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Three-dimensional stress analyses in composite laminates with an elastically pinned hole

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Abstract

We present a three-dimensional (3-D) stress analysis for composite laminates with an elastically pinned circular hole. The effects of friction, bearing force and bypass loading on the stress redistribution are studied in detail. The numerical approach is based on a multilayer boundary element method (MLBEM), a non-traditional BEM particularly designed for anisotropic composite laminates, coupled with the traditional BEM for the pin filling the hole. The unique characteristic of the MLBEM is that the fundamental solution employs Green's functions that satisfy the interfacial continuity conditions and top- and bottom-surface traction-free and symmetry conditions. This fundamental solution allows us to design a BE scheme without involving discretization on the interfaces and surfaces unless the laminates are imposed by different boundary conditions. Consequently, in this case of pinned joint, only the hole surface among the composite boundary and interfaces needs to be discretized. A Coulomb-type friction law is used to simulate the frictional contact interaction between the composite and pin. To solve the frictional contact problem, an iterative scheme of successive over-relaxation has been proposed where the contact location and frictional contact condition are determined at the same time in the iteration solution. By applying the MLBEM, stress analyses are performed for a laminate plate with the stacking sequence $(0/\mp 45/\overline{90})_s$. The issues of engineering interests, such as the loading-sequence and cycling dependencies of stress state due to the presence of friction, are addressed. The solutions, shown by complicated contact maps and stress states around the hole, suggested that a 3-D approach to pinned composite joints is necessary for the interpretation of the underlying physics.

Keywords: Three-dimensional stress analysis; Composite laminates; Bolted joint; Bearing and bypass loading; Frictional contact; Boundary element method

1. Introduction

Owing to their unique light weight/high strength feature, composite laminates have been extensively used in various engineering structures, in particular, in aircraft and space structures. The structural composites

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are commonly jointed by fastening, bonding, or a combination of these two for transferring load from one component to the other. Each joint method has its own advantages and deficiencies (Lubin, 1982; Schwartz, 1984).

It is well known that stress concentrations near the fastener holes could initiate delamination or other types of damage modes, which could then lead to final failure (Persson et al., 1998). Apart from the experimental approach (e.g., Daniel et al., 1974), various analytical methods have been proposed to examine the stress field around an open hole, such as the boundary layer method (Tang, 1977, 1979), the linear laminate finite element method (FEM) (Waszczak and Cruse, 1971; Soni, 1981), the three-dimensional (3-D) discrete layer FEM (Rybicki and Hopper, 1973; Rybicki and Schmuesser, 1976; Nishioka and Atluri, 1982; Raju and Crews, 1982), and the spline variational method (Iarve, 1996). More recently, an efficient and accurate *non-traditional* multilayer boundary element method (MLBEM) has been proposed by the authors for the stress analysis around an open hole in composite laminates (Pan et al., 2001).

The mechanical behavior of a composite laminate structure with filled mechanical fastener is more complicated than that in the open hole case. While a comprehensive review was given by Camanho and Matthews (1997), an experimental program was conducted by Ireman et al. (2000) in order to measure and characterize the development of damage in the vicinity of fastener holes in graphite/epoxy composite laminates. Also, several simplified models were proposed to numerically study the stress field and failure processes in mechanically fastened joints in composite laminates. For example, Dano et al. (2000) proposed a two-dimensional (2-D) FEM model to predict the response of fastener-loaded composite plate, where the fastener is assumed to be rigid. The traditional 2-D BEM has also been proposed recently to analyze similar problems by Lie et al. (2000) and Lin et al. (2000), with the fastener treated as a one-dimensional spring in the former and as a rigid medium in the latter. The 3-D FEM analyses were carried out by Chen et al. (1995), Ireman (1998), and Persson et al. (1998). In these studies, the fastener was assumed to be elastic and no friction was allowed along the interface between the fastener and composite except the study by Ireman (1998). In a similar study, Iarve (1997) proposed a B-spline approximation approach with no-friction assumption. On the other hand, Marshall et al. (1989) using the FEM concluded that the pin-hole contact friction is as equally important as the laminate stiffness to the stress and failure behavior of composite laminates.

In this article, we propose an efficient and accurate numerical method for the analysis of the mechanical behavior of a composite laminate plate with an elastic fastener in a circular hole under a bearing force on the fastener and/or a bypass loading in the composite. Each ply of the composite laminates is assumed to be generally anisotropic. The fastener is considered as isotropic. The interfaces between the lamina plies are assumed to be perfectly bonded. The interaction between the composite and fastener is followed by a Coulomb-type friction law. The problem is solved by using a novel 3-D boundary element formulation, in which the fundamental solution satisfies the interfacial continuity conditions and the traction-free and symmetry conditions on the top and bottom surfaces (Yuan et al., in press; Pan et al., 2001; Yang and Pan, 2002). Consequently, only the hole surface of the composite plate needs to be discretized. This leads to a substantial reduction of the numerical approximations and the resulting system of discretized equations is much smaller compared to that in the FEM and the conventional BEM. To simulate the nonlinear interaction and predict the unknown frictional contact zone between the composite and the pin, an efficient iterative scheme of successive over-relaxation is proposed. Numerical examples are then carried out for a laminate plate with the stacking sequence $(0/\mp 45/\overline{90})_s$. It is shown that a finite friction coefficient along the hole has substantial effects on the stress redistribution. It is further shown that the contact stress state in different plies can be very different due to the stiffness difference in the plies. This suggested that a 3-D approach of the laminate pinned joint is necessary. Finally, we observed that the loading sequence (first bearing force and then bypass loading, and vice versa) and cycling has only a slight influence on the final stress distribution in the case of perfect fitting between the hole and pin.