UNIVERSITY OF EAST SARAJEVO

FACULTY OF MECHANICAL ENGINEERING

4th INTERNATIONAL SCIENTIFIC CONFERENCE

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PROCEEDINGS

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Jahorina, Republic of Srpska, B&H

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ZBORNIK RADOVA

PROCEEDINGS

Istočno Sarajevo – Jahorina, BiH, RS
27 - 30. Novembar 2018.

East Sarajevo – Jahorina, B&H, RS
27th – 30th November 2018.

ZBORNIK RADOVA SA 4. MEĐUNARODNE
NAUČNE KONFERENCIJE
"Primijenjene tehnologije u mašinskom inženjerstvu"
COMETa2018, Istočno Sarajevo - Jahorina 2018.

PROCEEDINGS OF THE 4th INTERNATIONAL
SCIENTIFIC CONFERENCE
"Conference on Mechanical Engineering
Technologies and Applications"
COMETa2018, East Sarajevo - Jahorina 2018.

Organizator:	Univerzitet u Istočnom Sarajevu Mašinski fakultet Istočno Sarajevo
Organization:	University of East Sarajevo Faculty of Mechanical Engineering East Sarajevo
Izdavač:	Univerzitet u Istočnom Sarajevu Mašinski fakultet Istočno Sarajevo
Publisher:	University of East Sarajevo Faculty of Mechanical Engineering East Sarajevo
Za izdavača: *For publisher:*	Assistant professor Milija Kraišnik PhD
Urednici: *Editors:*	Full professor Dušan Golubović PhD Assistant professor Aleksandar Košarac PhD Assistant professor Dejan Jeremić PhD
Tehnička obrada i dizajn: *Technical treatment and desing:*	Davor Milić, senior assistant Jelica Anić, senior assistant
Izdanje: *Printing:*	Prvo 1st
Register: *Register:*	ISBN 978-99976-719-4-3 COBISS.RS-ID 7818520

ENERGY AND ENVIRONMENTAL PROTECTION

Chairpersons: Dušan Golubović, Mirko Dobrnjac, Blaža Stojanović

COMETa 2018
4th INTERNATIONAL SCIENTIFIC CONFERENCE
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Conference on Mechanical Engineering Technologies and Applications

A COMPARISON OF TRUSS STRUCTURAL OPTIMIZATION TYPES WITH AND WITHOUT BUCKLING DYNAMIC CONSTRAINTS

Nenad Petrović[1], Nenad Kostić[2], Nenad Marjanović[3]

Abstract: Most research to date which covers the topic of truss structural optimization either doesn't consider, or uses fixed constraints for buckling. This paper presents a comparison of truss structural optimization types with and without the use of Euler buckling dynamic constraints. The difference is presented on a standard test model with 17 bars using continuous variables for cross section and node positions. The optimization method used is genetic algorithm for optimizing sizing, shape, topology, and their combinations. The implementation of dynamic constraints significantly increases the complexity of the calculations, however the results of using such an approach leads to practically applicable results.

Key words: Dynamic constraints, Euler buckling, Genetic algorithm, Structural optimization, Truss

1 INTRODUCTION

Truss structural optimization is a complex engineering problem which considers many variables and constraints. Minimal weight optimization can be approached through optimizing aspects of sizing, shape, and topology or their combinations. Truss sizing optimization observes each cross-section geometry as a variable, shape optimization varies the geometrical configuration's set node positions, and topology optimization creates new geometrical configurations by removing elements. The goal of this process is to achieve a truss design conceptwith a minimal weight, and consequently decrease costs.

In order to achieve practically applicable results the resulting truss construction must be able to withstand applied stress and avoid buckling, while keeping displacement within limits. Researchers have only recently started to include buckling constraints in optimization. This is largely due to the fact that buckling constraints change with every iteration of the optimization process according to the current truss setup. As a result

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using this constraint increases the problem complexity, and thereby calculation times drastically. The optimization of just one, or a combination of two or all three, of these types has been the subject of a lot of research using a broad range of heuristic optimization methods.

Researchers in [1] have used natural frequency bounds for truss optimization using an improved method in order to minimize truss weight. Khatibinia and Yazdani have in [2] used a multi-gravitational search algorithm for truss sizing optimization on 10, 18, 72, and 200 bar truss problems without considering buckling constraints on all examples. Tejani et al. [3] conducted simultaneous sizing, shape and topology optimization of planar and space trusses without considering buckling, but accounting for possible unacceptable topologies using Grubler's criterion. Assimi et al [4] considered a static critical buckling load constraint for sizing and topology optimization, using genetic programing.

Dynamic buckling constraints have only recently become part of structural optimization calculations when it comes to testing new methods. Ozbasaran [5] even added frequency analyses to further validate optimization results, and tested them on basic planar and space truss models. Degertekin et al [6] used Jaya algorithm for sizing shape and topology design optimization in order to minimize weight and tested it on common benchmark problems. Authors in [7-9] included dynamic constraints for buckling in their research using various optimization methods. Comparison of optimization results with and without buckling was done in [10], using continuous variables on a 10 bar truss example, and a sizing optimization comparison was done by researchers in [11], showing the drastic increases in weight when these constraints are implemented. Further research done in [12] shows the influence of using discrete variables as opposed to continuous for cross-section dimensions on all combinations of truss optimization types on a 10 bar truss problem.

This research is focused on showing the difference in using buckling constraints for solving complex truss structural optimization problems and gives a comparison of results on a typical 17 bar truss problem. The example is optimized for sizing, topology, shape and all their combinations in order to illustrate the importance of using dynamic buckling constraints on all types of structural optimization problems.

2 PROBLEM FORMULATION

The general problem of structural truss optimization implies the simultaneous optimization of sizing, topological, and shape aspects of the initial model. Nevertheless, practice shows that the combination of two, or all three of these aspects is not always possible or desired. The goal of this research is to analyse and show difference in results of optimizing any single, or any combination of these aspects on one of the most frequently used examples for truss optimization with and without using buckling constraints.

The objective functions of all optimization configurations used aim to find the combination of variables that minimize weight. For truss optimization found in literature the minimum weight design problem, limited by a range of cross-section areas and displacement, can be defined as:

$$\begin{cases} minW\left(A,\ n,\ l\right) = \sum_{i=1}^{i=n} \rho_i\ A_i l_i \text{ with } A = \left(A_1, \ldots, A_n\right) \\ \text{subjected to} \begin{cases} A_{min} \le A_i \le A_{max} & \text{for } i = 1, \ldots, n \\ u_{min} \le u_j \le u_{max} & \text{for } j = 1, \ldots, k \end{cases} \end{cases} \tag{1}$$

In (1) ,n is the number of used truss elements, k is the number of nodes, l_i is the length of the i^{th} element, A_i is the area of the i^{th} element cross section, u_j is displacement of the j^{th} node. This objective function criteria, depending on which combination or single optimization is conducted, changes accordingly, while the constraints remain the same for all problems.

2.1 Euler Buckling Constraint

Truss elements are subjected to either compression or tension forces. In order to ensure a stable construction, compressed elements must be checked for buckling. F_{Ai} is the axial compression force, F_{Ki} is Euler's critical load, E_i is the modulus of elasticity, and I_i is the minimum area moment of inertia of the cross section of the of the i^{th} element.

Since the same areas figure as denominators in the Euler buckling expression, the critical force load (2) can be used as the buckling constraint to minimize calculation. Therefore the constraint used in this research is given as (3).

$$F_{Ki} = \frac{\pi^2 \cdot E_i \cdot I_i}{l_i^2} \tag{2}$$

$$\left|F_{Ai}\right| \le F_{Ki} \text{ for } i = 1,...,n \tag{3}$$

As force distribution changes in shape and/or topology optimizations and their combinations and the minimal area moment of inertia changes with every iteration of sizing optimization this constraint is considered to be dynamic. Dynamic constraints are very complex as the constraint value changes with each iteration making the search space much more difficult for the algorithm to navigate without getting a local optimum. This is why, especially with the combination of all three simultaneous optimizations, it is necessary to repeat the optimization multiple times to ensure a global optimum. This type of optimization problem requires the use of non-linear optimization and in this paper genetic algorithm (GA) was used due to availability and its favorable characteristics.

2.2 The Design Problem

In order to show the difference between optimal models which do not consider buckling and ones that do, this research uses the 17 bar truss problem. The initial truss model bar and node layout is given in figure 1. This is one of the more commonly used examples from literature for truss optimization. For this example the material characteristics are: Young modulus 206842.719MPa, and density of 7.4g/cm^3. A single point load of 444.82kN is applied in node 9, as shown in figure 2. Each bar cross section is an independent variable minimal area of all members is limited to 0.643cm^2 for full circular cross-section profiles. The only other fixed constraint is a displacement limitation for all nodes of ±0.0508m of all nodes in both x and y directions.

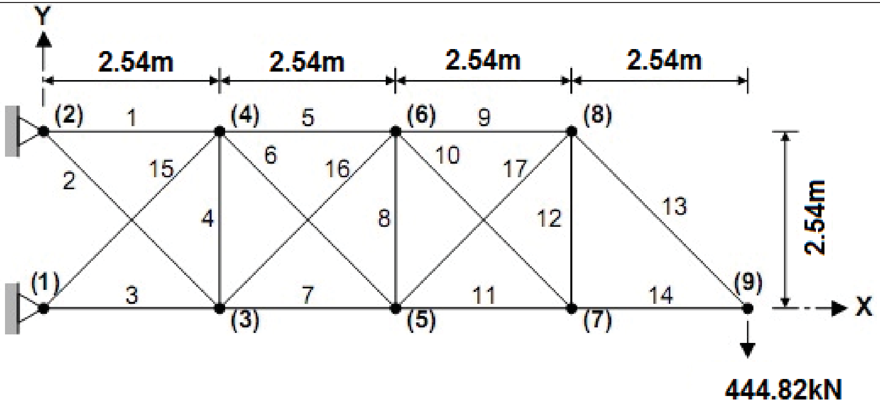


Figure 1. *Initial 17 bar truss model configuration*

The initial cross-section area for all calculations is 8659.01mm^2 (105mm diameter). This model has a weight of 3181.777kg and is calculated by optimizing the initial model which would have the same diameter of all bars and a minimal weight in such a configuration for the example with buckling. For examples which do not consider sizing the areas are 6361.73mm2 (90mm diameter) without buckling, and 8659.01mm^2 (105mm diameter) with buckling. Topology optimization is limited to the removal of at most 6 bars. A 1mm precision for node location is set when using shape optimization. Shape optimization observes the *x* and *y* positions of nodes 3-8 as variables, as well as the *y* position of node 9.

3 RESULTS

The originally software used for all calculations was verified in [10] and used in this paper for examples both with and without buckling. Sizing results with and without buckling are the same as in [11]. All three individual types of optimization, their three combinations of two, and a complete structural optimization using all three simultaneously were conducted according to the aforementioned setup without buckling, and repeated with buckling included. Table 1 gives the optimal cross-section areas, weight and displacement for the 17 bar truss example without using the buckling constraint. Cross-section areas marked in bold do not meet buckling criteria, while the ones in italic are also subjected to compression but are loaded below the buckling threshold.

Table 2 shows the optimal coordinates of nodes with variable positions for the results which take into account shape optimization without buckling constraints. Since node 9 only has a variable for its y coordinate, the x coordinate is the same for all four cases.

Optimal results for all three optimization types and their combinations is given in table 3. Coordinates for the results which take into account shape optimization with the buckling constraints are given in table 4.

Table 1. *Optimal solutions of the 17 bar truss problem without buckling constraints*

Area of bar [cm^2]	Sizing	Topo.	Shape	Sizing and topology	Sizing and shape	Topology and shape	Sizing, topology and shape
1	90.883	63.317	63.317	83.046	74.199	63.317	71.742
2	13.98	63.317	63.317	39.549	41.279	63.317	44.602
3	88.314	**63.317**	**63.317**	*110.916*	*92.793*	**63.317**	*94.952*
4	0.645	63.317	*63.317*	**31.164**	**8.793**	63.317	**9.194**
5	64.084	63.317	63.317	57.694	65.659	63.317	64.746
6	22.763	63.317	63.317	40.997	2.749	63.317	2.817
7	64.636	**63.317**	**63.317**	**90.019**	**43.572**	**63.317**	**43.433**
8	0.645	*63.317*	*63.317*	*31.18*	1.726	*63.317*	3.996
9	41.186	63.317	63.317	31.107	34.842	63.317	32.218
10	23.089	63.317	63.317	42.817	15.138	63.317	14.809
11	39.158	*63.317*	*63.317*	*61.154*	*38.27*	*63.317*	36.241
12	9.805	*63.317*	*63.317*	**31.809**	**0.662**	*63.317*	**0.646**
13	36.981	63.317	63.317	41.192	29.868	63.317	29.579
14	30.296	*63.317*	**63.317**	**31.54**	**30.24**	**63.317**	**29.984**
15	25.136	-	*63.317*	-	**6.08**	-	-
16	14.517	-	*63.317*	-	**25.527**	-	**31.59**
17	11.113	-	*63.317*	-	**7.52**	-	**6.419**
Weight [kg]	**1183.071**	**1839.241**	**2133.025**	**1463.045**	**1070.09**	**1656.366**	**1068.898**
Displ. [m]	**0.508**	**0.508**	**0.508**	**0.508**	**0.508**	**0.508**	**0.508**

Table 2. *Optimal coordinates without buckling constraints where shape is optimized*

Opt. type / Node	Shape	Sizing and shape	Topology and shape	Sizing, topology and shape
3 (x; y) [m]	(2.88; 0.059)	(2.253; -0.172)	(2.063; 0.003)	(2.225; -0.138)
4 (x; y) [m]	(2.887; 2.548)	(3.507; 2.873)	(3.777; 2.476)	(3.882; 2.2848)
5 (x; y) [m]	(5.302; 0.295)	(6.229; 0.041)	(5.132; 0.219)	(6.317; -0.076)
6 (x; y) [m]	(5.331; 2.271)	(5.271; 2.789)	(6.051; 2.335)	(5.215; 2.818)
7 (x; y) [m]	(6.753; 0.291)	(7.6; 0.095)	(6.917; 0.486)	(7.753; 0.012)
8 (x; y) [m]	(7.09; 2.086)	(8.449; 2.076)	(7.518; 2.3)	(8.464; 2.018)
9 (x; y) [m]	(10.16; 1.042)	(10.16; 1.26)	(10.16; 1.245)	(10.16; 1.193)

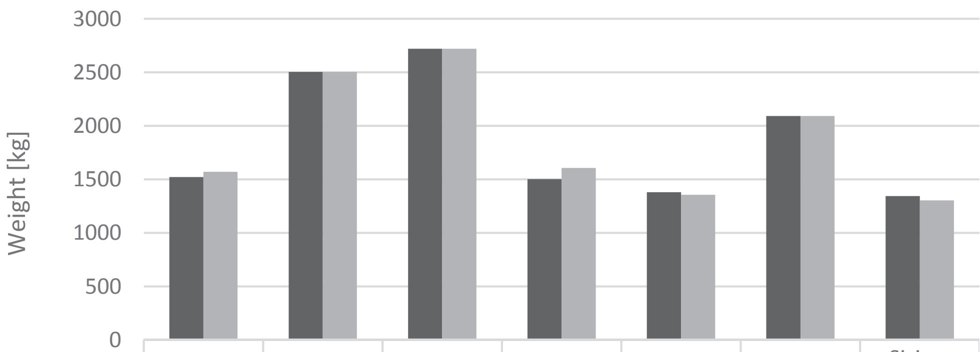
Table 3. *Optimal solutions of the 17 bar truss problem without buckling constraints*

Area of bar [cm²]	Sizing	Topo.	Shape	Sizing and topology	Sizing and shape	Topology and shape	Sizing, topology and shape
1	79.794	86.59	86.59	80.269	78.254	86.59	62.467
2	6.962	86.59	86.59	32.662	13.465	86.59	26.469
3	93.299	86.59	86.59	107.101	94.455	86.59	93.592
4	15.636	86.59	86.59	42.494	1.825	86.59	0.669
5	56.137	86.59	86.59	56.941	59.775	86.59	64.587
6	0.774	86.59	86.59	41.937	12.859	86.59	34.21
7	59.62	86.59	86.59	88.991	71.12	86.59	71.2
8	4.695	86.59	86.59	42.382	0.655	86.59	32.394
9	31.191	86.59	86.59	29.254	52.748	86.59	35.391
10	35.44	86.59	86.59	38.146	12.844	86.59	29.162
11	55.431	86.59	86.59	64.149	64.51	86.59	42.798
12	35.57	86.59	86.59	42.211	0.6959	86.59	27.721
13	30.352	86.59	86.59	41.01	57.076	86.59	35.775
14	41.459	86.59	86.59	42.125	67.148	86.59	42.63
15	61.006	-	86.59	-	50.437	-	39.921
16	68.013	-	86.59	-	31.262	-	-
17	38.345	-	86.59	-	25.147	-	-
Weight [kg]	**1522.064**	**2503.411**	**2720.756**	**1501.902**	**1380.235**	**2091.971**	**1345.12**
Displ. [m]	**0.0508**	**0.0375**	**0.0508**	**0.0508**	**0.0508**	**0.0508**	**0.0508**

Table 4. *Optimal coordinates with buckling constraints where shape is optimized*

Opt. type / Node	Shape	Sizing and shape	Topology and shape	Sizing, topology and shape
3 (x; y) [m]	(2.679; 0.104)	(2.491; 0.359)	(2.886; 0.052)	(2.765;- 0.096)
4 (x; y) [m]	(3.003; 2.211)	(3.933; 2.495)	(2.764; 2.404)	(2.751; 2.375)
5 (x; y) [m]	(5.37; 0.315)	(5.171; 0.741)	(5.384; 0.23)	(5.1; 0.188)
6 (x; y) [m]	(5.467; 1.799)	(6.176; 2.272)	(5.006; 2.249)	(2.254; 242)
7 (x; y) [m]	(6.873; 0.274)	(7.013; 1.039)	(7.310; 0.409)	(7.379; 0.5)
8 (x; y) [m]	(6.642; 1.712)	(7.390; 2.308)	(6.660; 2.158)	(8.174; 2.22)
9 (x; y) [m]	(10.16; 0.968)	(10.16; 1.547)	(10.160; 1.305)	(10.16;1.334)

Figure 2 shows a graphic comparison of optimal weights between continuous and discrete cross-section models.



	Sizing	Topology	Shape	Sizing and topology	Sizing and shape	Topology and shape	Sizing, topology and shape
continuous	1522.064	2503.411	2720.756	1501.902	1380.235	2091.971	1345.12
discrete	1571.875	2503.411	2720.756	1607.739	1355.876	2091.971	1303.889

Figure 2. *Comparison of discrete and continuous optimization results according to type*

4 CONCLUSION

In real-world applications it is impossible to produce trusses which are the result of optimization with continuous cross-sectional variables, simply because of the costs linked to the production of specific, non-standard, dimensions of cross-sections in high enough tolerances. It was noted that even the slightest variations in cross-section diameter of optimal solutions with continuous variables leads to the construction not meeting constraint criteria. This paper showed the influence of using discrete cross-section variables, and compared results of all types, and combinations of truss structural optimization on a 17 bar truss example. In addition to the use of discrete variables, in order to ensure practically useable designs, the optimization process was constrained using dynamic buckling constraints. As a result the resulting structures which use achieved using this method weigh more than their counterparts from literature which do not consider buckling constraints.

The use of discrete variables gives models with similar weights. The difference between continuous and discrete variable models is around 3% for sizing optimization, around 7% for sizing and topology, around -2% for shape, and around -3% for sizing, shape and topology optimization. Since the Euler buckling constraint is added, it is very difficult for the method to achieve an absolute optimum, hence the continuous models have, an unexpectedly greater weight than their discrete counterparts, however this difference is negligible and is most likely caused by method parameters. The more complex the optimization, with more aspects being optimized and the addition of constraints which further divide the search space, the more difficult it is to achieve global optima. It can also be noted, that the topology optimization and shape optimization for both examples give the same results. This is because in order to define a cross-section to use for these two cases the initial model was optimized for sizing first, with using the same cross-section for all elements. The resulting value for both continuous and discrete models were close to 86.59cm^2, which is a discrete diameter of 90mm, so the results were considered to be the same.

The intent of this research was to prove that there are insignificant differences in optimal weight between continuous and dynamic constraints. It can be concluded from the results that using discrete variables in optimization gives useable results when combined with buckling constraints. Further research in this field will include the influence of cross-section standard tolerances on optimal models in terms of satisfying set constraints.

ACKNOWLEDGMENT

This paper is a result of the TR32036 and TR33015 projects, which are investigations of the Technological Development of Republic of Serbia. The projects are titled “Development of software for solving the coupled multi-physical problems” and “Research and development of a Serbian net-zero energy house” respectively. We would like to thank to the Ministry of Education, Science and Technological Development of the Republic of Serbia for their financial support during this investigation.

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