Weight Optimization of Square Hollow Steel Trusses Using Genetic Algorithm

* A.N. Ede¹, O.O. Oshokoya¹, J.O. Oluwafemi¹, S.O. Oyebisi¹, O.M. Olofinnade¹, A. I. Akpabot

¹Civil Engineering Department, College of Engineering, Covenant University, Ota, Ogun State, Nigeria,

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 subjected to point loads were tested in the genetic algorithm, the resulting optimized truss structures were then subjected 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. 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. 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). 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. 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.

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. 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.

![Cross section of a square hollow steel section](image)

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.
(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        |
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 5970.723496Kg
Displacement Vertical = 53.916mm
Horizontal = 12.21mm

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       |
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       |
| 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.

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References

[1] Anthony, N. E., Gideon, O. B., Oluwarotimi, M. O., David, O. O., Gideon, A. A., & Ben, U. N. (2016). Impact of Reliable Built Structures in Driving the Sustainable Development Goals: A look at Nigerian Building Structures. 3rd International Conference on African Development Issues (CU-ICADI 2016) (pp. 350-353). Ota: Covenant University Press.

[2] Mark, S., Eric, L., Chung-Soo, D., & David, S. (2009). Optimization Tools for the design of Structures. SEAOC 2009 Coventio Proceedings, 1-17.
[3] Kaveh, A., & Kalatjari, V. (2004). Size/geometry optimization of trusses by the force method and genetic algorithm. ZAMM – Zeitschrift für Angewandte Mathematik und Mechanik., 84(5), 347-357.

[4] Rory, C. (2013). Algorithm Selection in Structural Optimization (1st ed.). Massachusetts: Massachusetts Institute of Technology.

[5] Margaret, E. K. (2012). A Two-Phase Genetic Algorithm for Simultaneous Dimension, Topology, and Shape Optimization (1st ed.). Ohio: The Ohio State University.

[6] Anthony, N. E., Olatunbosu, A., & Oluwarotimi, M. O. (2015). Modelling, Analysis and Design of a MultiStorey Storey Helipad-Car Park: a Proposal for Canaan. International Journal of Innovative Science and Modern Engineering (IJISME), Volume - 3 Issue-4, pp43-47.

[7] Singiresu, S. R. (2009). Engineering Optimization (1st ed.). New Jersey: John Wiley & Sons, Inc.

[8] Reeves, C. R., & Rowe, J. E. (2002). Genetic Algorithm: Principles and Perspectives- A Guideto GA Theory. New York.

[9] Deb, K., & Gulati, S. (2000). Design of Truss-Structures for Minimum Weight using Genetic Algorithms. Finite Elements in Analysis and Design, 447-465.

[10] Osman, S., Atef, E., Tharwat, S., & Osman, H. (2014). Optimization of Plane and Space Trusses Using Genetic Algorithms. International Journal of Engineering and Innovative Technology (IJIEIT), 3(7), 66-73.

[11] Austrell, P. E., Dahlblom, O., Lindemann, J., & Olsson, A. (2004). CALFEM- A Finite Element Toolbox. Lund: Structural Mechanics.

[12] BSI (2000). Structural use of steelwork in building - Part 1: Code of practice for design - Rolled and welded sections. BSI.

[13] MathWorks. (2017). Genetic Algorithm and Direct Search Toolbox 2.4.2. Retrieved November 17, 2017, from www.mathworks.com