

Shape design sensitivity analysis with respect to the positioning of features in composite structures using the boundary element method

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Abstract

This paper presents the application of the boundary element method to the shape design sensitivity analysis of composite structures with holes and cutouts. A two-dimensional (2D) anisotropic domain, which contains a number of voids of arbitrary shapes will be considered. The objective is to perform the design sensitivity analysis of the structure with respect to the translation and rotation of the voids using the boundary element method. A directly differentiated form of the boundary integral equation, with respect to geometric design variables is used to calculate the shape design sensitivities for anisotropic materials. The response sensitivity analysis, with respect to the design variables such as feature positions and orientations, is achieved by the definition of appropriate design velocity fields for these variables. To find the optimum positions of the features within an anisotropic structure with the highest stiffness, the elastic compliance of the structure has been minimized subject to constraints upon stresses and geometry. Due to the non-linear nature of the mean compliance and stresses, the numerical optimisation algorithm used is the feasible direction method, together with the golden section method for the 1D search. A couple of test cases have been performed to verify the proposed method.

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1. Introduction

Laminated composites are gaining importance in aircraft structural applications because of their attractive performance characteristics, e.g. high strength-to-weight ratio, high stiffness-to-weight ratio, superior fatigue properties, and high corrosion resistance. The phenomenon of progressive failure in laminated composite structures is yet to be understood, and as a result, reliable strategies for designing optimal composite structures for desired life and strength are in demand. The analytical formulation of two- and three-dimensional (3D) anisotropic elasticity, using the finite element method (FEM) or boundary integral equation techniques (BIE), has been well developed in the last three decades. This paper discusses the shape design sensitivities of 2D anisotropic structures with respect to the positioning and orientation of their holes and cutouts.

In a project sponsored by the United Kingdom Atomic Energy Authority (UKAEA), two general purpose computer

programs using the BEM [1–4] for shape optimisation of isotropic structures; weight minimization and maximum stress minimization, respectively, were developed. In 1990 [1], it represented a novel application of the boundary element method to practical design optimisation problems, and showed great potential for further development in the field of design optimisation.

The BEM, being a boundary-oriented technique, can overcome a number of the difficulties associated with its main rival, the FEM. In respect of the continuously changing geometry, the accuracy of the FE analysis using an initial mesh of elements may become inadequate during the optimisation process. If during the optimisation process, the finite element mesh has to be re-generated, the cost is relatively high. The sensitivity analysis in the calculation of the derivatives, with respect to the design variables, may be obtained directly [1] in the boundary element approach rather than by approximate methods, such as finite difference schemes.

In a study by the author [5], a directly differentiated form of the BIE, with respect to boundary point coordinates, was used to calculate stress and displacement derivatives for 2D anisotropic structures. The accuracy was compared with

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Notation

a_{mn}	elastic compliance matrix $a_{11} = \frac{1}{E_1}$, $a_{12} = -\frac{\nu_{12}}{E_1} = -\frac{\nu_{21}}{E_2}$, $a_{16} = \frac{\eta_{12,1}}{E_1} = \frac{\eta_{1,12}}{G_{12}}$, $a_{22} = \frac{1}{E_2}$, $a_{26} = \frac{\eta_{12,2}}{E_2} = \frac{\eta_{2,12}}{G_{12}}$, $a_{66} = \frac{1}{G_{12}}$	t_j	traction vector
A_{jk}	complex constants	$T_{jk}(P, Q)$	the j th component of the traction vector at point Q due to a unit point load in the k th direction at P
$C_{jk}(P)$	the limiting value of the surface integral of $T_{jk}(P, Q)$	u_j	displacement vector
D_s ($s = 1, 4$)	operator	U_{jk}	the j th component of the displacement vector at point Q due to a unit point load in the k th direction at P
E_k	Young's modulus in the x_k direction	X	$X_i = [X_1, X_2, \dots, X_n]^T$; design variable vector
E_s	elastic compliance	x_i	rectangular Cartesian coordinates
$(E_s)_0$	elastic compliance at initial step	z_j	complex coordinates
F	objective function	α_j, β_j	real constants
F_0	objective function at initial step	δ_{jk}	Kronecker delta
G_{12}	shear modulus	ε_{jk}	strain tensor
$g_j(X)$	inequality constraints	ζ_i	coordinates of load point
$J(\xi)$	Jacobian of transformation from global Cartesian coordinates to intrinsic coordinates of the element	ξ	intrinsic coordinates of isoparametric quadratic element
m_{1k}, m_{2k}	unit vectors tangent and normal to the surface	$\eta_{jk,1}$ and $\eta_{1,jk}$	coefficients of mutual influence of the first and second kind, respectively
n_1, n_2	direction cosines of the unit outward normal vector to the surface of the elastic body	A_1, A_2	real functions of the Cartesian and intrinsic coordinates at each integration point
$N^c(\xi)$	quadratic shape function corresponding to the c th node of the element	μ_s	roots of the characteristic equation
OXY	global coordinate system	ν_{jk}	Poisson's ratio
$o\tau_i, o\omega_i$	local coordinate system of each void	\bar{x}_1, \bar{x}_2	local coordinates on an element
P	load point at the surface of the elastic domain	σ_{jk}	stress tensor
Q	field point at the surface of the elastic domain	σ_{\max}	maximum equivalent stress
r_{jk}	complex constants	ϕ	airy stress function
s	the domain boundary	ψ	shape variable such as translational or rotational position of a typical void
s_b	b th-element of the discretized boundary	Ω_1, Ω_2	real functions of the Cartesian and intrinsic coordinates at each integration point

the results of the finite difference applied to the boundary element analysis. Not surprisingly, the results obtained by analytical differentiation are much more accurate. In another study by the author [6], the weight minimization of anisotropic structures with stress constraints using the BEM is presented. The design sensitivity analysis using the BEM was combined with an optimisation algorithm to form an optimum shape design program for anisotropic structures. Different materials were analysed to investigate the effect of engineering constants on the optimum shape design of the components.

In a recent study by the author [7], the optimal shape design of an anisotropic elastic body of maximum stiffness and minimum weight under specified loadings and using the boundary element method, was obtained. The elastic compliance of the structure was minimized while there were constraints on the maximum stress and weight of the structure. To demonstrate the effectiveness of this procedure, a series of design problems were analysed and discussed in detail. These results were compared with those results, which were obtained with just minimizing the weight subject to stress and geometrical constraints [6].

It should be noted that to the author's knowledge, no other publications are available on the shape optimisation of composite materials using the boundary element method.

The objective of this work is directed towards the optimal positioning of features in anisotropic structures, using the boundary element method, for maximum stiffness while the weight remains unchanged. The elastic compliance will be minimized while there are constraints on the maximum stress and the geometry of the structure. Design sensitivity analysis, which is the calculation of quantitative information for how the response of a structure is affected by changes in the design variables that define its shape, has been validated through test cases with known solutions. To demonstrate the effectiveness of this procedure, a couple of design problems will be analysed and discussed in detail.

2. Constitutive equations for plane anisotropic elasticity

Combining the stress–strain relations, the compatibility equation of strains and the equilibrium equation, the governing equation for the 2D problem of homogeneous and anisotropic

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