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Optimal Design of Composite Structures: A Historical Review

Ranjan Ganguli

Abstract | Composites are widely used in aerospace structures; however, most designs do not exploit the inherent tailorability of composites. Optimization methods can be used to design composite structures by tailoring the ply angles and stacking sequences. Typical objectives include minimum weight and constraints include strength, buckling, displacements and frequencies. This paper covers some of the literature in the area, with the objective of understanding the historical evolution of the field. Some ideas for future research are provided. It is hoped that the review will provide new researchers with a basic idea about the growth of the field and point them towards useful references for further information.

Keywords: *composite structures, optimal design, nonlinear programming, stochastic optimization, minimum weight design.*

1 Introduction

Composite structures have come a long way from being used in niche aerospace applications to becoming ubiquitous in engineering and technology. This revolution has occurred due to the low weight, high stiffness to weight ratio and improved fatigue characteristics of composites, relative to metals. In particular, fibre reinforced composites have become the material of choice in many aerospace applications. Aircraft wings, helicopter rotor blades and wind turbine blades are being routinely designed using composite materials. A high degree of confidence has been developed in the analysis tools used for the modelling of fibre reinforced composite materials, and they have been extensively verified with experimental data. The deployment of composite aircraft has also yielded flight data and maintenance information which can be used for better modelling and structural health monitoring of composites.

Despite all these advantages of composites over metals, the design of composites often fails to take advantage of the tailorability of these materials. Thus, to use a common adage, composites are being used as "black aluminium" and the full power of composites is not being exploited in many applications. Consider a simple laminated composite plate as an example. Such a plate may be designed by using a combination of 0, +45/−45 and +90/−90 plies. Typically, a symmetric laminate is used to ensure and the design is selected such that couplings are avoided and the composite material behaves in a manner analogous to a metal structure. This approach to design is largely driven by the inherent conservatism of structural engineers, who are often trained in metal based design practices. However, if it was possible to arbitrarily select the ply angles and their locations along the thickness direction of the plate, various composite couplings can be induced. Such composite couplings can sometimes be deleterious, but in many cases can be tailored to yield surprising benefits, such as ensure aeroelastic flutter stability of an aircraft wing which would otherwise be unstable, and therefore impossible to design, if metals were used. For example, forward swept wing configurations are possible with tailored composite structures.

The field of optimal design of composites has expanded enormously and a plethora of papers have been written on this topic. A historical evolution of the subject is brought out in this review by taking a sampling of research work over the past three decades. A discussion of the future research problems in the area is elucidated. It is hoped that this summary will introduce new researchers in the area to take up some of the research topics for further study.

Visiting Professor, Department of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore.

ganguli@aero.iisc.ernet.in
drganguli@gmail.com

2 Background

The review is divided into several parts, based on the time of publication of the papers. This approach gives an idea about the historical evolution of the field. The papers published in the 1970's are discussed under the heading called "pioneering research". The period of 1980's is called "early research", 1990's is called "moving towards design", from 2000 to 2010 is called "the new century", and after 2010 is called "current research". These names serve to classify the large numbers of papers.

Typically, the papers discussed in this review apply optimization methods to the design of composite structures. The optimal design problem involves posing an engineering design problem in the following mathematical form.

Minimize the multivariate function

$$f(\mathbf{x}) = f(x_1, x_2, \cdots, x_n) \tag{1}$$

Subject to equality and inequality constraints

$$\begin{aligned} h_i(\mathbf{x}) &= 0, \quad i = 1,2,\cdots,p \\ g_j(\mathbf{x}) &\leq 0, \quad j = 1,2,\cdots,m \end{aligned} \tag{2}$$

Here, the vector **x** represents the design variables. If only Eq. (1) is minimized, the problem is called an *unconstrained* optimization problem. If Eq. (1) is minimized while ensuring that the design variables also satisfy the constraints in Eq. (2), the problem is called a *constrained* optimization problem. Generally, the design variables can take any real number value. However, if they are allowed to take only integer values, we have an *integer programming* problem. The subject of optimization is also sometimes called *mathematical programming*. The values of the design variables obtained following the optimization process is called the *optimal design*. There are a multitude of methods which have been developed to solve the optimization problem. Many methods are based on Taylor's series expansions of the functions in Eqs. 1 and 2 are these typically require derivatives of these functions, also known as gradients. This class of methods is called *gradient based methods*. There is an alternate class of methods which do not use gradient information. They only use function values. A subclass of these *zero order methods* are the *stochastic optimization* methods which use algorithms based on random numbers to move about in the design space. Gradient based methods are computationally efficient but can get stuck in local minimum points. Stochastic optimization methods are robust to local minima and can locate global minimum points. However, they are computationally expensive and do not have well defined convergence measures. In some optimization problems, there are multiple objectives and these are called *multiobjective* optimization problems.

A typical composite laminate is shown in Figure 1. It consists of many plies or laminas. Each ply can have an orientation and a thickness associated with it. The terms ply angle and ply thickness are often used to indicate these properties. A major advantage of composite materials is that ply angles can be different from one another. This allows the exploitation of directional properties of the composite materials.

3 Pioneering Research

One of the first papers on optimal design of composites was written by Khot et al.[1] back in 1973. They presented an efficient optimization method based on strain energy distribution and a numerical search for the minimum weight design of fibre reinforced composites. The optimal design approach accounted for multiple loading conditions and displacement constraints on the structures. In,[2] Khot et al. used an optimality criterion based method for the minimum weight design of

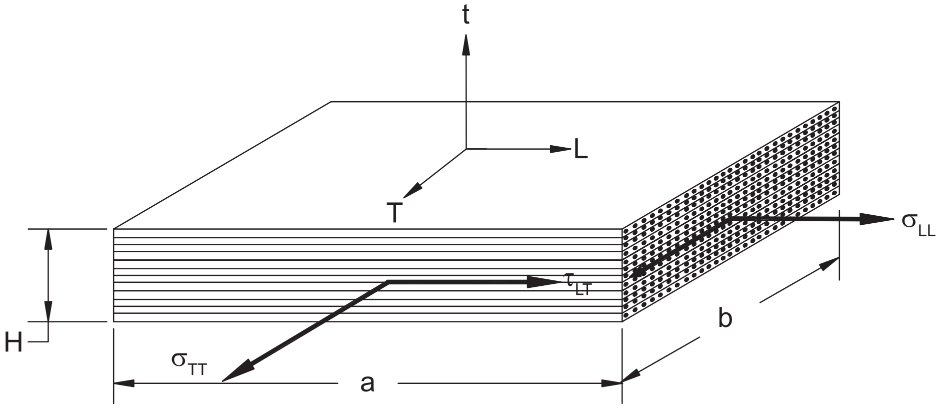

Figure 1: A typical composite laminate.

fibre reinforced composite structures and included stress and displacement constraints. A recurrence relation based on the optimality criteria was used to modify the design variables during the optimization process. These works showed that optimal design of composite structures was a feasible problem.

Bert[3] presented an approach for finding the optimal laminate design for a thin plate made of multiple layers of carbon fibre reinforced plastics. The optimal design objective was the maximization of the fundamental frequency of the structure. Such a problem is often solved in structural dynamics design in order to avoid the problem of resonance. He also addresses composites with epoxy matrices and fibres of boron, glass and organic fibre.

Starnes and Haftka[4] addressed the problem of aircraft wing design using optimization. The objective was minimum weight design and constraints were imposed on panel buckling, strength and displacement. Balanced, symmetric laminated composites were considered and results were obtained for graphite epoxy, graphite epoxy with boron spar caps and all aluminium construction. They showed that composite materials have an advantage relative to aluminium designs as they can often satisfy additional constraints with small mass increases. They point out that this advantage comes largely due to the additional design freedom of changing the lamina orientations rather than the total laminate thickness. The derivatives of the constraints with respect to the design variables were obtained analytically, thereby alleviating the onerous computer time requirements of those days. This work clearly laid out the path for many further works on composite optimization and heralded the applicability of optimization to actual aircraft wing design problems.

4 Early Research

At the beginning of the 1980's, the stage was set for structural optimization research, largely due to the increasing power of computers and the increase in the mathematical training of engineers. The algorithms of mathematical programming had begun to encroach into aerospace and structural engineering departments. One problem with composite optimization is the need for discrete/integer ply angle design variables. Schmit and Fleury[5] extended approximation concepts and dual methods to solve structural synthesis problems involving a mix of discrete and continuous type of design variables. Pure discrete and pure continuous design variables could be handled as special cases by this approach. The optimization problem was converted into a series of explicit approximate primal problems of separable form. Then, these problems were solved by creating continuous explicit dual functions, which were maximized subject to simple non-negativity constraints on the dual variables. The power of this approach was demonstrated on a problem which involved pure discrete variable treatment of a metallic swept wing and a mixed discrete-continuous variable solution for a thin delta wing with fibre composite skins.

Triplett[6] conducted studies on the use of directional properties of composite material to provide design improvements for fighter aircraft. A computer program named TSO, an acronym for Aeroelastic Tailoring and Structural Optimization, was developed and used for these investigations. This program used nonlinear programming method to find the optimum composite skin thickness distributions and ply angles that satisfy flutter and strength constraints, based on aeroelastic loads. He studied the F-15 composite wing, a horizontal tail, a prototype aircraft wing, and a future conceptual aircraft. He predicted both drag reduction and increased roll effectiveness for the F-15 composite wing, with no additional weight penalty. A unique minimum weight design was found for the horizontal tail, where the anisotropic characteristics of the composite material were used to provide strength and flutter balance weight.

Composite materials can lead to designs which would otherwise not be feasible. Weisshaar[7] studied the effects of tailoring of composites on flexible lifting surface divergence, lift effectiveness, and spanwise-centre-of-pressure locations. He found that tailoring of forward swept wing divergence is likely to be effective and that lateral control effectiveness can be enhanced by composite wing tailoring. Schmit and Mehrinfar[8] addressed wing box structures with composite stiffened panel components. They sought minimum weight designs while ensuring that failure modes such as panel and/or local buckling as well as excessive strain and displacement were not activated. The optimal design problem was broken into a system level design problem and a set of uncoupled component level problems. Results were obtained through a process of iterations between the system and component level problems. In later years, multilevel approaches to optimization became very popular in the design of aerospace composite structures.

Wurzel[9] developed rules for the application of laminated composites. He showed some simple examples and developed charts to showcase the advantages of composites in terms of weight.

Nshanian and Pappas[10] determined the optimal ply angle variation through the thickness of symmetric angle-ply shells of uniform thickness. They used continuous piecewise-linear segment approximations or discontinuous piecewise-constant segment approximations to the ply angle function. A mathematical programming problem was formulated and the design variables were the segment ply angles and the thickness of the plies. The objective was to maximize the minimum frequency or buckling load of a thin, simply supported, circular, cylindrical, angle-ply shell. They found that large performance gains can result from the use of variable ply angles as design variables.

Adali[11] mentions that "design optimization of composite structures gained importance and urgency in recent years as the engineering applications of fibre reinforced plastics have increased and weight savings became an essential design objective". Written in 1985, this statement shows the growing importance of optimal design, and is even valid today in some measure. He optimized a symmetric angle-ply laminate under cyclic loads with respect to fatigue failure load. The design variables were fibre angles, ply thickness and fibre content of the laminate. A fatigue failure criterion was used to find the maximum fatigue load. The results were obtained for an E-glass fibre reinforced epoxy material. He found that the optimal value can "increase or decrease unexpectedly with respect to a certain parameter". This statement does show an early appreciation of the need for robust design methods for composite structures and the indication of non-robust local minimum points.

Shirk et al.[12] point out that too much emphasis was given to the issue of minimum weight design. Though this is an important and legitimate goal of structural optimization, this "narrow view" did not utilize the enormous potential of aeroelastic tailoring. They point out that minimum weight is a subset of the objectives of aeroelastic tailoring, but the use of structural deformation of a lifting surface to fulfil aircraft performance objectives must also be considered. Some such objectives include maximization of the lift-to-drag ratio, expansion of the flight envelope, improved vibration and noise levels and improved controllability. They provide a definition of aeroelastic tailoring as follows: "Aeroelastic tailoring is the embodiment of directional stiffness into an aircraft structural design to control aeroelastic deformation, static or dynamic, in such a fashion as to affect the aerodynamic and structural performance of that aircraft in a beneficial way". This definition clearly brings in the need for composite materials through the "directional stiffness" requirements. The paper reviews the main research taking place during that period on aeroelastic tailoring and clearly brings out the potential of composite structures for this task.

Watkins and Morris[13] conducted a multilevel optimization for a laminated composite structure. They considered two objective functions namely a weight function and a strain energy change function. These two functions were combined into a composite function using weighting functions. This composite function was minimized numerically. We see the beginning of the realization for the need to consider multiple objectives and methods to combine them in this work. Minimizing of change in strain energy was used to ensure load path continuity in the structure when switching occurred between the upper and lower levels of optimization. They used continuous ply angle thickness and variation as the design variables. Constraints were imposed on strain and bucking. They studied the effect of the weighting coefficients on the optimal design and also considered the problem of single objective weight optimization.

During this period, researchers started realizing that the use of continuous design variables and finally rounding off the optimal ply angles was an ad hoc approach and typically lead to a suboptimal design. Mesquita and Kamat[14] showed that nonlinear mixed-integer programming was a better approach. The problem considered involved maximization of frequencies of stiffened laminated composite plates subject to frequency separation constraints and an upper bound on weight. The number of ply angles and given fiber orientations and the stiffener areas were considered as the design variables.

Grenestedt[15] tried to find the layup that maximized the lowest free vibration frequency of classical laminates. He described the normalized vibration frequency using two lamination parameters which could describe all layup possibilities of orthotropic laminates. He studied the influence of bending-twist coupling. Results were obtained numerically using a finite difference approach and analytically using a perturbation approach.

5 Moving Towards Design

The 1990's saw an enormous growth of computer power. The earlier research had set the stage in terms of algorithm development and feasibility studies showing the potential of optimal design for composites. During this decade, an effort was made to address more realistic composite structures and a realistic combination of design variables, constraints and objective.

Librescu and Song[16] addressed the problems of sub-critical aeroelastic response and divergence instability of swept-forward aircraft wing structures made from anisotropic composite materials. Such studies were also done earlier, however, to quote the author verbatim: "in contrast to the classical plate-beam or solid-beam models traditionally used in the study of these problems, the thin-walled anisotropic composite beam model is adapted here". This change is important as thin walled composite structures which are widely used in aerospace applications lead to a number of non-classical effects such as transverse shear deformation and primary and secondary warping effects. The aeroelastic tailoring results were now obtained with this new and improved model of the aircraft wing.

Haftka and Walsh[17] mentioned that practical applications limit the ply angles to 0, 90 and ±45 degrees and the laminate thickness to integer multiples of the ply thicknesses. The determination of the stacking sequence of the composite laminate therefore becomes an integer-programming problem, a nonlinear programming problem with integer or discrete design variables. However, they showed that stacking sequence design of a laminated plate for bucking can be expressed as a *linear* integer programming problem, if ply orientation identity design variables were used. Here, design variables which define the stacking sequence of the laminate are expressed as 0–1 integers. They considered the problem of the design of symmetric and balanced laminated plates under bi-axial compression. Two problems were formulated: maximization of bucking load for a given total thickness and minimization for the total thickness subject to a buckling constraint. Numerical results could be obtained using commercial software packages based on the branch and bound algorithm, a well-known integer programming method. Nagendra et al.[18] extended the formulation in[17] to include strain constraints. Since strains are nonlinear functions of both ply thickness and ply identity variables, a linear approximation for strains was developed. Results were compared with global optimum designs obtained using a genetic search approach. In later years, genetic algorithms and other stochastic optimization methods played a major role in the optimal design of composites, largely due to their ability to handle integer and discrete design variables and find global minimum points.

Graesser et al.[19] considered the design problem for a laminated composite stiffened panel which was subjected to multiple bending moments and in-plane loads. The objective was to minimize structural weight while satisfying panel maximum strain and minimum strength requirements. The skin and stiffener ply orientation angles and stiffener geometry were considered as design variables. The authors also addressed the fact that ply angles may need to be limited to user specified values.

Barthelemy and Haftka[20] present a review on approximation methods, which had started becoming an active area of research. They classify approximations into local, global and mid-range. The mid-range approximations try to enhance local approximations to imbue them with global qualities. In particular, the use of truncated Taylor's series approximations for the constraints and design variables are mentioned. The authors also mention the difference between function approximations where an attempt is made to express complicated functions for the objective and constraints in a simple form and problem approximations where the attempt is made to replace a complicated optimization problem by a simple problem which is easier to solve.

Miki and Sugiyama[21] found that in-plane and flexural stiffnesses become functions of the lamination parameters for symmetric and orthotropic laminates. They use lamination parameters, which are in turn functions of the stacking sequence, as the fundamental design variables in designing laminates.

In addition to fixed wing aircraft, composites have an enormous potential for helicopters. In particular, helicopter rotor blades are often made of composites and there exists the potential of tailoring their ply angles for reducing vibration levels and enhancing aeroelastic stability. Ganguli and Chopra[22] modelled the helicopter rotor blade as a composite box-beam and showed that ply angles have a significant impact on blade elastic stiffness, vibratory hub loads and aeroelastic stability of the soft-inplane composite hingeless rotor. They used a combination the six vibratory hub loads as the objective function and imposed constraints on frequency placement and aeroelastic stability in forward flight. They showed that aeroelastic tailoring using composite materials is possible for helicopter rotors and found that lag bending-torsion coupling can raise the lag mode damping by over 200 percent. A notable feature of their study was the use of analytical sensitivity derivatives which were included as part of the aeroelastic analysis. This allowed them to compute the gradients of flutter stability eigenvalues at a fraction of the computer time required using finite difference analysis. Furthermore, the analytical derivatives were typically more accurate than finite difference derivatives and avoided the problems of roundoff and truncation errors. In a subsequent paper, Ganguli and Chopra[23] extended their modelling to two-cell composite box-beams, which are better representatives of an actual helicopter blade. In this paper, they used a Vlasov theory based approach for calculating the blade elastic stiffness and composite couplings. Numerical results showed that a reduction in the vibratory hub loads of about 33 percent could be obtained by tailoring the ply angle design variables using design optimization. These two studies[22–23] were however, limited to continuous ply angle design variables and used a gradient based optimization method. However, their advocacy of composite couplings for helicopters has been proved experimentally in recent years by Bao et al.[24] Bao et al.[24] tested five sets of Mach scale composite tailored rotors. The baseline rotor had no composite coupling, two rotors had uniform spanwise flap-bending torsion coupling, and two other rotors had spanwise segmented flap-bending torsion couplings. They found reductions of upto 58 percent in the 4/rev vertical hub force could be obtained by using composite couplings.

Nagendra et al.[25] mention that the design of the stacking sequence is a combinatorial optimization problem. In early work, they had used integer programming to solve this problem but in this paper, they point out that genetic algorithms (GA) are well suited for this problem. One advantage of GA is that "many local optima with comparable performance may be found". They also pointed out the huge computer time requirement by GA's. In those days, the power of computers was limited, and computer time was a major issue. They also showed that somewhat better designs for the buckling design of stiffened panels could be obtained using the GA approach.

Kodiyalam et al.[26] applied the genetic search method for tailoring sandwich components of satellites. They considered avoidance of local instabilities of such structures and the constraints. They also used a linear least square fit approximation along with the genetic search to reduce computational effort. This kind of hybrid approach is often a good idea for solving realistic discrete optimization problems.

Ganguli and Chopra[27] found that minimizing helicopter vibration alone can lead to an increase in the vibratory loads which cause dynamic stresses, thereby negatively impacting the blade fatigue life. They considered a 4-bladed helicopter rotor and minimized both vibration and dynamic stresses using a composite objective function. The ply angles of the two-cell box beam walls were used as design variables. It was found that vibration reduction of up to 60 percent and peak-to-peak bending moments of up to 14 percent could be obtained through composite tailoring. Moreover, it was possible to convert an aeroelastically unstable design into a stable design by using bending-torsion couplings, with an increase in lag mode damping of over 200 percent compared to the starting design. In another work[28] Ganguli and Chopra addressed the use of composite couplings in advanced geometry blades which had sweep, droop and planform taper. The objective functions included helicopter vibration and blade fatigue life. Constraints were imposed on blade rotating frequencies, aeroelastic stability and autorotational inertia. The design variables were ply angles of the box-beam walls, sweep, anhedral and planform taper, along with non-structural mass and it's chordwise offset from the elastic axis. This study was a comprehensive work which clearly demonstrated the advantages of design optimization for helicopter rotors and the possibility of combining composite ply angles and blade geometry as design variables. Such concepts can be used for problems involving micro air vehicles or unmanned air vehicles today.

Venter et al.[29] suggested the use of polynomial approximations called response surfaces for expressing the objective function and constraints of a problem in terms of design variables. While Taylor's series used in earlier studies were *local* approximations, response surfaces were *global*. They constructed response surfaces for the stresses and buckling loads of a plate. Generally, second order polynomials are used for response surfaces. The reason for this choice is that most functions can be approximated as a second order curve in a local sense. Venter et al. also used higher order polynomials such as cubics and quartics for response surfaces. A representation of the metamodel concept is shown in Figure 2.

Eastep et al.[30] conducted an optimization study for the design of a composite wing. Their objective was to investigate the influence of composite ply angles on the optimized wing weight. Constraints were placed on strength, roll-reversal velocity and flutter velocity. They used a multidisciplinary design optimization (MDO) code named ASTROS in this study. At this point, we see the shift starting to take place from structural optimization to MDO, as the physical modelling and optimization algorithms had become powerful enough to handle problems involving structural, aerodynamic and even control design variables.

The series of papers emanating from ample funding for composite structural optimization research during the 1990's has led to gargantuan strides in this field. The stage was set for a text book on the topic of optimal design of composite structures and this contribution was done by Gurdal, Haftka and Hajela.[31] Indeed, their book is an excellent starting point for a researcher delving into the field.

6 The New Century

Eastep et al.[30] mention the term "information superhighway" in their paper and point out that as computer power doubles every few years, more and more problems become amenable to the tools of design optimization. Thus, some of the computer time problems with the use of stochastic optimization methods such as genetic algorithms become less obstructive. An increasing experimentation with new methods can be seen from the papers published after 2000. Soremekun et al.[32] found that GA's using generalized elitist selection procedures can find isolated optimum points surrounded by many designs with performance that is almost optimal. Walker and Smith[33] used genetic algorithms to minimize a weighted sum of the mass and deflection of a symmetrically laminated composite plate. They used ply angles and thicknesses as design variables and the Tsai-Wu failure criteria. Optimal structures were found for different load distributions and boundary conditions.

Keane[34] mentions about the emergence of response surface methods based on the theory of design of experiments as an important tool for design optimization. Computationally expensive analysis codes could be replaced by function approximations, which were sometimes called metamodels. An illustration of this concept is shown in Figure 2 where $\hat{f}$ represents the estimate of the objective function and $\hat{g}$ and $\hat{h}$ represent the estimates of the constraints obtained using metamodels. The main advantage of these metamodels is that they decoupled the analysis problem and the optimization problem. Also, they smooth out local changes in the objective functions and constraints. Such local changes can lead to the optimizer settling into a local minimum point which may not be robust to small changes in the design variables and system parameters.

During this time, the application of design optimization to helicopters had also reached a considerable level of maturity, with several papers addressing the problems of composite rotor blades. This field was covered in a comprehensive review by Ganguli.[35]

Murugan and Ganguli[36] developed a two level optimization approach to reduce the helicopter vibration levels and increase the stability damping of a helicopter rotor. In the upper level problem, response surface approximations of expensive vibration and stability analysis were created in terms of blade stiffness design variables. In the lower level problem, a composite box-beam was designed using genetic algorithms to match the stiffness values predicted by the upper level problem. This approach also allowed them to consider different composite materials for the lower level problem. In addition, various combinations of discrete ply angles were obtained for the optimal box-beam design.

Bruyneel[37] used approximation concepts and mathematical programming to design composite structures with weight, strength and stiffness criteria. He considered the monotonous and non-monotonous variation of the functions and used this information for the approximation. The Tsai-Hill criterion was used for the failure analysis. He used ply angles and thicknesses as design variables and considered a part of a railway vehicle for design.

Kathiravan and Ganguli[38] considered the optimum design of a composite box-beam subject to strength constraints. Box-beams are the main load carrying members of helicopter rotor blades. They considered ply angle design variables and tried to

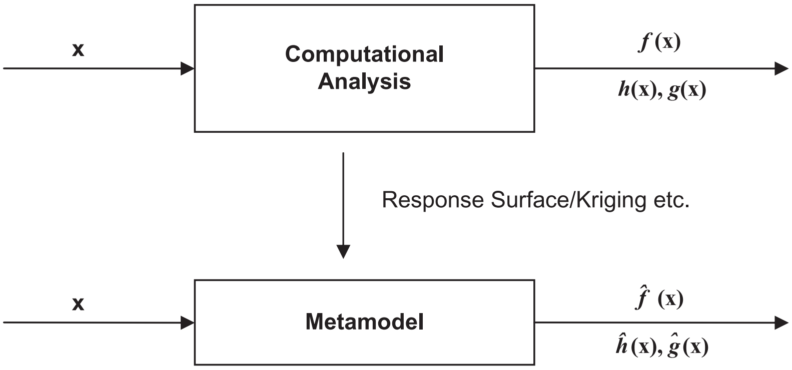

Figure 2: The metamodel of a computational analysis for optimization applications produces approximations of the objective functions and constraints.

maximize the failure margins with respect to the applied loading. The Tsai-Wu-Hahn failure criterion was used to calculate the reserve factor for each wall and ply. The minimum reserve factor was maximized. A novel feature of this study was a comparison between a gradient based method and particle swarm optimization (PSO). Unlike GA, which is based on the biological theory of survival of the fittest, PSO is based on sociobiology of insect swarms. While GA believes that competition is the best approach to success, PSO models elements of cooperation and the fact that by following the winner and the food supply (objective), good results can be obtained. They found that optimization led to the design of box-beam with greatly improved reserve factors. Also, while PSO yields globally best designs, the gradient based method can also be used to obtain useful designs efficiently.

Naik et al.[39] performed minimum weight design of a composite laminate using three different failure criteria: maximum stress, Tsai-Wu and failure mechanism based (FMB). Figure 3 shows an example of these failure envelopes. The FMB failure criterion considered different physical models of failure in composites such as matrix cracking, matrix crushing, fiber breaks and fiber compressive failure. They used GA for the optimization and found that Tsai-Wu led to excess weight in the laminate compared to the FMB and maximum stress criteria.

7 Current Research

Satheesh et al.[40] superimposed the three failure criteria (Tsai-Wu, maximum stress and FMB) over one another and created a new failure envelope based on the lowest absolute values of the predictions of these criteria. They called this as a conservative failure criterion and used it for minimum weight design of a composite laminate. They recommended the use of the conservative design approach for load carrying composite structures.

Banos[41] pointed out that optimization was being applied to the design of composite wind turbine rotor blades. Naik et al.[42] developed a failure criterion for minimum weight design where the least conservative parts of the Tsai-Wu, maximum shear and FMB failure criteria was used. They recommended this approach for unmanned and autonomous systems. Gyan et al.[43] pointed out that dispersion of the ply angles can lead to a damage tolerant design. They created a dispersion function and performed minimum weight design of a composite laminate using genetic algorithm. Since composite design spaces have several local minima, they selected the design which was most damage tolerant as indicated by the dispersion of the ply angles. Apalak[44] used artificial bee colony algorithm to maximize the first frequency of symmetrically laminated composite plates. The optimal stacking sequence was found to be in good agreement with those obtained by genetic algorithm and with other publications.

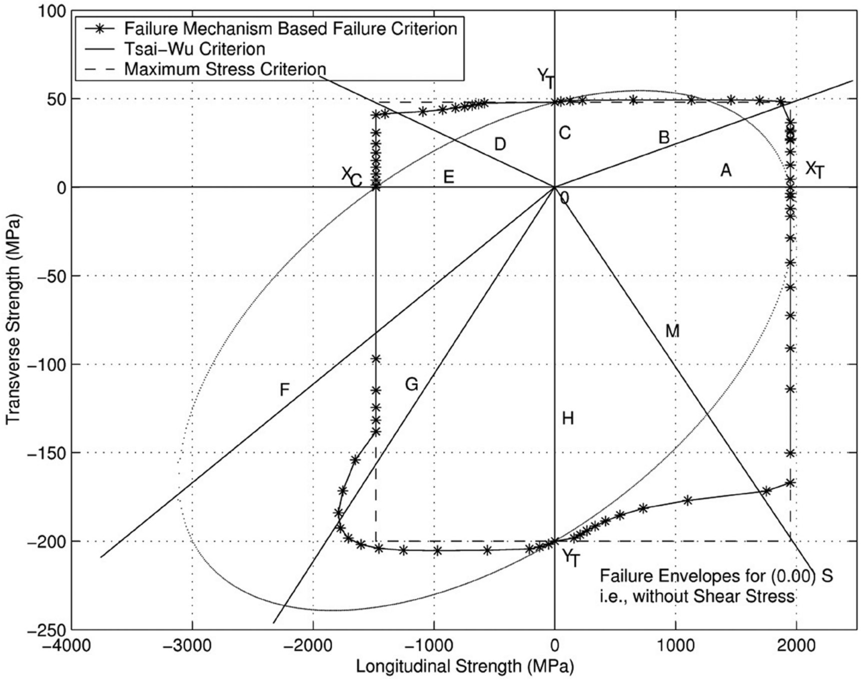

Figure 3: Comparison of failure envelopes obtained for carbon/epoxy lamina.

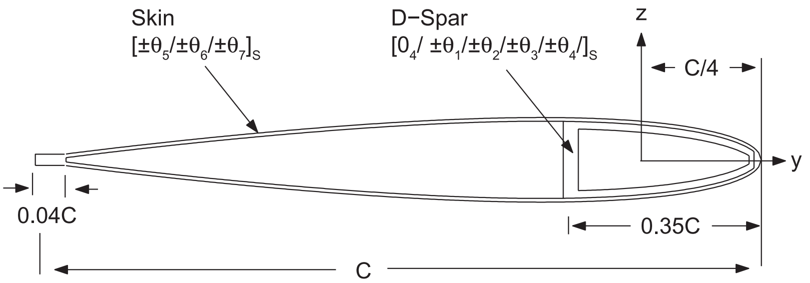

Figure 4: Composite airfoil design optimization problem with ply angle design variables.

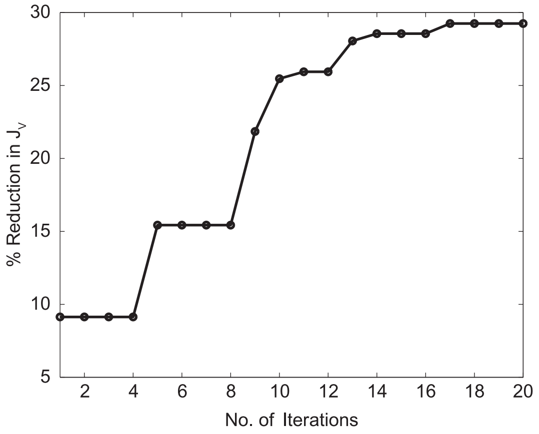

Figure 5: Reduction in vibration as iterations of the genetic algorithm progresses.

Murugan et al.[45] performed design optimization of a composite helicopter rotor blade. They wanted to reduce helicopter vibration while keeping the blade aeroelastically stable. They considered the ply angles of the D-spar and skin of the composite rotor blade with NACA 0015 airfoil section, as shown in Figure 4. They used space filling experimental designs along with polynomial response surfaces to create surrogate models of the objective function with respect to cross-section properties. A real coded GA was used to find the optimal stacking sequence. Figure 5 shows the reduction in vibration levels as the GA iterations progressed. They considered the effects of uncertainty in composite material properties and found that the response surface based approach lead to a relatively robust design.

Lee et al.[46] addressed hybrid composite structures (HCS) which are made of alternating layers of fibre-reinforced polymers and metal sheets. They used multi-objective genetic algorithm and robust design method for the optimization. They point out that robust design ensures that the structure tolerates to perturbations in loading and operating conditions away from the design conditions. They consider a problem of maximizing the stiffness of the structure while minimizing its weight. In the robust design approach, they considered the mean and standard deviations of the displacement for critical load cases.

The issue of robust design is very important for composites, as they can have unwanted uncertainty in the ply angles and thicknesses. Sarangapani and Ganguli[47] have shown that these uncertainties cause unwanted couplings in balanced laminates and can change the behaviour of the composite structure from its desired behaviour. These uncertainties need to be taken into account during the design of composite structures.

8 Discussion and Concluding Remarks

It is remarkable that the somewhat esoteric and abstruse tools of mathematical optimization have been extensively used for the optimal design of composite structures. Much of the credit for this goes to the few early researchers who started the field. Early research in the 1970's and 1980's was largely on structural optimization, and only a few intrepid researchers addressed composites during this time. However, it became clear from aeroelastic studies such as for the design of the forward swept wing that composite tailoring of bending-torsion coupling could alleviate the aeroelastic instability problem of reduced divergence speed. A forward swept wing is shown in Figure 6 (from Wikepedia). Such an aircraft is possible due to composite tailoring and fly by wire control systems.

Over the years, we see two key developments in the areas of *methods* and *analysis*. The optimization methods have advanced from gradient based methods based of feasible directions[48,49] and generalized reduced gradients[50] to sequential quadratic programming[51] and stochastic optimization methods.[52–59] There has been much progress in the development of approximation methods ranging from Taylor's series based approaches to response surfaces, kriging and neural network metamodels.[60–64] There is now a branch of thought which suggests that it is better to spend time for

Figure 6: Forward swept wing in X-29 aircraft.

creating accurate metamodels and then use them with optimization algorithms which now come programmed in software, for example the Matlab *fmincon* routine. The proliferation of stochastic optimization methods such as particle swarm optimization, ant colony optimization, artificial bee colony, etc. have opened a Pandora's Box in terms of publications in this area. However, one should realize that a simultaneous increase in *analysis quality* and *problem formulation* accuracy is very important to get useful *design* optimization results and that the research on methods should not shadow the work required for analysis and design.

The analysis problem is critical for the success of optimal design using composites in the industry.[65–67] The prediction of the analysis codes is used to go from the baseline design to the optimal design. If the prediction code is erroneous, the results will be useless for practical design. Fortunately, much progress has also been made on physics based modelling over the last two decades and good codes are available for the composite and aircraft design problem. However, in many multidisciplinary problems where composites are being used in a complex aerodynamic or aerothermodynamic environment, the predictions of codes is not so good. For example, helicopter and turbomachinery aeroelasticity need more research in terms of modelling and these should be well validated with experiments.[68,69] There are issues of numerical noise resulting from insufficient discretization and convergence problems which can make optimization of composite structures complicated when placed in the context of multidisciplinary analysis.

Most composite optimization research has focussed on minimum weight design and strength/buckling/frequency constraints. However, optimization could also be used to increase damage tolerance, aeroelastic flight envelopes, manufacturability, cost of manufacture and maintenance cost.[70–73] In fact, a large part of the costs incurred by airlines is due to maintenance and overhaul. New aircraft such as the Boeing 787 and the Airbus 350 have fuselage made from composite materials. These designs should address maintenance cost issues as an integral part of the optimal design process. Design optimization can be used to create composite structures which address many or all of these issues in a multi-objective optimization framework.[74–77] It is also necessary to move away from the single objective mind-set to a multi-objective mind-set. Tools such as multi-objective evolutionary algorithms can play an important role in this area. This area has seen a plethora of research and is ready for wide application to the optimal design of composite aircraft.

This review has considered fibre reinforced composite materials where high stiffness fibres are placed inside the epoxy resin matrix. There have been many studies of the dispersion of nanofibers in the epoxy, which can lead to better stiffness and in particular conductivity and damping properties.[78–80] Nanocomposites can offer advantages for lightning strike protection issues. Analysis methods for nanocomposites are making rapid progress. Optimization can be used to tailor the design of nanocomposites. Another recent trend in structural design is the use of biological inspiration for design. For example, wood inspired composites are being researched.[81] Other studies are going on in the area of morphing wings, which would change shape in order to improve the aeroelastic and aerodynamic behaviour of the wing.[82,83] Although some research on optimal design has been directed in this direction, a great possibility exists of using MDO for this problem.

Unmanned air vehicles and micro air vehicles have emerged as important flight vehicles in recent years. Frequently, they are made of composite materials.[84–87] Since they do not have human safety concerns, design optimization can be used to make extremely efficient low weight composite aircraft which gets the maximum benefit from the structure.

Finally, the composite materials are prone to uncertainties in their material properties and geometry due to the manufacturing processes. These need to be considered using the tools of reliability based optimization and robust design.[88–92] Some researchers have addressed this issue. Much more work needs be done on this problem with reference to composite aircraft design.

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References

1. Khot, N.S., Venkayya, V.B., Johnson, C.D., and Tischler, V.A., "Optimization of Fiber Reinforced Composite Structures" International Journal of Solids and Structures, Vol. 9, no. 10, 1973, pp. 1225–1236.
2. Khot, N.S., V.B. Venkayya, and L. Berke. "Optimum design of composite structures with stress and displacement constraints." *AIAA Journal* 14, no. 2 (1976): 131–132.
3. Bert, C.W. "Optimal design of a composite-material plate to maximize its fundamental frequency." *Journal of Sound and Vibration* 50, no. 2 (1977): 229–237.
4. Starnes Jr., James H., and Raphael T. Haftka. "Preliminary design of composite wings for buckling, strength, and displacement constraints." *Journal of Aircraft* 16, no. 8 (1979): 564–570.
5. Schmit, Lucien A., and C. Fleury. "Discrete-continuous variable structural synthesis using dual methods." *AIAA Journal* 18, no. 12 (1980): 1515–1524.
6. Triplett, William E. "Aeroelastic tailoring studies in fighter aircraft design." *Journal of Aircraft* 17, no. 7 (1980): 508–513.
7. Weisshaar, Terrence A. "Aeroelastic tailoring of forward swept composite wings." *Journal of Aircraft* 18, no. 8 (1981): 669–676.
8. Schmit, Lucien A., and Massood Mehrinfar. "Multilevel optimum design of structures with fiber-composite stiffened-panel components." *AIAA Journal* 20, no. 1 (1982): 138–147.
9. Wurzel, Dietmar P. "On the design and optimization of bidirectional composites." *Journal of reinforced plastics and composites* 2, no. 3 (1983): 178–195.
10. Nshanian, Y.S., and M. Pappas. "Optimal laminated composite shells for buckling and vibration." *AIAA journal* 21, no. 3 (1983): 430–437.
11. Adali, S. "Optimization of fibre reinforced composite Laminates Subject to Fatigue Loading." In *Composite Structures 3*, pp. 43–55. Springer Netherlands, 1985.
12. Shirk, Michael H., Terrence J. Hertz, and Terrence A. Weisshaar. "Aeroelastic tailoring-theory, practice, and promise." *Journal of Aircraft* 23, no. 1 (1986): 6–18.
13. Watkins, R.I., and A.J. Morris. "A multicriteria objective function optimization scheme for laminated composites for use in multilevel structural optimization schemes." *Computer Methods in Applied Mechanics and Engineering* 60, no. 2 (1987): 233–251.
14. Mesquita, Luis, and Manohar P. Kamat. "Optimization of stiffened laminated composite plates with frequency constraints." *Engineering Optimization* 11, no. 1–2 (1987): 77–88.
15. Grenestedt, Joachim L. "Layup optimization and sensitivity analysis of the fundamental eigenfrequency of composite plates." *Composite Structures* 12, no. 3 (1989): 193–209.
16. Librescu, Liviu, and Ohseop Song. "On the static aeroelastic tailoring of composite aircraft swept wings modelled as thin-walled beam structures." *Composites Engineering* 2, no. 5 (1992): 497–512.
17. Haftka, Raphael T., and Joanne L. Walsh. "Stacking-sequence optimization for buckling of laminated plates by integer programming." *AIAA Journal* 30, no. 3 (1992): 814–819.
18. Nagendra, Somanath, Raphael T. Haftka, and Z. Gurdal. "Stacking sequence optimization of simply supported laminates with stability and strain constraints." *AIAA Journal* 30, no. 8 (1992): 2132–2137.
19. Graesser, D.L., Z.B. Zabinsky, M.E. Tuttle, and G.I. Kim. "Optimal design of a composite structure." *Composite structures* 24, no. 4 (1993): 273–281.
20. Barthelemy, J.-F.M., and Raphael T. Haftka. "Approximation concepts for optimum structural design—a review." *Structural Optimization* 5, no. 3 (1993): 129–144.
21. Miki, Mitsunori, and Yoshihiko Sugiyama. "Optimum design of laminated composite plates using lamination parameters." *AIAA Journal* 31, no. 5 (1993): 921–922.
22. Ganguli, Ranjan, and Inderjit Chopra. "Aeroelastic optimization of a helicopter rotor with composite coupling." *Journal of Aircraft* 32, no. 6 (1995): 1326–1334.
23. Ganguli, Ranjan, and Inderjit Chopra. "Aeroelastic optimization of a helicopter rotor with two-cell composite blades." *AIAA Journal* 34, no. 4 (1996): 835–841.
24. Bao, Jinsong, V.T. Nagaraj, Inderjit Chopra, and Andreas P.F. Bernhard. "Wind tunnel test of five sets of Mach scale composite tailored rotor with flap-bending/torsion couplings for vibration reduction." *Journal of the American Helicopter Society* 53, no. 3 (2008): 215–225.
25. Nagendra, Somanath, D. Jestin, Zafer Gürdal, Raphael T. Haftka, and Layne T. Watson. "Improved genetic algorithm for the design of stiffened composite panels." *Computers & Structures* 58, no. 3 (1996): 543–555.
26. Kodiyalam, Srinivas, Somanath Nagendra, and Joel DeStefano. "Composite sandwich structure optimization with application to satellite components." *AIAA Journal* 34, no. 3 (1996): 614–621.
27. Ganguli, Ranjan, and Inderjit Chopra. "Aeroelastic optimization of a helicopter rotor to reduce vibration and dynamic stresses." *Journal of Aircraft* 33, no. 4 (1996): 808–815.
28. Ganguli, Ranjan, and Inderjit Chopra. "Aeroelastic tailoring of composite couplings and blade geometry of a helicopter rotor using optimization methods." *Journal of the American Helicopter Society* 42, no. 3 (1997): 218–228.
29. Venter, Gerhard, Raphael T. Haftka, and James H. Starnes. "Construction of response surface approximations for design optimization." *AIAA Journal* 36, no. 12 (1998): 2242–2249.
30. Eastep, F.E., V.A. Tischler, V.B. Venkayya, and N.S. Khot. "Aeroelastic tailoring of composite structures." *Journal of Aircraft* 36, no. 6 (1999): 1041–1047.
31. Gürdal, Zafer, Raphael T. Haftka, and Prabhat Hajela. *Design and Optimization of Laminated Composite Materials*. Wiley, 1999.

32. Soremekun, G., Z. Gürdal, R.T. Haftka, and L.T. Watson. "Composite laminate design optimization by genetic algorithm with generalized elitist selection." *Computers & Structures* 79, no. 2 (2001): 131–143.
33. Walker, Mark, and Ryan E. Smith. "A technique for the multiobjective optimisation of laminated composite structures using genetic algorithms and finite element analysis." *Composite Structures* 62, no. 1 (2003): 123–128.
34. Keane, A.J. "Wing optimization using design of experiment, response surface, and data fusion methods." *Journal of Aircraft* 40, no. 4 (2003): 741–750.
35. Ganguli, Ranjan. "A survey of recent developments in rotorcraft design optimization." *Journal of Aircraft* 41, no. 3 (2004): 493–510.
36. Murugan, Senthil, and Ranjan Ganguli. "Aeroelastic stability enhancement and vibration suppression in a composite helicopter rotor." *Journal of Aircraft* 42, no. 4 (2005): 1013–1024.
37. Bruyneel, M. "A general and effective approach for the optimal design of fiber reinforced composite structures." *Composites Science and Technology* 66, no. 10 (2006): 1303–1314.
38. Kathiravan, R., and Ranjan Ganguli. "Strength design of composite beam using gradient and particle swarm optimization." *Composite Structures* 81, no. 4 (2007): 471–479.
39. Narayana Naik, G., S. Gopalakrishnan, and Ranjan Ganguli. "Design optimization of composites using genetic algorithms and failure mechanism based failure criterion." *Composite Structures* 83, no. 4 (2008): 354–367.
40. Satheesh, R., G. Narayana Naik, and Ranjan Ganguli. "Conservative design optimization of laminated composite structures using genetic algorithms and multiple failure criteria." *Journal of Composite Materials* 44, no. 3 (2010): 369–387.
41. Banos, R., F. Manzano-Agugliaro, F.G. Montoya, C. Gil, A. Alcayde, and J. Gómez. "Optimization methods applied to renewable and sustainable energy: A review." *Renewable and Sustainable Energy Reviews* 15, no. 4 (2011): 1753–1766.
42. Naik, G. Narayana, Sonali Gyan, R. Satheesh, and Ranjan Ganguli. "Minimum weight design of fiber-reinforced laminated composite structures with maximum stress and Tsai-Wu failure criteria." *Journal of Reinforced Plastics and Composites* 30, no. 2 (2011): 179–192.
43. Gyan, Sonali, Ranjan Ganguli, and G. Narayana Naik. "Damage-tolerant design optimization of laminated composite structures using dispersion of ply angles by genetic algorithm." *Journal of Reinforced Plastics and Composites* 31, no. 12 (2012): 799–814.
44. Kemal Apalak, M., Dervis Karaboga, and Bahriye Akay. "The Artificial Bee Colony algorithm in layer optimization for the maximum fundamental frequency of symmetrical laminated composite plates." *Engineering Optimization* ahead-of-print (2013): 1–18.
45. Herencia, J. Enrique, Raphael T. Haftka, and Vladimir Balabanov. "Structural optimization of composite structures with limited number of element properties." *Structural and Multidisciplinary Optimization* 47, no. 2 (2013): 233–245.
46. Lee, DongSeop, Carlos Morillo, Sergio Oller, Gabriel Bugeda, and Eugenio Oñate. "Robust design optimisation of advance hybrid (fiber-metal) composite structures." *Composite Structures* 99 (2013): 181–192.
47. Sarangapani, G., and Ranjan Ganguli. "Effect of Ply-Level Material Uncertainty on Composite Elastic Couplings in Laminated Plates." *International Journal for Computational Methods in Engineering Science and Mechanics* 14, no. 3 (2013): 244–261.
48. Hajela, P., and C-J. Shih. "Optimal design of laminated composites using a modified mixed integer and discrete programming algorithm." *Computers & structures* 32, no. 1 (1989): 213–221.
49. Fukunag, Hisao, and Garret N. Vanderplaats. "Stiffness optimization of orthotropic laminated composites using lamination parameters." *AIAA Journal* 29, no. 4 (1991): 641–646.
50. Vanderplaats, Garret N. "An efficient feasible directions algorithm for design synthesis." *AIAA Journal* 22, no. 11 (1984): 1633–1640.
51. Swan, C.C., and Jasbir S. Arora. "Topology design of material layout in structured composites of high stiffness and strength." *Structural Optimization* 13, no. 1 (1997): 45–59.
52. Jenkins, W.M. "Towards structural optimization via the genetic algorithm." *Computers & Structures* 40, no. 5 (1991): 1321–1327.
53. Perez, R.E., and K. Behdinan. "Particle swarm approach for structural design optimization." *Computers & Structures* 85, no. 19 (2007): 1579–1588.
54. Lee, Kang Seok, and Zong Woo Geem. "A new structural optimization method based on the harmony search algorithm." *Computers & Structures* 82, no. 9 (2004): 781–798.
55. Omkar, S.N., J. Senthilnath, Rahul Khandelwal, G. Narayana Naik, and S. Gopalakrishnan. "Artificial Bee Colony (ABC) for multi-objective design optimization of composite structures." *Applied Soft Computing* 11, no. 1 (2011): 489–499.
56. Omkar, S.N., Rahul Khandelwal, T.V.S. Ananth, G. Narayana Naik, and S. Gopalakrishnan. "Quantum behaved Particle Swarm Optimization (QPSO) for multi-objective design optimization of composite structures." *Expert Systems with Applications* 36, no. 8 (2009): 11312–11322.
57. Omkar, S.N., Dheevatsa Mudigere, G. Narayana Naik, and S. Gopalakrishnan. "Vector evaluated particle swarm optimization (VEPSO) for multi-objective design optimization of composite structures." *Computers & Structures* 86, no. 1 (2008): 1–14.
58. Omkar, S.N., Rahul Khandelwal, Santhosh Yathindra, G. Narayana Naik, and S. Gopalakrishnan. "Artificial immune system for multi-objective design optimization

of composite structures." *Engineering Applications of Artificial Intelligence* 21, no. 8 (2008): 1416–1429.

59. Murugan, M.S., S. Suresh, R. Ganguli, and V. Mani. "Target vector optimization of composite box beam using real-coded genetic algorithm: a decomposition approach." *Structural and Multidisciplinary Optimization* 33, no. 2 (2007): 131–146.
60. Wang, G. Gary, and S. Shan. "Review of metamodeling techniques in support of engineering design optimization." *Journal of Mechanical Design* 129 (2007): 370.
61. Kleijnen, Jack P.C. "Kriging metamodeling in simulation: a review." *European Journal of Operational Research* 192, no. 3 (2009): 707–716.
62. Gholizadeh, Saeed, and Eysa Salajegheh. "Optimal design of structures subjected to time history loading by swarm intelligence and an advanced metamodel." *Computer Methods in Applied Mechanics and Engineering* 198, no. 37 (2009): 2936–2949.
63. El-Beltagy, Mohammed A., and A.J. Keane. "Metalmodeling techniques for evolutionary optimization of computationally expensive problems: promises and limitations." (1999): 196–203.
64. Ong, Yew S., Prasanth B. Nair, and Andrew J. Keane. "Evolutionary optimization of computationally expensive problems via surrogate modeling." *AIAA Journal* 41, no. 4 (2003): 687–696.
65. Venkataraman, S., and R.T. Haftka. "Structural optimization complexity: what has Moore's law done for us?" *Structural and Multidisciplinary Optimization* 28, no. 6 (2004): 375–387.
66. Peri, Daniele, and Emilio F. Campana. "High-fidelity models in global optimization." In *Global Optimization and Constraint Satisfaction*, pp. 112–126. Springer Berlin Heidelberg, 2005.
67. Agte, Jeremy, Olivier de Weck, Jaroslaw Sobieszczanski-Sobieski, Paul Arendsen, Alan Morris, and Martin Spieck. "MDO: assessment and direction for advancement—an opinion of one international group." *Structural and Multidisciplinary Optimization* 40, no. 1–6 (2010): 17–33.
68. van der Wall, Berend G., Joon W. Lim, Marilyn J. Smith, Sung N. Jung, Joëlle Bailly, James D. Baeder, and D. Douglas Boyd Jr. "The HART II International Workshop: an assessment of the state-of-the-art in comprehensive code prediction." *CEAS Aeronautical Journal* (2013): 1–30.
69. Shah, S.R., S.V. Jain, R.N. Patel, and V.J. Lakhera. "CFD for Centrifugal Pumps: A Review of the State-of-the-Art." *Procedia Engineering* 51 (2013): 715–720.
70. Sebaey, T.A., E.V. González, C.S. Lopes, N. Blanco, and J. Costa. "Damage resistance and damage tolerance of dispersed CFRP laminates: Effect of ply clustering." *Composite Structures* (2013).
71. Sebaey, T.A., E.V. González, C.S. Lopes, N. Blanco, and J. Costa. "Damage resistance and damage tolerance of dispersed CFRP laminates: The bending stiffness effect." *Composite Structures* (2013).
72. Gupta, Abhishek, Piaras Kelly, Matthias Ehrgott, and Simon Bickerton. "Applying Bi-level Multi-Objective Evolutionary Algorithms for Optimizing Composites Manufacturing Processes." In *Evolutionary Multi-Criterion Optimization*, pp. 615–627. Springer Berlin Heidelberg, 2013.
73. Hu, Weifei, Dohyun Park, and DongHoon Choi. "Structural optimization procedure of a composite wind turbine blade for reducing both material cost and blade weight." *Engineering Optimization* ahead-of-print (2013): 1–19.
74. Srinivas, Nidamarthi, and Kalyanmoy Deb. "Muiltiobjective optimization using nondominated sorting in genetic algorithms." *Evolutionary Computation* 2, no. 3 (1994): 221–248.
75. Rajagopal, S., and Ranjan Ganguli. "Conceptual design of UAV using Kriging based multi-objective genetic algorithm." *Aeronautical Journal* 112, no. 1137 (2008): 653–662.
76. Rajagopal, S., and Ranjan Ganguli. "Multidisciplinary Design Optimization of Long Endurance Unmanned Aerial Vehicle Wing." *Computer Modeling in Engineering & Sciences(CMES)* 81, no. 1 (2011): 1–34.
77. Coello Coello, Carlos A. "Evolutionary multi-objective optimization: a historical view of the field." *Computational Intelligence Magazine, IEEE* 1, no. 1 (2006): 28–36.
78. Njuguna, James, and Krzysztof Pielichowski. "Polymer nanocomposites for aerospace applications: properties." *Advanced Engineering Materials* 5, no. 11 (2003): 769–778.
79. Voevodin, A.A., and J.S. Zabinski. "Nanocomposite and nanostructured tribological materials for space applications." *Composites Science and Technology* 65, no. 5 (2005): 741–748.
80. Sasikumar, K., N.R. Manoj, R. Ramesh, and T. Mukundan. "Carbon nanotube–polyurethane nanocomposites for structural vibration damping." *International Journal of Nanotechnology* 9, no. 10 (2012): 1061–1071.
81. Saavedra Flores, E.I., M.S. Murugan, M.I. Friswell, and E.A. de Souza Neto. "Reorientation of Fibres and Local Mechanisms of Deformation in a Wood-Inspired Composite." *Journal of Multiscale Modelling* 4, no. 01 (2012).
82. Murugan, Senthil, Erick, I. Saavedra Flores, Sondipon Adhikari, and M.I. Friswell. "Optimal design of variable fiber spacing composites for morphing aircraft skins." *Composite Structures* 94, no. 5 (2012): 1626–1633.
83. Gamboa, P., J. Vale, F.J.P. Lau, and A. Suleman. "Optimization of a morphing wing based on coupled aerodynamic and structural constraints." *AIAA Journal* 47, no. 9 (2009): 2087–2104.
84. Hailian, Yin, and Yu Xiongqing. "Integration of manufacturing cost into structural optimization of composite wings." *Chinese Journal of Aeronautics* 23, no. 6 (2010): 670–676.
85. Lee, Myoung Keon, Chang Min Cho, and Se Yong Jang. "HALE UAV Composite Wing Structure Design." *Advanced Materials Research* 123 (2010): 105–108.

86. De Leon, D.M., C.E. de Souza, J.S.O. Fonseca, and R.G.A. da Silva. "Aeroelastic tailoring using fiber orientation and topology optimization." *Structural and Multidisciplinary Optimization* 46, no. 5 (2012): 663–677.
87. Deaton, Joshua D., and Ramana V. Grandhi. "A survey of structural and multidisciplinary continuum topology optimization: post 2000." *Structural and Multidisciplinary Optimization* (2013): 1–38.
88. Reddy, Mahidhar V., Ramana V. Grandhi, and Dale A. Hopkins. "Reliability based structural optimization: a simplified safety index approach." *Computers & Structures* 53, no. 6 (1994): 1407–1418.
89. Chiachio, Manuel, Juan Chiachio, and Guillermo Rus. "Reliability in composites–A selective review and survey of current development." *Composites Part B: Engineering* 43, no. 3 (2012): 902–913.
90. Rouhi, M., and M. Rais-Rohani. "Modeling and probabilistic design optimization of a nanofiber-enhanced composite cylinder for buckling." *Composite Structures* (2012).
91. Wang, Zequn, and Pingfeng Wang. "A nested extreme response surface approach for time-dependent reliability-based design optimization." *Journal of Mechanical Design* 134 (2012): 121007.
92. Zou, T., and S. Mahadevan. "A direct decoupling approach for efficient reliability-based design optimization." *Structural and Multidisciplinary Optimization* 31, no. 3 (2006): 190–200.

Ranjan Ganguli obtained his M.S. and Ph.D. in Aerospace Engineering from the University of Maryland, College Park, in 1991 and 1994, respectively, and his B.Tech degree in Aerospace Engineering from the Indian Institute of Technology, Kharagpur, in 1989.

Following his Ph.D., he worked at the Alfred Gessow Rotorcraft Center of the University of Maryland as an Assistant Research Scientist until 1997 on projects on rotorcraft health monitoring and vibratory load validation for the Naval Surface Warfare Center and United Technology Research Center, respectively. He also worked at the GE Research Lab in Schenectady, New York, and at Pratt and Whitney, East Hartford, Connecticut, from 1997 to 2000. He joined the Aerospace Engineering department of IISc as an Assistant Professor in July 2000. He was promoted to Associate Professor in 2005 and to Full Professor in 2009. He has held visiting positions at TU Braunschweig, University of Ulm and Max Planck Institute of Metal Research, Stuttgart, in Germany; University Paul Sabatier and Institute of Mathematics, in Toulouse, France; Konkuk University in South Korea, the University of Michigan, Ann Arbor, in USA, and the Nanyang Technological University, Singapore.

Prof. Ganguli's research interests are in helicopter aeromechanics, aeroelasticity, structural dynamics, composite and smart structures, design optimization, finite element methods and health monitoring. He has published 152 articles in refereed journals and 93 conference papers. His publications have been cited over 1450 times in ISI Web of Science and his h-index is 21.

He was awarded the ASME best paper award in 2001, the Golden Jubilee award of the Aeronautical Society of India in 2002, the Alexander von Humboldt fellowship in 2007 and the Fulbright Senior Research fellowship in 2010. Prof. Ganguli is a Fellow of the American Society of Mechanical Engineers, a Fellow of the Royal Aeronautical Society, UK, a Fellow of the Indian National Academy of Engineering and an Associate Fellow of the American Institute of Aeronautics and Astronautics.

He has taught courses on flight and space mechanics, engineering optimization, helicopter dynamics, aircraft structures, structural mechanics, aeroelasticity and navigation. He has supervised the thesis of 10 Ph.D. and 35 Masters Degree students. He has written books on "Engineering Optimization" and "Gas Turbine Diagnostics", both published by CRC Press, New York, and a book titled "Structural Damage Detection using Genetic Fuzzy Systems" published by Springer. He is an Associate editor of AIAA Journal and the Journal of the American Helicopter Society, and several other journals.