engineering proceedings

Proceeding Paper

Sensitivity Analysis of Internally Reinforced Beam-Subjected Torsion Loading †

Hugo Miguel Silva [1,2,*] and Jerzy Wojewoda [2]

[1] proMetheus, Instituto Politécnico de Viana do Castelo, Rua Escola Industrial e Comercial Nun'Álvares, 34, 4900-347 Viana do Castelo, Portugal
[2] Division of Dynamics, Lodz University of Technology, Stefanowskiego 1/15, 90-924 Lodz, Poland; jerzy.wojewoda@p.lodz.pl
* Correspondence: hugosilvasci@gmail.com
† Presented at the 4th International Electronic Conference on Applied Sciences, 27 October–10 November 2023; Available online: https://asec2023.sciforum.net/.

Abstract: The objective of this study was to examine various techniques aimed at improving the mechanical performance and maneuverability of industrial machinery that incorporates movable components under the influence of three-point torsional loads. Multiple measures were implemented to achieve the goal of creating effective technical solutions. A sensitivity analysis was performed on one of the beams to assess the impact of each parameter within the mass and displacement parameter space. Previous studies have shown that the process of parameterizing the ANSYS input file is advantageous in assessing the system's suitability to the design factors being considered. The parameters analyzed were the distance of the inner side plates to the center of mass (VA1), the distance of the inner upper and bottom plates to the center of mass (VA2) and the thickness of all the plates (VA3). The methodology followed was based on the parametrization of an ANSYS input file that was run every time the value of a parameter was changed. This work has potential applications in design optimization procedures, as well as in practical engineering applications, such as laser cutting and engraving machines, and industrial printers, including 3D printers. In future investigations, further research could be undertaken to employ the methodology in diverse circumstances and/or models.

Keywords: finite element method; static analysis; sensitivity analysis

check for updates

Citation: Silva, H.M.; Wojewoda, J. Sensitivity Analysis of Internally Reinforced Beam-Subjected Torsion Loading *Eng. Proc.* **2023**, *56*, 284. https://doi.org/10.3390/ASEC2023-15815

Academic Editor: Ana Paula Betencourt Martins Amaro

Published: 2 November 2023

Copyright: © 2023 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

Motor-driven, high-speed moving parts find application in several industrial equipment contexts. These motors provide an acceleration that is twelve times more than the acceleration due to gravity. To accommodate accelerations, it is necessary to enhance the strength and robustness of structures. The efficacy of a given apparatus is not exclusively contingent upon its power; rigidity also constitutes a significant factor. It is conceivable that the existence of accelerations may induce a deflection in the apparatus, thus resulting in a reduction in output [1]. Previous studies have shown that geometric optimization has a more pronounced effect on improving stiffness when compared to material selection [1,2]. In fact, design improvements presented in [1,2] were proven to result in substantial improvements compared to the selection of a steel of a higher grade, for structural applications. Design improvements were suggested in [3], where beams of novel geometries were presented. Those beams were subjected to design optimization in [4]. The significant improvements obtained confirm the higher effectiveness of design improvements and design optimization in relation to material selection. Hollow solid sections are deemed more suitable for engineering applications compared to bulk beams with an equivalent outer section size and shape due to their interior reinforcing capacity and superior stiffness-to-mass ratio [3,4]. Plates and shells are required to exhibit a specific level of rigidity. To enhance structural rigidity, several techniques such as the use of ribs, lattice structures, and curved walls are employed. To achieve this goal, it is imperative to incorporate the initial two components. The incorporation of ribs and webbing enhances the structural robustness of components with thin walls [5]. The mechanical parameters related to reinforcing structures were investigated by Vieira et al. [6]. The incorporation of the author's design has the potential of improving the mechanical behavior of engineering parts, in practical engineering applications. The potential exists to improve the mechanical performance of mass units by implementing effective reinforcement designs on the beams examined in this investigation. Based on the findings outlined in a referenced scholarly publication [7], the incorporation of diagonal ribs into slender beams enhances their resistance to torsional forces when subjected to static loading. According to the findings presented in reference [8], it is possible to enhance the bending and torsion strength of thin-walled steel columns without introducing additional weight. During the transportation process, Liu and Gannon engaged in the act of welding plates onto a steel W-shaped beam. The prediction of reinforcement patterns, welding preload quantities, and flaws in unreinforced beams was conducted using the finite element approach [9]. The authors of the cited reference [10] offer recommendations regarding the appropriate specifications, dimensions, and positioning of stiffeners. Heins and Potocko conducted an estimation of the torsional response of box-stiffened I-sections via the utilization of two analytical methodologies. According to the reference cited as [11], the strategies encompass compatibility links and fundamental torsion theory. The objective of this study is to improve the mechanical properties of slender beams by employing a design approach that incorporates rectangular hollow-box beams featuring ribs, webs, and sandwich panels.

2. Numerical Procedure

A single finite element method (FEM) model was used to complete the sensitivity analysis. Specific focus sites placed at both the perimeter (two sites) and the center (one site) were selected to assemble the data reported in this academic research (see Figure 1, right panel).

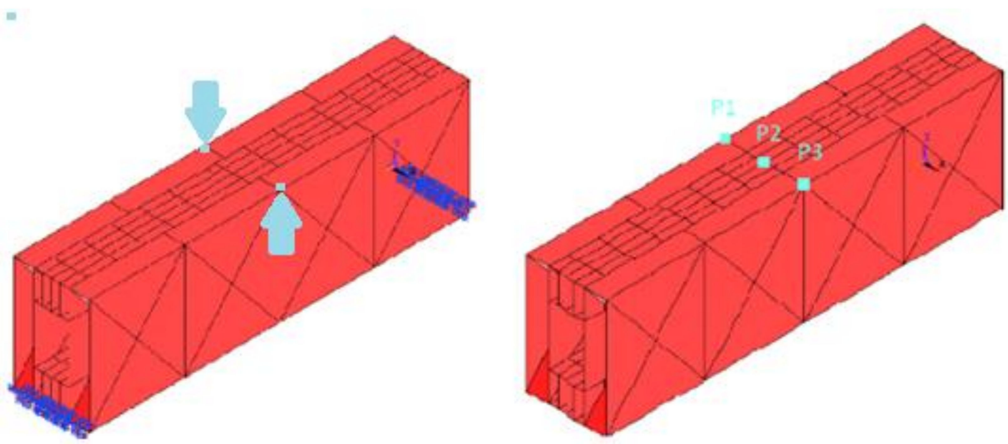
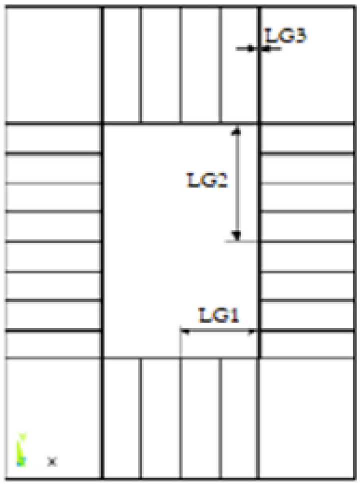


Figure 1. Applied load and DOF constraints (**left**); points used to calculate displacements in sensitivity analysis and on the calculation of the objective function in the optimization procedure (**right**) [12].

Points P1, P2 and P3 were selected, because they are at the midspan, which is where the maximum deflections are expected to occur. The choice of these key points is based on the condition that their coordinates remain constant during the optimization process, irrespective of the value of the variable. Those sections have strong rib support. As such, due to the contact between the inner ribs and the upper plate, where the points P1, P2 and P3 are located, the membrane effect, typical of shell structures/elements, is not expected to be substantial at the designated thicknesses. The findings align with the observations made during the linear static analysis. The analysis is excluded from this study due to its scope limitations. The study conducted on the VA3 variable involved the evaluation of thickness values ranging from 2 to 4 mm. In all other cases, the thickness consistently measures 3 mm. The mechanical behavior of lateral reinforcements holds greater significance when compared to that of sandwich panels. As a result of this specific event, there is a reduction in the vertical dimensions of the sandwich panels. The chosen locations were situated at spots where the coordinates remained consistent irrespective of alterations to the geometric variables. The implementation of this method helps to reduce the immediate impact of changes made to the design parameters on the resulting outcomes. If the collection of local data involved querying sites with varying coordinates due to changes in geometric variables, the resulting findings would undoubtedly be false. The present study employs a Young's modulus (E) of 210 GPa, density of 7890 kg/m^3, and Poisson's ratio of 0.29 as material properties. The applied load is a binary loading, originating torsion, and has an intensity of 1500 N. The investigation utilized a quadrilateral free mesh of an average element size of 2.5 mm and the SHELL63 element type. Three design factors were chosen for the sensitivity analysis and optimization of each model. Figure 2 illustrates the geometric variables VA1, VA2, and VA3.



LG1 is the distance from the center of the beam to the inner wall of the beam in the direction of the section width.

LG2 is the distance from the center of the section of the beam to the inner wall of the beam in the direction of the section height.

LG3 is the thickness of all the walls of the beam.

Figure 2. Geometric variables of the FEM model used in design optimization [12].

Typically, the proportions of the outside part remain constant. From an industrial perspective, there is a belief that the complete collection of timbers should be produced using sheets of a consistent thickness. The objective is to design reinforcements that can be easily fabricated within an industrial context.

3. Results and Discussion

This section presents the sensitivity analysis results for the variables VA1, VA2 andVA3. The results for each variable, which shows their relationship with the linear deflection, in the y (vertical) axis, are shown in Figures 3–5. A fit to each chart was conducted to obtain analytical models for the prediction of the stiffness behavior of the studied variables. The data presented in Figures 3–5 were collected using ANSYS MECHANICAL APDL. The ANSYS input file was performed in an iterative manner, where the value of a single variable was modified in each iteration. The values of the remaining geometrical variables are kept constant. The mass of the beam will fluctuate even if a single geometric variable is modified. A linear regression analysis was performed to assess the level of linearity between the variables and the mass, as well as between the variables and the deflections. The results illustrated in Figures 3–5 were obtained through the summation of absolute deflection values at these sites for all possible combinations of variable values.

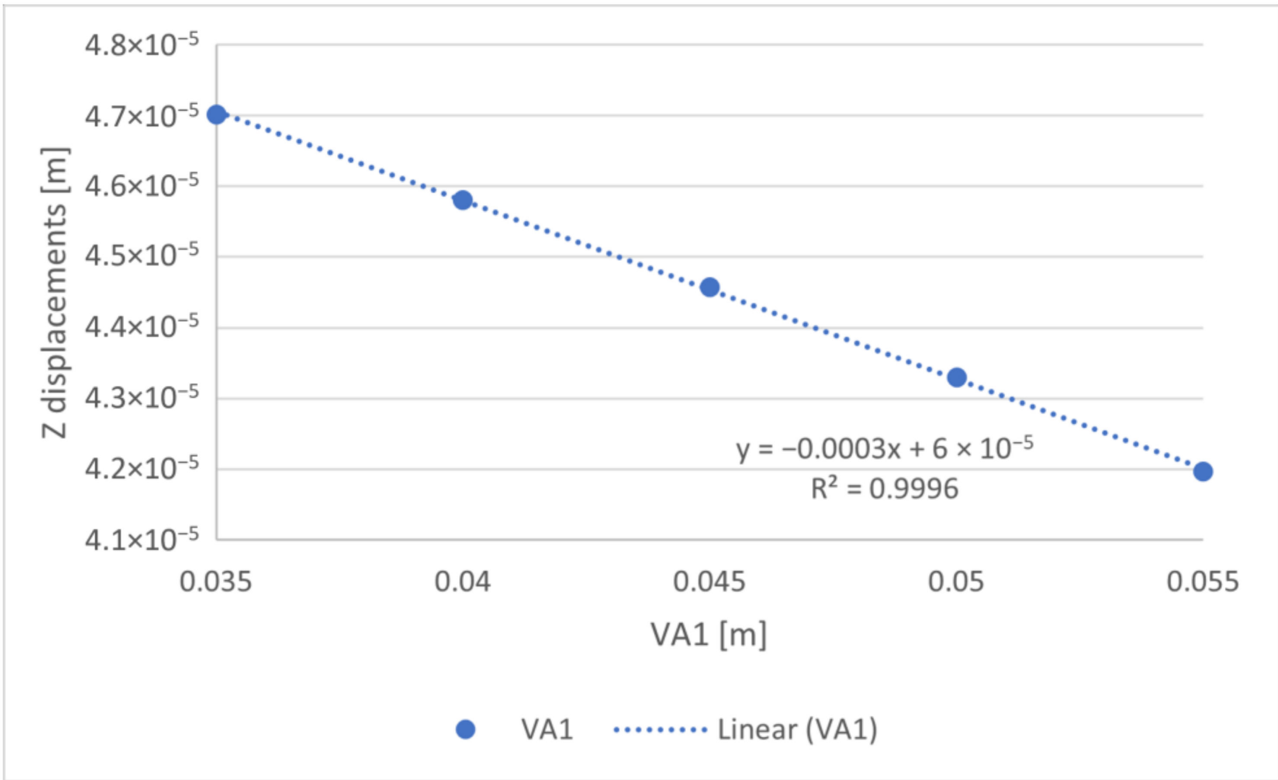


Figure 3. Variation in the z deflections with the VA1 variable [12].

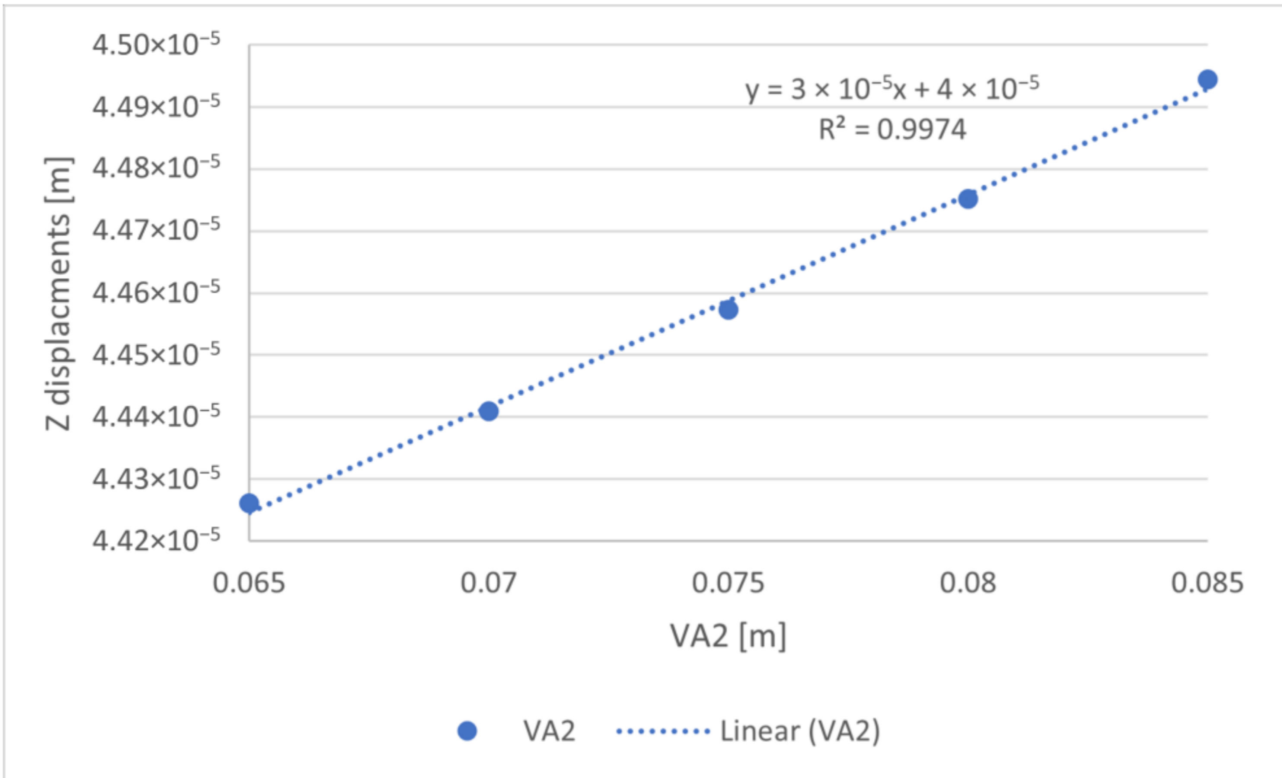


Figure 4. Variation in the z deflections with the VA2 variable [12].

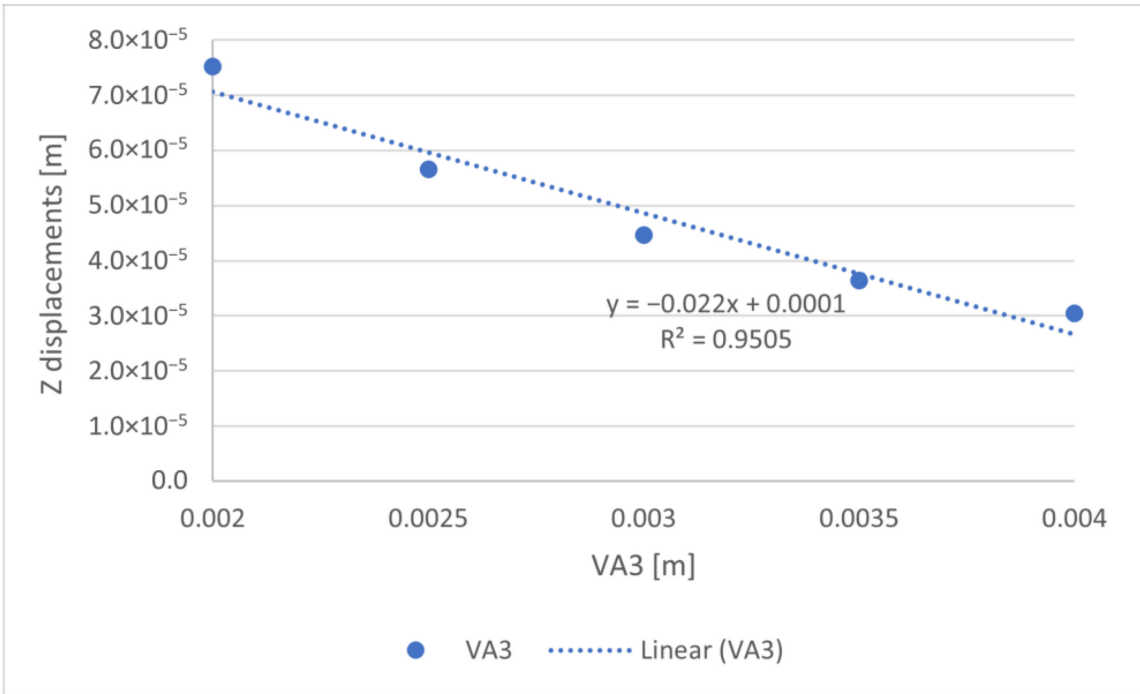


Figure 5. Variation in the *z* deflections with the VA3 variable [12].

In comparison to the deflections reported at the other two key points, which are approximately 1×10^{-5} m in magnitude, the deflections observed at point P2 ($3–4 \times 10^{-11}$ m) are of trivial magnitude. Significant decreases in deflection are observed at points P1 and P3, whereas no noticeable change in variable VA1 is evident at point P2. There exists a direct relationship between the magnitude of the VA2 variable and the deflection. The data collected from both locations P1 and P3 demonstrate a clear correlation between the increase in variable VA3 and the ongoing decrease in deflection. When variable j undergoes a transition from 1 to 2, the deflection demonstrates a marginal increase in relation to point P1, accompanied by small-scale oscillations. A continuous and statistically significant decrease in the amount of the deflection is observed within the specified range of j values, which spans from 2 to 5. Table 1 presents relevant details about the analytical models, obtained from the results of Figures 3–5.

Table 1. Analytic models obtained.

		Coefficient		
Variable	**Type**	**m**	**b**	**R^2**
VA1	Linear, dz = m × VAx + b where x = 1,2,3.	-3×10^{-4}	6×10^{-5}	0.9996
VA2		3×10^{-5}	4×10^{-5}	0.9974
VA3		-2.2×10^{-2}	1×10^{-4}	0.9505

One can see that variables VA1 and VA2 have a very good correlation (r squared value R^2), with values very close to 1. However, variable VA3 has a correlation slightly higher than 0.95. Each variable was only studied in isolation, so the influence of each variable on others was not considered in this study. However, if design optimization studies are performed in the future, the relationships between the variables must be considered. This study has the implications of evaluating if the selected design variables are suitable for future optimization purposes, as their sensitivity was studied, under torsion loadings.

4. Conclusions

The following are the key findings of this study:

- It is evident that the geometric variables VA1, VA2, and VA3 have been appropriately chosen for the optimization technique.
- The findings suggest that the deflections of the finite element method (FEM) model exhibit a high degree of sensitivity to the elements indicated earlier.
- The models demonstrate geometric restrictions, particularly with respect to their interior arrangement. To avoid the interference of structural elements from the sides or top/bottom, it is necessary for the variables VA1 and VA2 to possess a significant magnitude, hence enabling the continuation of optimization analyses without hindrance.
- The approach followed mitigates the inability to identify the most ideal solution.
- It is imperative that the size of the parameter remains within a modest range to facilitate the development of lightweight components that align with the specific aims of the study. Simultaneously, it should be sufficiently high to avoid substantial nonlinear effects in any future practical applications.
- Prior studies have established that the utilization of parameterization in the ANSYS input file is a viable approach for assessing the system's responsiveness to the design factors under investigation. This has implications on practical applications, considering that the behavior of the manufactured structure, if properly optimized, is much better than if the optimization setup is not the best, i.e., does not lead to the best results, according to the objective. Therefore, the results obtained from the sensitivity analysis have the potential to inform future decision-making processes in the determination of variable weights for optimization techniques and procedures.

Author Contributions: Conceptualization, H.M.S.; methodology, H.M.S.; software, H.M.S.; validation, H.M.S.; formal analysis, H.M.S.; investigation, H.M.S.; resources, H.M.S.; data curation, H.M.S.; writing—original draft preparation, H.M.S.; writing—review and editing, J.W.; visualization, H.M.S.; supervision, J.W.; project administration, J.W.; funding acquisition, J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by a Dean's grant for Ph.D. studies at the Lodz University of Technology, Poland, whose recipient was Hugo Miguel Silva.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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

References

1. Silva, H.M. Determination of Material/Geometry of the Section Most Adequate for a Static Loaded Beam Subjected to a Combination of Bending and Torsion. Master's Thesis, University of Minho, Guimaraes, Portugal, 2011.
2. Silva, H.M.; Meireles, J.F. Determination of material/geometry of the section most adequate for a static loaded beam subjected to a combination of bending and torsion. *Mater. Sci. Forum* **2013**, *730–732*, 507–512. [CrossRef]
3. Silva, H.M.; Meireles, J.F. Feasibility of internally reinforced thin-walled beams for industrial applications. *Appl. Mech. Mater.* **2015**, *775*, 119–124. [CrossRef]
4. Silva, H.M.; Meireles, J.F. Structural Optimization of internally reinforced beams subjected to uncoupled and coupled bending and torsion loads for industrial applications-Accepted for publication n in the journal Mechanics and Mechanical Engineering. *Mech. Mech. Eng.* **2017**, *21*, 731–753.
5. Orlov, P. *Fundamentals of Machine Design*, 1st ed.; MIR Publishers: Moscow, Russia, 1976.
6. Vieira, D.G.; Meireles, J.F.; Nunes, J.P. Improving the Dynamical Behavior of a Laser Cutting Equipment by Using a Carbon. *Mater. Sci. Forum* **2013**, *730*, 349–354.
7. Weckman, R. Diagonal ribs increase torsional rigidity. 1988. Available online: https://www.scribd.com/doc/98726339/DCI388 (accessed on 1 November 2023).

8. Liu, Y. Design enhancement of thin-walled steel beams with improved stiffness and reduced weight. *Int. J. Des. Eng.* **2008**, *1*, 149–165. [CrossRef]
9. Liu, Y.; Gannon, L. Finite element study of steel beams reinforced while under load. *Eng. Struct.* **2009**, *31*, 2630–2642. [CrossRef]
10. Szewczak, R.; Smith, E.; DeWolf, J. Beams with Torsional Stiffeners. *J. Struct. Eng.* **1983**, *109*, 1635–1647. [CrossRef]
11. Heins, C.P., Jr.; Potocko, R.A. Torsional Stiffening of I-Girder Webs. *J. Struct. Div.* **1979**, *105*, 1689–1698. [CrossRef]
12. Silva, H.M. Optimization of the Mechanical Behavior of Hollow-Box Beams. Ph.D. Thesis, Lodz University of Technology, Łódź, Poland, 2018.

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.