WEIGHT OPTIMIZATION OF COMPOSITE DRIVE SHAFT USING PSO ALGORITHM FOR AUTOMOTIVE APPLICATIONS.

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Abstract - In this work Particle Swarm Algorithm is used for the optimization of composite driveshaft using MATLAB . mathematical formulation is coded in MATLAB to optimize the stacking sequence of the plies with an objective of minimization of weight of the driveshaft by considering the Toque transmission capacity ,Torsional buckling strength and Natural bending strength as design constraints and number of plies, stacking sequence and thickness of ply as design variables .We have developed design procedure for composite driveshaft and later coupled with PSO algorithm. Our objective function is 'single objective' i.e. weight reduction of composite drive shaft. We have evaluated the PSO performance by varying the parameters of it and the optimization results are compared with the results of GA.

Introduction - Optimization is the act of obtaining the best result under given circumstances. In design,Construction, and maintenance of any engineering system, engineers have to take many Technological and managerial decisions at several stages. The ultimate goal of all such decisions is either to minimize the effort required or to maximize the desired benefit. Optimization Procedures are proved to make better decisions. Over the past decades a number of evolutionary computational methods have been derived such as Genetic Algorithm, ant colony optimization, simulated annealing, and particle swam optimization algorithm. Among them PSO algorithm is better due to fewer function evaluations while leading to better or the same quality of results. Particle swarm optimization is a "Stochastic", population based-evolutionary computer algorithm for problem solving. It is a kind of swarm intelligence that is based on social-psychological principles and provides insights into social behavior as well as contributing to engineering applications. The PSO algorithm was first described in 1995 by a social psychologist, James Kennedy and an electrical engineer, Russell C.Eberhart. In addition, easiness of implementation as it does not required specific domain knowledge information makes it more attractive. Furthermore, it is a population-based algorithm, so it can be efficiently parallelized to reduce total computational effort. Recently the PSO has been proved useful on diverse engineering design applications such as logic circuit design, control design and power system design but still the PSO has not applied in the field of design optimization of machine parts. So this project work is intended to implement the PSO in the above domain. In this work we are taking Composite drive shaft as a case study because we have existing optimization results using genetic algorithm for design optimization of composite driveshaft which has been mathematically formulated in C-language. Design optimization involves lot of matrix operation but C-programming offers limited scope in matrix manipulations. Often matrix operation requires huge RAM memory of a computer results in increase time and computational cost. This drawback can overcome by MATLAB, An excellent tool for matrix manipulations, it possessing many advantages compared to conventional computer languages (eg.,C, FORTAN) for solving technical problems, it integrates computation, visualization, and programming environment.

Composite Driveshaft as a Case Study- In order to study the performance of particle swarm optimization algorithm's performance composite driveshaft as a case study. Our objective function is weight reduction (single objective) and result obtained is compared with existing genetic algorithm result. Composites materials are those in which two or more materials are combined in macroscopic level to produce material of superior qualities. Here, constituents are not soluble in each other. The advanced composite materials such as graphite, carbon, boron, Kevlar and glass with suitable resins are widely used because of their high specific strength (strength/density) and high specific modulus (modulus/density). Advanced composite materials seem ideally suited for long, power driver shaft applications. Composite material elastic properties can be tailored to increase the torque carrying capacity as well as rotational speed at which they operate. The drive shafts are used in the areas like automotive, aircraft applications. To propose an optimization procedure to design a multilayered composite driveshaft for given torque, speed and length to achieve minimum weight using Particle Swarm Optimization (PSO) technique. To compare the design optimization results of Genetic Algorithm (GA) and PSO. To use the discrete variable optimization technique available in the PSO, to optimize ply thickness, number of plies and ply orientations (optimal stacking sequence) to meet driveshaft performance requirements. To explore the extent of suitability of composite materials for automobile driveline applications.

Literature review on optimization of composite driveshaft-

O.A.Bauchau et al (1986) have experimentally measured torsional buckling loads of Graphite/Epoxy shafts and have been compared with theoretical predictions. They found good agreement between measured buckling loads and their theoretical counterparts. From their work it is recognized that torque direction and stacking sequence can drastically affect critical loads.

Naveen Rasthogi, (2004), has presented a comprehensive approach to design drive shafts for automobile applications. He has given two important aspects of driveshaft design viz., (i) Design of composite drive shaft involving ply thickness and ply orientation optimization to meet drive shaft performance requirements, and (ii) Design of adhesively bonded tubular joint between the yoke and the tube in order to carry the applied torque load. For each case, he developed preliminary design tools, to aid quick analysis and design of complete driveshaft system. He also generated FEA models to perform a more detailed analysis at each stage, and also validate the preliminary design tools.

T Rangaswamy et al (2004) have made an attempt for design optimization of composite drive shafts for power transmission applications. They have designed the one-piece composite drive shaft to replace conventional steel drive shaft of an automobile using E-glass / epoxy and high modulus (HM) carbon/epoxy composites. A formulation and solution technique using genetic algorithms (GAs) for design optimization of composite drive shafts is used by them.

Mahmood M. Shokrieh et al (2004) have studied the effects of boundary conditions and the stacking sequence of the composite layers on the strength of the drive shaft. They have shown that increase of applied torque on the shaft reduces the natural frequency and the boundary conditions of the shaft do not have much effect on the buckling torque. The finite modeling presented in this analysis is able to predict the buckling torque.

T Rangaswamy et al (2005) have explained the orientations of fiber direction in layers and number of layers and the thickness of the layers as well as material of composites play a major role in determining the strength and stiffness. A formulation and solution technique using genetic algorithm (GA) for design optimization of composite drive shaft which is subjected to the constraints such as torque transmission, torsional buckling capacities and fundamental lateral natural frequency was discussed.

Literature review on Particle Swarm Optimization (PSO) Algorithm

Reynolds [24] [1987], Heppner and Grenander [22] [1990] have presented simulations of bird flocking. Reynolds was intrigued by the aesthetics of bird flocking choreography and Heppner, a zoologist, was interested in discovering the underlying rules that enabled large number of birds to flock synchronously, often changing directions suddenly, scattering and regrouping.

As Wilson [29] [1993], a socio biologist has written, in reference to fish schooling, "In theory at least, individual members of the school can profit from the discoveries and previous experience of all other members of the school during the search of the food. This advantage can become decisive, outweighing the disadvantages of competition for food items, whenever the resource is unpredictably distributed in patches". This statement suggests that social sharing of information among conspeciates offers an evolutionary advantage. This hypothesis was fundamental to the development of Particle Swarm Optimization.

Kennedy and Eberhert [18] [1995] have first reported the Particle Swarm Algorithm (PSO). PSO is a stochastic, population – based evolutionary computer algorithm for solving problems. It is a kind of swarm intelligence that is based on socio – psychological principles and provides insights to social behavior, as well as contributing to engineering applications The initial ideas on particle swarms of Kennedy (a social psychologist) and Eberhart (an electrical engineer) were essentially aimed at producing computational intelligence by exploiting simple analogues of social interaction, rather than purely individual cognitive abilities.

Donald et al [9] [2005] have considered and compared the results of five recent evolutionary – based algorithms. They are genetic algorithms, memetic algorithms, particle swarm systems, ant colony systems and shuffled frog leaping. Brief descriptions of five algorithms are presented along with a pseudo code to facilitate the implementation and use of such algorithms by researchers and practitioners. Benchmark comparisons among the algorithms are presented for both continuous and discrete optimization problems, in terms of processing time, convergence speed and quality of results.

Engelbrecht et al [13] [2005] have derived a heuristic algorithm for the initialization of the inertia weight and acceleration coefficient values of the PSO to guarantee convergent trajectories. They overviewed current theoretical studies, and extended their studies to investigate particle trajectories for general swarms to include the influence of the inertia term. They also provided a formal proof that each particle converges to a stable point.

Alexandros Leontitsis et al [2] [2006] have tried to improve the performance of PSO algorithms by introducing the concept of the repellor. So far, the PSO algorithm is guided by the optimum of each particle and the optimum found by all the particles. The authors have added to the algorithm the location of the worst point found so far and location the worst point found by all the particles. These worst points have the property of repelling the particles to the local and the global optima, respectively. This way the PSO algorithm is improved in the sense that the swarm is able to locate the global optimum more rapidly. Empirical results are presented on archaeological data.

PSO Algorithm and Flowchart

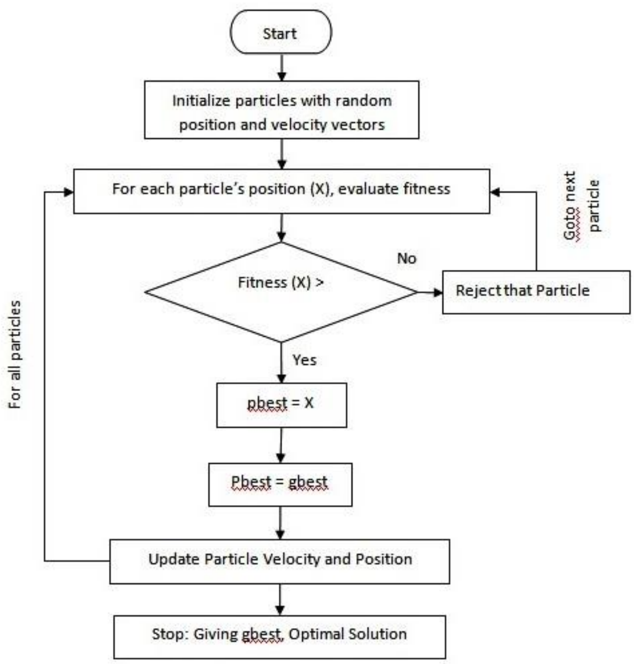


Figure - Flow chart of Particle Swarm Optimization

PSO for Design Optimization

Particle swarms have not been used in the field of design optimization until very recently, but new developments have shown promising results in the areas of shape optimization as well as topology optimization.

In recent years, PSO s has emerged as a robust, practical and reliable search method. PSO has provided an alternative technique, different from the usual gradient method. PSO uses a directed random search technique to find the optimal solution in the complex area. Design optimization using mathematical programming was prohibitively expensive in the early stages of its development and hence applications to practical problems were limited in scope. Moreover, majority of the mathematical programming techniques assume that the design variables are continuous which is not always true. The process of optimal design is generally characterized by finite, often large, members of variables of discrete type. Universal steel beams available to the designer are discrete in dimension and properties. The thickness of a laminate is discrete variable in their practical dimensions and will vary by discrete intervals. PSO approaches are well suited for optimize mechanical systems using both continuous and discrete structural elements.

Optimal Problem Formulations

The formulation of the problem takes roughly fifty percent of the total effort needed to solve it. Therefore, it is critically important to follow well-defined procedures for formulating design optimization problems, as they provide systematic and efficient ways of creating and comparing new design solutions in order to achieve an optimal design. The purpose of the formulation procedure is to create a mathematical model of the optimal design problem, which then can be solved using optimization technique. Since an optimization technique accepts an optimization problem in a particular format, every optimal design must be formulated in that format.

Objective Function

The objective for the optimum design of the composite drive shaft is the minimization of weight, so the objective function of the problem is given as

$$\text{Weight of the shaft}, \quad m = \rho A L \quad \text{or} \quad m = \rho \frac{\pi}{4}\left(d_o^2 - d_i^2\right) L;$$

Design Variables

In optimization techniques, the variables, which are very sensitive in altering the value of objective function, are known as design variables. In the present problem of composite drive shaft optimization, the design variables considered are number of plies[n], stacking sequence [θ_k] and thickness of the ply [t_k]. Table presents the design variables with their limiting values.

Table Design variables and their limiting values

Design variables	Limiting values of the design variables	
Number of plies[n]	n > 0 ;	n = 1, 2,3…32
Stacking Sequence[θ_k]	$-90 \le \theta_k \le 90$;	k =1, 2… n
Thickness of the ply[t_k]	$0.1 \le t_k \le 0.5$	

The number of plies required depends on the design constraints, allowable material properties, thickness of plies and stacking sequence. Based on the investigations it was found that 32 plies are sufficient.

Design Parameters

The parameters, which are sensitive in changing the objective function value but required to be kept as constants (for example material properties) are known as design parameters. The design parameters considered in this problem are given in Table

Table of Design parameters of steel and composite drive shafts considered

Parameter	Units	Steel (SM45C)	E-Glass /Epoxy	Kevlar49 /Epoxy	HM Carbon /Epoxy	Boron /Epoxy
Do	mm	90	90	90	90	90
L	mm	1250	1250	1250	1250	1250
T_{max}	Nm	3500	3500	3500	3500	3500
N_{max}	rpm	6500	6500	6500	6500	6500
t_k	mm	3.318	0.4	0.12	0.12	0.12

Working with Particle Swarm Optimization (PSO)

PSO is initialized with a group of random particles (solutions) and then searches for optima by updating swarms. In every iteration, each particle is updated by following two "best" values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called pbest. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called gbest. Following two equations 5.4 and 5.5 are used to update current velocity and position of a particle.

v[ ] = v[ ] w+ C_1 rand( ) (pbest [ ] – present [ ]) + C_2 rand ( ) (gbest [ ] – present [ ]) present [ ] = present [ ] + v [ ]

Where, v[ ] is the particle velocity, present[ ] is the current particle (solution), w is inertia weight, pbest[ ] & gbest[ ] are particle best & global best, rand( ) is a random number and C_1, C_2 are learning factors

In particle swarm optimization algorithm the number of iteration or particles are grouped as swarms. Each swarm is of "i" number of particle and "t" such swarms are taken for consideration. In each swarm, best value known as particle best or simply pbest is found. This value is best value for that particular swarm. After completion of first swarm evaluation, the pbest value will be considered as the global best or gbest. This gbest will be updated if the next swarm's pbest is value is better then previous swarm's pbest value.

Input PSO parameters for Matlab

Inertia weight, w	Varies in between 0 to 1
Random numbers, r1 and r2	Varies in between 0 to 1
Leaning Factors, C_1 & C_2	2
Particle Size	50
Number of swarms	150

Summary of PSO Results

A single piece composite driveshaft for rear wheel drive automobile was designed optimally by using particle swarm algorithm for e-glass/epoxy, high modulus carbon/epoxy, kevlar49/epoxy and born/epoxy shafts. The procedure described in the previous sections has been applied to the design of composite drive shaft tube for minimum weight. The design parameters such as ply thickness, number of plies required, stacking sequence were optimized with the objective of minimizing the weight of the composite shaft, which is subjected to the constraints such as torque transmission capacity, torsional buckling strength and fundamental lateral natural frequency. The result obtained from PSO for steel and different composite material drive shafts are as shown in table

Comparison of PSO results

Parameter	**Steel (SM45C)**	**E-Glass/ Epoxy**	**Kevlar49/ Epoxy**	**HM Carbon/ Epoxy**	**Boron/ Epoxy**
Optimum Layers	-	16	17	17	15
Thickness t(mm)	3.32	6.4	6.8	2.04	1.8
Optimum Stacking sequence	-	[4/-13/-13/-72/67/85/-70/18]s	[-46/73/39/50/-43/20/-24/-43/ $\overline{38}$] s	[-23/-51/68/-56/-72/47/-20/46/ $\overline{22}$] s	[58/61/-32/-82/-75/ -29/21/ $\overline{63}$] s
T (Nm)	3501	3508	3519	3810	3519
Weight(N)	86.04	42.02	33.33	11.27	12.47
Weight* saving (%)	-	51.16	61.26	86.89	85.50

***** taking steel shaft weight as datum

it is observed that, in comparison with conventional steel drive shaft 50% to 90% weight reduction can be achieved by using the composite driveshaft. In addition to weight reduction torque transmission capacity of the composite drive shaft is also more.

Summary of PSO Results

Variation of objective function value and number of layers of e-glass/epoxy, kevlar49/epoxy, HM carbon/epoxy and boron/epoxy shafts and number of generations obtained for each swarm size of the PSO are given in Figures 7.1 to 7.8. For the first 130 swarm size of E-glass/epoxy shaft, 140 swarm size of Kevlar49/ Epoxy shaft, 90 swarm sizes HM-Carbon/epoxy shaft and 130 swarm size of Boron/ Epoxy shaft, the weight is found to be fluctuating. The fluctuation is reduced to a minimum from generation numbers 90-140 in E-Glass/Epoxy shaft and 70 to 90 in HM Carbon/Epoxy shaft, but later they get converged.

PSO Graphs

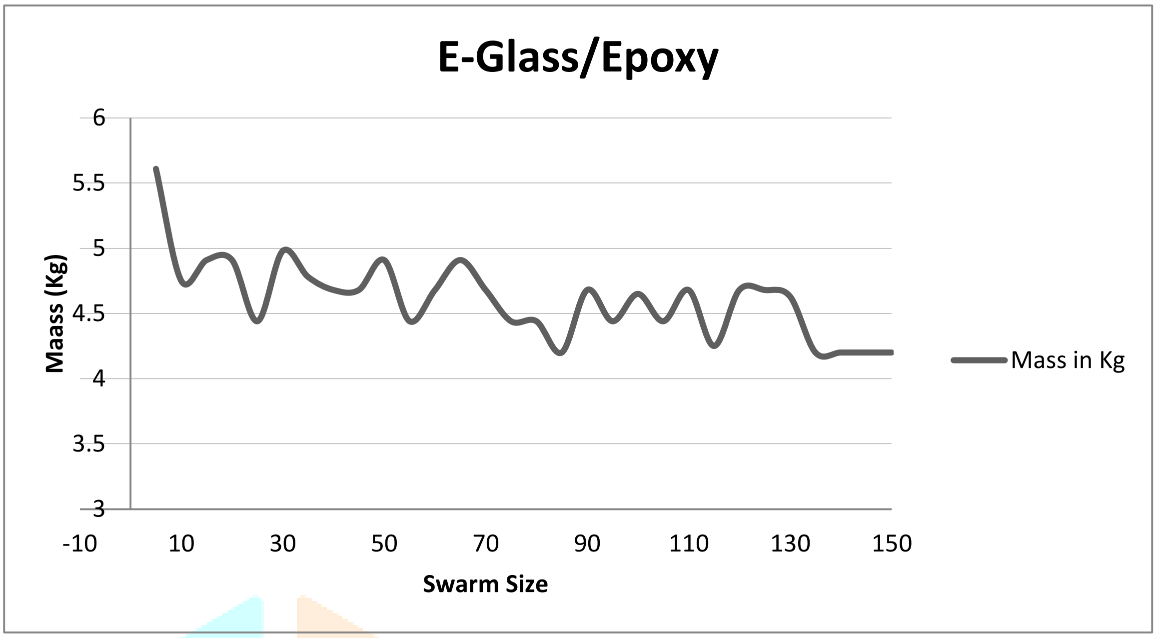


Figure Variations of mass of E-Glass/Epoxy drive shafts with swarm size

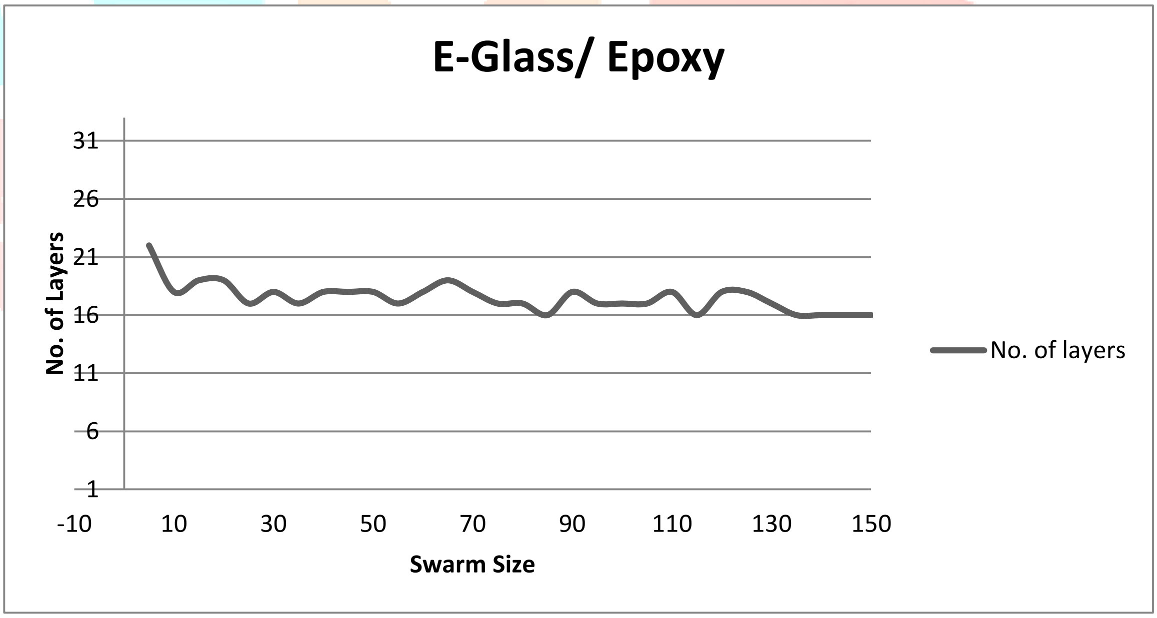


Figure Variations of number of layers of E-glass/Epoxy drive shafts with swarm size

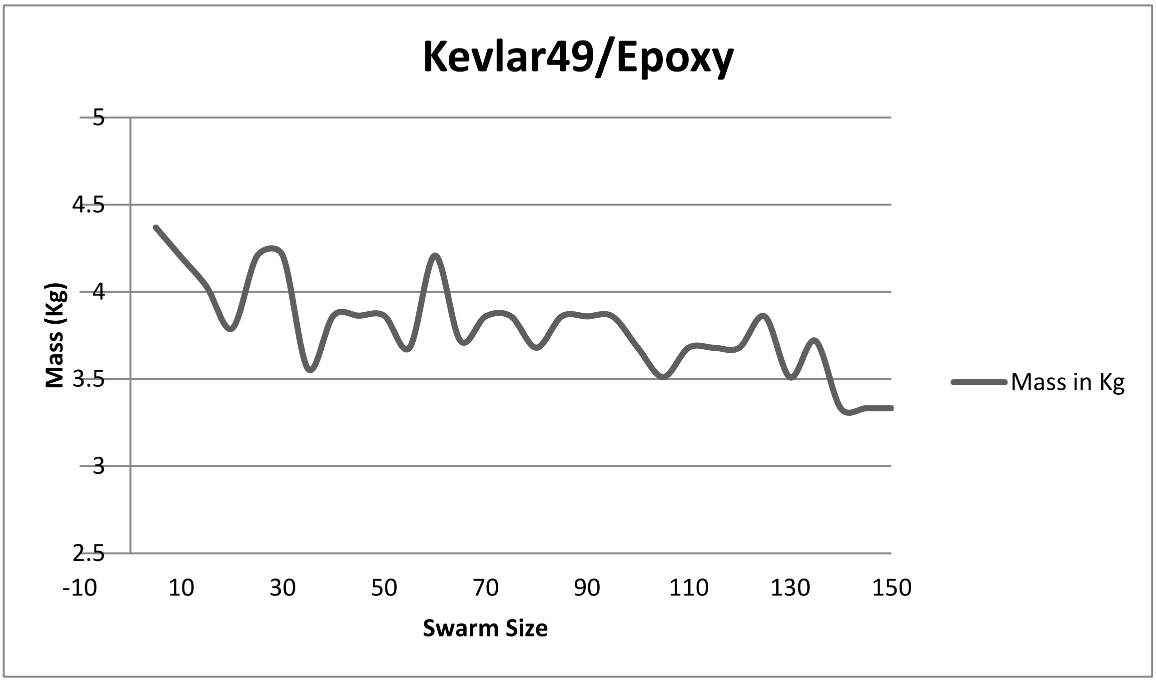


Figure Variations of mass of Kevlar49/Epoxy drive shafts with swarm size

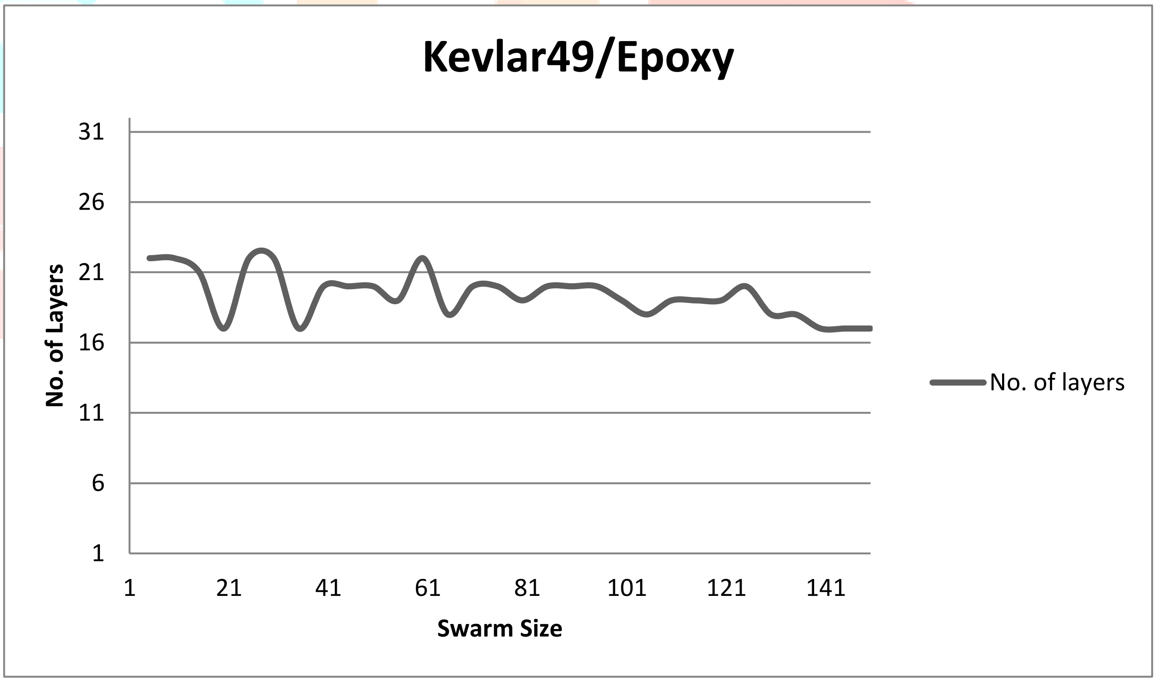


Figure Variations of number of layers of Kevlar/Epoxy drive shafts with swarm size

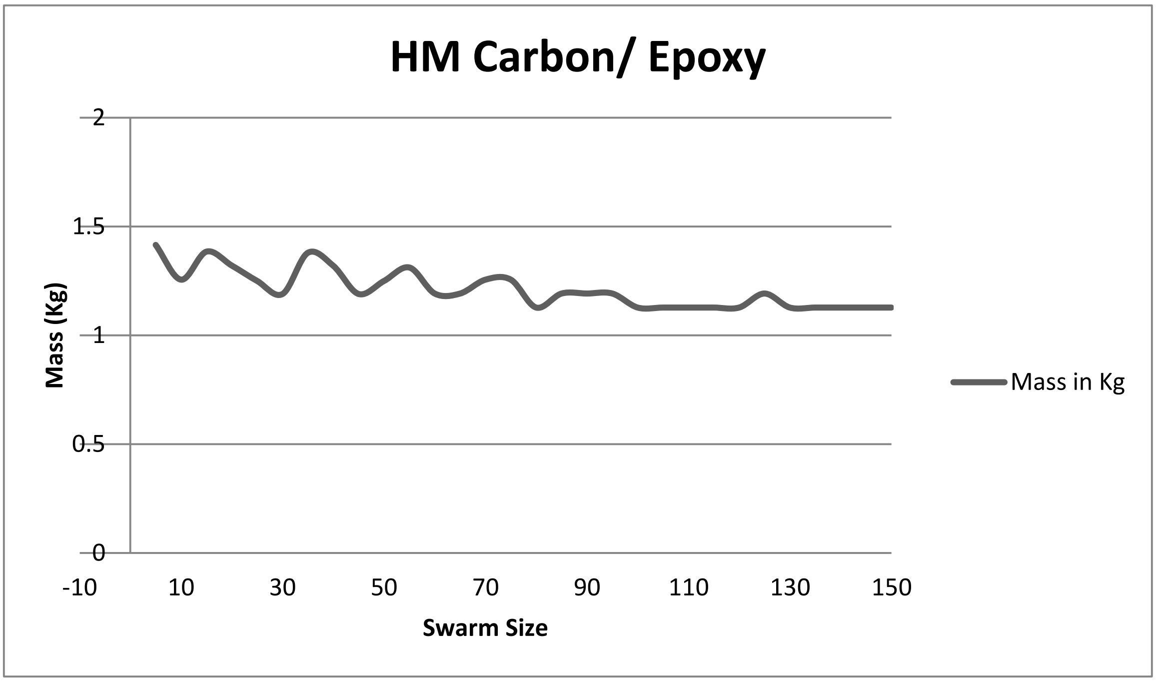


Figure Variations of mass of HM Carbon/Epoxy drive shafts with swarm size

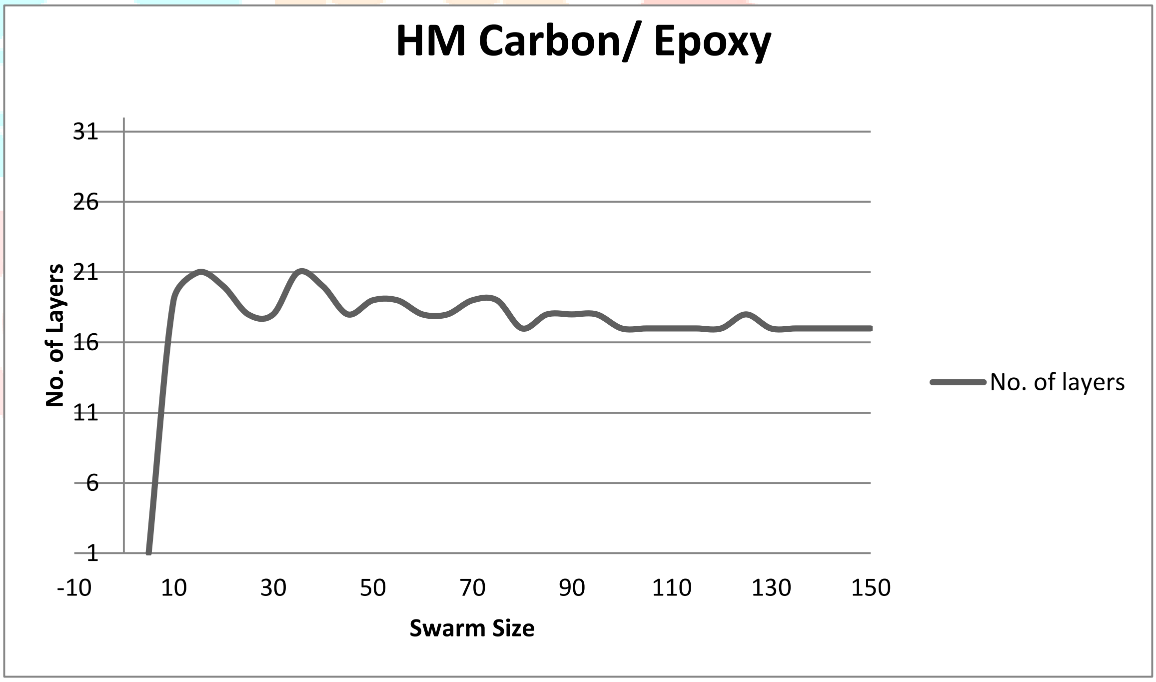


Figure Variations of number of layers of HM Carbon/Epoxy drive shafts with swarm size

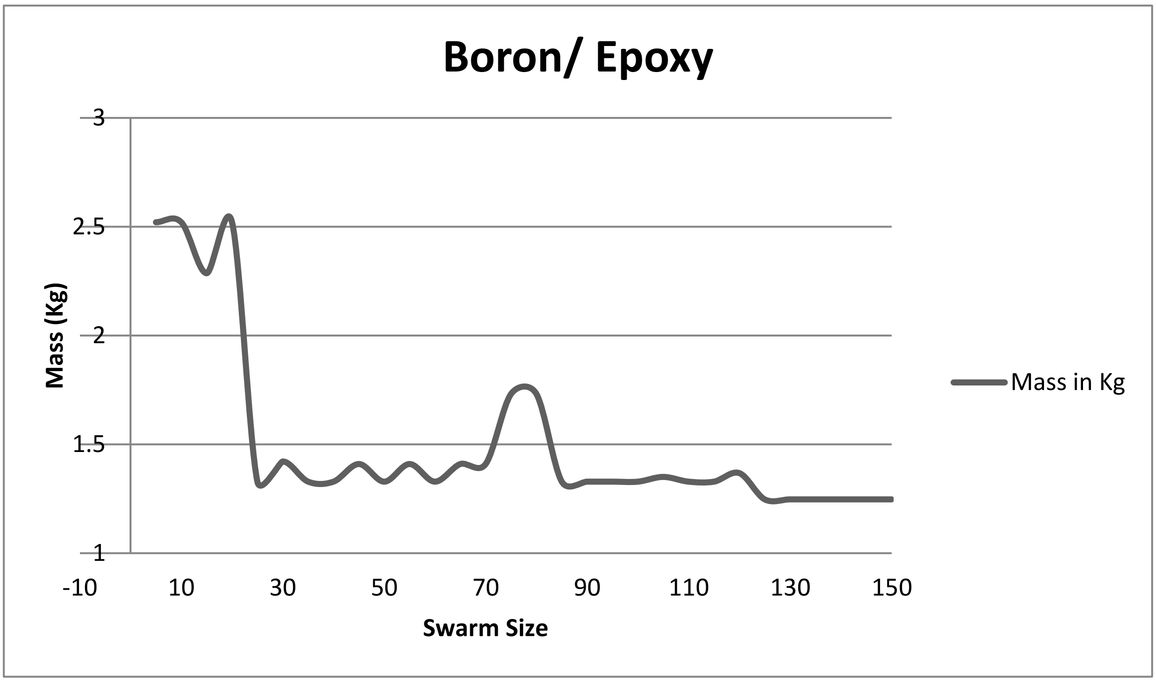


Figure Variations of mass of Boron/Epoxy drive shafts with swarm size

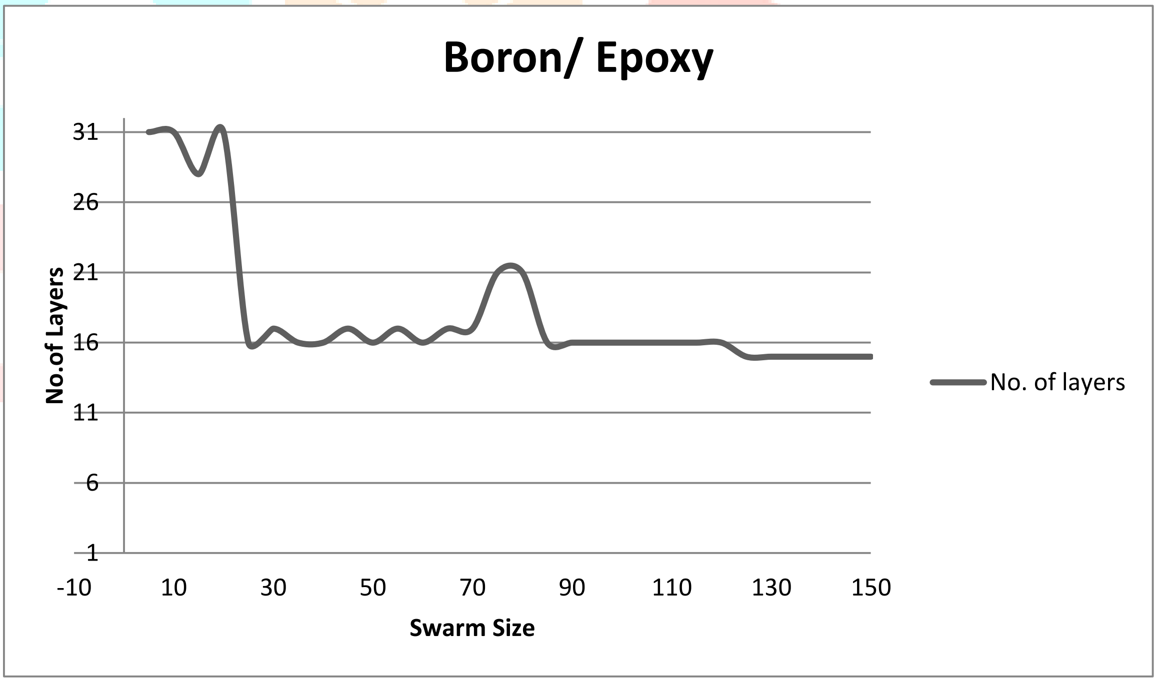
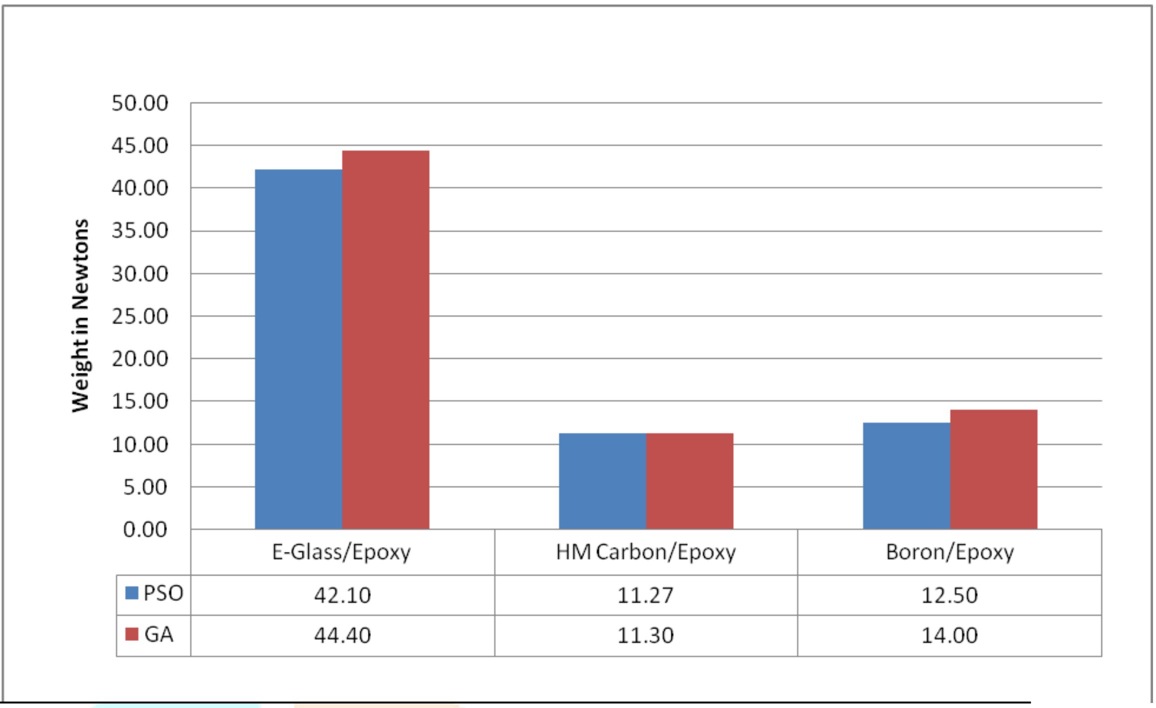


Figure Variations of number of layers of Boron/Epoxy drive shaft with swarm size

Weight of the shaft directly related to number of layers, if the number of layer is more the weight is also more. Therefore fluctuations in both graphs, weight Vs swarm size and number of layer Vs swarm size, are almost same.

Comparison PSO results with GA results



Comparision of PSO and GA results

The results obtained from the Particle Swarm Optimization (PSO) algorithm are compared with the Genetic Algorithm (GA) results taken from the reference [28] and [29]. The figure 6.9 shows the weight comparison of e-glass/epoxy, high modulus carbon/epoxy and boron/epoxy composite drive shafts. It is observed from the figure that the results obtained from the PSO yielded better results than GA.

Conclusions

In this work, an optimization procedure is proposed to design a multilayered single piece composite drive shaft for a given Torque, speed and length to achieve minimum weight using PSO approach. Composite materials like E-glass/epoxy, Kevlar49/epoxy, HM carbon/epoxy and Boron/epoxy are considered for single piece shaft automotive application. The optimized stacking sequence is generated using PSO to minimize the weight to meet the functional and performance requirements. The weight savings of different material shafts using PSO and Genetic Algorithm are compared and the result found that the PSO have better results than GA. From the research work it can be concluded that PSO approach yields better results.

Scope for future work

1. Shear bending and flexural stresses developed in the driveshaft may be considered for the further research, which will give more realistic results.
2. The advanced PSO version, known as convergent PSO can be used to get the more optimized results in very less time.
3. Using the results obtained from the present study, the virtual prototyping models can be created for further analysis.

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