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# Topology Optimisation of Continuum Structures in Civil Engineering using Firefly Algorithm -III

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***Abstract***
*This paper is in continuation of the ongoing research work on topology optimization in structural engineering. Metaheuristics are widely used for structural optimization and firefly algorithm has been consistently giving better designs. In this paper, a few civil engineering structures are designed and analysed. The results were compared with those existing in the literature.*

**Keywords:** *Topology, Structural Optimisation, Bridge, Arch, Column, MBB, Firefly, Civil Engineering, Metaheuristics*

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## INTRODUCTION

Design of engineering structures has always been a challenging task. Heavy Structures such as bridges require a lot of time and computational effort. Meta-heuristics meaning higher know how are derived from nature. These nature inspired algorithms have been consistently performing better than the conventional algorithms. The focus of this paper is to perform topology optimization of a few civil engineering structures in a given domain. Firefly algorithm is used to identify the distribution of material in the given domain with the least computational effort possible [1]. In this paper, the firefly algorithm is used for topology optimization of a few civil engineering continuum structures. Next section discusses the literature review. Subsequent section briefly discussed on the methodology and a separate section presents the analysis and their results. Conclusions and references are presented towards the end.

### Objective

The objective is to determine the optimum distribution of material within the given domain for a few commonly used civil engineering structures.

### Scope of the Study

1. The study is performed within the linear elastic limits
2. The study does not include buckling analysis

## LITERATURE REVIEW

Messerschmidt Bolkow Blohm (MBB) beam is one of the typical structures any optimizer can be used. Sui et al. [2] optimized using Independent Continuum Map method to optimize the beam as shown in the Figure 1. Guo et al. [3] in his paper optimized MBB Beam used a minimum volume constraint approach to optimize a biomaterial MBB beam (Figure 2).

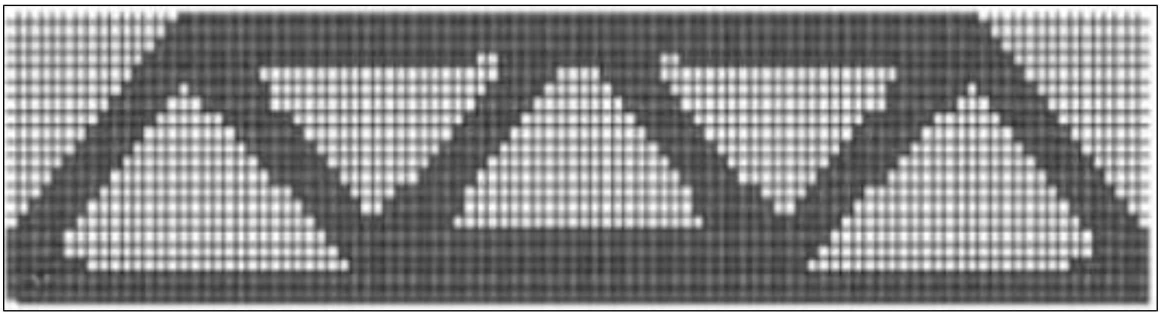

***Fig. 1:*** *Showing the MBB Beam using Independent Continuum Map Method Sui et al. [5].*

He used a volume constraint of $V_1$ = 10% and $V_2$ = 30% for each of the materials. Browne [4] in his PhD thesis used mesh size 1200 x 480 = 480,000 elements having a total of 962,800 degree of freedom. The optimization is performed on a server computer and the unfiltered optimum distribution is as shown in Figure 3a. Browne applied filters and refined the output to obtain a final topology of MBB Beam which is as shown in the Figure 3b.

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The mesh size is 1200 x 480 = 480,000 elements having a total of 962,800 degree of freedom.

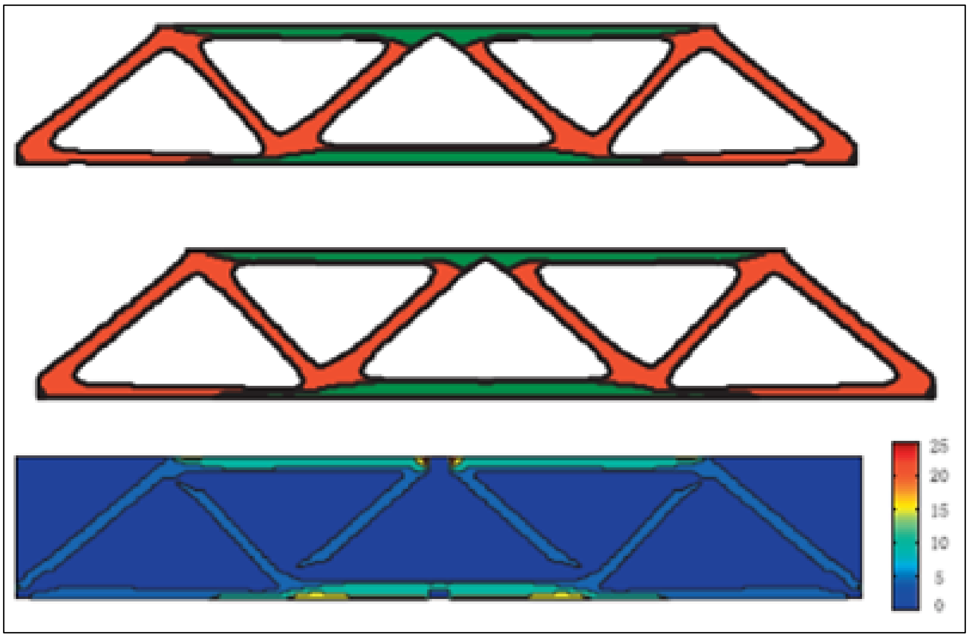



***Fig. 2:*** *Showing the Topology Optimization of MBB Beam Guo et al. [3].*

***Fig. 3a:*** *Unfiltered Output -Right half of the Beam.*

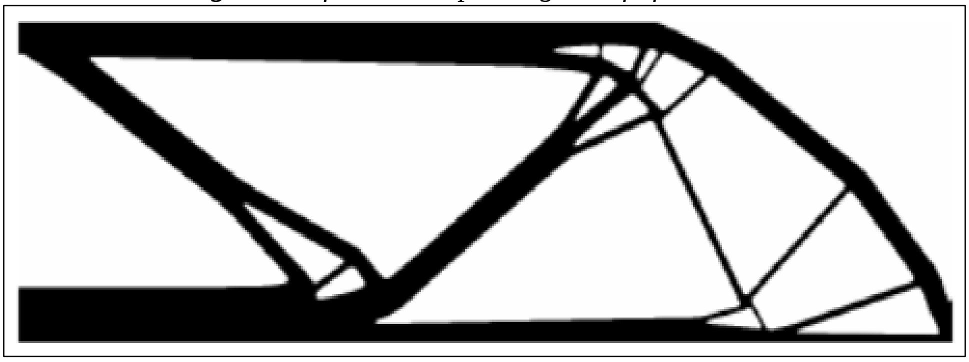


***Fig. 3b:*** *After applying Filters.*
***Fig. 3:*** *Showing the Topology Optimization of MBB Beam [4].*
*(Source: Philip Anthony Browne, PhD Thesis, 2013, UBath, UK).*

In his paper Yang [6] performed topology optimization of continuous structures with design dependent loads. Yang optimized a hinged beam structure with a minimum volume constraint of 20%. The initial structure is subjected to two types of loading conditions, top and bottom. The distribution clearly shows that an arch structure is the most ideal form to carry the load. In this paper, the analysis is performed for one case of top loading. The stress distribution of the elements along the arch clearly shows that the principal stresses are inclined at $45^0$ along the line joining the corners of the elements, forming a line of thrust. This line of thrust can be called as the theoretical arch which carries only compressive stresses and there is no bending at all. Lee [7] in his paper used stress constraint topology optimisation with design dependent loading. He used both compliance based minimization approach with volume constraints and mass minimization approach subjected to stress constraints. He solved a few examples of self-weight arch and self-weight column carrying load. Archana [8] in her paper performed the optimization of the self-weight arch using firefly algorithm. In this paper, the self-weight column problem is solved here.

## METHODOLOGY

A few commonly used structures in civil engineering have been solved using the proposed approach. Firstly, a bridge is designed using first order quadrilateral elements. The loading is applied along the top edge and the supports are provided at the bottom left end. Only one half of the structure is analysed due to symmetry. Secondly, a self-weight column is optimized using firefly algorithm. The entire design domain is discretized using four node quadrilateral elements. Lastly, a beam is designed using a similar approach. The beam designed here is Messerschmidt –Bolkow-Blohm beam (MBB beam). The load is applied at the mid-point on the top edge, and the supports are provided at the corners of the bottom edge. Only one half of the structure is analysed due to its symmetry. The final distribution of material in the domain is designed.

## ANALYSIS

### Assumptions

1. The first order quadrilateral elements cannot transfer any moment when connected at the corners only. In other words, the elements are edge connected with each other with two nodes in common. In the topology optimization of bridge problem, we observe that a few elements forming an arch are corner connected. The analysis has been done and the reasons were explained in the numerical problem below. These elements which are corner connected carry only one principal stress and the load is transferred along the line joining the diagonals of these elements, a theoretical line of thrust forming an arch
2. The stresses are calculated at the centroid of each element
3. The element carrying no stress can be assigned a relative density equal to 1e-5 to avoid any numerical situation
4. The allowable stress in tension and compression is considered as equal
5. The material is homogeneous and Isotropic, obeys Hooke’s Law

A program in C++ is used to perform the Topology Optimization. The configuration of the notebook is i7 microprocessor chip having 4 core and 4GB RAM.

### Arch Bridge [9]

The design domain is a rectangle having dimensions 5 x 2.5 m as shown in the Figure 4. The domain is discretized using 1250 first order quadrilateral elements in plane stress condition. Each element has four nodes. The material properties are as follows: Young’s Modulus of Elasticity is taken as 210 GPa and the Poisson’s ratio is taken as 0.3. The density of the material is taken as equal to 7800 kg/m$^3$. The thickness of the material is taken as equal to 0.05 m. The permissible stress is taken equal to 230 MPa. The domain carries a load of 30 N acting vertically downward is applied at each node along the top surface. One half of the structure is analysed due to symmetry. The number of elements is 625 and the number of nodes is 676. A total of 780 N is applied on one half of the structure. The optimum distribution of the material is shown in the Figure 5. Figure 5 shows that the optimum distribution of material is in the form of an arch. Figure 6 showing the distribution of the material by Bruyneel [x].

Figure 5 clearly shows that the elements which are corner connected carry only compressive stress and no moment. The number of element in the output was 99 out of a total of 625 elements, which is equal to 15.84% by weight of the structure.

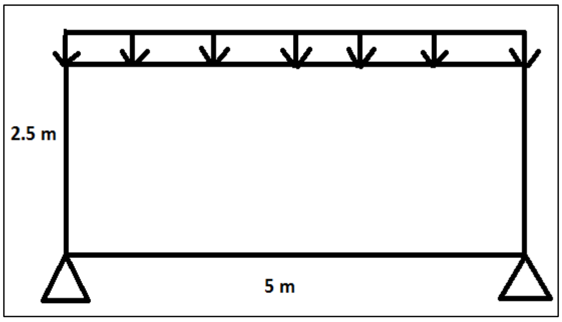



***Fig. 4:*** *The Design Domain is 5 x 2.5 m.*

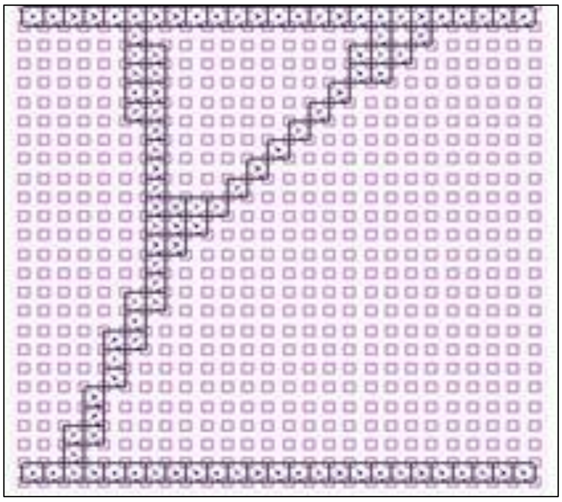


***Fig. 5:*** *Showing the Topology Optimisation of Bridge using Firefly (Left half of the structure by symmetry).*

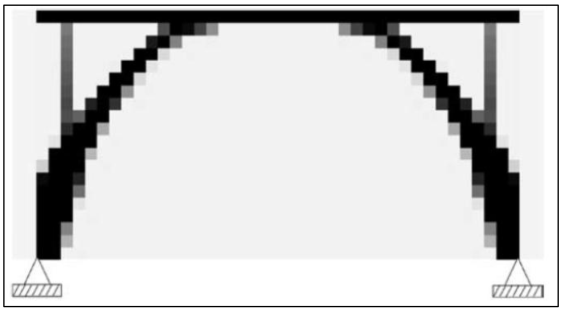
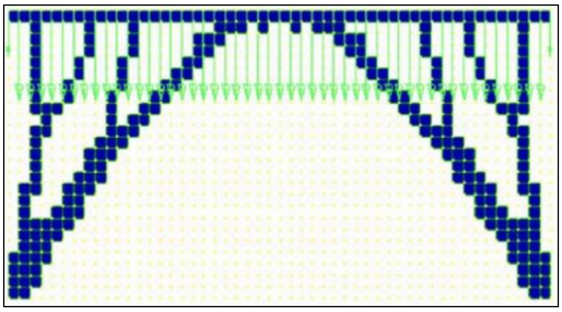
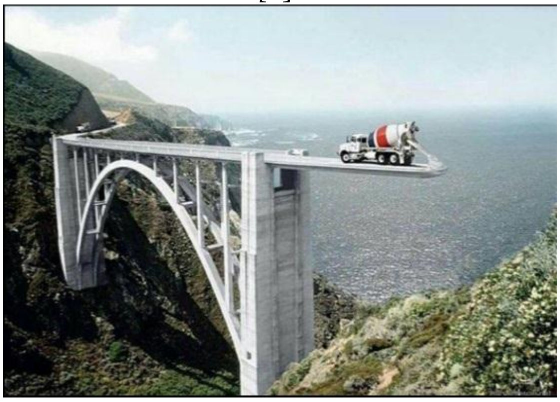


***Fig. 6:*** *Showing the Topology Optimization of Bridge by Bruyneel and Duysinx [10].*



*(a) Topology optimization of Deck type bridge [9].*



*(b) Real time Bridge Construction in RCC [11].*

***Fig. 7:*** *Showing the Distribution of Material in the given Domain and a Real Time Bridge Built in RCC.*

***Analysis of the Stress Field***

The output contains a few elements which are corner connected. Let us examine further, the stress carried by an element, say #386.

The stress field shows that

$$\sigma_x = \sigma_y = \tau_{xy} = -74908.9$$

Location of the principal plane

$$tan2\theta = \frac{2\tau_{xy}}{\sigma_x - \sigma_y} = tan90^0$$

The principal planes are inclined at $45^0$ to the plane containing the major normal stress, in other words the diagonal of the element. The magnitude of the principal stress is calculated as the eigen values of the stress matrix = -149818, 0. The negative sign indicates that the principal stress is compressive in nature. These elements which carry the material are connected at the corners to form an arch (Figure 7). These elements connected at the corner cannot transfer any moment and the line joining the diagonal of these elements can be the line of thrust for an arch. The stress carried by the row of elements at the lower end of the domain from left end to the centre is 0.02% of the maximum stress.

**Topology Optimisation of Column [9]**
A rectangular domain of 1.0 by 0.6 m as shown in the Figure 8 is meshed with 1500 elements first order quadrilateral elements. The number of nodes is 1581. The domain is fixed at the bottom. A load of 100 kN is applied at the top. The load is distributed to avoid any stress concentration. The material properties are taken as follows: The Young's Modulus of Elasticity is 2.1 x $10^5$ MPa and the Poisson Ratio is taken as 0.3. The density of the material is 7800 Kg/$m^3$. The maximum permissible stress is taken as 6.5 MPa.

The distribution of the material is as shown in the Figure 9.

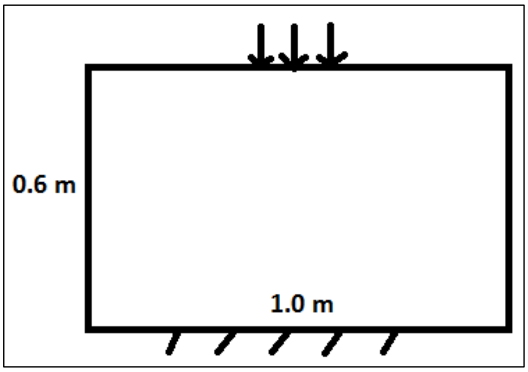
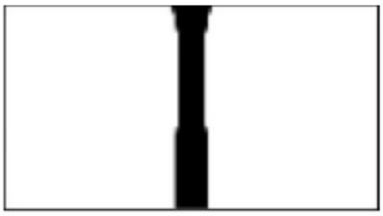
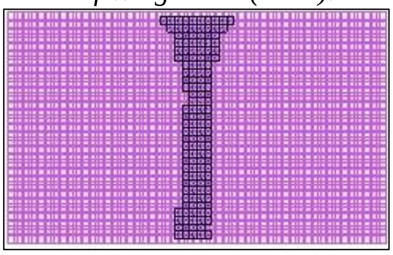



***Fig. 8:*** *Initial Design Domain 1.0 x 0.6 m.*



*(a) Optimum Topology of a Column including Self Weight Lee (2012).*



*(b) Optimum topology of a Column (No SelfWeight) Using Firefly Algorithm.*
***Fig. 9:*** *Topology Optimisation of Column using FFA.*

**Topology Optimisation of MBB Beam [2]**
As shown in the figure the entire design domain has a size of 2000 x 400 x 9 mm as shown in the Figure 10. The Young's Modulus of Elasticity is 68890 MPa and Poisson's ratio as 0.3. This beam is also known as Messerschmidt-Bolkow-Blohm (MBB) beam. Only one half of the beam is analysed. The dimensions of one half of the domain are 1000 x 400 x 9 mm. A load of 2000 N is applied at the centre of the beam as shown. The domain is discretized using 1000 four node first order quadrilateral elements. The total number of nodes is 1071. The maximum permissible stress is taken as 100 MPa. The number of elements which carry material at convergence is 151 which amount to 15.1% of total volume.

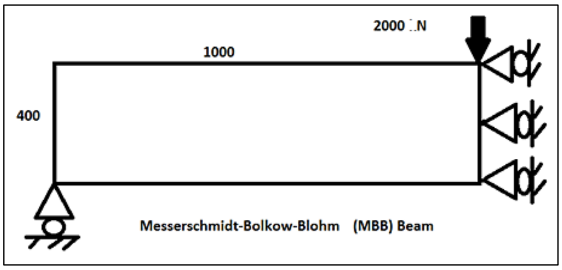
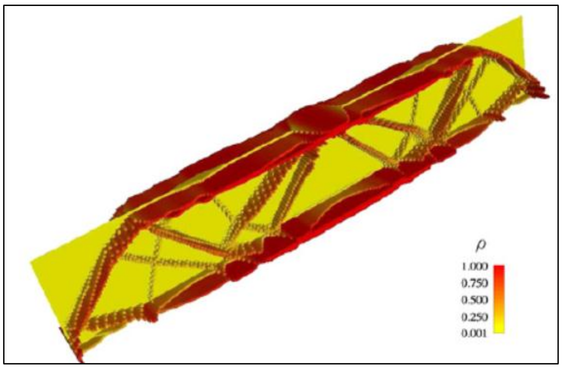
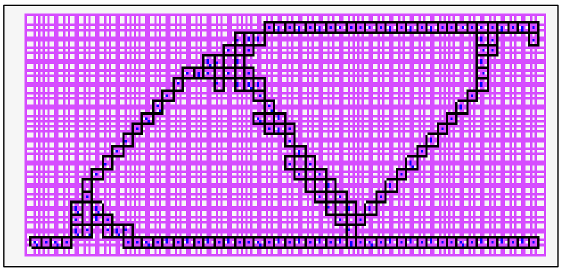



***Fig. 10:*** *Showing the Domain of the Left Half of MBB Beam (Dimensions in mm).*




*(a). 3D view of the optimum distribution by Paris et al. [12].*



*(b) Distribution of the material using FFA.*
***Fig. 11:*** *Showing the Distribution of Material for an MBB Beam.*

The load is distributed over five nodes to avoid any stress concentration. The support at the left end is spread over four nodes. The optimum distribution of the material is as shown in the Figure 11. Figure 11a shows the distribution of material by Paris et al. [12]. Figure 3a shows the result of the optimization of MBB Beam using mesh size 1200 x 480 = 480,000 elements having a total of 962,800 degree of freedom. The refined filtered output in Figure 3b shows the final design of MBB Beam.

**Limitations**

The given continuum is analysed using first order quadrilateral elements due to computational limitations. However, a higher order mesh can generate a better solution.

## CONCLUSIONS

This paper focus on the study of optimizing civil engineering structures using firefly algorithm. Firefly algorithm is one the best metaheuristic algorithms which can optimize in a relatively fewer number of iterations. In this paper, a bridge structure, MBB Beam and a column have been used examples. The distribution clearly shows that firefly algorithm can be effectively used to distribute the material in a given domain. Due to computational limitations only one engine is used in this paper.

**Future Study**

The study can be further extended to large structures such as two decks flyovers, shells.

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