DEMI 2021

15th International Conference on Accomplishments in Mechanical and Industrial Engineering

Banja Luka
28–29 May 2021.

www.demi.mf.unibl.org

Effects of shape optimization on the 10 bar truss example

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Abstract *This research focuses on determining the effects of structural optimization on 10 bar trusses. Structural optimization is one in Rhino 6, using GA optimization. Shape optimization was done to find savings in used material in relation to total element lengths. The new optimized structure which meets all constraint criteria has different element lengths to the initial design. Optimal values are compared to initial values showing that the total length of elements can be decreased by roughly 28%. By individually observing elements it is possible to see that some elements are now longer and some shorter than in the initial model, but the overall length is decreased. This shows significant savings which are possible through shape optimization, as well as the significance of the entire process.*

Keywords *Truss optimization, shape optimization, mass minimization, element lengths*

1. INTRODUCTION

Optimization is a tool which is being used more and more in planning and designing in order to achieve greater gains and decrease negative effects. This process requires certain time and effort, but compared to the positive effects gained from it, it is cost-effective. The goal is to always balance optimization types (sizing, topology and shape) in order to have the input effort (knowledge, time and resources) at a minimum and to achieve maximal effects (financial, structural, etc.). This is why it is important to see the effects of specific parts of structural optimization, as well as their combinations and determine what the best course of action is for a given problem.

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In recent years a lot of research has been done in the field of truss structural optimization. The implementation of realistic variables for sizing optimization showed that using continuous variables like in [1, 2] cannot be created and therefore discrete variables have started becoming the norm. Researchers in [3, 4] showed the differences in using discrete versus continuous variables. Discrete sets of cross-section parameters can be used to represent the possible stock cross-sections which are available for a certain material. Another important factor to consider is the use of constraints. Realistic constraints allow for the design of structures which can be directly implemented in construction. These constraints are still not a standard in research, however they have been used in the past [5-8]. Paper [9] presented the difference in using buckling constraints compared to models optimized without this constraint. Other effects are being researched in this field such as the overall outer surface area [10] and environmental impact.
This research covers the use of sizing and shape optimization. All cross-sections in the examples

will have the same area, this is done to minimize the number of different stock used and to show possibilities in savings on material using shape optimization. The motivation is to show the significance of using shape optimization and to determine its efficiency.

2. STRUCTURAL OPTIMIZATION PROBLEM

The problem of structural truss optimization implies optimization of sizing, topological, and shape aspects of an initial model configuration. In practice this is not always possible, and furthermore it is usually more practical to use a single bar cross-section for a structure than to use several due to the possibility of saving in bulk as well as increasing simplicity of construction. The goal of this research is to show the possible improvements of using shape optimization when using a single profile cross-section for constructing a truss.

The objective functions of all structural optimization aim to find the variable combination which would minimize the overall mass, cost or some other factor. In the case of a minimum weight design problem using shape optimization the goal function can be defined as:

$$\begin{cases} minW(l) = \sum_{i=1}^{i=n} \rho A l_i \\ \text{subjected to} \begin{cases} \sigma_{min} \le \sigma_i \le \sigma_{max} & \text{for } i = 1, \dots, n \\ u_{min} \le u_j \le u_{max} & \text{for } j = 1, \dots, k \\ \left| F_{Ai}^{comp} \right| \le F_{Ki} & \text{for } i = 1, \dots, n \end{cases} \end{cases} \quad (1)$$

where n is the number of truss elements, k is the number of nodes, l_i is the length of the i^{th} element, A is the cross section area, σ_i is the stress of the i^{th} element, u_j is displacement of the j^{th} node . F_{Aicomp} is the axial compression force, F_{Ki} is Euler's critical load (2).

$$F_{Ki} = \frac{\pi^2 \cdot E \cdot I}{l_i^2} \quad (2)$$

E is the modulus of elasticity, and I is the minimum area moment of inertia of the element cross section. Since the buckling constraint changes with each iteration as a result of the change of element lengths with the change in node location, this constraint is considered a dynamic constraints, and its addition drastically increase the complexity of the optimization problem.

3. THE DESIGN PROBLEM

The 10 bar truss is one of the most commonly used examples in truss structural optimization, and presents a good representation for comparing element length changes in shape optimization as it has two points, (1) and (3), which have variable coordinates. The movement of these two points causes a change in the length of 7 bars. The full round cross-sections used are made out of Aluminium 6063-T5 (Young modulus 68947MPa, and density of 2.7g/cm^3). Point loads are F=444.82kN in nodes (2) and (4) in the –y direction. The displacement is limited to ±0.0508m of all nodes in all directions and axial stress is limited to ±172.3689MPa for all bars. Fig. 1 shows the initial configuration of the 10 bar truss problem.

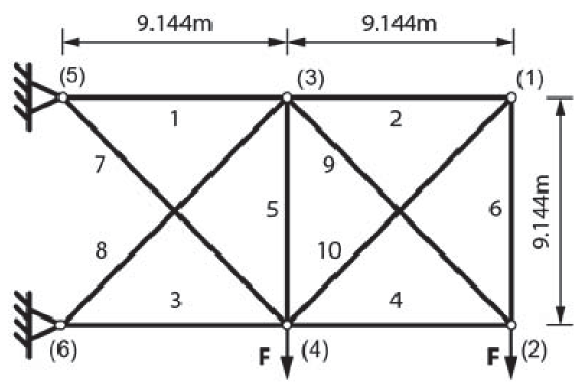

Fig. 1. 10 bar truss problem [4].

Aside from displacement and stress constraints Euler buckling constraints are also used for all elements subjected to compression forces and a minimal element length constraint set at 0.5m for all bars, in order to achieve practically applicable results.

The 10 bar truss used for this research uses the same cross-sections for all elements with a diameter of 240mm. This is determined as the analytical solution to this problem sized according to the most stressed element subjected to buckling and using standard profile diameter values.

The optimization method used is genetic algorithm (GA). An original software was developed for solving this type of problem using Rhino 6 Grasshopper and the Karamba plugin.

Shape optimization will be used to compare savings in element lengths and total mass.

4. RESULTS AND DISCUSSION

Using shape optimization the initial configuration is modified to the shape shown in fig. 2. Results shown are the best results out of 10 consecutive optimizations all with the same starting configuration as the initial model shown in fig.1.

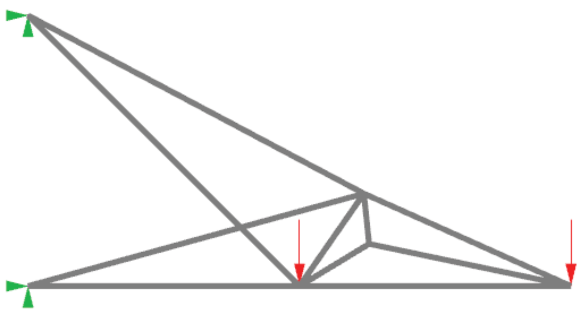

Fig. 2. Optimal shape for the 10 bar truss problem.

The results show that only one bar element has increased in length while all others have been decreased by the optimization process. A comparison of bar element lengths is shown in figure 3.

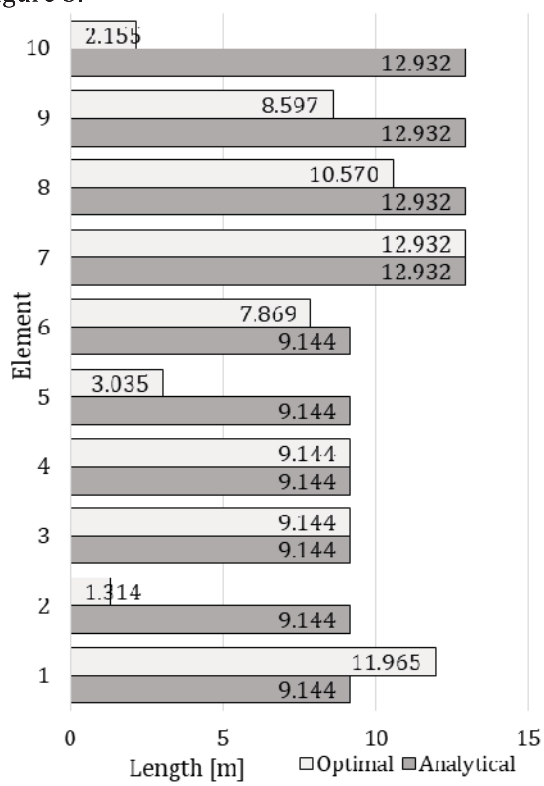

Fig. 3. Bar element length comparison of analytical and optimal models.

Comparing the savings in length by bar element is shown in figure 4. Here the significant difference in savings is much more obvious.

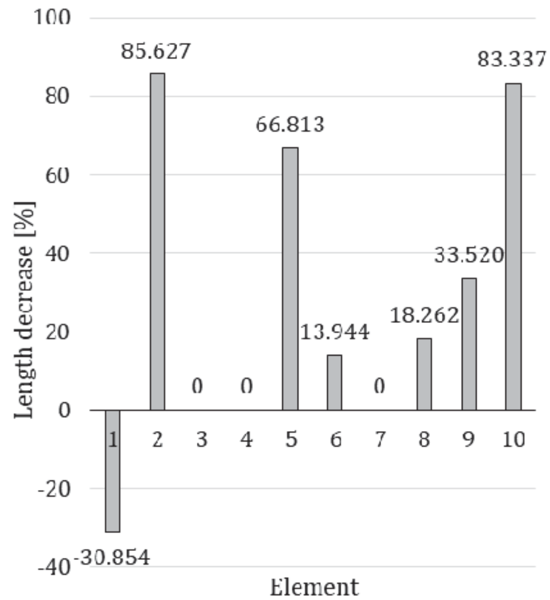

Fig. 3. Savings in element length, by bar, using shape optimization compared to the initial model.

The achieved results, regardless of the individual lengths, show that the total length of elements, and thereby the total material used has significantly decreased. This decrease in length is 28.02% from the initial configuration, which is the exact savings in mass from an initial 13019.482kg to an optimal 9371.591kg.

5. CONCLUSION

Truss optimization can achieve significant improvements in the design process leading to lighter structures which are cheaper to produce while maintaining structural integrity. It is not always cost-effective to conduct all optimization types simultaneously, nor is it always possible due to other influencing factors. Depending on the complexity of the initial design and the constraining problems the use of optimization might be overly complicated, slow or expensive compared to conventional design methods. The future of optimization is in its commercialization and integration into existing CAD software.

Shape optimization can provide significant savings in overall mass, and thereby the same savings in bar lengths if the same cross-section profile is used when optimizing. In this paper a typical 10 bar truss example was used to demonstrate the effects of shape optimization on element length. The overall savings in length, and mass is 28.02% using the same cross-section diameter which was analytically calculated for the initial solution. This is a substantial difference, especially considering that it was achieved by using only 4 variables (x and y coordinates of two nodes).

The use of other optimization types such as sizing and topology would be able to additionally decrease mass. There is a need to bring optimal solutions closer to practical application. Research in this field needs to strive towards applicable solutions in order to allow further developments.

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