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COST MINIMIZATION OF WELDED BEAM DESIGN PROBLEM USING NONTRADITIONAL OPTIMIZATION THROUGH MATLAB AND VALIDATION THROUGH ANSYS SIMULATION

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ABSTRACT

The objective functions used in Engineering Optimization are complex in nature with many variables and constraints. Conventional optimization tools sometimes fail to give global optima point. Very popular methods like Genetic Algorithm, Pattern Search, Simulated Annealing, and Gradient Search are useful methods to find global optima related to engineering problems. This paper attempts to use new non-traditional optimization algorithms which are used to find the minimum cost of designing welded beam to obtain global optimum solutions. The cost, number of iterations and the total elapsed time to complete the problems are all compared using these ten non-traditional optimization methods and the results are validated using Ansys

Keywords: Welded beam design, Pattern search, Simulate annealing, Pattern search, GODLIKE, Cuckoo search, Firefly algorithm, Flower pollination, Ant lion optimizer, Gravitational search algorithm, Multi-verse optimizer

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1. INTRODUCTION

Welding can be defined as a process of joining metallic parts by heating to a suitable temperature with or without the application of pressure. Welding is an economical and efficient method for obtaining a permanent joint of metallic parts. There are two distinct applications of welded joints.

- A welded joint can be used as a substitute for a riveted joint

- A welded structure can be used as an alternative method for casting or forging.

Welding process are broadly classified with the following two groups

- Welding process that use heat alone to join the two parts
- Welding process that use a combination of heat and pressure to join the two parts.(Bhandari.V.B)

The welding process that uses heat alone is called fusion welding process. In this method the parts to be joined are held in position and molten metal is supplied to the joint. The molten metal can come either from the parts themselves called Parent metal or external filler metal is supplied to the joint. The joining surface of two parts becomes plastic or even molten under the action of heat. When the joint solidifies, the two parts fuse into a single unit.

A beam is a member subjected to loads applied transverse to the long dimension, causing the member to bend. Beams are frequently classified on the basis of supports or reactions. A beam supported by pins, rollers or smooth surfaces at the ends is called simple beam. A beam support will develop a reaction normal to the beam but will not produce a moment at the reactions. If either or both ends of a beam projects beyond the supporters, it is called simple beam with overhang.

2. DESCRIPTION

A beam A is to be welded to a rigid member B. The welded beam is to consist of 1010 steel and is to support a force P of 6000 lb. The dimensions of the beam are to be selected so that the system cost is minimized. A schematic of the system is shown in the figure 1.

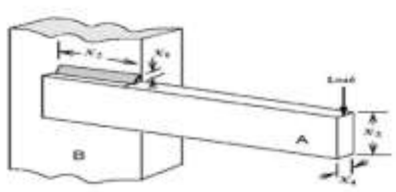


Figure 1: Welded Beam.

The diagram illustrates a rigid member (A) welded onto a beam. A load is applied to the end of the member. The beam is to be optimized for minimum cost by varying the weld and member dimensions $X = (h,l,t,b) = (x_1, x_2, x_3, x_4)$.

This includes limits of the shear stress, bending stress, buckling load and end deflection. The variables x_1 and x_2 are integer multiples of 0.0625 inch, but for this application are assumed continuous. (Amie Mesari, 2012) (Hong-Shaung Li, Siu-Hui Au, 2010)

2.1. PARAMETERS: (Welded Beam Design Optimization)

Young's Modulus (psi)

$$E = 30 \times 10^6 \ psi$$

Shearing modulus for the beam material (psi)

$$G = 12 \times 10^6 \ psi$$

Overhang length of the member (inch)

$$L = 14 in$$

Design stress of the weld (psi)

$$\tau_{max} = 13600 psi$$

Design normal stress for the beam material (psi)

$$\sigma_{max} = 30000 psi$$

Maximum deflection (inch)

$$\delta_{max} = 0.25 in$$

Load (lb)

$$P = 6000 lb$$

2.2. COST FUNCTION: (Welded Beam Design Optimization)

The performance index appropriate to this design is the cost of a weld assembly. The major cost components of such an assembly are (1) set up labour cost, (2) welding labour cost, and (3) material cost:

$$f(X) = C_0 + C_1 + C_2$$

where $f(X)$ = cost function

C_0 = set up cost

C_1 = welding labor cost

C_2 = material cost

2.2.1. Setup Cost C_0

The company has chosen to make this component a weldment, because of the existence of a welding assembly line. Furthermore, assume that fixtures for setup and holding of the bar during welding are readily available. The cost C_0 can therefore be ignored in this particular total-cost model.

2.2.2. Welding Labour Cost C_1

Assume that the welding will be done by machine at a total cost of \$10/hr (including operating and maintenance expense). Furthermore, suppose that the machine can lay down a cubic inch of weld in 6 min. The labour cost is then $C_1 = \left(10 \frac{\$}{hr}\right)\left(\frac{1}{60}\frac{hr}{\min}\right)\left(6\frac{\min}{in^3}\right)V_w = 1\left(\frac{\$}{in^3}\right)V_w$

Where V_w = weld volume, in^3.

2.2.3. Material Cost C_2

$$C_2 = C_3 V_w + C_4 V_B$$

where C_3 = cost per volume per weld material, \$/in^3 = (0.37)(0.283)

C_4 = cost per volume of bar stock, \$/in^3 = (0.17) (0.283)

V_B = volume of bar A, in^3.

From the geometry,

$$V_w = 2\left(\frac{1}{2}h^2 l\right) = h^2 l$$

Volume of the weld material (inch^3)

$$V_{weld} = x_1^2 x_2$$

And $V_B = tb(L+l)$,

Volume of bar (inch^3)

$$V_{bar} = x_3 x_4 (L + x_2)$$

Therefore the cost function become $f(X) = h^2 l + C_3 h^2 l + C_4 tb(L+l)$

Or, in terms of the x variables,

$$f(X) = (1+C_3)x_1^2 x_2 + C_4 x_3 x_4 (14.0 + x_2)$$

$$f(X) = 1.10471 x_1^2 x_2 + 0.04811 x_3 x_4 (14.0 + x_2)$$

2.3. ENGINEERINGRELATIONSHIP:(Hasancebi.O, 2012)

To complete the model, it is necessary to define the important stress states.

Weld stress

$$\tau(X) = \sqrt{\tau_1^2 + 2\tau_1\tau_2\cos\theta + \tau_2^2} \text{ Where } \cos\theta = \frac{x_2}{2R}$$

Weld stress has two components τ_1 and τ_2, where τ_1 the primary stress acting over the weld throat area and τ_2 is a secondary torsional stress.

Primary stress acting over the weld throat

$$\tau_1 = \frac{P}{\sqrt{2}\, x_1 x_2} = \frac{6000}{\sqrt{2}\, x_1 x_2}$$

Secondary torsion stress

$$\tau_2 = \frac{MR}{J}$$

Moment of P about centre of gravity of weld setup

$$M = P\left(L + \frac{x_2}{2}\right) = 84000 + 3000\, x_2$$

$$R = \sqrt{\frac{x_2^2}{4} + \left(\frac{x_1 + x_3}{2}\right)^2}$$

Polar moment of inertia of weld

$$J = 2\left\{\sqrt{2}\ x_1 x_2 \left[\frac{x_2^2}{12} + \left(\frac{x_1 + x_3}{2}\right)^2\right]\right\}$$

Bar bending stress: The maximum bending stress can be shown to be equal to

$$\sigma(X) = \frac{6PL}{x_4 x_3^2} = \frac{504000}{x_4 x_3^2}$$

Bar deflection. To calculate the deflection, assume the bar to be a cantilever of length

$$\delta(X) = \frac{4PL^3}{E x_3^3 x_4} = \frac{2.1952}{x_3^3 x_4}$$

The buckling load is approximated by

$$P_c(X) = \frac{4.013E\sqrt{\frac{x_3^2 x_4^6}{36}}}{L^2}\left(1 - \frac{x^3}{2L}\sqrt{\frac{E}{4G}}\right) = 64746.022(1 - 0.028234x_3)x_3 x_4^3$$

2.4. CONSTRAINT

The shear stress at the beam support location cannot exceed the maximum allowable for the material

$$\tau(X) \le \tau_{max} \qquad \tau(X) \le 13600$$

The normal bending stress at the beam support location cannot exceed the maximum yield strength for the material

$$\sigma(X) \le \sigma_{max} \qquad \frac{504000}{x_4 x_3^2} \le 30000 \qquad 16.8 \le x_4 x_3^2$$

The weld thickness is less than the material thickness

$$x_1 \le x_4$$

$$c_3 x_1^2 + c_4 x_3 x_4 (L + x_2) \le 5.0$$

$$0.10471 x_1^2 x_2 + 0.04811 x_3 x_4 (14.0 + x_2) \le 5.0$$

The defined minimum must be less than the weld thickness

$$0.125 \le x_1$$

The deflection cannot exceed the maximum deflection

$$\delta(X) \le \delta_{max}$$

$$\frac{2.1952}{x_3^3 x_4} \leq 0.25$$

$$8.7808 \leq x_3^3 x_4$$

The applied load is less than the buckling load

$$P \leq P_c(X)$$

$$6000 \leq 64746.022(1-0.028234x_3)x_3 x_4^3$$

$$0.0926697859 \leq (1-0.028234x_3)x_3 x_4^3$$

Size constraints

$$x_1 \geq 0.1$$

$$x_2 \geq 0.1$$

$$x_3 \leq 10$$

$$x_4 \leq 2$$

Hence the minimum cost and optimized dimensions are Solution = optimization minimize (f(X), cons, bounds)

3. MATHEMATICAL FORMULATION

(Janga Reddy.M, D.Nagesh Kumar, 2007)(Ali Riza Yildiz, 2008)

The mathematical formulation of the objective function $f(X)$ which is the total fabrication cost mainly comprised of the set-up, welding labour and material cost is as follows

The objective is to minimize the cost of the welded beam design problem.

Minimize $f(X) = 1.10471x_1^2 x_2 + 0.04811x_3 x_4(14.0 + x_2)$

Subject to

$$\tau(X) \leq \tau_{\max}$$

$$\sigma(X) \leq \sigma_{\max}$$

$$x_1 \leq x_4$$

$$0.10471x_1^2 x_2 + 0.04811x_3 x_4(14.0 + x_2) \leq 5.0$$

$$0.125 \leq x_1$$

$$\delta(X) \leq \delta_{\max}$$

$$P \le P_c(X)$$

Where

$$\tau(X) = \sqrt{\tau_1^2 + 2\tau_1\tau_2\left(\frac{x_2}{2R}\right) + \tau_2^2}$$

$$\tau_1 = \frac{P}{\sqrt{2}\, x_1 x_2}$$

$$\tau_2 = \frac{MR}{J}$$

$$M = P\left(L + \frac{x_2}{2}\right)$$

$$R = \sqrt{\frac{x_2^2}{4} + \left(\frac{x_1 + x_3}{2}\right)^2}$$

$$J = 2\left\{\sqrt{2}\, x_1 x_2\left[\frac{x_2^2}{12} + \left(\frac{x_1 + x_3}{2}\right)^2\right]\right\}$$

$$\sigma(X) = \frac{6PL}{x_4 x_3^2}$$

$$\delta(X) = \frac{4PL^3}{E\, x_3^3 x_4}$$

$$P_c(X) = \frac{4.013E\sqrt{\frac{x_3^2 x_4^6}{36}}}{L^2}\left(1 - \frac{x^3}{2L}\sqrt{\frac{E}{4G}}\right)$$

Size constraints

$$0.1 \le x_1 \le 2$$

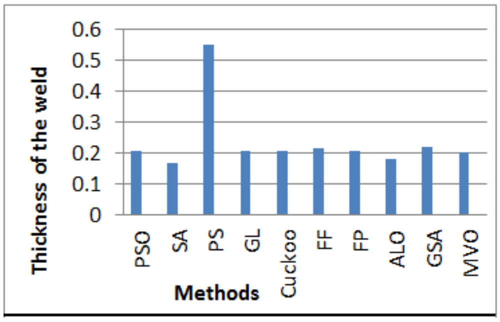
$$0.1 \le x_2 \le 10$$

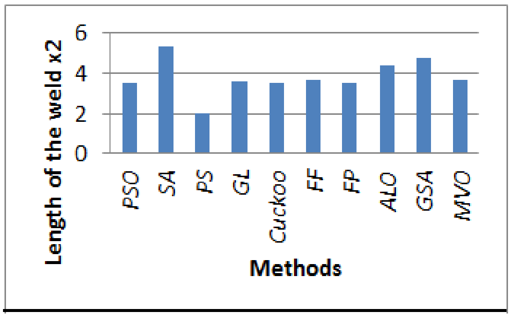
$$0.1 \le x_3 \le 10$$

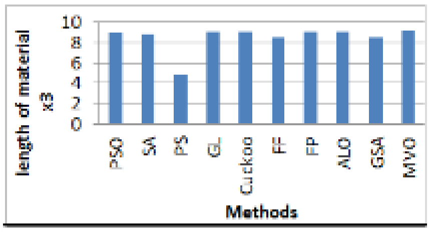
$$0.1 \le x_4 \le 2$$

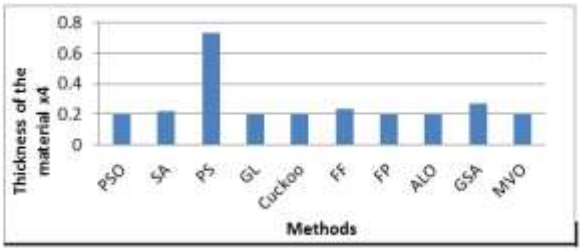
4. COMPARATIVE RESULTS

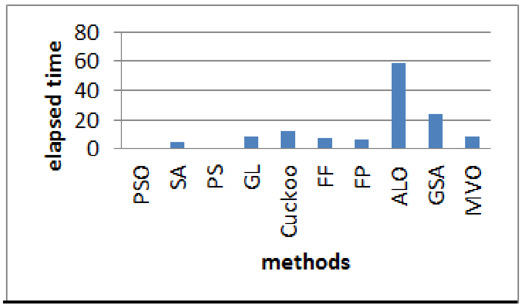
Trial No	PSO	SA	PS	GL	Cuckoo	FF	FP	ALO	GSA	MVO
Thickness of the weld X_1	0.206412	0.165306	0.55	0.204164	0.20573	0.214698	0.205729	0.177859	0.219556	0.199033
Length of the weld x_2	3.528353	5.294754	2.028512	3.565391	3.519497	3.655292	3.519502	4.393466	4.728342	3.652944
Length of the material x_3	8.988437	8.872164	4.798717	9.05924	9.036624	8.507188	9.036628	9.065462	8.50097	9.114448
Thickness of the material x_4	0.208052	0.217625	0.729557	0.206216	0.20573	0.234477	0.20573	0.20559	0.271548	0.205478
Cost	1.742326	1.939196	3.37756	1.7428	1.731527	1.864164	1.731528	1.796793	2.295076	1.749834
Iteration	178	4666	5	66573	100000	20000	2000	1000	1000	1000
Time	1.235504	4.38926	0.746971	8.338414	12.45931	8.083191	7.041082	59.04323	23.97281	8.962193

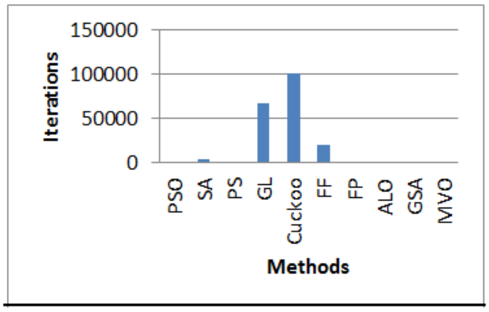


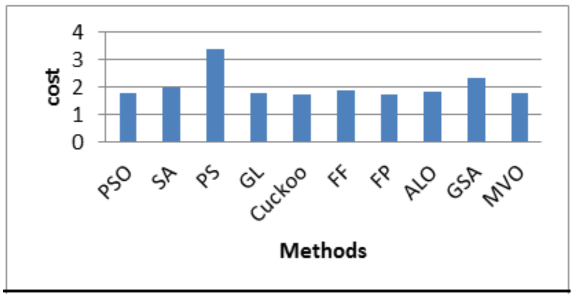












5. RESULTS AND DISCUSSION

With the two extreme values of the parameters the optimization is carried out with different solvers. As they are stochastic type the results may vary from trial to trial. So the problem is made to run for 20 trials. (Elbeltagi.E., Tarek Hegazy.I., Grierson D., 2005)And averages of all trials are taken as a final value of the parameter by the solver. The solvers are compared with three different criteria.

1. Consistency

Consistent result of the cost was observed in pattern search with the value of $3.37756.

2. Minimum run time

Minimum run time of the problem was observed 0.746971 seconds in Pattern Search whereas the minimum run time was 1.235504 seconds in Particle Swarm Optimization.

3. Minimum Evaluation

This Criterion will determine the effectiveness of the algorithm. From the table 3.6 we see that Pattern Search and Particle Swarm Optimization algorithm have minimum evaluation of 5 and 178 respectively.

4. The Simplicity of Algorithm

The simplicity of algorithm presents the computational simplicity and easily read by the observer. Pattern Search algorithm is considered to be the most simplest followed by Particle Swarm Optimization.

Therefore from the above consideration, it is concluded that Pattern Search scores above all solvers, but the cost becomes maximum whereas the cost of Particle Swarm Optimization is $1.7423. Therefore, the Particle Swam Optimization has minimum cost and proceeding time 1.2355 seconds and 178 iterations, so is taken as the best solution. It is apparent from the result that Particle Swarm Optimization is able to provide solutions with less objective evaluations. This desirable characteristic of Particle Swarm Optimization algorithm in such engineering problems which entail higher computational effort.

6. SIMULATION FOR VALIDATING OPTIMIZED RESULTS

The welded beam problem is also simulated practically to evaluate the stresses developed when there is load of 6000lb applied at the edge of the beam which is fixed to a plate by a weld. The following constrains are checked with simulation for practicality of the optimized geometry:

1. Maximum Allowable deflection = 6.35mm
2. Stress in the beam not to exceed 30000psi.
3. Stress at the weld section is not to exceed 13600 psi.

In simulation the constraints are tested for each geometry namely lower bound geometry, upper bound geometry and optimum boundary from Particle Swarm optimization algorithm as it gives the most optimum cost.

BOUNDARY VALUES OF WELDED BEAM DESIGN

	Thickness of the weld (x_1)		**Length of the weld (x_2)**		**Length of the material (x_3)**		**Thickness of the material (x_4)**	
	inch	mm	inch	mm	inch	mm	inch	mm
Upper Bound	2	50.8	10	254	10	254	2	50.8
Lower Bound	0.1	2.54	0.1	2.54	0.1	2.54	0.1	2.54
Optimum	0.206412	5.242864	3.528353	89.620166	8.988437	228.306299	0.208052	5.2845208

The geometry was modelled in CAD (Solid works) and the mesh generation was done in Ansys Mesher with Tet & Hex Scheme. The boundary conditions were applied & structural analysis was carried out.

6.1. Results of Lower bound geometry

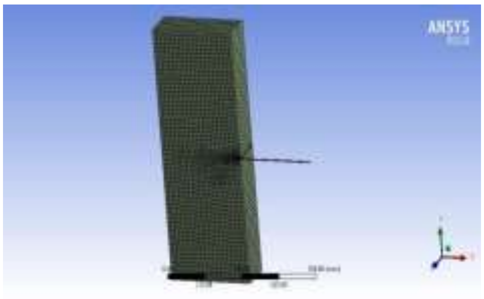


Figure 2 Meshed lower bound geometry

The mesh is generated for lower bound geometry. The meshed model for lower bound geometry is given in Figure 2. From the figure it is evident that the mesh flow is progressive without any discontinuity

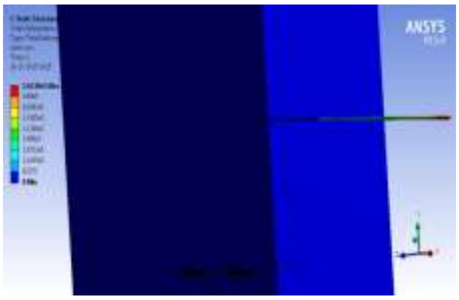


Figure 3 Total deformation of the beam

The total deformation of the beam for lower bound geometry is given in Figure 3. It is evident that total deformation is $5.6138*10^5$ mm which exceeds the minimum deflection 6.35mm.

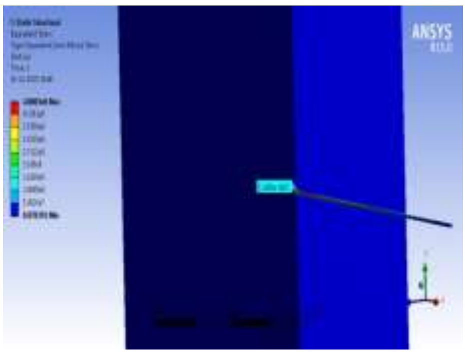


Figure 4 Stress developed in the weld section

The stress developed in the weld section for lower bound geometry is shown in Figure 4. Stress developed in the weld section is $4.8803*10^8$ psi which exceeds the allowable stress limit of 30000psi.

The lower bound geometry is not satisfying deflection constrain and stress constrain. Hence it is not practical to use the lower bound geometry.

6.2. Results of Upper bound geometry

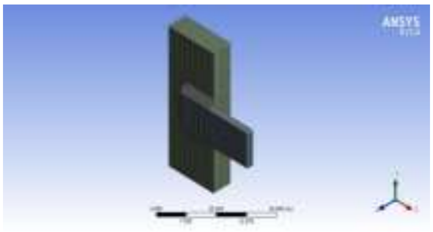


Figure 5 Meshed upper bound geometry

The mesh is generated for lower bound geometry. The meshed model for upper bound geometry is given in Figure 5. From the figure it is evident that the mesh flow is progressive without any discontinuity.

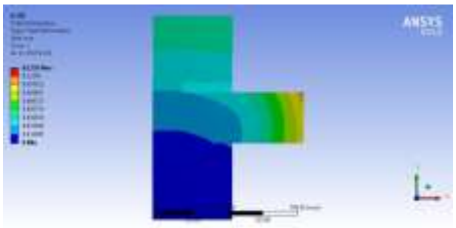


Figure 6 Total deflection in the beam

The total deformation of the beam for upper bound geometry is given in Figure 6. It is evident that total deformation is 0.1255mm which is within the minimum deflection of 6.35mm

Figure 7 Stress developed in the beam

The stress developed in the beam for lower bound geometry is shown in Figure 7. The stress limit of the beam is 22343 psi which is within the allowable stress limit of 30000psi.Hence it is practically safe to use the upper bound geometry. Since the problem is based on cost minimization, the cost with upper bound geometry is $890485.29 which is very expensive. So upper bound is economically not an optimal design.

6.3. Results of Optimum bound Geometry

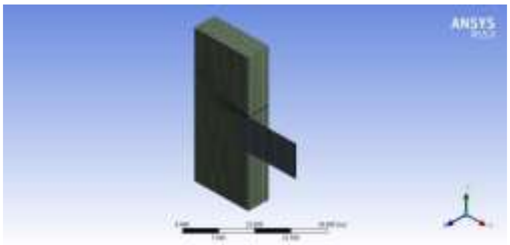


Figure 8 Mesh generation of the optimum geometry

The mesh is generated for optimum bound geometry. The meshed model for upper bound geometry is given in Figure 8. From the figure it is evident that the mesh flow is progressive without any discontinuity.

Figure 9 Deformation in the geometry

The total deformation of the beam for optimum bound geometry is given in Figure 3.23. It is evident that total deformation is 0.011555mm which is within the minimum deflection of 6.35mm.

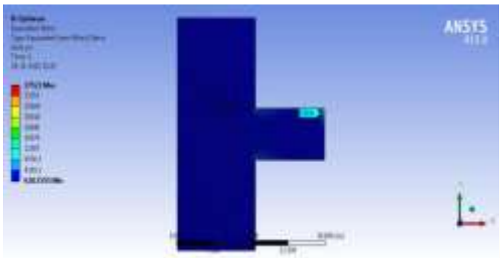


Figure 10 Stress developed in the beam

The stress developed in the beam for optimum bound geometry is shown in Figure 10. The stress limit of the beam is 2564 psi which is within the allowable stress limit of 30000psi. The optimum bound geometry satisfies the deflection constrains and stress constrain. Also the calculated cost of welded beam is Rs. 1.7423. Hence it is practically safe to use the optimum bound geometry.

6.4. Conclusion from Simulation

The welded beam design model has been simulated for different geometry, lower bound, upper bound and optimum geometry. Lower bound geometry leads to failure of the model due to great deflection in the beam and high stress of the beam. Upper bound geometry solved this problem and the stress is within the limit, but manufacture cost is very high. The simulation was repeated with optimized boundary condition. The results showed that the practical stress and deflection constraints are satisfied, hence safe to use and economically the best with low manufacturing cost.

7. CONCLUSION

For the study of design of welded beam with optimum cost of manufacturing, a beam welded to a rigid member was taken which is to support a force of 6000 lb. The designed welded beam was carried out with four design variables i) Thickness of the weld (h) ii) Length of the weld (l) iii) Length of the material (t) and iv)Thickness of the material (b). The objective was to minimize overall fabrication cost of the welded beam.

We have used MATLAB to solve the Welded Beam problem. Ten non- traditional optimization methods were used to solve the cost model of the welded beam and concluded that Particle Swarm Optimization method gives the minimum cost even though the Pattern

Search also takes minimum run time and simplicity among all other algorithms. Hence it was concluded that Particle Swarm Optimization Method would be the best algorithm.

To validate the results, simulation of the design was carried out using Ansys and solidwork software packages. The upper, lower and optimum boundary conditions were used to evaluate the stresses developed in the beam when a load of 6000lb is applied at the edge of the beam, which is fixed to a plate by a weld. The results indicate that there is high deflection in the weld section ($5.6138*10^5$ mm) which exceeds the minimum deflection by 6.35mm and the stress developed in the weld section is very high ($4.8803*10^8$ psi) which exceeds the allowable stress limit of 30000psi. Therefore it was observed that the lower bound geometry is not practically safe for use.

In case of upper bound geometry, the total deflection of the beam is 0.1255mm which is within the minimum deflection 6.35mm and the stress occurred was 22343 psi which is within the allowable stress limit of 30000psi.Hence it is practically safe to use the upper bound geometry. Since the problem is based on cost minimization, the cost with upper bound geometry is $.890485.29 which is very expensive. So upper bound is economically not an optimal design.

In case of Optimum bound geometry the total deformation is 0.011555mm which is within the minimum deflection of 6.35mm and stress limit of the beam is 2564 psi which is within the allowable stress limit of 30000psi. The calculated cost of welded beam is $1.7423. Hence it is practically safe to use the optimum bound geometry.

When the lower bound design parameters are used it was practically not safe, when the upper bound is used it was practically safe but economically not suitable. Therefore, the optimum value derived from Particle Swarm Optimization was used. It was evident that the total deflection and stress are well within the limit, with minimum cost of manufacturing.

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