



Sensitivity analysis and optimal design of geometrically non-linear laminated plates and shells

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Abstract

A high order shear deformation theory is used to develop a discrete model for the sensitivity analysis and optimization of laminated plate and shell structures in non-linear response. The geometrically non-linear analysis is based on an updated Lagrangian formulation associated with the Newton–Raphson iterative technique, which incorporates an automatic arc-length procedure. Fiber orientation angles and vectorial distances from middle surface to the upper surface of each layer are considered as the design variables. Different objectives, such as generalized displacements at specified nodes, volume of structural material, and limit load, and constraints of displacement and stress failure criterion are considered. The design sensitivities are evaluated analytically and are compared with sensitivities evaluated by the global finite difference. Numerical examples are given to show the accuracy of the proposed model in the non-linear response and the corresponding design sensitivity analysis, and to show the applicability in the optimal design. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The mechanical properties of a laminate are strongly dependent of the fiber directions and because of that the laminate should be designed to meet the specific requirements of each particular application in order to obtain the maximum advantages. Accurate and efficient structural analysis, design sensitivity analysis and optimization procedures are fundamental to accomplish this task. Design sensitivity analysis is very important to accurately know the effects of design variables changes on the performance of structures by calculating the search directions to find an optimum

design. To evaluate this sensitivities efficiently and accurately it is important to have appropriate techniques associated to good structural models, which also must be efficient with regard to computation time, especially when non-linear analysis are involved. The use of high strength composite materials and survival of structures under extreme environments and the need to obtain savings by considering design optimizations using non-linear structural formulation is the main motivation for the present work.

To carry out the large displacement analysis an updated Lagrangian formulation given by Bathe [1], Bathe and Bolourchi [2], Bathe and Ho [3], has been implemented in association with Newton–Raphson incremental iterative method, which has an automatic arc-length load control technique [4], to contemplate

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the occurrence of snap-through situations with arbitrary structures. The discrete model, which has been developed and implemented, is based on a triangular flat plate element, based on Reddy’s higher order displacement field [5], having 24 degrees of freedom. By assuming that plane sections before deformation, remain plane after deformation and perpendicular to middle surface, i.e., by neglecting the transverse shear deformation, the Kirchhoff laminated model (CPT), with 18 degrees of freedom, is also easily obtained.

In the research field of design sensitivity analysis for non-linear response considerable works have been developed, mainly in isotropic structures, during the last two decades. Among others, we call for works of Khot [6], Kamat and Ruangsilasingha [7], Ryu et al. [8], Wu and Arora [9], Santos and Choi [10], Park and Choi [11], Haftka [12], Mróz and Haftka [13], and Kleiber [14], that presented different methods for calculation of design sensitivity of the critical load, displacement and stress, with respect to the design variables. Research work in optimization of non-linear structures, using different methodologies, can be found in papers of Haririan et al. [15], Ringertz [16], Oblak et al. [17], Ohsaki and Nakaruma [18], Polynkin et al. [19], Reitingner and Ramm [20], Mróz and Piekarski [21], among others.

The objective of this paper is to present the development and to show illustrative simple applications of a discrete finite element model to evaluate design sensitivities of geometric non-linear response for laminated plate and shell type structures. These sensitivities of response are evaluated analytically with respect to angle orientation of the fiber of each layer and the vectorial distances (indirectly the thickness of each layer). The

subsequent optimal design problem is then solved by some techniques of non-linear mathematical programming described by Vanderplaats [22].

2. Displacement field

The assumed displacement field, (Fig. 1), for the numerical higher order finite element model, is a third order expansion in the thickness coordinate for the in-plane displacements and a constant transverse displacement, conjugated with the condition that the transverse shear stresses vanish on the top and bottom faces, which is equivalent to the requirement that the corresponding strains be zero on these surfaces [5].

$$\begin{aligned}
 u(x, y, z) &= u_0(x, y) - z\theta_y(x, y) \\
 &\quad + z^3 \frac{4}{3h^2} \left[\theta_y(x, y) - \frac{\partial w_0}{\partial x} \right] \\
 v(x, y, z) &= v_0(x, y) + z\theta_x(x, y) \\
 &\quad + z^3 \frac{4}{3h^2} \left[-\theta_x(x, y) - \frac{\partial w_0}{\partial y} \right] \\
 w(x, y, z) &= w_0(x, y)
 \end{aligned} \tag{1}$$

The displacement field can be represented in matrix form as

$$\mathbf{u} = \mathbf{Zd}$$

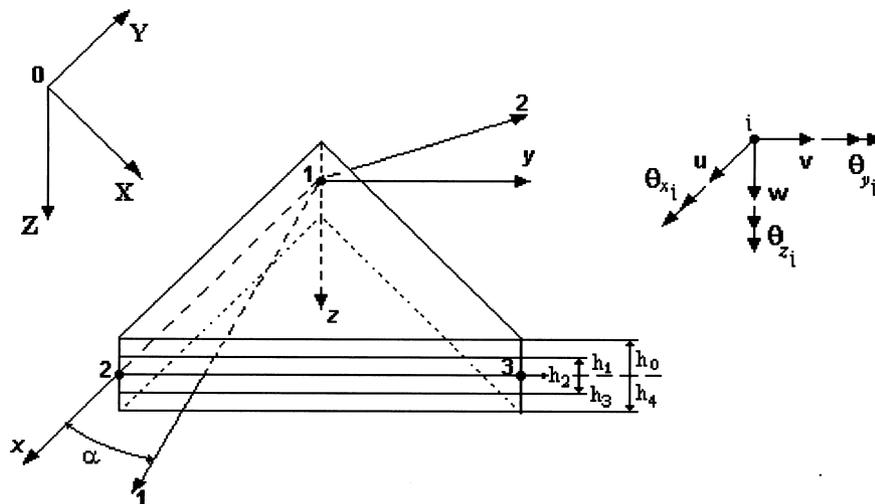


Fig. 1. Element with local and global co-ordinate systems.

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