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Topology Optimization of Composite Structure Using Bi-Directional Evolutionary Structural Optimization Method

X. F. SUN[a*], J. YANG[a], Y. M. XIE[b], X. HUANG[b], Z. H. ZUO[b]

[a]*School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Australia*
[b]*School of Civil, Environmental and Chemical Engineering, RMIT University, Australia*

Abstract

This paper deals with topology optimization of composite structure using Bi-directional Evolutional Structural Optimization (BESO) method. By redefining the criteria of the optimization evolution progress, the proposed method is able to extend current BESO method from isotropic material to anisotropic composite material. The initial modification of BESO method is to allow for inefficient Material Element String (MES) to be removed while efficient MES to be added in the thickness direction of a composite structure. This modification can reduce the chance of high stress concentration in a composite structure and also produce the geometry which is easy to fabricate using fabrication techniques currently available. The results of a cantilever composite laminate under uniform in-plane pressure are presented, showing that the proposed method can produce shape and topology for composite structures with optimal structure stiffness.

Keywords: Topology optimization, composite structure, Bi-directional Evolutional Structural Optimization, Material Element String (MES)

* Corresponding author and Presenter
Email: xiangfeng.sun@rmit.edu.au

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1. Introduction

Composite materials are becoming more and more popular in structural applications such as aerospace, automotive and civil engineering due to their advantages of lightweight, good fatigue resistance, high energy absorption and better crashworthiness etc. Traditional design methods use safety factors to ensure that the structure complies with performance requirements, while being also robust to variability on the design parameters. Unfortunately, these safety factors are often rather empirical and may greatly overestimate the actual variability. For composite materials, this could lead to structures that are heavier than needed, thus producing too conservative designs that do not fully exploit the real benefits that lightweight composite materials can offer. Topology optimization is one of the effective approaches that optimize the structure geometry such that the designed structure meets a prescribed set of performance targets. In recent years, various optimization methods such as the solid isotropic microstructure with penalization method (SIMP) (Bendsøe 1989; Zhou and Rozvany 1991; Mlejnek 1992) and the evolutionary structural optimization (ESO) method (Xie and Steven 1993; 1997) have found increasing applications. The ESO method was originally proposed by Xie and Steven (1993) to obtain the optimum shape and topology of continuum structures. In this method, inefficient material is slowly removed from the design domain. Bi-directional evolutionary structural optimization (BESO) is an extension of ESO, which allows for material to be added to where it is most needed and at the same time, for the inefficient material to be removed. The BESO method proves to be more robust than the ESO method (Yang et al. 1999; Huang and Xie 2007). However, all of the above approaches are for isotropic materials only and have not been used for anisotropic composite materials.

In this paper, 3D Finite Element Analysis (FEA) elements are used to implement the optimization. A through thickness MES are applied to the optimization process to get a feasible optimization solution which suit current composite material fabrication methods.

2. Optimization Problem and Sensitivity Number

For many industrial applications, the maximum stiffness of a structure is pursued. One way to achieve that is by minimizing the mean compliance of the structure that is defined with the area below the load-deflection curve and is equal to the external work in quasi-static condition (Huang and Xie 2008). When a nonlinear structure is subjected to the external force {F}, the optimization problem for minimizing the compliance can be formulated with the volume constraint, using the element as the design variable. The optimization problem is thus written:
Minimize:

$$C=\int_0^t \{F\}^T \{\dot{u}\} dt \tag{1}$$

Subject to:

$$g = V^* - \sum_{i=1}^{n} V_i x_i = 0 \tag{2}$$

$$x_i \in \{0,\ 1\} \tag{3}$$

where $\{\dot{u}\}$ represents the velocity vectors, t is the integration limit that corresponds to the final state, V_i is the volume of an individual element, V^* is the prescribed total structural volume, and the binary design variable x_i declares the absence (0) or presence (1) of an element.

When the *i*th element is removed from a structure, the overall stiffness of the structure reduces and, consequently, the total strain energy increases. In a linear system, the increase of the total strain energy is equal to the elastic strain energy in the *i*th element. Similarly, the total elastic and plastic strain energies stored in the *i*th element is a first-order approximation of the variation of the mean compliance for a nonlinear system, (For a detailed sensitivity analysis, see Buhl et al. 2000; Jung and Gea 2004.)

$$\Delta C_i = E_i^e + E_i^p \tag{4}$$

Therefore, the sensitivity number (or strain energy density) of the ith element can be defined by its strain energy divided by its volume:

$$\alpha_i = \frac{E_i^e + E_i^p}{V_i} \tag{5}$$

Thus, sensitivity numbers for all elements in the present structure are obtained. These sensitivity numbers will be linearly extrapolated to void elements surrounding the structure that may be added.

However, due to the nonlinearity and fabrication characteristics of composite materials, the optimized structure could be infeasible in manufacturing. For example, there should be no hollow part in the composite laminate. The uniform strain energy density (Venkayya et al. 1968) in one direction can be used in the optimization. In this paper, Material Element String (MES), which includes all FEA elements throughout the thickness direction of the design domain, is defined to facilitate the removal or adding of materials during the optimization process. In the MES, each element has the same sensitivity number which equal to the averaged sensitivity number of the whole MES:

$$\alpha_1 = \alpha_2 = \alpha_3 = \ldots = \alpha_n = \frac{\sum_{i-1}^{n} \alpha_i}{n} \tag{6}$$

where α_i is the sensitivity number of one element in the MES, and n is is the total number of the MES in FEA. The MES will be either removed from or added to the structure. As a result, no hollow part or void will appear within the composite material in the design domain.

MES in the present structure will be removed when:

$$\alpha_i \le \alpha_{th} \tag{7}$$

Those MES surrounding the present structure will be added if:

$$\alpha_i > \alpha_{th} \tag{8}$$

where α_{th} is the threshold of the sensitivity number that is determined by the target material volume in each iteration. For example, if the target volume for the present iteration is 50%, then elements for which the sensitivity numbers are ranked at the top 50% of all elements (including the void ones) will remain solid or be added, and all other elements will be deleted or remain void.

The cycle of Finite Element Analysis and element removal and addition will be repeated until the objective material volume V^* is reached and the termination criterion defined in the later section is satisfied. The total material volume must be decreased gradually by introducing an evolutionary removal volume ratio RV:

$$V_{j+1} = V_j(1 - RV)\text{, j=0, 1, 2, 3…} \tag{9}$$

RV is a constant that is specified by the user. Once the prescribed material volume V^* is reached, RV is set to be zero.

3. Performance Index and Termination Criterion

In the original BESO method (Yang et al. 1999; Querin et al. 2000), the optimization procedure is stopped when the prescribed material volume is reached. However, the design can be further improved by adjusting the elements and keeping the total material volume constant. Thus, the present BESO procedure continues after the prescribed material volume is reached and a new termination criterion needs to be defined. Before we define the termination criterion, a performance index (PI) is first introduced. The performance index is used to identify the efficiency of the optimal designs. In optimization problems for maximized structural stiffness, the stiffness per unit volume denotes the efficiency of the usage of the material and can therefore be used as performance index which is written as:

$$\text{PI}=1/CV_c \tag{10}$$

where C and V_c are the total mean compliance and the volume of the current design. The design with the highest performance index is the one with the highest stiffness for the same material volume. In the later stage of the present BESO method, the topology of the design continues to adjust by removing and adding elements after the objective volume V^* is reached. Thus, the performance index will be increased step by step. When the performance index of the design has an insignificant improvement over the last design, the optimization process can be stopped. So the performance index of two successive designs is used to define the termination criterion:

$$error_j = \frac{|PI_j - PI_{j-1}|}{PI_j} \le error^* \tag{11}$$

where error $_j$ is the defined performance error for the jth iteration, and error* is the maximum allowable error that is specified by the user, normally 0.01%.

4. Example and Discussion

The design domain of an orthotropic composite laminate is shown in Figure 1. A pressure load of 100Pa is applied to one side of the laminate and another side is fixed. The material has: E_1=265GPa, E_2=2.5GPa, E_3=2.5GPa, $\gamma_{12}=\gamma_{13}=\gamma_{23}$=0.25, $G_{12}=G_{13}=G_{23}$=3.5GPa. Element C3D8 is used in the finite element analysis using Abaqus®. The purpose of this optimization is to get the highest structural stiffness while 50 per cent of the material is to be removed.

The improved BESO method search all of the elements in the design domain and take all elements with nodes sharing the 2 same x and y coordinates as one Material Element String (MES).

It can be seen from Figure 2 that the improved BESO method can achieve a more uniform stress distribution while the original BESO adds or removes elements from each layer which results in some areas with high stress concentration. It is also very clear that the optimized structure shape produced by improved BESO is much easier to be fabricated.

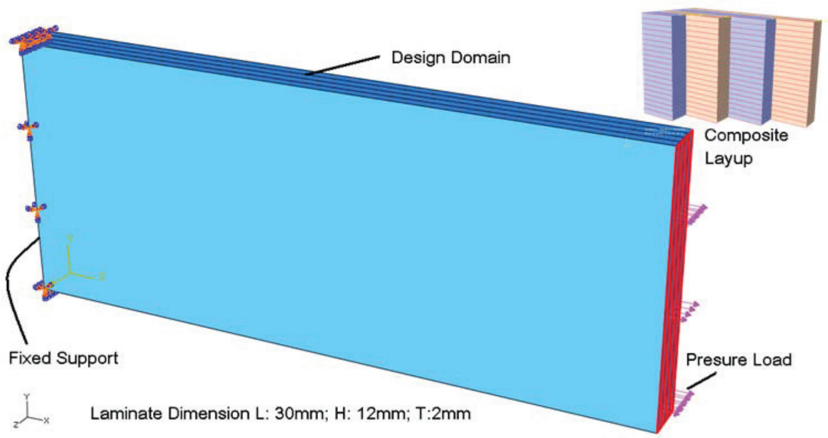

Figure 1: Dimensions of the design domain, boundary and loading condition and composite layup for the laminate.

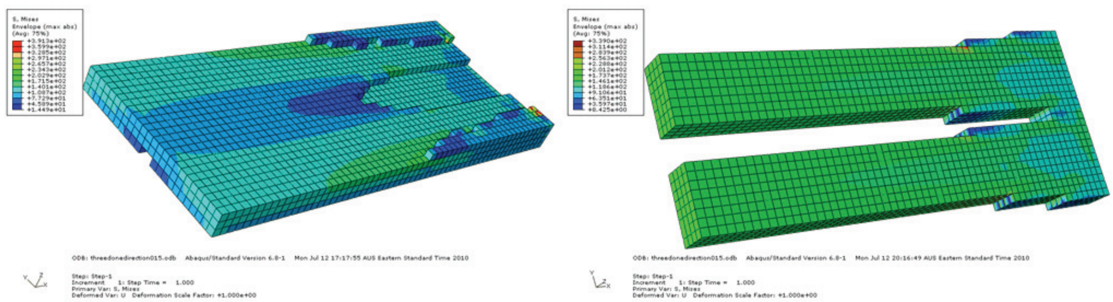

Figure 2: Comparison of composite optimization in the 15th iteration using current BESO method (left) and improved BESO method (right).

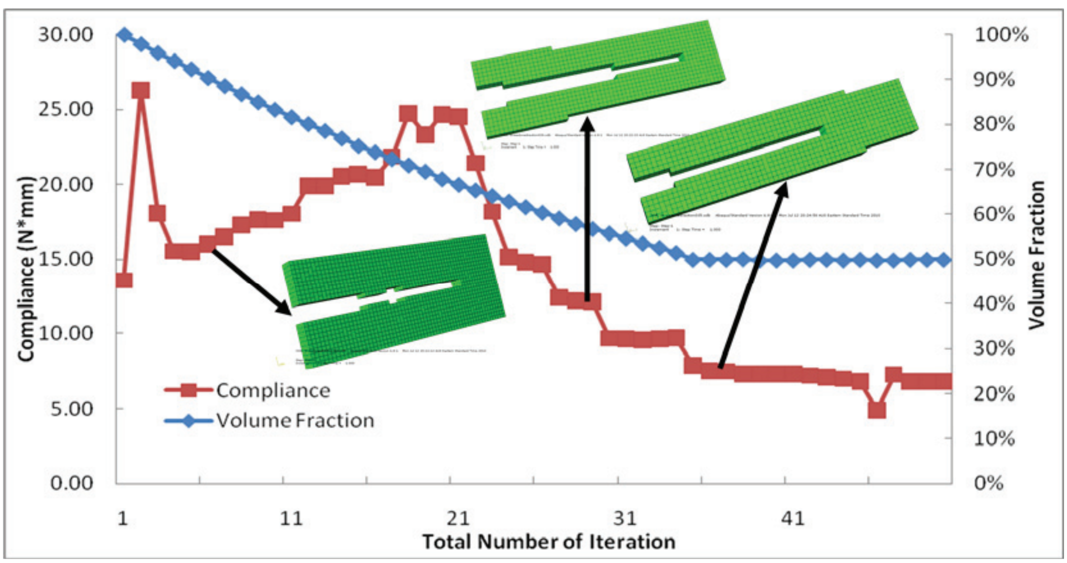

Figure 3: Evolution histories and optimized topology of the composite laminate using improved BESO method.

The optimization reached its volume constraint after 35 iterations. Then the process kept going, and the structure stiffness kept improving. After iteration 47, the Performance Index PI reached the termination criteria (a steady state) and the whole optimization process stops.

5. Conclusions

A topology optimization procedure for composite structures with maximized structure stiffness is proposed by introducing the use of Material Element String (MES) into the bidirectional evolutionary structural optimization (BESO) method. In this procedure, the optimization problems are solved by removing and adding Material Element String through one direction of the design domain. The illustrative example shows that the proposed method is effective in the topology optimization design of composite structures and can produce shape design with uniform stress distribution, thus reducing the chance of structural failure due to high stress concentration.

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