Application of Genetic Algorithms for optimal design of composite materials

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Abstract

Genetic Algorithms have been widely accepted as a robust and efficient technique for optimization problems in varied disciplines of science and technology in the recent past. One such application in a major field of research in materials science has been elucidated here. Composites have been a boon to the materials fraternity. They find applications in various engineering and commercial fields. Such wide application of these fascinating materials requires the need of optimum design of these materials. Here the concept of using Genetic Algorithms (GA) procedures in layout optimization of composite structures has been described. Basically the GA is applied in conjunction with the finite element analysis (FEA) in optimizing the stacking sequence, shape and size of composites layout.

Introduction

One of the most popular and common application of composites are in cylindrical pressure vessels. The same technology is also being used in strategic applications such as reservoirs, chemical containers, pipes, aircraft and ship elements. The increasing use of laminated composites has led to the necessity to obtain an appropriate layout of a structure so that it withstands the imposed loads safely and economically. The layout of a structure refers to the stacking sequence, shape and size (thickness, volume, weight etc.). The design of composite laminates has often been formulated as a continuous optimization problem, with ply thickness and ply orientation angles as design variables. However, for many practical problems, ply thicknesses are fixed and ply orientation angles are limited to a small set of angles, such as 0°, 90° and ±45°. The design of the laminate then becomes a stacking sequence optimization problem, which can be formulated as an integer programming problem. Interest in the application of genetic algorithms (GA) to such integer programming problems has increased over recent years.

In this paper an approach has been made to extend and point out the applicability of GA in layout optimization problems for laminated structures made of unidirectional composite materials. It is universally known that the degree of orthotropy of composite materials involves lot of problems in optimization of 2D structures as compared to the similar cases in isotropic materials. Therefore an attempt has been made to build very flexible external subroutines that would provide optimal solutions using GA and also combining with existing FE analysis. The basic procedure is schematically represented in figure 1.

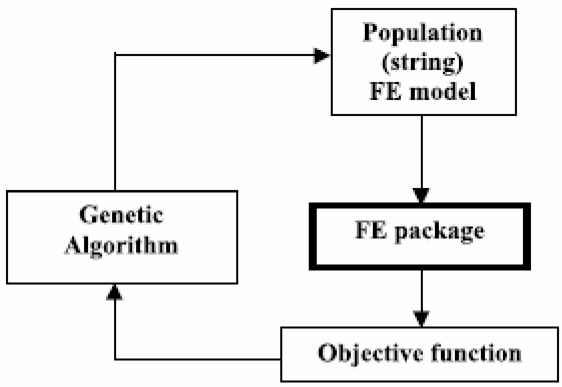

Fig.1 Schematic representation of the procedure adopted here for layout optimization.

Genetic Algorithms

GAs are search based algorithms which simulate the mechanics of natural genetics for artificial systems based on natural selection. These methods have been basically inspired from nature based on Darwin's theory of evolution, a process of continuous change from a lower, simpler or worse to a higher, complex or better state. Natural selection is a process where only the fittest individuals have the highest probability of survival. Genetics is a modern science and it reveals in detail how the process of natural selection works. This led to the modern theory of evolution. Each character is called a gene and these genes can exist in alternative forms called the alleles. Alleles control the alternative traits of a character. Genes are transmitted from one generation to the next without any change. When a population of biological species evolves over generations, characteristics that are useful for survival tend to be passed on to future generations as these characteristics aid breeding of the individuals possessing them.

The idea of implementing the above idea of natural selection to optimization problems was introduced first by John Holland and his colleagues in 1981. Since then GA has been implemented in various fields of science and technology.

The structure of GA basically consists of three main operations: function evaluation, selection and reproduction, and the two main classes of operators: mutation and crossover. By the proper definition of selection, mutation and crossover operators any optimization can be performed with ease.

A technique for using GAs together with finite element analysis to minimize both the mass and deflection of fiber reinforced symmetrically laminated structures with several discrete design variables is described. The design constraint implemented is based on the Tsai–Wu failure criterion, although any suitable failure criterion can be implemented. Rectangular plates are used to demonstrate the method, have eight layers, and are symmetric about the midplane. Thus, the four fiber orientations and laminae thicknesses are to be determined optimally. To determine the best configuration, optimal ply angles for each layer are selected from amongst a predefined set of fiber orientations, commonly used in industry. This approach leads to cost-effective designs by virtue of allowing the use of standard composite plies. The most common orientations are 0°, ±30°, ±45°, ±60° and 90° which are the ones used in the present study. Also, the laminate thicknesses must be multiples of a standard ply, thickness; eg. 0.001.

Model Idea

The basic idea of this model is the generation of a FE mesh describing completely the physical problem. Then GA is used to optimize this mesh for best solutions. The mesh generated for this analysis may or may not be changed during optimization but it is not adopted during optimization in the classical sense. The best advantage of GA is its non differential parameters which mean GA does not require sensitivity analysis and classic mesh adaptivity. Also GA is fully automated and even insensitive to the wrong selection of initial strings as they are eliminated during optimization procedure. However it is important to arrange the process of coding the input data for FE manipulation and also obtaining the output data economically thus avoiding the need to manipulate the code of the FE package.

Optimization problems

Stacking sequence optimization.

The stacking sequence optimization of multilayered, 2-D structures, such as plates or shells is one of the simplest optimization problems and is considered here. If the total thickness of the laminate is equal to t, constructed of an arbitrary number N of orthotropic layers with each layer t/N thick as shown in fig. 2. The laminate is assumed to be symmetric and balance which is why only N/4 ply orientations are required to describe the laminate configuration.

The optimization problem has been formulated as :

$$Max_s Min_{m.n} \lambda_b (S; m, n) \tag{1}$$

Here S denotes the set of design variables, and m and n are wave numbers in buckling λ_b is the objective function computed directly by FEA and denotes a buckling load parameter (Fig 2).
The symbol S denotes the set being a bit string representation of possible solutions to the optimization problem in (1). The fibers as shown in fig. 2(b) are oriented in 0°,45°,90° sequence in the first case and 0°,22.5°,45°,67.5°,90° in second case. Therefore the input data for FEA reduces to combinations of stacking sequences as in eqn. (2).

$$[1,2,1,1]_{sym} = [1,5,4,3]_{sym} \qquad (2)$$

Then these are directly fed as input data.

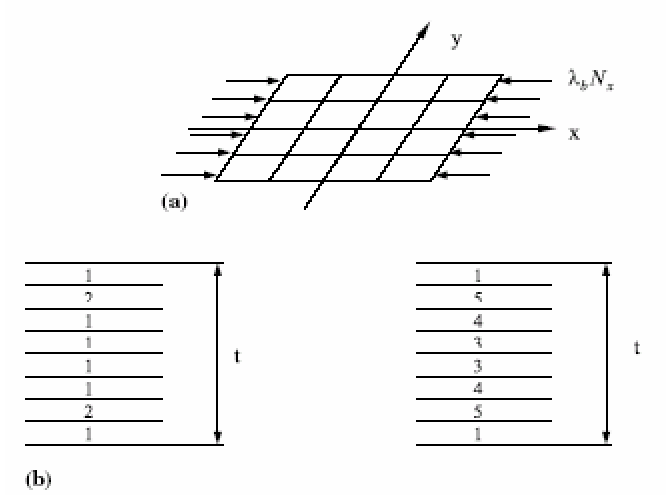

Fig. 2 (a), Finite element discretization of a compressed multilayered plate. (b) Definition of strings for different numbers of design variables.

Shape Optimizations.

Here the objective function can be formulated as:

To calculate,
$Min(MaxU)$ over feasible shapes C. (3)
Under the set of N additional constraints describing the geometrical properties of the curve C, i.e.:

$$F_n = Const. \quad n=1, 2, 3\ldots\ldots\ldots N \qquad (4)$$

U is the function that describes the failure criterion. The FEA gives an appropriate and convenient parameterization of the curve C. It is possible to express the curve C as:

- The set of points describing the nodal point positions of FE discretisations.
- The set of parameters defining uniquely the considered curve C.

Among the various forms of shape parameterizations cubic splines are very popular owing to its numerical simplicity and stability. The cubic spline described here is called the cubic Bezier curve and can be represented as:

$$[p(h)]^{\mathrm{T}} = [h^3, h^2, h, 1] \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} a_0^{\mathrm{T}} \\ a_1^{\mathrm{T}} \\ a_2^{\mathrm{T}} \\ a_3^{\mathrm{T}} \end{bmatrix},$$
$$h \in [0, 1], \qquad (5)$$

Where a_i, are the position vectors of the control vertices A_i. For computer simulation a Bezier spline segment was considered passing through a set of key points P_i, which lie on the curve C and have position vectors p_i. The chromosome hence can be considered as these points which are represented by a real number in binary form and can be expressed as:

$$\text{chromosome} = \left\langle \underbrace{00111}_{P_1}\underbrace{01100}_{P_2}\underbrace{01111}_{P_3}\underbrace{10001}_{P_4} \right\rangle. \tag{6}$$

In the above case there are 4 key points as shown in figure 3.

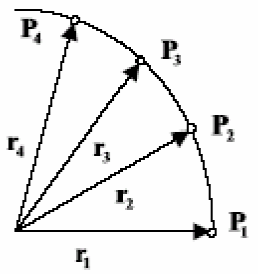

Fig 3. The curve C with four key points.

Thus by choosing proper genetic parameters for the optimization a proper optimized curve shall be obtained. Now the optimized shape is generated using FEA and hence the complete optimized shape is obtained.

Size Optimizations.

This optimization is mainly concerned with the material optimization. There are a few such optimizations which have been research in the past viz. homogenization methods by Bendsoe and Kikuchi, a ground structure approach by Rozvany and Zhou. The underlying principle in all these methods are the same that is, they start from a discrete structure and remove obsolete members. In order to optimize we assume the number of elements in the initial structure to be M. M denotes the total number of bars or trusses in the structures or the number of finite elements modeling the structure. Hence the optimization problem has been formulated as:

$$MinV(s) \quad s=1, 2, 3.......M, \tag{7}$$

V here is the total volume of the structure and s is the design variable. Now this problem is subjected to a set of constraints to simulate the real case.

$$F_i \leq F_{oi} \quad i=1, 2, 3......K, \tag{8}$$

K is the total number of constraints.

The whole initial structure is discretised in the beginning with the use of arbitrary finite elements. The position of each finite element is coded in the string in binary form i.e. 1 means the element exists in the structure and 0 means it doesn't. Thus if 20 finite elements are considered the string will look like:

$$[1,1,1,\ 1,1,1,\ 1,1,1,\ 1,1,1,\ 1,1,1,\ 1,1,1,\ 1,1]. \tag{9}$$

There is one stumbling block for this kind of optimization; there are too many elements hence the optimization is broken up into two steps.

- The initial structure is divided into smaller groups of elements so that (9) is replaced by four sets of (10)

  $$[1,1,1,1,1]. \tag{10}$$

- Now when GA is applied to (10) then lots of unwanted elements will be eliminated and then we can revert back to the mesh representation in (9) and apply GA again.

For finer meshes the crossover and mutation methods govern the efficiency of optimization. Although it is necessary to add a command line which ensures that the existing elements in the mesh representation are at least connected with one another along one edge.

Application to a composite propeller plate.

A high skew propeller is considered here as an example the properties of which are governed by (11)

$$\text{Advance Coefficient } J = \frac{V_a}{nD}$$

$$\text{Torque Coefficient } K_Q = \frac{Q}{\rho n^2 D^5} \quad (11)$$

Here n=1708 rpm, V_a= 7.716 m/s, J= 0.889, K_Q=0.05204.
Where D is the diameter V_a is the axial velocity; n is the rotational speed Q is the propeller torque, ρ is the fluid density.

Assuming the rectangular shape as shown in Fig. 4 L_x/L_y=2, t/L_x=0.01 modeled with the use of plane strain triangular finite elements. The method used for testing as depicted in Fig. 9 is that tit is loaded in the middle and both the ends are fixed to avoid translation along X, Y axes. The propeller plate has to be optimized for minimum material volume with constraints of Mises equivalent stresses as well as for transverse translation at the load point. This is achieved using the above described method for optimization.

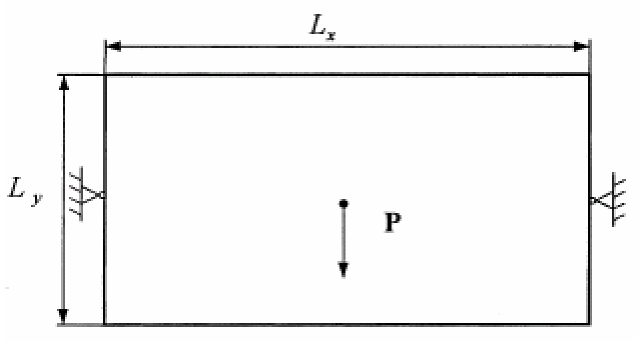

Fig . 9, The layout of the structure.

Summary and conclusions.

In this paper an approach for layout optimization for laminated structures using Genetic Algorithms with the aid of Finite Element Analysis has been elucidated. The major problem in this approach is the formulation of the objective function. The accuracy and efficiency of this optimization technique depends on mainly on the GA operations. The design constraint implemented is based on the Tsai–Wu failure criterion, although any suitable one can be substituted.

GAs are well suited to structural optimization problems since they are discrete in nature. They are based on probabilistic not deterministic rules hence they are indifferent to problem specific data. The algorithms work with the parameter set and not the parameters themselves. A binary code is more suitable for coding continuous variables or large data sets.

Thus it can be concluded that;

- Proper coding of design variables and then selection of a new population is essential for optimization.
- Optimization procedures here do not require any sensitive studies which seem to be a great advantage over classical optimization techniques.

- Although the process of optimization is very simple and easy but it is not fast. Some optimizations do tend to take a large amount of time which is why the use of evolutionary methods is encouraged.

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