

Structural Optimization by Successive Correction to Nodal Positions

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ABSTRACT: Optimization of structures has always been a subject of continuous interest in the field of structural engineering. The amount of research work and publications in this field show various mathematical approaches adopted to effectively use materials used for construction. A novel iterative Perfect Nodal Position Search Method (PNPSM) for the evolution of optimum design of trusses is presented. This method does the analysis, design, generates the optimum topology, and arrives at minimum sizes of members, subjected to given stress and movement constraints. Efficiency of a member is determined at every level of iteration, end nodes are moved to improve the efficiency of the member.

KEYWORDS: Structural Optimization, Topology, Sizing, Shape, Trusses, Iterative Process, nodal position

I. INTRODUCTION

Two dimensional trusses are basic and commonly used form of construction. Evolutionary ideas in optimizing the size of members, shape and topology lead to preservation of precious material.

In the analysis of a structure by the Standard Direct Stiffness Matrix Method, a Global Stiffness Matrix is assembled from individual element stiffness matrices. Support conditions are imposed by manipulation of corresponding elements in global stiffness matrix. With the force vector on the right hand side, simultaneous equations are solved to get displacements at nodes and forces in members and Stresses are determined.

Sizing is mainly governed by the permissible stresses in the material under different conditions. The tensile stress limit could be a factor of the yield stress. An ideal situation is the one for which the material strength gets fully exploited for all the members, simultaneously.

Shape Optimization involves finding out a shape of a truss which gives minimum weight. Trying to find out the perfect shape of truss, some members may turn out to be totally inefficient, with the cross sectional areas demanded by size optimization reducing to minimum. Judicious removal of such members from the configuration of the truss, give rise to the best topology.

II. EVOLUTION OF PERFECT NODAL POSITION SEARCH METHOD

The proposed method uses the Direct Stiffness Matrix Method for the analysis of the truss, with the initial values of member properties like A (Cross sectional area) and E (Young's Modulus of the material) and l (Length of the member) are taken as inputs for the determination of element stiffness.

Solution is obtained for forces and the axial stresses. The ratio of actual stress to the permissible stress in the material at a cross section of a member is called utility ratio of that member, U. If $U > 1$, the member is unsafe.

At a typical node, let us assume that there are ‘m’ number of members connected to it. Let the cross sectional areas be $A_1, A_2, A_3, \dots, A_m$ and lengths be $l_1, l_2, l_3, \dots, l_m$. Performing the analysis and getting a safe design, need not lead to an optimum design. Let us assume the utility ratios of the members be $U_1, U_2, U_3, \dots, U_m$, all of them being less than unity for a safe design. Utility ratios of members is the guiding premise for the formulation of Perfect Nodal Position Search Method (PNPSM) that lead to optimum design through a sequential achievement of the following criteria

Criterion-1: Sizing optimization is achieved by forcing change in cross sectional areas of members to reach values that give utility ratios close to unity.

Achieving this condition for all the members, necessitates search for strategic node location, which has prompted the criterion given below.

Criterion-2 : If a node can be moved to a new position such that all the members connected to it reach the utility ratios very close to unity simultaneously, then that position is deemed to be the perfect position for the node.

Criterion-3 : In the search process, If a member area demanded is negligible Cross sectional area) the indication is that such members are ineffective and the truss can perform without that member in question, as a part of the current configuration.

Criterion-4: If all the members at a node are ineffective, then the truss can survive without that node, indicating it can be collapsed to any node.

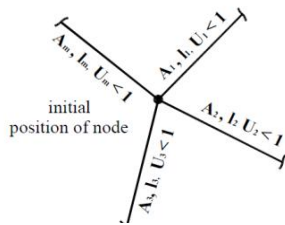


Fig. 1. Initial Position of Node

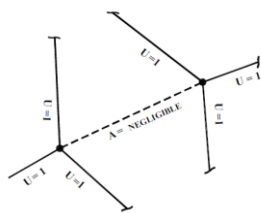


Fig. 3. Criterion for Removal of a Member

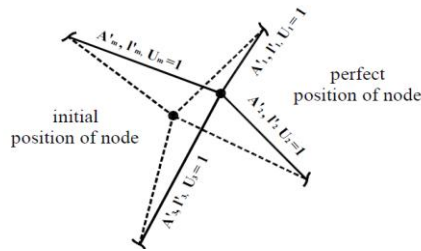


Fig. 2. Perfect position of Node

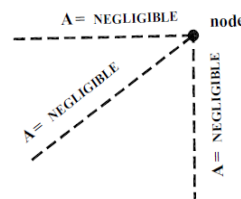


Fig. 4. Criterion for Removal of a Node

The multi objective optimization of trusses with same material can now be viewed as finding out the perfect nodal positions such that all the members of the truss, subjected to given set of constraints

- a) have non negligible cross sectional areas
- b) have utility ratios equal to unity (ideal situation)
- b) have a set of lengths such that total weight of the truss W , is minimum

$$\text{Where } W = \text{Unit wt} \times \text{Sum of } (A_i \times l_i) \text{ -- Eq. 1}$$

$i = 1$ to m , where A_i is cross sectional area and l_i is the length of of the i th member.

Movement of node changes the lengths of members connected to the node. The reverse is also true. The change in lengths of members connected to a node, moves the node. To achieve the minimum, the problem is approached from three angles. 1)reduce the length, if cross sectional area is to remain the same 2)Reduce the cross sectional areas if the

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lengths is to remain the same. 3) Increase the effectiveness. With these in mind, the lengths of members connected at a node are changed based on their relative qualification.

Factor for weight consideration (C_1) $C_{1i} = w_i / \text{sum of } (w_i)$ ---- Eq. 2

$i = 1$ to m , where w_i is the weight of the i th member

Factor for area consideration (C_2) $C_{2i} = A_i / \text{sum of } (A_i)$ ---- Eq. 3 $i = 1$ to m , where A_i is sectional area of the i th member

Factor for inefficiency (C_3) $C_{3i} = 1 - U_i$ ---- Eq. 4

where U_i is utility ratio of the i th member

Total forced change in length of i th member, dl in the direction of member

$$dl_i = MF \cdot C_{1i} C_{2i} C_{3i} l_i \text{ ---- Eq. 5}$$

where MF is the maximum percentage modification desired per iteration. When the member length changes by dl , the node will be moved with respect to its original position by dxl in the global X axis and dyl in the Global Y axis.

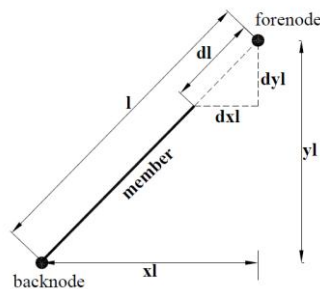


Fig. 5. Forced Change in Length of a member

$$X_{\text{new}} = X_{\text{old}} + \text{sum of } (dxl) \text{ ---- Eq. 6}$$

$$Y_{\text{new}} = Y_{\text{old}} + \text{sum of } (dyl) \text{ ---- Eq. 7}$$

If all the members at a joint are efficient, the node is not moved. This ensures the convergence of the solution for optimization. On the other hand, the node will be forced to move relatively when every member is subjected to a forced change in length, every time checking the node position for a possible set of movement restrictions specified in the problem.

III. ITERATIVE PROCEDURE

The PNPSM is an iterative procedure with distinct loops for sizing and shape optimization. Topology optimization is achieved during the course of shape optimization.

After every loop for solution for stresses, member lengths are modified as per Eq. 5 to effect change in nodal positions and the whole procedure is repeated to get another set of stabilized utility ratios. The procedure is repeated till we get a stabilized set of utility ratios of all effective members equal to unity.

While iterative loop in progress, some of the members of the truss are identified ineffective and Young's modulus values of such members are considered negligible for the consecutive loop. Fig.9 shows the flowchart for the implementation of the PNPSM.

IV. NUMERICAL EXAMPLE

The 15 bar truss problem, shown in Fig.6, solved by many researchers [6] has been treated as benchmark to check the efficiency of the PNPSM algorithm. The optimum design is to be achieved with the properties and movement restrictions stated in Table 1.

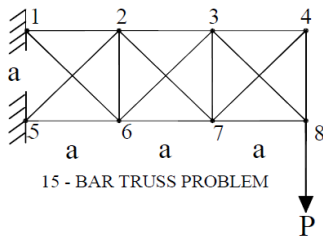


Fig. 6. Benchmark Problem

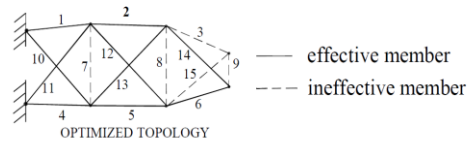
$P = 10$ kips (44.48 kN)
 $a = 120$ in (3048 mm)
 density = 0.1 lb/cu. in (2768 kg/ Cu. m)
 $E = 10000$ ksi (68947.6 N/ Sq. mm)
 limit = 25 ksi (172.0 N/ Sq. mm)

Table 1. Constraints for Nodal Movements

JOINT No.	CO-ORDINATES		Permissible Freedom			
	X	Y	Min X	Max X	Min Y	Max Y
1	0	120	0	0	120	120
2	120	120	100	140	100	140
3	240	120	220	260	100	140
4	360	120	360	360	50	90
5	0	0	0	0	0	0
6	120	0	100	140	-20	20
7	240	0	220	260	-20	20
8	360	0	360	360	20	60

ons : $X_6 = X_2$, $X_7 = X_3$, $X_8 = X_4$

Fig 7. Configuration for Minimum Weight - Topology



V. RESULTS AND DISCUSSION

The optimum topology evolved is shown in Fig. 7. Table 2 shows the set of Length, Area and Utility ratio for every member at the instance of optimum design. PNPSM clearly identifies member numbers 3,7,8,9 and 15 as ineffective. Table 3 shows the sizing and layout variables obtained by PNPSM in comparison with the results given in references. shows the weight reduction of the truss corresponding to iterations performed with a typical Modification Factor 5%

A study has been conducted to know the effect of Modification Factor (MF) in PNPSM on the convergence to the optimum design of the 15-Bar Truss. Fig. 9 shows the flow chart for PNPSM.

Fig 8. Typical Graph Showing Weight Reduction of Truss

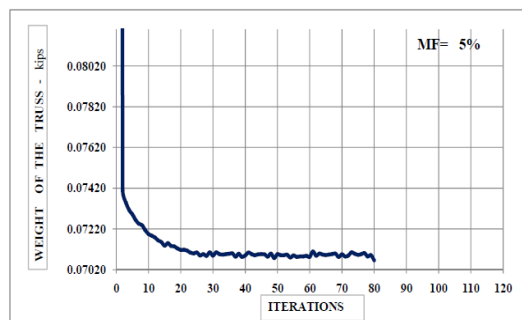


Table 2. Final Sectional Areas and Utility Ratios

MEMB AREAS - COMPARISON OF RESULTS						
MEMB	EARLIER WORKS [6]					Present Work
	Gholizadeh	Tang et	Hwang and He	Rahami	Kulkarni	
Sizing variables (in. ²)						
A1	0.95	1.08	0.95	1.08	0.95	0.87
A2	0.54	0.54	1.08	0.54	0.54	0.73
A3	0.27	0.29	0.44	0.29	0.11	0.00
A4	1.08	0.95	1.17	0.95	0.95	1.13
A5	0.54	0.95	1.49	0.54	0.54	0.47
A6	0.17	0.22	0.03	0.14	0.35	0.41
A7	0.11	0.11	0.27	0.11	0.11	0.00
A8	0.11	0.11	0.35	0.11	0.11	0.00
A9	0.44	0.29	0.22	0.54	0.11	0.00
A10	0.44	0.22	0.44	0.44	0.44	0.47
A11	0.35	0.44	0.35	0.54	0.44	0.10
A12	0.22	0.44	0.22	0.27	0.17	0.10
A13	0.22	0.11	0.27	0.22	0.17	0.47
A14	0.17	0.22	0.44	0.14	0.35	0.52
A15	0.27	0.35	0.22	0.29	0.11	0.00
Wt (lbs)	73.93	79.82	104.57	76.69	72.52	70.66

Table 3. Comparison of Results for Benchmark Problem.

RESULTS WITH REDUCTION FACTOR = 5 %				
15 - MEMBER TRUSS - OPTIMUM DESIGN				
	AREA	STRESS	Allow. Stress	RATIO
Mem	Sq. in	ksi	ksi	
1	0.8671	25.00	25.00	1.00
2	0.7321	25.00	25.00	1.00
3	0.0000	0.00	25.00	0.00
4	1.1332	-25.00	25.00	1.00
5	0.4670	-25.00	25.00	1.00
6	0.4050	-25.00	25.00	1.00
7	0.0000	0.00	25.00	0.00
8	0.0000	0.00	25.00	0.00
9	0.0000	0.00	25.00	0.00
10	0.4700	25.00	25.00	1.00
11	0.0951	-25.00	25.00	1.00
12	0.0960	25.00	25.00	1.00
13	0.4710	-25.00	25.00	1.00
14	0.5200	25.00	25.00	1.00
15	0.0000	0.00	25.00	0.00

VI. CONCLUSIONS

Perfect Nodal Position Search Method is appealing, as convergence is faster and the optimum shape, topology and member sizing is accomplished simultaneously. Suitable modifications to element stiffness matrix, extends its usage potential to 3D trusses too.

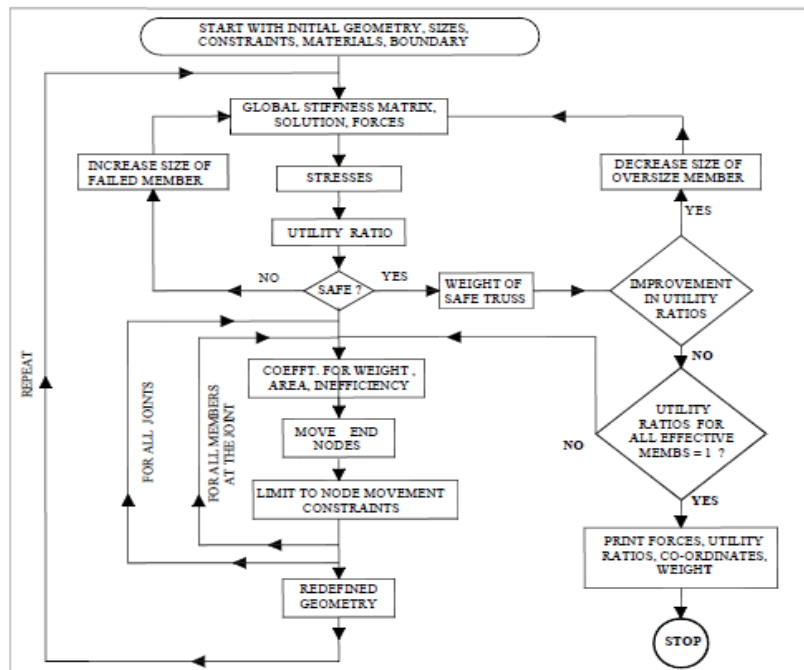


Fig. 9. Flowchart for the Perfect Nodal Position Search Method

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