IOP Conference Series: Materials Science and Engineering

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To cite this article: A.N. Ede *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **413** 012044

Weight Optimization of Square Hollow Steel Trusses Using Genetic Algorithm

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Abstract. Conceptual design in structural engineering entails a large amount of trial and errors or extensive expertise to obtain the most economical and functional design solutions for large engineering projects. In this paper a modern optimization technique called Genetic algorithm, adopting its concept from genetic evolution is used to optimize the shape, size and topology of a plane truss structure with the aim of minimizing the total weight of the truss. A genetic algorithm developed in MATLAB was implemented in this paper to optimize the weight of plane truss structures. The objective function of the optimization problem is subjected to constraints such as stress limits, buckling constraints, tension and compression capacity according to British steel design code BS 5950. The plane trusses which were subject to point loads were tested in the genetic algorithm, the resulting optimized truss structures were then subject to real life loading to determine their feasibility to withstand real life loading. The optimized trusses presented by the algorithm were modelled in a structural analysis and design software called SAP 2000, where they were subjected to dead and live loads. After design the weight saving discovered between the original trusses and the optimized version was between 37 - 47%. The results show that the genetic algorithm implemented in this study is useful in optimizing the weight of a plane truss structure.
Keywords: Steel, Structural optimization, Genetic Algorithm

1. Introduction

Sustainability of the environment involves the optimum usage of resources to create infrastructures or projects that meet present day needs and will still be useful to meet future needs [1] An important topic in the sustainability of civil engineering structures is the topic of structural optimization. Structural optimization is a concept that is introduced during the conceptual design stage of engineering structures. During the conceptual design stage, a lot of trial and error or intuition by experts is required to obtain a good structural solution. However, with structural optimization the designer can define the objectives of the design and the constraints to help obtain good and optimal structural solutions [2].
Structural optimization can be categorized into shape optimization, topology optimization and size optimization. Shape Optimization treats the geometry of the truss as the design objective and the design variable considered is the node coordinates. In topology optimization the connectivity of the members is the objective while the number of nodes is the variables. For size optimization the members size is the objective while the design variable is area of available cross-sectional profiles (discrete) or a specified range of member area (continuous) [3].
Researches in structural optimization can be dated back to the 1900's when Michell presented theoretical optimum shapes for statically determinate trusses. Since then, many other researches have continued in that path, it became more intense with the increase of computational capabilities [4]. This study was therefore carried out to optimize the weight of plane steel trusses by considering topology, size and shape using genetic algorithm technique. When the optimization problem is without constraints it is called a non-constrained optimization but when the optimization process is subjected to one or more constraints, it is referred to as a constrained optimization [5].

2. Truss Optimization using Genetic algorithm

A truss system consists of straight bars joined together at ends to produce rigid framework which will aid easy load distribution and transfer to the corresponding support in form of purely axial force [6]. Optimization techniques are categorized into classical and modern methods of optimization. Classical

Methods are analytical and make use of differential calculus for locating optimum solutions e.g. Linear programming, nonlinear programming etc. While modern methods adopt their operation from nature. It is a probabilistic based approach e.g. genetic algorithm, particle swamp optimization, ant colony optimization etc. [7].

The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution. Some of the concepts adopted form this field are chromosome, genes, reproduction, mutation, crossover, populations, genotype etc. The technique was first consolidated by John Holland in 1975 [8].

Deb and Gulati [9] used binary encoded genetic algorithms to optimize an 11-member and six node 2D truss structure that was constrained by stress limits and buckling capacity according to Eurocode 3. The optimized structure gave an overall weight of 4899.15 kg, a much lighter weight than previous researches. Osman et al. [10] also developed a genetic algorithm using a different optimization process to find the optimum weight of plane and space trusses. The proposed genetic algorithm was used to reduce computation time significantly by reducing the required design variables for the optimization.

2. Development of genetic algorithm in MATLAB

The genetic algorithm and direct search toolbox embedded in the MATLAB software was used as a tool in developing the genetic algorithm. MATLAB is a powerful language and it has the relevant built-in functions to run the algorithm [13]. The finite element method was used for the analysis of the truss structures produced during operation of the algorithm. It is used to determine the fitness values of the various truss solutions. Finite element method is a robust and effective analysis technique for computer solutions of various engineering problems. It is used to solve complex engineering problems that analytical methods cannot accurately solve [11].

For the optimization of the size, topology and shape of the plane truss structures, design constraints were considered to ensure feasibility of the truss structures. The constraints considered were; material constraints in which the sections used were limited to the ones available commercially, the truss structure must have all basic nodes (support nodes and load nodes), the truss structure must be kinematically stable and the displacement limit of the node is between Lx/250 and Lx/240, as stated in BS 5950. After the genetic algorithm produces results of an optimized truss structure, the configuration of the optimized truss and original truss were analyzed in an analysis and design software called SAP 2000. Figure 1 shows a cross-section of the square hollow steel section used in this paper.

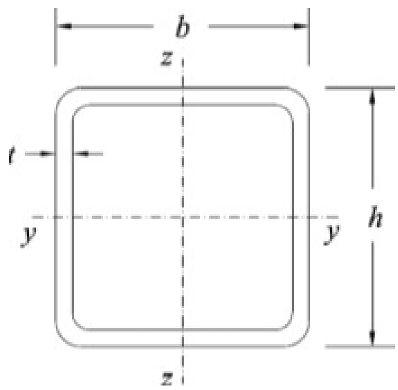
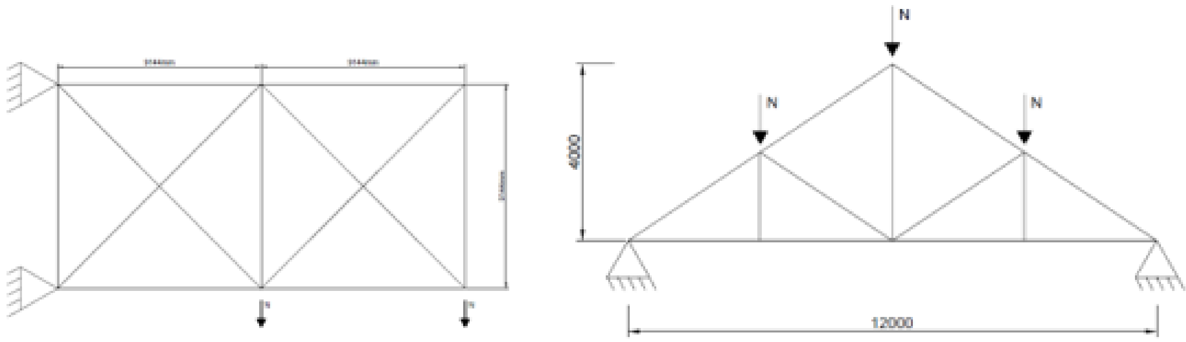


Fig 1: Cross section of a square hollow steel section [12]

3. Results and Discussion

The genetic algorithm developed in MATLAB was tested on two truss problems. The trusses are, a cantilever truss structure and a pitched truss. Figures 2a and 2b show a representation of the trusses.

IOP Conf. Series: Materials Science and Engineering **413** (2018) 012044 doi:10.1088/1757-899X/413/1/012044



(a) Cantilevered truss with 6 nodes 2-point 2-point and 2 support nodes (b) Pitched truss structure With 6 Nodes

Fig 2: Plane truss test problems

Table 1 Result of optimized cantilever truss in the algorithm

Member	Cross-sectional profile	Weight	Start coordinates (x1, y1)	End coordinates (X2, y2)	% allowable stress	Stress (N/mm2)
2	300x300x6.3	528.5232	0, 0	9.144, 0	97.2612	-180.5268
3	150x150x6.3	363.3771	0, 9.144	9.144, 0	90.283	248.2783
4	160x160x5	425.7522	0, 9.144	16.6, 3.1	87.4321	240.4383
5	200x200x5	245.4731	9.144, 0	16.6, 3.1	84.6533	-127.1448
8	120x120x4	61.7711	16.6, 3.1	18.288, 0	99.3574	273.2328
10	160x160x5	220.9704	18.288, 0	9.144, 0	92.5886	-78.2301
	Total weight	1849.9258kg				
	Displacement	Horizontally 11.267 mm Vertically 71.3408 mm				

Figures 3,4 and 5 show the original and optimized cantilever truss structure with the details being presented in tables 1, 2 and 3. The optimized cantilever structure was thereafter modelled in SAP 2000 software and subjected to dead and live loads. The result of analysis and design showed that all truss members successfully passed stress checks in accordance to BS 5950 requirements. The total weight saving of the optimized cantilever truss structure compared to the original truss is 47%. For the cantilever truss the weight of the original truss when subjected to dead and live loads gave a value of 5970.22 kg and the optimized truss gave a weight value of 3146.2Kg. From the original truss the number of members were 10 but when the algorithm optimized the truss the number of members reduced to 6 showing that 4 members in the original truss were non-critical.

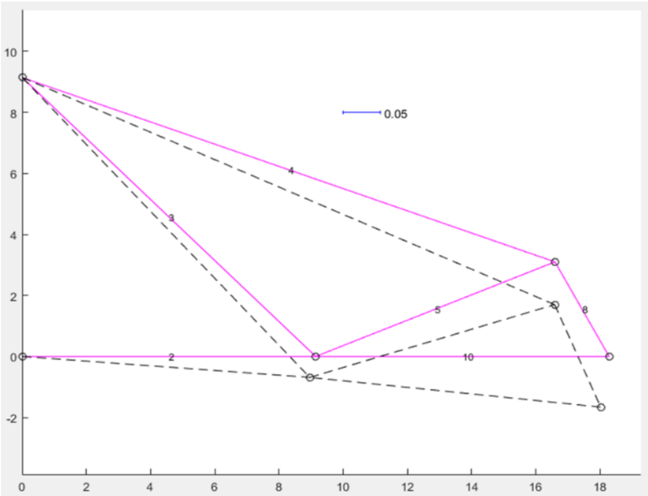


Fig 3: Optimized cantilever truss in the algorithm

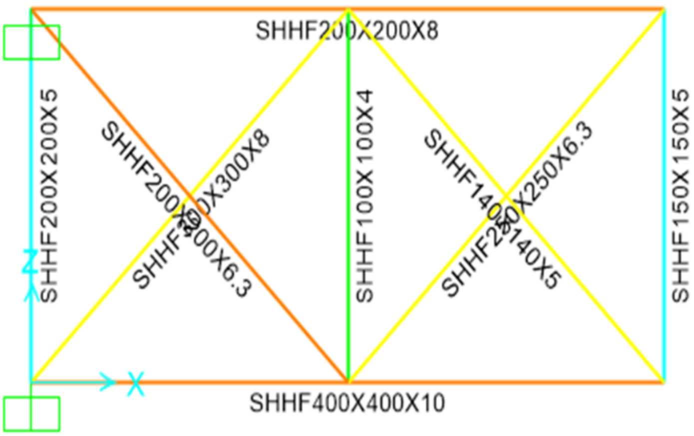


Fig 4: SAP 2000 model and section sizes of the original cantilever truss

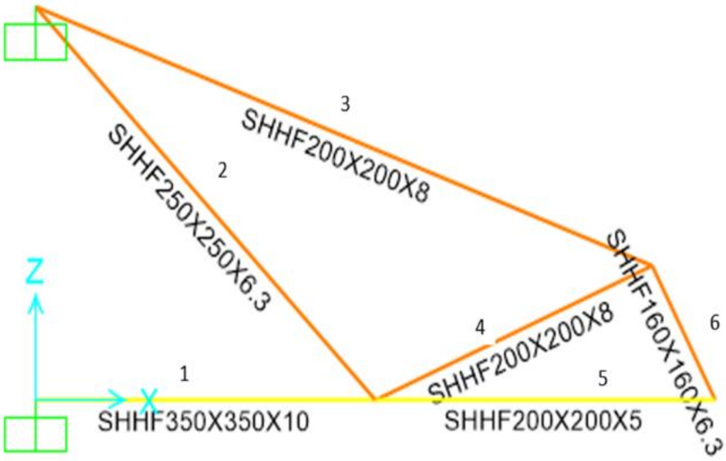


Fig 5: SAP 2000 model and section sizes of the optimized cantilever truss

Table 2 Sap 2000 design result for the original truss

Member	Cross-sectional profile	Length (m)	Weight (Kg)	Stress (N/mm2)
1	400X400X10	18.288	2231.136	-147.416
2	150X150X5	9.144	206.6544	114.576
3	200X200X8	18.288	872.3376	256.576

4	200X200X5	9.144	277.976	0.492
5	100X100X4	9.144	108.8136	-122.206
6	300X300X8	12.93157	941.418296	160.037
7	250X250X6.3	12.93157	619.4222	-85.804
8	200X200X6.3	12.93157	491.3997	263.567
9	140X140X5	12.93157	271.5657	244.275

	Total weight	5970.723496Kg
	Displacement	Vertical = 53.916mm Horizontal = 12.21mm

Table 3 Sap 2000 design result for the optimized cantilever truss

Member	Cross-sectional profile	Length (m)	Weight (Kg)	Stress (N/mm2)
1	350X350X10	9.144	969.264	-122.945
2	250X250X6.3	12.93157	619.44	152.684
4	200X200X8	17.66607	842.6715	125.359
5	200X200X8	8.07477	381.6	-81.612
6	160X160X6.3	3.52978	106.2463	135.073
7	200X200X5	9.144	227.9776	-63.862

	Total weight	3147.1994Kg
	Displacement	Vertical = 38.82mm Horizontal = 7.02mm

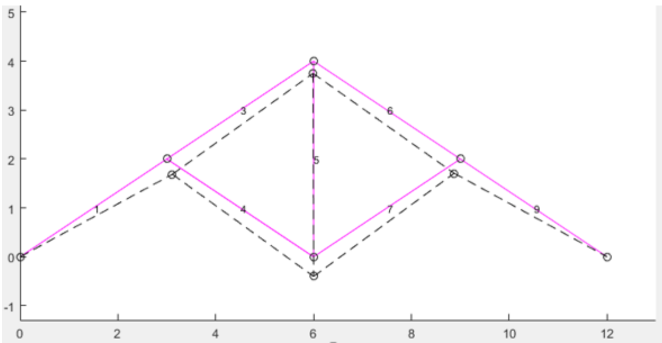


Fig 6: Optimized pitched truss in the algorithm

Table 4 Result of optimized pitched truss in the algorithm

Member	Cross sectional profile	weight	Start coordinates (x1, y1)	End coordinates (X2, y2)	% of allowable stress	Stress (N/mm2)
1	120x120x4.9	63.0971	0,0	3,2	78.6274	-159.8234
3	100x100x5	53.0016	3,2	6,4	85.2432	-142.3244
4	80x80x3.2	27.5104	3,2	6,0	73.992	-91.6939
5	50x50x4	22.5600	6,4	6,0	98.8142	271.7391

6	120x120x4	51.9199	6,4	9,2	71.1524	-145.6985
7	80x80x3.2	27.5104	6,0	9,2	73.992	-91.6939
9	160x160x5	86.8938	9,2	12,0	48.8696	-116.3081

	Total weight	336.6586kg
	Displacement	Horizontally 4.3712 mm, 27.32% of the limit Vertically 13.9069 mm, 28.9728% of the limit

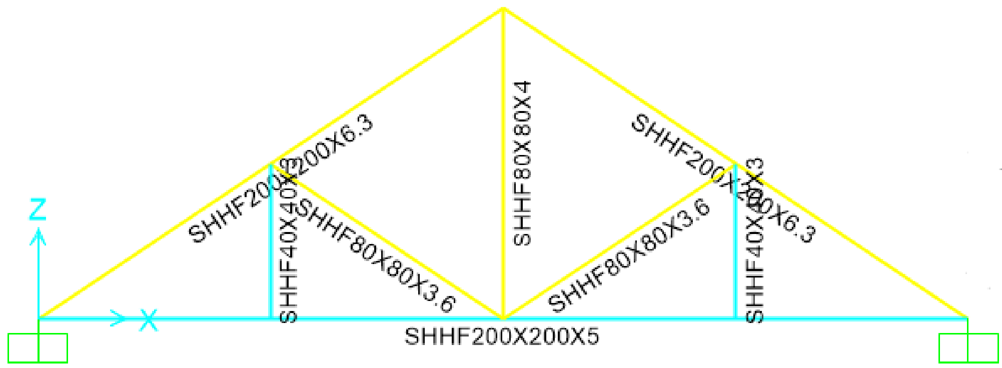


Fig 7: SAP 2000 model and section sizes of the original pitched truss

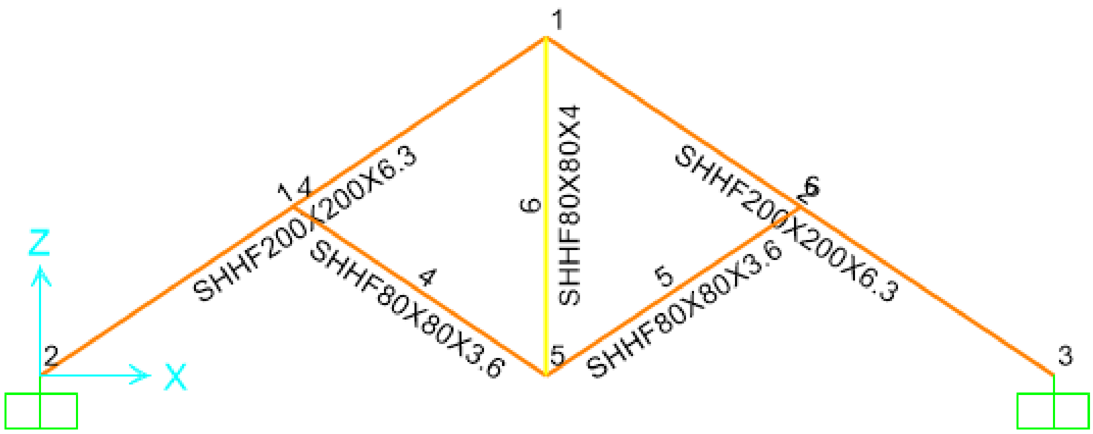


Fig 8: SAP 2000 model and section sizes of the original pitched truss

Figure 6 shows the optimized pitched truss after the optimization process in the algorithm. The original truss structure had 10 members but after the optimization the truss structure had 5 members. The optimized pitched truss with the original truss structure were modelled in SAP 2000 as shown in figures 7 and 8. The reduction in weight of the pitched roof truss is about 37-47 %. As presented in tables 4, 5 and 6, the weight of the original truss structure after being subject to dead and live load was 1097.9 kg, but after optimization the truss weight was reduced to 688.08 kg.

Table 5 Sap 2000 design result for the original pitched truss

Member	Cross-sectional profile	Length (m)	Weight (Kg)	Stress (N/mm2)
1	200X200X6.3	7.2111	270.218	-116.383

2	200X200X6.3	7.2111	274.0218	-116.383
3	200X200X5	12	406.8	48.484.
4	80X80X3.6	3.60555	51.19881	-68.769
5	80X80X3.6	3.60555	51.19881	-68.769
6	80X80X4	4	37.64	150.498
7	40X40X3	2	6.82	-22.084
8	40X40X3	2	6.82	-22.084
	Total weight	1097.89742Kg		
	Displacement	Vertical – 6.708mm Horizontal – 2.16mm		

Table 6 Sap 2000 design result for the optimized pitched truss

Member	Cross sectional profile	length	Weight (Kg)	Stress (N/mm^2)
1	200X200X6.3	7.2111	274.0218	-120.391
2	200X200X6.3	7.2111	274.0218	-120.391
4	80X80X3.6	3.60555	51.19881	-74.952
5	80X80X3.6	3.60555	51.19881	-74.952
6	80X80X4	4	37.64	153.105
	Total Weight	688.08122Kg		
	Max displacement	Vertical – 6.85mm Horizontal – 2.25mm		

4. Conclusion

A genetic algorithm was developed in MATLAB to optimize the weight of plane truss structures and the optimized trusses were modelled in a structural analysis and design software called SAP 2000 where they were analyzed and designed under real life loads. The trusses that were optimized showed significant reduction in the total weight by 30 - 40% showing that the algorithm is a useful tool for engineers in obtaining structures of optimal weight during design. All structures optimized were within acceptable stress and displacement limits. For further research works the genetic algorithm used in this paper can be implemented in the design of other structural elements using other available steel profiles provided in the design codes. Also, further researches are suggested for the optimization of 3D trusses such as tower cranes using genetic algorithm technique.

Acknowledgement
The authors wish to show their appreciation to the chancellor and the management of Covenant University for the Platform created to ensure the successful completion of this research work.

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