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Topology Optimization of Plane Truss Structures Utilizing Bamboo Materials

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ABSTRACT :*.In general, plane truss structures are constructed using steel. However, this study deviated from usual practices by utilizing bamboo, a sustainable material. In addition to the consideration of materials, the shape or configuration (topology) of the plane truss structure is another important component to be considered during the design process. The topology of a structure plays a crucial role in determining its stability and strength to withstand the load. This study aims to utilize the binary dragon fly method for the purpose of identifying the most optimal shape or configuration (topology) in plane truss structures that consist of 4-nodes and 6-nodes. The binary dragonfly algorithm is a discrete version of the continuous dragon fly method. The objective function employed is to minimize the weight of the plane truss structure. The cross-sectional employed are consistent for every member. The binary dragonfly algorithm successfully achieved the optimal shape/configuration (topology) in both studied case studies, as indicated by the obtained results. Ineffective members will display the binary numeral 0. The design criteria encompass the stability of the plane truss structure, the slenderness factor, and the stresses experienced by each member.*
KEYWORDS *topologyoptimization, plane truss structures, bamboo material*

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I. INTRODUCTION

In designing a structure, it is essential to determine the optimal cross-sectional of its members. The purpose of this is to enhance the efficiency of material utilization, enhance structural integrity, increase stability, and minimize the impact of lateral load. Structures with sub-optimal cross-sectional tend to be unnecessarily heavy. Insufficient structural weight can also impact the overall structural performance, including the ability to withstand lateral loads. The lack of use of optimization methods is one of the many factors that causes the ineffectiveness of determining the size of structural cross-sections.

A few research have been conducted concerning the optimization of a plane truss structure's cross-sectional member area. [1] optimized the cross-sectional size using a genetic algorithm to obtain minimum weight. [2] conducted a study on topology optimization of plane truss structures utilizing steel materials. Most of this research employed steel materials. The study involved substituting steel with bamboo as a sustainable and renewable material in the construction of plane truss structure. The binary dragonfly algorithm was utilized in prior studies to optimize the cross-sectional dimensions of individual elements in both plane truss structures and space truss structures [3,4]. This study focused on optimizing the shape/configuration (topology) of a plane truss construction made of bamboo material.

Bamboo provides the capacity to be utilized in the domain of building construction. Bamboo cultivation requires minimal capital input, exhibits rapid growth, and serves as a sustainable material for construction projects of varying sizes. The inherent durability of bamboo is a primary contributing element to its utilization as a construction material [5]–[9]. Bamboo exhibits significant strength despite its very low density. The peculiar fibre structure of bamboo, characterized by oblique fibres, contributes to its strength and stability. Bamboo possesses a notable modulus of elasticity, enabling it to effectively absorb and distribute loads [10,11]. Utilizing bamboo as a construction material can effectively mitigate the present issue of carbon footprint [12-13]. Bamboo can serve as a viable substitute for steel material in specific circumstances [14].

II. PLANE TRUSS STRUCTURE

Truss structures are generally structures consisting of slender elements connected to each other at the ends. The connection at the ends is assumed to be a pin connection to form a stable and rigid structure. Typically, plane truss structures are composed of interconnected triangle shapes, each consisting of three parts. In modelling a truss structure, elements are only considered to bear axial forces (tensile axial forces or compressive axial forces) so that the elements do not experience bending or shear moments, whereas the word plane itself is because the truss structure is only in one plane (XY plane or XZ plane or YZ plane).

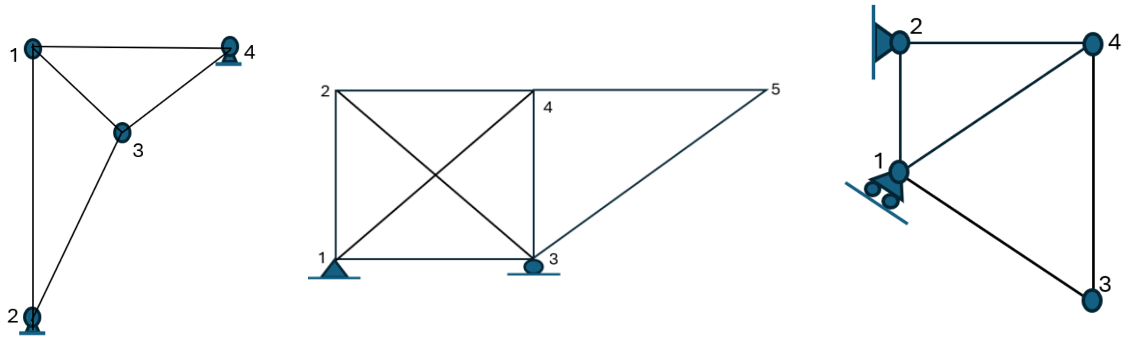

Fig.1. The illustration of plane truss structures [15]

In general, the structural analysis of a plane truss is as follows [16]:

1. Form a stiffness matrix in local coordinates and a transformation matrix,
2. Form a stiffness matrix in global coordinates,
3. Assemble the bar stiffness matrix in global coordinates into a structure stiffness matrix according to the ID vector,
4. Create a load vector matrix,
5. Calculating global displacement,
6. Calculate the deformation and forces of the bar.

III. TOPOLOGY OPTIMIZATION

Topology optimization is optimization carried out to obtain the optimum structure shape/configuration. Topology optimization selects from all possible shapes/configurations of a plane truss structure. Figure 2 shows an example of a possible structural form of a plane truss structure with 4 nodes. To determine the number of shapes/configurations of plane truss structures can be seen in equation (1)

$$p_m = (nodes - 1) * 0.5 * nodes \tag{1}$$

where: p_m is number of possible members and $nodes$ are the number of nodes in structure.

Hence, based on equation (xx), the possible shapes or configuration can be seen in Figure 2.

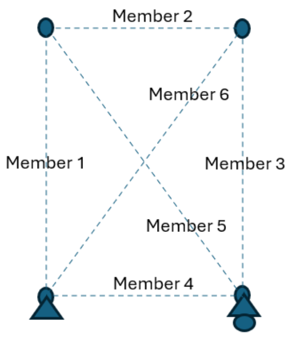

Fig.2. Possible shapes / configurations (topology) in plane truss structures with 4-nodes

Binary type optimization is employed to achieve the optimal shape/configuration of the plane truss structure. The binary value will accurately represent the shape or configuration of the plane truss structure. Illustrated in Figure 3 are the outcomes of a binary representation displaying the sequence [0 1 0 1 1 1] for a 4-nodes plane truss structure. The binary number obtained represents the configuration of the plane truss structure.

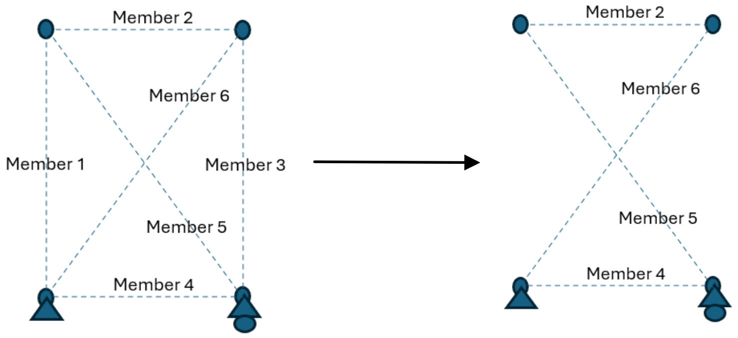

Fig.3. Illustration of binary numbers in topology optimization

IV. BINARY DRAGON FLY ALGORITHM

The dragonfly algorithm simulates the exploratory and exploitative mechanisms through dragonfly interactions to discover the most optimum solutions. The dragonfly algorithm involves five distinct behaviors shown by dragonflies, which include separation, alignment, cohesiveness, attraction, and distraction. The dragonfly utilizes these five behaviors to adjust its posture. Separation is intended to prevent individuals from colliding with each other in their surroundings. Alignment enables the synchronization of the velocity of each member within a flock or sub-herd. Cohesion pertains to the extent to which individuals in the dragonfly group deviate from the center of mass. Attraction implies that an individual must experience a sense of allure towards a food supply. Disturbance indicates that the individual must divert their attention away from potential threats.

Each behavior is defined as follows [17]:

1. Separation

   The purpose of separation is to avoid static collisions between the current and its neighboring individual. Theoretically, separation is expressed as follows:

$$S_i = -\sum_{j=1}^{M} X - X_j \tag{2}$$

where, X represents the location of a dragonfly in a D-dimensional space, M is the number of neighbor individuals, and X_j is the position of the neighbor individual.

2. Alignment

   Alignment facilitates the matching of individual’s velocities within a swarm or sub-swarm. The alignment is computed using the following formula:

$$A_i = \frac{\sum_{j=1}^{M} V_j}{M} \tag{3}$$

where, V_j is the velocity of neighborindividuals.

3. Cohesion

   Cohesion is the measure of how far an individual's position deviates from the center of mass of its neighboring individuals. Cohesion can be defined as follows:

$$C_i = \frac{\sum_{j=1}^{M} X_j}{M} - X \tag{4}$$

4. Attraction

Attraction implies that the individual ought to experience a natural inclination towards sources of food. Mathematically, the attraction is represented by the following equation:

$$F_i = X_f - X \tag{5}$$

where, X_f denotes the location of a food origin.

5. Distraction

Distraction is redirecting the attention of the individual away from a predator. The calculation for the distraction is as follows:

$$E_i = X_e + X \tag{6}$$

where, X_e represents the enemy's position.

The movement of dragonflies in DA is governed by these five actions. To update the position of each dragonfly, the subsequent step vector is computed:

$$\Delta X_i(t+1) = (s.S_i + \alpha.A_i + c.C_i + f.F_i + e.E_i) + w.\Delta X_i(t+1) \tag{7}$$

where: s, α, c, f, e are the weight of each behavior, w is inertia weight, t represents the current iteration and ΔX_i is step vector.

The position vectors of BDA are modified using the following equations:

$$TF(\Delta X) = \left|\frac{\Delta X}{\sqrt{\Delta X^2 + 1}}\right| \tag{8}$$

$$X_i^d(t+1) = \begin{cases} 1 - X_i^d(t) & rand < TF(\Delta X_i^d(t+1)) \\ X_i^d(t) & rand \geq TF(\Delta X_i^d(t+1)) \end{cases} \tag{9}$$

where, X_i^d is the d-th position of i-th dragonfly, $rand$ is randomly generated number within the range of 0 and 1, TF is transfer function.

V. METHODOLOGY

This research considered two case studies of plane truss structures, specifically those with 4-nodes and 6-nodes, as depicted in Figure 4.

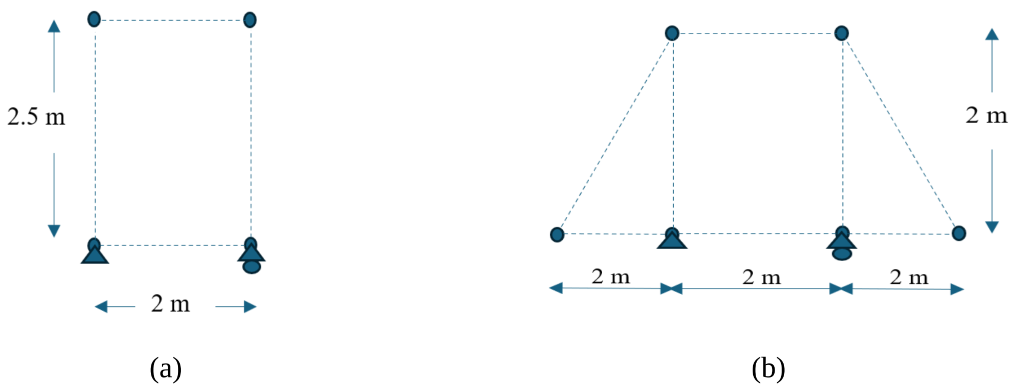

Fig.4. Plane truss structures (a) 4-nodes, (b) 6-nodes

The research utilizes bamboo material that has undergone experimental testing to determine its characteristics [3]. Every member in the current study has a homogeneous cross-sectional dimension of 3382.71 mm2. The designing criteria employed includes the slenderness limits of each component and the allowable tensile/compressive stress of the bamboo material utilized. The allowable compressive stress is set at 40 MPa, while the allowable tensile stress is 280 MPa, with a modulus of elasticity of 15000 MPa. The compressive stress and tensile stress are determined as follows:

1. Compressive stress
   The compressive stress is determined based on the slenderness ratio of each member, taking into consideration the potential occurrence of buckling. Three equations are utilized to compute the design compressive stress value, which is contingent upon the slenderness number of the bar [18]. These equations are:

$$\text{If } \frac{le}{d} \leq 11 \; then Fa = Fc \tag{10}$$

$$\text{If } 11 \leq \frac{le}{d} \leq K then Fa = Fc.\left[1 - \frac{1}{3}\left(\frac{le/d}{K}\right)^4\right] \tag{11}$$

$$\text{If } K \leq \frac{le}{d} \leq 50 \; then \; Fa = \frac{0{,}3E}{(le/d)^2} \tag{12}$$

where, K is a constant with a value of $0.671\sqrt{E/Fc}$, le is unbraced length of member(cm), d is bamboo diameter (cm), Fa isdesigned compressive strength (kg/cm^2), Fc isallowable compressive strength (kg/cm^2), E is elastic modulus of bamboo (kg/cm^2)

The compressive stress may be determined using a simple equation, specifically

$$F_{comp} = \frac{P_{comp}}{A}, F_{comp} \leq 0{,}22Fa \tag{13}$$

where, F_{comp} isoccured compressive strength (kg/cm^2), P_{comp} iscompressive axial force inmember (kg), A is cross-sectional of member (cm^2)

The value of 0.22 is a safety factor derived from ISO 22156:2004, which applies to both compression and tension members [19].

2. Tensile stress
   For members subjected to tension, the magnitude of the tensile stress remains unaffected by the slender nature of the rod. Therefore, there is no need to adjust the allowable tensile stress value, as it may be directly compared to the tensile axial stress that arises. Equation (13) displays the computation for tensile stress.

$$F_{tens} = \frac{P_{tens}}{A}, F_{tens} \leq 0{,}22Fti \tag{14}$$

where, F_{tens} isoccuredtensile strength (kg/cm^2), P_{tens} istensile axial force in member (kg), A is cross-sectional of member (cm^2), Fti is allowable tensile stress (kg/cm^2)

The aim is to decrease the weight of the plane truss structure by utilising bamboo material. The fitness value provides an indicator for this. Hence, the equation for the objective function (fitness) is as follows:

$$Fitness = \sum_{k=1}^{n} \rho A_k l_k \tag{15}$$

where, ρ is density, A_k is cross-sectional of member-k and l_k is the length of member-k

Topology optimization algorithm, calculation and analysis of the plane truss structures were developed using MATLAB R2022a [20-22].

VI. RESULT AND DISCUSSIONS

1. STUDY CASE-1: 4-NODES PLANE TRUSS STRUCTURE

Figure 5 illustrates the loading condition considered in the analysis. Specifically, a load of 1.5 kN is applied to the top chord of plane truss structure, while hinge and roll are positioned at the bottom nodes. Figure 6 (a) shows the possible shape/configuration of the plane truss structure for the first case study. According to equation (1) and assuming there are 4 nodes, the plane truss construction can have a total of 6 potential members. The optimal shape/configuration of the structure is represented by figure 6 (b). The results indicate that the utilization of member-4 is ineffective, as the structure remains stable and fulfil the design criteria even in its absence.

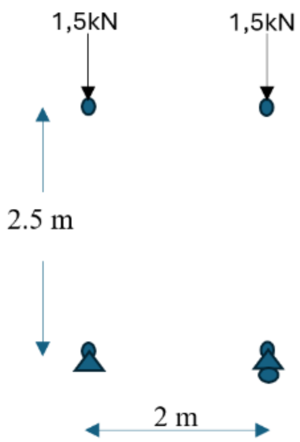

Fig.5. Loading condition for first case study of plane truss structure

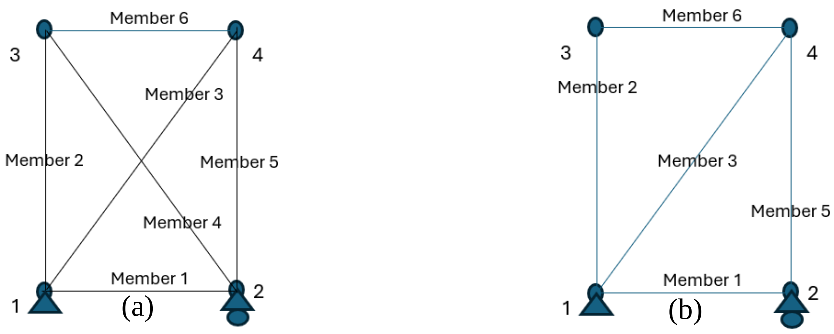

Fig.6. (a) Possible topology, (b) Optimized topology for first study case

Figure 7 illustrates the gradual decline in the fitness value for each iteration. The analysis reveals that the binary dragon fly algorithm achieved the optimal solution in less than 10 rounds although 100 iterations was used as initial consideration. Table 1 presents the outcomes of topology optimization, including the binary value and structure weight. The obtained weight of the structure is 29,3048 kg, assuming that the cross-sectional area for each member is uniform at 3382.71 mm2.

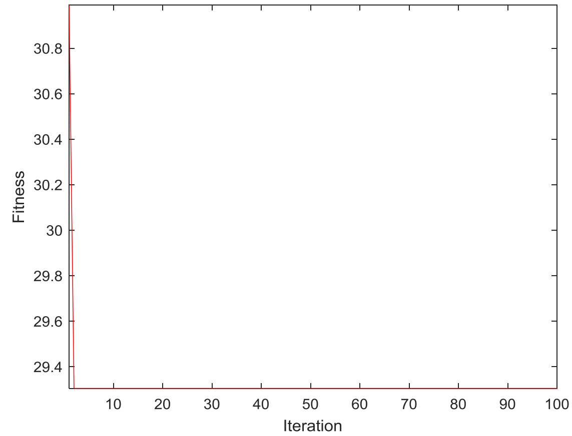

Fig.7. Fitness for each iteration for first study case

Table 1. Binary value of each member and total weight of plane truss structure after optimization for first study case

Member	Binary Value	Cross-sectional area (mm^2)	Length (mm)
1	1	3382.71	2000
2	1	3382.71	2500
3	1	3382.71	3201.5621
4	0	0	0
5	1	3382.71	2500
6	1	3382.71	2000
Weight of Plane Truss Structure (kg)			29.3048

2. STUDY CASE-2: 6-NODES PLANE TRUSS STRUCTURE

The second case study involves a 6-node planar truss system. According to equation (1), the number of possible members in this plane truss structure is 12 for a configuration with 6 nodes. Figure 9(a) displays the possible shape or configuration (topology) for the second scenario. Similarly, to the first scenario, a load of 1.5 kN is applied to the top chord, as shown in Figure 8. At nodes 2 and 3, restraints in the form of hinges and rolls are used. The optimal topology for the second scenario is depicted in Figure 9.(b). Based on Figure 9.(b), members 9, 10, and 12 are ineffective for use. Table 2 presents the total weight of the structure, which comes out to 49.2 kg.

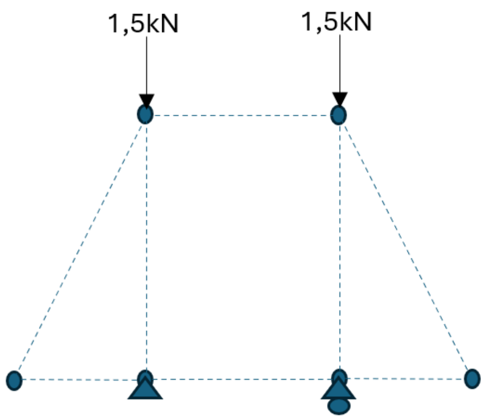

Fig.8. Loading condition for second study case

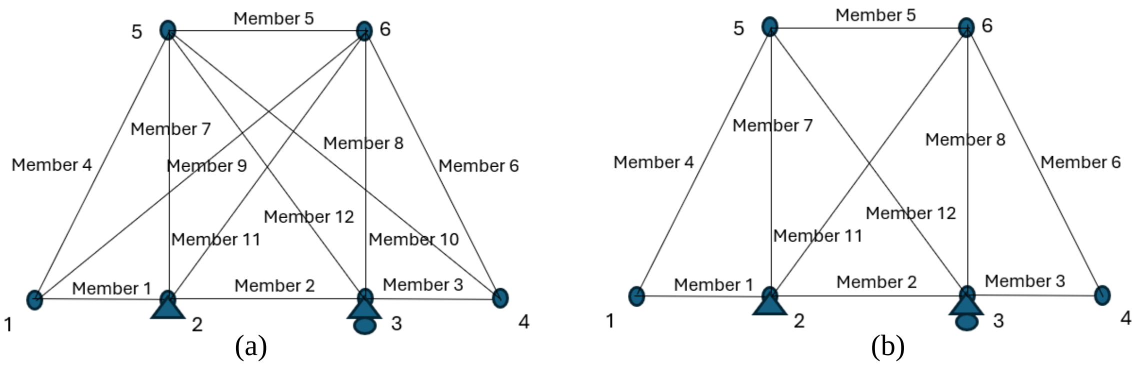

Fig.9. (a) Possible Topology, (b) Optimized Topology for Second Study Case

Figure 10 displays the fitness value for each iteration in the second study case. Similarly, to the previous case (first study case), the binary dragonfly algorithm can identify the optimal topology within a limited number of iterations (less than 50 iterations out of a total of 500 iterations).

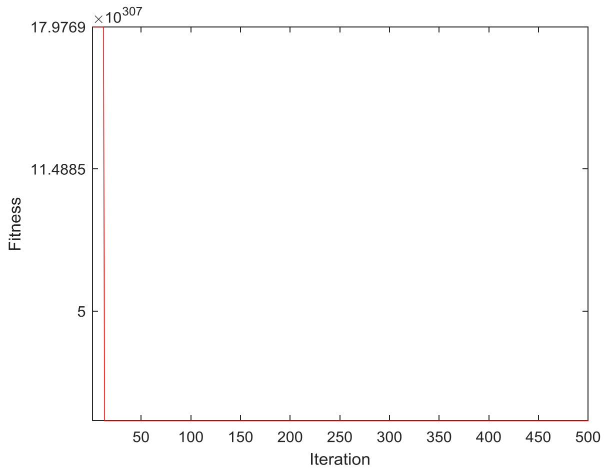

Fig.10. Fitness for each iteration for second study case

Table 2. Binary value of each member and total weight of plane truss structure after optimization for second study case

Member	Binary Value	Cross-sectional area (mm^2)	Length (mm)
1	1	3382.71	2000
2	1	3382.71	2000
3	1	3382.71	2000
4	1	3382.71	2828.4271
5	1	3382.71	2000
6	1	3382.71	2828.4271
7	1	3382.71	2000
8	1	3382.71	2000
9	0	0	0
10	0	0	0
11	1	3382.71	2828.4271
12	0	0	0
Weight of Plane Truss Structure (kg)			49.2000

VII. CONCLUSION

This paper presents a study concerning topology optimization of plane truss structures, focusing on two specific case studies. The potential members are represented by the binary digits 0 and 1. A binary number of 0 indicates the absence of a member, whereas a binary number of 1 indicates the presence of a member at a certain location. The binary dragonfly method has been employed for this objective. The main objective is to minimize the weight of the plane truss construction while considering the design criteria. The binary dragonfly algorithm has proven to be effective in determining the optimal topology for plane truss structures. This may be observed from both the first and second case studies. The ineffective member has not been considered in the outcome. The optimized weight of the structure is 29.3048 kg for the first study case and 49.2 kg for the second study case.

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