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Sizing and shape optimization material use in 10 bar trusses

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Abstract. Truss optimization has the goal of achieving savings in costs and material while maintaining structural characteristics. In this research a 10 bar truss was structurally optimized in Rhino 6 using genetic algorithm optimization method. Results from previous research where sizing optimization was limited to using only three different cross-sections were compared to a sizing and shape optimization model which uses only those three cross-sections. Significant savings in mass have been found when using this approach. An analysis was conducted of the necessary bill of materials for these solutions. This research indicates practical effects which optimization can achieve in truss design.

1 Introduction

Modern tendencies in engineering are more and more oriented in the direction of using a wide spectrum of knowledge which can be used to ensure the creation of various constructions as well as secure their existence on the market. The use of some form of optimization becomes inevitable and the way it is used determines the success of the final construction [1-3]. Benefits of optimization are primarily seen through economic means both directly and indirectly.

The minimization of mass has been the primary goal of most published research on the topic of truss optimization. In recent years authors have been slowly moving towards using more practical variable setups and constraints to bring truss optimization closer to direct real-world application. Researchers in [4,5] showed the need for using discrete cross-section variable sets in order to match available, standard, dimensions of cross-section profiles. The implementation of Euler buckling constraints has increasingly started becoming part of the mathematical model in most research [6-8]. Optimization of trusses without buckling constraints gives low masses like in [9-12], but unstable constructions. In [13,14] the differences in optimal mass of models with and without using buckling constraints were compared. The use of buckling constraints can also be found in [15] where researchers compared both mass and overall outer area of different topological cases of a roof truss to show that the minimal mass solution does not always result in savings in all other areas.

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Authors of [16] have gone a step further in using truss optimization to design trusses which have a specific number of different cross-sections. This method simulates real design practice with the use of only a few different cross-sections in order to minimize the complexity of the structure as well as costs in unused stock.

A sustainable approach to truss structural optimization was presented by authors in [17] which made the best use of stock through analysing reuse potential. Research of this nature pushes forward the development of novel techniques in truss design and optimization.

The practical problem of the application of optimization is identifying realistic variables and actual goals which need to be achieved. Often, the achieved effects using optimization which are seemingly significant do not have a great impact in practice. There are also solutions which are aimed at showing the quality of the optimization process but are inapplicable in real-world construction. The motivation behind this research is in identifying real effects of optimization on a specific problem. The 10 bar truss problem is observed through the aspects of costs while maintaining structural stability.

2 Problem definition

The 10 bar truss problem is one of the most common examples used when testing new ideas in the field of truss structural optimization. In order to determine practical effects of the 10 bar truss problem, an array of tests and analyses were conducted for various cases of optimizing this problem. The 10 bar truss problem is in accordance with numerous resources from literature in this field.

The initial model's bar and node layout is given in Fig. 1. The material of the truss elements is Aluminium 6063-T5 whose characteristics are: Young modulus 68947MPa, and density of 2.7g/cm^3. Point loads are F=444.82kN in nodes (2) and (4) as shown in Fig. 1. The model is limited to a maximal displacement of ±0.0508m of all nodes in all directions, axial stress of ±172.3689MPa and Euler buckling constraints for all bars.

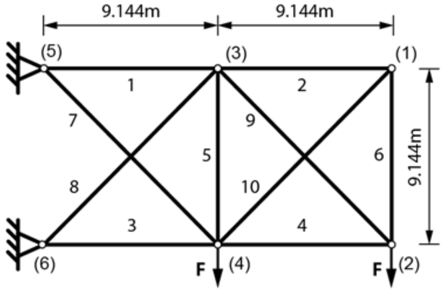


Fig. 1. 10 bar truss problem [5]

The example analysed in this paper will use the results from [16] for the 10 bar truss load case 1 optimization where the number of different cross-sections was limited to 3 bars as the initial model configuration. This example is analysed since in practice the number of different cross-sections which are used for this type of problem in practice is 3 bars at most. This solution presented in [16] uses only cross-section diameters of 240, 200 and 100mm, these cross-sections will be the only ones used. This model has been optimized for shape to find the best positions for nodes (1) and (3) for this configuration as well as sizing and shape just using the three optimal cross-sections as sizing variables. The analytical solution for this problem if only one cross-section is used uses 240mm cross-sections [16].

An original software developed in Rhino's Grasshopper was used for this research using the genetic algorithm optimization method.

3 Results and discussion

The achieved results can indicate key problems in the construction of trusses. The analytical solution has the advantage of being simplified in the sense that it uses the same cross-section for all bars making it easy to produce. This solution was compared to optimization results with the same three cross-section diameters for three different cases: the initial sizing optimized (sizing) [16], shape optimized from the initial model (shape), and simultaneous sizing and shape optimized (sizing shape). The masses of these models are presented in Fig. 2.

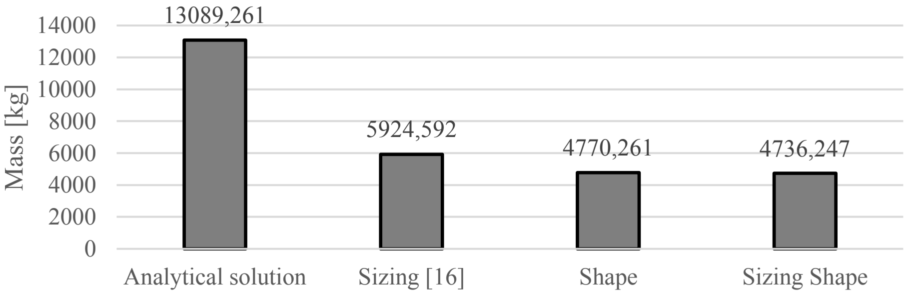
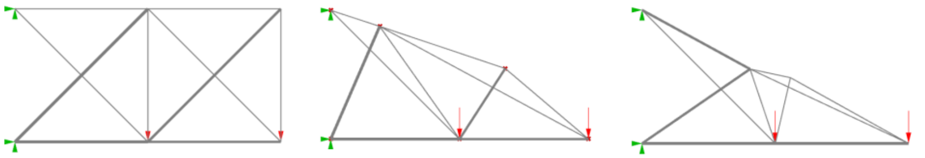


Fig. 2. Optimal masses of 10 bar models.

Optimized models and their node coordinates are shown in Fig. 3 which also shows coordinates of nodes (1) and (3). Position of supports and the nodes in which force is applied are not variable. For all models element masses, cross-section diameters and element lengths are shown in Table 1. Results show that a significant reduction in costs can be made by implementing optimization.

Table 1. Masses, cross-sections and lengths of elements according to solution type.

Element	Element masses [kg]				Cross-section diameter [mm]				Element lengths [m]			
	Analytical	Sizing	Shape	Sizing shape	Analytical	Sizing	Shape	Sizing shape	Analytical	Sizing	Shape	Analytical
1	1122.881	194.945	77.976	1122.881	240	100	100	240	9.144	9.144	3.658	9.144
2	1122.881	194.945	200.346	1122.881	240	100	100	240	9.144	9.144	9.397	9.144
3	1122.881	1122.881	1122.881	256.098	240	240	240	100	9.144	9.144	9.144	12.012
4	1122.881	779.779	779.779	60.421	240	200	200	100	9.144	9.144	9.144	2.834
5	1122.881	194.945	209.088	275.693	240	100	100	100	9.144	9.144	9.807	12.932
6	1122.881	194.945	165.122	114.794	240	100	100	100	9.144	9.144	7.745	5.385
7	1587.994	275.694	275.693	197.723	240	100	100	100	12.9316	12.9316	12.932	9.274
8	1587.994	1587.994	1071.414	720.043	240	240	240	200	12.9316	12.9316	8.725	8.444
9	1587.994	275.694	358.947	767.084	240	100	100	200	12.9316	12.9316	16.837	8.995
10	1587.994	1102.773	509.014	98.628	240	200	200	100	12.9316	12.9316	5.969	4.626
Total	13089.26	5924.595	4770.26	4736.246	-	-	-	-	106.590	106.590	93.358	82.790



	Sizing [16]	Shape	Sizing Shape
1	(18.288, 9.144, 0)	(12.384, 5.013, 0)	(10.183, 4.508, 0)
3	(9.144, 9.144, 0)	(3.475, 8.003, 0)	(7.411, 5.098, 0)

Fig. 3. Optimal models and coordinates of nodes (1) and (3).

In order to produce a truss it is necessary to acquire the necessary materials according to the bill of materials. Generally for this type of cross-section the most commonly found length of stock is 6m long, which has been taken as the standard stock length for the purposes of this research. If stock lengths are taken into account for calculating costs there is no longer a direct correlation between cost and mass. Table 2 shows total lengths of cross-sections according to the solution, the bill of materials and a factor of cost for materials and waste. The waste is calculated as the difference between the total needed length and total length of the needed number of whole pieces of stock.

Table 2. Cost for materials and waste comparison.

	Cross-section [mm]	Length [m]	Waste [m]	Needed pieces of stock (rounded up to whole no.)	Cost unit	Total cost units
Analytical	100	0	0	0	0	43.2
	200	0	0	0	0	
	240	106.590	1.410	18	43.2	
Sizing	100	62.439	3.561	11	11	28.6
	200	22.076	1.924	4	8	
	240	22.076	1.924	4	9.6	
Shape	100	60.376	5.624	11	11	24.2
	200	15.113	2.887	3	6	
	240	17.869	0.131	3	7.2	
Sizing Shape	100	47.063	0.937	8	8	23.6
	200	17.439	0.561	3	6	
	240	18.288	5.712	4	9.6	

It is clear that the waste values in practice will vary from this, but it is a good indicator of roughly how much stock is unused at the end of the construction process.

Unit cost is taken into account since market costs vary but are generally proportional to the cross-section diameter. Since used cross-sections are 100, 200 and 240mm, it can be calculated that the unit cost per 1m for 100mm cross-section is 1 cost unit, for 200mm stock as 2 units, and for 240mm stock as 2.4 units. From table 2 it is clear that the cost are lowest when optimizing sizing and shape (reorganizing the cross-sections from the initial configuration in [16] to best suit the optimal shape) than in the other solutions. Every optimization allows for great savings compared to the analytical model, and the decision for which type depends on the complexity of the problem and other possible constraints. Lastly, the engineer is left to choose how complex the problem is and how to implement optimization in order to balance the input work (namely time) and effects which are achieved by optimization.

4 Conclusion

The use of structural optimization has a significant role in practice as it can lead to great savings and improvements in stiffness while maintaining loadbearing capabilities and usefulness of a truss. It is necessary to identify clear criteria and indicators which can define which solutions are acceptable for realization when optimizing. This research showed an optimization of 10 bar trusses for several cases and compared the savings and amount of waste according to stock lengths.

Results show that the initial mass of the truss is 13089.26kg when using a single cross-section for all elements. Using sizing optimization mass can be decreased by 54.7% (5924.59kg) [16] when optimizing cross-sections with a set limit of 3 different cross-sections which can be used. This significant decrease in mass can be further improved by subsequently conducting shape optimization using the same cross-section layout to get a 63.56% decrease from the analytical solution (4770.26kg). Using the model from [F] as a starting reference and only using the cross-sections used in that solution as variables an even greater decrease in mass can be achieved by simultaneously optimizing cross-sections and the shape of the truss to achieve a 63.82% decrease (4736.25kg).

It has been determined that material costs do not directly depend on the mass. Assuming the lengths of stock available are in 6m pieces, the total number of pieces of stock was determined as well as the waste after cutting. It should be noted that the figures for waste should be adjusted and that the values given here are just the difference between total lengths needed and total length of stock. Additional calculations should be conducted in order to determine exact waste according to cutting schemes. Results show that material costs for constructing the sizing solution [16] are decreased by 33.796% from the analytical solution while for the shape optimization of that solution the decrease is 43.981% and the sizing shape optimized solution gives 45.37% savings in material costs.

The choice of solution in practice, regardless of savings, depends on a number of external factors, possibility of applying optimization, possibility of using a different shape, etc. It is up to the engineer to determine what is rational for application, but the use of optimization of any type will always give the possibility of achieving some sort of savings and an alternative solution to analytical calculation which through conventional design methods would not be possible. The approach used in this paper opens possibilities for further research, where it is possible to analyse exclusively the material used, material wasted and their use in acceptable places, which would lead to additional savings in costs.

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