 100 beam widths is then calculated based on the selected input parameter, in this case 3.5. In our case, the cross-section with the dimensions 1590 × 455 meets the above-mentioned conditions (31,800/20 = 1590, 1590/3.5 = 454.3, rounded to 455). Since 31,800/15 = 2120 and 2120 − 1590 = 530, we will increase the cross-sectional dimensions with a step of 5.3 mm and round them to the whole numbers. Then, the next cross-sections will have the dimensions 1595 × 455, 1600 × 460, 1605 × 460, etc. Each of the proposed cross-sections is recalculated with beam web thickness values of 6, 8, 10, 12, and 15 mm.

Several different thicknesses of uprights and flanges are assigned to each section. In total, this produces 1700 different box sections. All further calculations and optimisations will be performed on this set of box cross-sections (Figure 10).

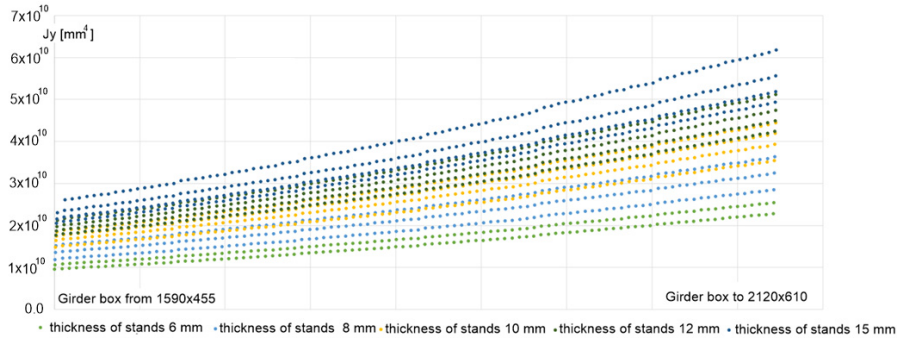


Figure 10. Quantity of all possible cabinet cross-sections.

From the 1700 cabinet cross-sections created, it is necessary to find the optimum cabinet dimensions and thicknesses of racks and strips. Finding the optimum based only on the rms moment of the cross-section Jy is not efficient because often the optimum values cause an increase in beam weight. Therefore, in the developed program, the optimum is searched based on both requirements, namely, the optimum weight and a satisfactory second moment of cross-sectional area. Thanks to this filter, real weight savings are possible while meeting standard conditions.

Once all of the input data have been entered, the created program automatically performs all the calculations and iterations. The input data in this case (apart from those already entered for selection of the cross-section) are the dynamic coefficients selected according to the relevant technical standard for the chosen specific load condition and load combination defined by the technical standard, as this is common during manual static calculations, which is a necessary part of the technical documentation elaborated for each crane. Out of the 1700 cross-sections created, the program automatically reduces this set and filters out 71 cross-sections that are compliant in terms of load carrying capacity (Figure 11).

These cross-sections are then converted according to the length and number of members to the total weight of the beam. From this set of 71 weights, the first 10 lightest beam designs are selected and, from the lightest to the heaviest, they are screened by calculations according to the standard. Once the calculations have been carried out, it is possible to check the calculations carried out on the "Result" page and obtain the recommended dimensions of the casing of the proposed beam.

All of this is possible thanks to efficient data processing. Despite the variability of factors, the program can provide fast and efficient processing of the entered data. Thanks to optimisation and efficient data processing, the program should meet this requirement in the vast majority of cases. Finally, the first standard-compliant beam is verified using the finite element method.



Figure 11. Quantity of suitable cabinet cross-sections.

The data are automatically shared with Dassault Systèmes SolidWorks v. 2023.

Once the program is started, the beam dimensions are automatically updated.

It is then necessary to enter the principal load from the load v and run the simulation (Figure 12).

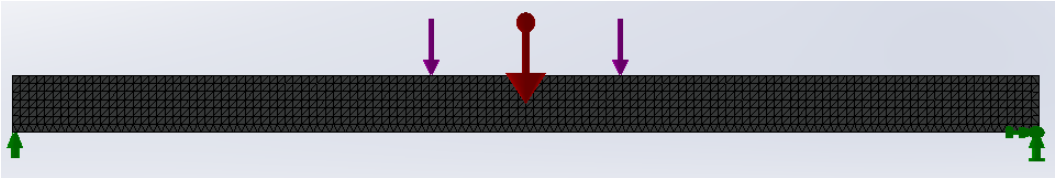


Figure 12. Proposed beam before FEA analysis. Red arrow—gravity, purple arrow—wheel pressures from the crane trolley, green arrows—fixation of the crane to the runway.

Dassault Systèmes SolidWorks performs the analysis using the Finite Element Method.

The results can then be compared with the program's calculations. Of course, the values obtained will have some deviation, since numerical analysis and the finite element method use different calculation principles.

3.2. Evaluation and Comparison with Existing Cranes

After optimisation, we obtained a beam cross-section for which the one-meter length weighed 656 kg.

The weight of the beam without cross bracings was 20.87 tonnes and with cross bracings it was 25.53 tonnes, with internal dimensions of the enclosure of 840 mm × 1900 mm, wall thickness of 12 mm, and flange thickness of 22 mm.

After performing the analysis using the finite element method in SolidWorks, we calculated the deflection of the existing beam w = 13.3 mm (Figure 13). In this case, the standard allowed a maximum deflection of 45 mm. According to this deflection value, we could conclude that the existing beam was oversized.

Given the same input data and boundary conditions, the generated optimisation program designed an enclosure with the same wall thickness of 12 mm and flange thickness of 22 mm, but with an internal enclosure dimension of 605 mm × 2105 mm. This designed beam had a mass per meter of length of 597 kg, so the mass of the designed beam without cross bracings was 19 tonnes and with cross bracings it was was 24 tonnes.

After performing the analysis using the finite element method in SolidWorks, we calculated the deflection of the designed optimised beam w_{opt} = 18.2 mm (Figure 14). In this case, the standard allowed a maximum deflection of 45 mm, the same as in the previous case. Hence, the designed beam also complied with the standard, but it was more slender.

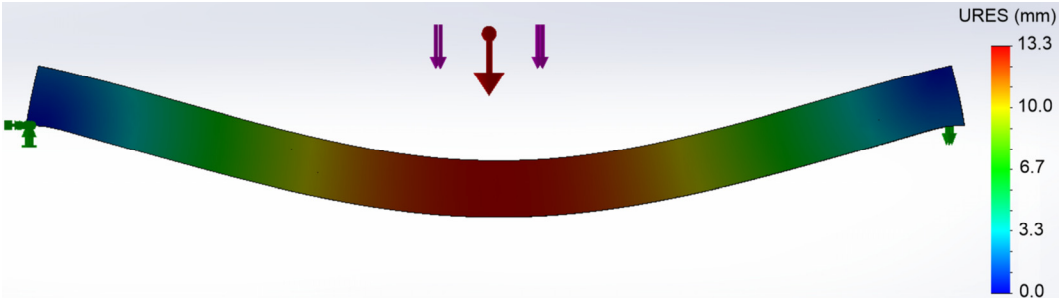


Figure 13. Deflection of the existing beam. Red arrow—gravity, purple arrow—wheel pressures from the crane trolley, green arrows—fixation of the crane to the runway.

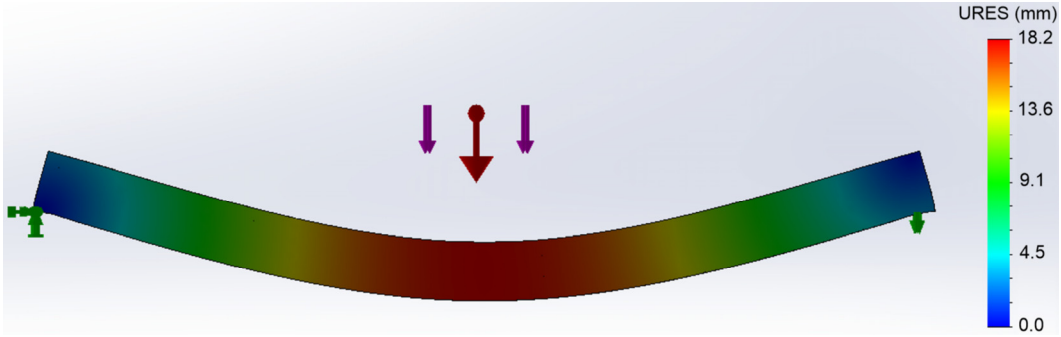


Figure 14. Deflection of the designed beam. Red arrow—gravity, purple arrow—wheel pressures from the crane trolley, green arrows—fixation of the crane to the runway.

By comparing the two beams overall, we could say that the optimised beam was 1.5 tonnes lighter than the existing beam, while meeting all of the conditions set out in the standard. This was a 5.8% weight savings. For a twin girder crane, this was a total material savings of 3 tonnes, which was already a significant value.

4. Conclusions

The article addresses the possibility of using modern mathematical optimisation methods and the finite element method in the design of the optimal cross-section of overhead cranes. The first step is the mathematical formulation of the optimisation problem, to which the methodology proposed in the paper is subsequently applied. CAEA nonlinear analysis considering the influence of imperfections represents the highest computational level of stability analyses today. The ultimate load of the beam is obtained by nonlinear stability analysis on already imperfected metamodels according to EC3 (for analyses using FEM).

The optimisation methods are applied as part of a comprehensive methodology that uses mathematical approximation methods to describe the objective function and optimisation constraints and parametric finite-element models to perform the structural analysis. The entire methodology is computerised to automatically obtain solutions without the intervention of a computational engineer.

In solving each problem, there are certain boundary conditions that need to be competently taken into account. It should therefore be stressed that the application of this methodology requires the creative thinking of an engineer who is familiar with the principles of all of the optimisation methods used.

After applying the proposed methodology on an existing crane beam, it was found that the beam was oversized and by the proposed beam cross-section optimisation procedure, we are able to save at least 5.8% of the beam's weight.

The developed methodology is able to design the girder in such a way that the material usage is optimal and, at the same time, the designed girder meets the legislative requirements.

Author Contributions: Conceptualization, M.M. and J.K.; methodology, M.M. and R.G.; software, M.M.; validation, J.K., R.G. and M.K.; formal analysis, M.S.; writing—original draft preparation, M.K.; writing—review and editing, S.M. and M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This article was elaborated within the projects KEGA 029TUKE-4/2021, VEGA 1/0224/23, and KEGA 044TUKE-4/2024.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Hrabovský, L.; Čepica, D.; Frydrýšek, K. Detection of mechanical stress in the steel structure of a bridge crane. *Theor. Appl. Mech. Lett.* **2021**, *11*, 100299, ISSN 2095-0349. [CrossRef]
2. Pástor, M.; Lengvarský, P.; Hagara, M.; Kuľka, J. Experimental investigation of the fatigue life of a bridge crane girder using SN method. *Appl. Sci.* **2022**, *12*, 10319. [CrossRef]
3. Kulka, J.; Mantič, M.; Fedorko, G.; Molnar, V. Analysis of crane track degradation due to operation. *Eng. Fail. Anal.* **2016**, *59*, 384–395. [CrossRef]
4. Pavlovic, G.V.; Savković, M.; Gašić, M.; Bulatović, R.; Zdravković, N. Optimization of the box section of the main girder of the double beam bridge crane according to the criteria of lateral stability and local stability of plates. *Mach. Des.* **2012**, *4*, 197–204.
5. Tian, G.; Zhang, S.; Sun, S. The Optimization Design of Overhead Traveling Crane's Box Girder. *Adv. Mater. Res.* **2012**, *538*, 2850–2855. [CrossRef]
6. Sun, C.; Tan, Y.; Zeng, J.; Pan, J.S.; Tao, Y. The Structure Optimization of Main Beam for Bridge Crane Based on An Improved PSO. *J. Comput.* **2011**, *6*, 1585–1590. [CrossRef]
7. Zuberi, R.H.; Long, K.; Zuo, Z. Design Optimization of EOT Crane Bridge. In Proceedings of the International Conference on Engineering Optimization, Rio de Janeiro, Brazil, 1–5 June 2008.
8. Yeşilbel, S.; Çimen, M.; Kalyoncu, M. Optimum design of overhead crane construction using the bees algorithm. *Int. J. Mater. Eng. Technol.* **2021**, *4*, 157–167.
9. Bećirović, A.; Vukojević, D.; Hadžikadunić, F. Optimization of double box girder overhead crane in function of cross section parameter of main girders. In Proceedings of the 15th International Research/Expert Conference Trends in the Development of Machinery and Associated Technology, Prague, Czech Republic, 12–18 September 2011.
10. Vajna, S. The Autogenetic Design Theory. An evolutionary view of the design process. *J. Eng. Des.* **2005**, *16*, 423–440. [CrossRef]
11. Krish, S. A practical generative design method. *Comput.-Aided Des.* **2011**, *43*, 88–100. [CrossRef]
12. Kazi, R.H. DreamSketch: Early Stage 3D Design Explorations with Sketching and Generative Design. In Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology—UIST'17, Quebec City, QC, Canada, 22–25 October 2017; ACM Press: New York, NY, USA, 2017; pp. 401–414.
13. Ribeiro, T.P.; Bernardo, L.F.A.; Andrade, J.M.A. Topology optimization in structural steel design for additive manufacturing. *Appl. Sci.* **2021**, *11*, 2112. [CrossRef]
14. Delyová, I.; Frankovský, P.; Bocko, J.; Trebuňa, P.; Živčák, J.; Schürger, B.; Janigová, S. Sizing and topology optimization of trusses using genetic algorithm. *Materials* **2021**, *14*, 715. [CrossRef] [PubMed]
15. Querin, O. *Topology Design Methods for Structural Optimization*; Academic Press: London, UK, 2017.
16. Tejani, G.; Savsani, V.; Patel, V.; Savsani, P. Size, shape, and topology optimization of planar and space trusses using mutation-based improved metaheuristics. *J. Comput. Des. Eng.* **2017**, *5*, 198–214. [CrossRef]
17. Sowa, L.; Piekarska, W.; Skrzypczak, T.; Kwiatoń, P. The effect of restraints type on the generated stresses in gantry crane beam. *MATEC Web Conf.* **2018**, *157*, 02046. [CrossRef]
18. Lemonis, M.E. Column Buckling Calculator [Online]. Available online: https://calcresource.com/statics-buckling-load.html (accessed on 28 June 2024).
19. Wenna, Z.; Feng, L.; Feng, X. Lateral Torsional Buckling of Steel Beams under Transverse Impact Loading. Available online: https://www.hindawi.com/journals/sv/2018/4189750/ (accessed on 28 June 2024).
20. Handrik, M.; Vasko, M.; Kopas, P. Parallel and distributed implementation of optimization algorithms in FE analyses. *Zesz. Nauk. Transp./Politech. Śląska* **2012**, *76*, 67–74.
21. Saga, M.; Vaško, M.; Ságová, Z.; Handrik, M. Effective algorithm for structural optimization subjected to fatigue damage and random excitation. *Zesz. Nauk. Transp./Politech. Śląska* **2018**, *99*, 149–161. [CrossRef]
22. Sapietová, A.; Saga, M.; Kuric, I.; Václav, Š. Application of optimization algorithms for robot systems designing. *Int. J. Adv. Robot. Syst.* **2018**, *15*, 1729881417754152. [CrossRef]

23. *EN 1993-1-5*; Eurocode 3: Design of Steel Structures. Part 1-5: Plated Structural Elements; Slovak Institute of Technical Standardization: Bratislava, Slovakia, 2008.
24. Kulka, J.; Mantič, M.; Puškár, M. *Bridge Type Cranes*, 1st ed.; TU: Košice, Slovakia, 2017; ISBN 978-80-553-2908-6.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.