Engineering Structures 174 (2018) 675–687

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Stochastic optimization of graphite-flax/epoxy hybrid laminated composite for maximum fundamental frequency and minimum cost

Melih Savran[a], Levent Aydin[b,*]

[a] The Graduate School of Natural and Applied Sciences, İzmir Katip Çelebi University, İzmir, Turkey
[b] Department of Mechanical Engineering, İzmir Katip Çelebi University, İzmir, Turkey

ARTICLE INFO

Keywords:
Hybrid laminated composite
Natural fiber
Fundamental frequency
Cost reduction
Stochastic optimization

ABSTRACT

Ecological approach in automotive, aerospace and marine industries have stated that natural fibers (especially flax) can be used as alternative reinforcing materials to glass fibers because of their inherent good vibration and cost performances. In this regard, the present paper is an attempt to show the usage of flax fiber as an alternative to E-glass in interply hybrid composite structures in terms of fundamental frequency and cost. Stacking sequences design and optimization of laminated composites based on Differential Evolution (DE), Nelder Mead (NM) and Simulated Annealing (SA) algorithms are considered. The optimization problem is to find the number of high stiffness and less expensive laminates maximizing the fundamental frequency and minimizing the cost by multi objective optimization approach. The results show that the proposed optimum graphite-flax/epoxy interply composite structure give better than the result of graphite-glass/epoxy in terms of maximum fundamental frequency and minimum cost. It is also found that DE, NM and SA algorithms show comparable performance versus Ant Colony Optimization (ACO) for the same laminated structure design problems.

1. Introduction

Laminated composites are fairly used in automotive, marine, aerospace and other branches of engineering applications because of their inherent tailorability. Traditional fiber reinforced composite materials generally have consisted of glass, carbon and/or combination of these. In addition to being strong and rigid, when these materials are mixed, they save up cost and weight. However, in recent years, automobile, aircraft and construction industries focus on eco-friendly materials including cheaper, lightweight and high mechanical properties [1]. Flax fiber is one of the natural fibers having high specific strength and low density and they can be used as an alternative to glass fiber in a composite system. A detailed discussion about the usage of flax fiber instead of glass in terms of vibration damping, cost efficiency and impact behavior can be found in [1–5]. In the literature, even though mechanical properties of flax fiber are handled by researchers, there are only few studies concerning damping and vibration capabilities.

In recent years, it is possible to obtain appropriate designs including desired physical features of anisotropic materials with the development of stochastic optimization methods. In this regard, the design of some engineering structures sometimes necessitates the maximization or minimization of the objective function for the process. In order to obtain the objective functions for design of laminated composite materials the usage of classical laminated plate theory (CLPT) is essential. Moreover, even if the classical laminated plate theory (CLPT) have some limitation, it is still common technique utilized to obtain quick and simple prediction in design of laminated composite plate. The main simplification of this theory is that structures are considered as 2D plate or shell located through mid thickness instead of 3D thick plate or shell and so the unknown variables reduced and the governing equations can be expressed easily in closed form solution. However, In CLPT, transverse shear deformation is neglected so that CLPT doesn't estimate good results for thicker laminated plates [6]. In this case, other plate theories are used to analyze laminated composite plate. In this respect, Khdeir and Reddy [7] proposed a complete set of linear equations for cross-ply and angle-ply laminated plates concerning free vibration utilizing second order shear deformation theory and gained analytical solutions with arbitrary boundary conditions for thin and moderately thick plates. Topal [8] tackled the applicability of extended layer wise optimization method (ELOM) to maximize the fundamental frequency of laminated composite plates with various aspect ratios and mixed boundary conditions. The first order shear deformation theory (FSDT) is utilized for the finite element solution of the laminated composites. The FSDT requires the use of shear correction factor to analyze laminated composite plate. These parameter can not be determined easily for all practical problems. Additionally, FSDT cannot meet shear stress-free

* Corresponding author.
E-mail address: leventaydinn@gmail.com (L. Aydin).

https://doi.org/10.1016/j.engstruct.2018.07.043
Received 10 March 2018; Received in revised form 19 June 2018; Accepted 15 July 2018

conditions for surfaces of plates. Hence, higher order theories have been proposed by researchers. In this regard, Sayyad and Ghugal [9] reported many displacement based higher order theory from literature for vibration analysis of plates. It is seen that A five or six variable plate theories are more accurate than four variable plate theories for the analysis of laminated composite or sandwich plates. Higher order shear deformation theories (HSDT) with four unknown variables are effectively applied to functionally graded plates only, their application to laminated composite and sandwich plates is still in primitive stage. Aagaah et al., [10] used third order shear deformation theory to obtain natural frequency of square laminated composite plates for different boundary conditions. The results are compared to the results of CLPT and FSDT. It is seen that CLPT overestimates natural frequency for thick laminated composite plate. Laminated composite plate theory have been examined under two different approaches; (i) the above-mentioned single-layer theories, which consider layers in a laminated composite structure as one equivalent single layer, (ii) discrete theory approach which considers each layer in the analysis and also known as zigzag theories. Lurlaro et al. [11] have been proposed refined zig zag theory to solve bending, buckling and free vibration of sandwich plates. The numerical results of considered zig zag theory and other ESL (FSDT, HSDT) and zigzag theories (linear and cubic zigzag models (LZZ and CZZ)) given in literature are compared with each other. It is found that refined zig zag theory correctly estimates deflection as denoted previous papers in literature and in addition to this provides very accurate results in terms of natural frequency and buckling.

In some cases, maximizing the natural frequency [12–17], maximizing critical buckling load factor [18–21], dimensional stability [22–26], minimization of failure index [27,28] are used in developing new materials systematically. However, the design and optimization of the engineering structures need to be maximized and/or minimized often conflicting more than one objectives, simultaneously. In this case, multi-objective formulation is utilized and a set of solutions are obtained with different trade-off which is called as Pareto optimal. There are several examples on the multi objective optimization problems for laminated composites in the literature in terms of cost-weight [29–31], frequency-cost [32,33], strength-mass [34], weight-cost-failure load [35], deflection-weight [36], stiffness-thermal expansion coefficient, critical buckling load- critical temperature rise and failure load [37], buckling and failure load factor [38]. In this approach, only one solution is to be chosen from the set of solutions for practical engineering usage. There is no such thing as the best solution with respect to all objectives in multi-objective optimization [39].

In dynamical engineering systems, fundamental frequency is an important issue in order to prevent resonance arising from external excitations, therefore many researchers have solved fundamental frequency optimization problems including practical applications of engineering. Bert [40], Reiss and Ramachandran [12] and Grenestedt [41] investigated the maximum fundamental frequency for laminated composite plates based on single objective approach by continuous design variables. Duffy and Adali [42] solved the same problem for cross ply laminates. In addition to mechanical point of view of laminated composite structures, it is also crucial to consider the cost and weight factors in engineering problems. Therefore, fundamental frequency, weight and cost of the structure can be preferred as an objective functions of the design and optimization problems. This attempt can be achieved either by multi objective or single objective approaches. For instance, by single objective approach: Adali and Duffy [43] viewed minimum cost design of antisymmetric, angle-ply hybrid laminates under fundamental frequency constraint. Adali and Verijenko [44] deal with fundamental frequency, frequency separation and cost factor for graphite-glass/epoxy symmetric interply hybrid laminates and determined the optimum discrete stacking sequence design. Moreover, it should be noted that interply hybrid laminated construction involves high-stiffness and expensive material in the surface layers and low-stiffness and cheap one in inner layers. This type of construction provides both suitable structural rigidity and low cost simultaneously. Therefore, multi objective optimization approach is usually preferred in the solution of the design problems for interply hybrid laminated composites. The previous studies about multi objective optimization problems in interply hybrid laminated composite exhibit that the designers can reduce cost and weight of laminated composite as well as providing safer design. In this regard, Abachizadeh and Tahani [45] solved multi objective optimization problem of composite graphite-glass/epoxy symmetric interply hybrid laminates for maximum fundamental frequency and minimum cost and Grosset et al. [46] carried out minimum cost-weight design under frequency constraint.

Design and optimization problems of laminated composites include complicated, highly nonlinear functions, hence stochastic optimization methods such as Genetic Algorithm and Simulated Annealing become appropriate to solve them. Genetic Algorithm is used for stacking sequence optimization of laminated composites for maximum buckling load under contiguity and strain failure constraints [18] and for maximum fundamental frequency of laminated plate with different edge conditions [47]. Simulated Annealing Algorithm is preferred in the solution of natural frequency and buckling optimization problems [16]. By considering the literature on laminated composite design, it is seen that optimum natural frequency maximization studies have a wide range of area based on the stochastic optimization methods. In this regard, the studies on Ant Colony Algorithm [45] including minimum cost, Differential Evolution method [48] considering different boundary conditions, Globalize Bounded Nelder Mead Method(GBNM) [49] can be found in the literature. Moreover, some researchers [39,50,51] compared different stochastic optimization methods such as Genetic Algorithm, Generalized Pattern Search, and Simulated Annealing for laminated composite optimization problems.

The researches on development of ecofriendly and lightweight engineering structures in the automotive industry have become obligatory due to End-of-Life Vehicles Directives and regulations on emission limits (Euro 5 & Euro 6). Therefore, it is very important that investigation of the potential usage of bio- based materials on the automotive structures as alternatives. In this regard, the present paper is an attempt to show the possibility of a bio-based natural (flax) fiber reinforced composite usage on the automotive applications. It is shown that flax fiber reinforced composites can be selected as an alternative bio-based material to E-glass reinforced ones in terms of fundamental frequency and cost for automotive applications.

In the present study, in order to maximize the fundamental frequency and minimize the cost, multi objective optimization of symmetric interply hybrid laminate which consist of graphite-flax/epoxy is considered by utilizing three stochastic optimization methods: Differential Evolution, Nelder Mead and Simulated Annealing. Fiber orientations, the numbers and the thicknesses of the surface and core layers are selected as design variables. Originality of the paper can be summarized as (i) the present paper is the first study considering natural fiber(flax) on fundamental frequency-cost optimization for laminated composite materials and the usage of flax fiber as an alternative to E-glass based on theoretical applicability in interply hybrid composite structures, (ii) in order to improve reliability and robustness of the design and optimization process and also to avoid inherent scattering of the stochastic algorithms, the different stochastic methods (DE, NM, SA) are performed for the same laminated composite design problems. (iii) in the present study, the proposed stochastic optimization algorithms (DE, NM, SA) have been compared to relatively more popular ACO method for the same laminated composite structure design and optimization problems.

2. Fundamental frequency analysis

Consider a simply supported specially orthotropic symmetric laminated plate with length a, width b, total thickness h and fiber