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硕士学位论文

复合材料厚壁管弯曲性能分析的统一参数法及杂交应力有限元最佳假设应力场构造的定量方法

The unified-parameter method for bending performance analysis of composite thick tube as well as the quantitave method to determine the optimal assumed stress fields for hybrid stress finite elements

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摘　要

复合材料厚壁管作为主承力构件在航空航天上已经得到了越来越广泛的应用，但其经典层合板壳近似难以满足工程设计中的精度要求，而由于层数众多且单层极薄，有限元等数值模拟也难以在厚度上逐层精细建模，因此，其弹性理论求解势在必行。本文在复合材料厚壁管的弯曲性能分析中发现以往方法对柱型正交各向异性层即缠绕角为 0°或 90°的特殊缠绕层由于参数奇异而难以求解，通过深入分析奇异性的根本原因，定义了新的统一系数及其非奇异的统一参数，并提出相应的统一参数法，可以分析包含特殊缠绕层和一般缠绕层的任意复合材料管如[90/45/0]。该方法由于可以给出复合材料厚壁管等效抗弯刚度的显式，特别有利于工程设计人员的直观分析。对六种简单复合材料厚壁管包括[90]、[90/0]、[90/45]、[90/45/0]、[90/45/-45/0]和[90/0/90/45]进行了实例分析，与 NASTRAN 数值结果吻合较好，并且计算了实际复合材料管[90/$(-25)_{45}$/25_{45}]和[90/$(-25/25)_{45}$]，与实验结果基本一致，说明该方法对复合材料管分析确实有效。在此基础上，利用统一参数法对不同层厚比例的复合材料管[90/45/-45/0]进行了失效分析，绘制了包括等效弯曲刚度、极限弯矩及其失效位置等随层厚比例变化的图版，方便设计人员直接使用。

为了制造满足所设计弯曲性能的复合材料厚壁管，需要采用目前最先进的自动纤维铺放（AFP）技术，其中包含粘弹性响应的热应力在线模拟是关键，而杂交应力元方法是一种高性能的数值分析工具，尤其适用于几乎不可压缩粘弹性材料。为提高杂交元性能，本文提出一种确定最优假设应力场的定量方法，不仅给出了自动挑选最优假设应力模式的系统方法，而且首次揭示了杂交元能解决位移元过刚的根本原因是保留了位移元中主要成分（即有利成分）而摒弃其次要成分（即不利成分）如寄生剪切应力等。该方法包含两个步骤：首先将位移场直接导出的基本应力模式分解成一系列子模式；然后通过计算各个子模式与其基本应力模式的相似度对它们进行定量比较，最大相似度说明该子模式代表原基本应力模式的主要成分从而是其有利部分，应该选取为最优假设应力模式。分析中定义了带材料矩阵的加权内积，由于对应范数具有明确物理意义即应力模式的柔度，从

而实现了不同应力模式之间的准确比较和定量分析，突破了传统能量内积只能定性判断应力模式和变形模式是否正交的局限。通过该方法构造了各向同性材料二维四节点和三维八节点杂交元的最优假设应力场，并且进一步推广到各向异性材料杂交元，针对工程中常用的碳纤维和玻璃纤维增强复合材料，计算了所有子模式相似度随铺层角的变化曲线，结果表明，虽然不同子模式的相似度随铺层角有不同的变化规律，但是最大相似度所对应的子模式基本上不随铺层角而变化，因此复合材料杂交元的最佳应力模式与各向同性材料杂交元一致。采用所形成各向同性材料杂交元和复合材料杂交元计算了多个经典数值算例，通过与其他单元的比较分析表明所提出方法及其杂交元的优越性。

关键词：复合材料厚壁管；纯弯曲；等效抗弯刚度；0°或 90°缠绕角；统一参数法；杂交应力元；基本应力模式；材料权重内积；定量挑选法；最佳假设应力场；相似度

Abstract

There are more and more applications of the composite thick tubes as primary components of structures in the aerospace. Their approximations of plate and shell by classical laminated theory (CLT) can hardly satisfy the accuracy requirement for the design in engineering. Due to the large number of laminated layers as well as their very small thickness for composite thick tubes, it is almost impossible to model the exact structure layer by layer along the thickness direction for the numerical simulations by finite element method (FEM). Therefore, the composite thick tubes have to be calculated by using the elastic theory. In this paper, it is found in an earlier approach that the solution for composite thick tube is difficult for the cylindrical orthotropic layers, i.e., the special layers of winding angles 0° or 90° since some of their parameters are singular. After investigations of the singularity for these specific parameters, the new unified coefficients as well as their nonsingular unified parameters are defined and a relating unified-parameters method is proposed which can be used to calculate the arbitrary composite tubes such as [90/45/0], including the special layers together with normal layers. The explicit expression of equivalent flexural stiffness can be provided which is particularly beneficial to the designers for the straightforward investigation of composite tubes in engineering. For examples, six simple composite thick tubes including [90], [90/0], [90/45], [90/45/0], [90/45/-45/0] and [90/0/90/45] are calculated. The results are in good agreement with NASTRAN. Besides, the real composite tubes [90/(-25)$_{45}$/25$_{45}$] and [90/(-25/25)$_{45}$] are calculated and the results are in substantial agreement with the experiments. These results indicate that the present method is available for the analysis for composite tubes. Moreover, the unified-parameter method is used for the failure analysis for the composite tubes of [90/45/-45/0] with every layer of different percent of thickness. Their equivalent flexural stiffnesses and ultimate moments as well as their failure positions with respect to the percent of the thickness of every layer are derived to make the map which is convenient for the application and design in engineering.

The state-of-the-art technology of automated fiber placement (AFP) should be used to manufacture the composite thick tubes to satisfy the desired bending performance. However, the in-situ simulation for thermal stress considering the viscoelastic response is the key in AFP. The hybrid stress element method is an efficient tool with high performance for numerical analysis, especially for the nearly incompressible viscoelastic material. In order to improve the performance of hybrid elements, a quantitative method is developed to determine their optimal assumed stress fields. This is a systematic approach to automatically select the optimal assumed stress modes. Moreover, it is the first time to report the reason that the hybrid stress element can overcome the problem of over rigidity from its displacement counterpart. This reason is that the main components (i.e., good components) inside the displacement element are remained and selected for the hybrid stress element while the minor components (i.e., unnecessary components) such as parasitic shear stresses are deleted. The procedures include two steps. Firstly, the basic stress modes are broken into a set of sub-modes. Secondly, all sub-modes are compared with their basic mode. The sub-mode with largest similarity degree with the basic mode implies that it represents the most important features inside the basic mode so it should be selected as the optimal assumed stress mode for hybrid element. A new inner product with material weighting matrix is defined to derive this quantitative method and the corresponding norms have the specific physical significance as the flexibility of stress mode. So the exact comparison as well as the quantitative analysis between different stress modes can be obtained. It breaks through the limitation of the conventional energy product which can only tell whether or not the stress and strain are orthogonal to each other. The present method is used to construct the optimal assumed stress fields for the 2D 4-node and 3D 8-node hybrid elements for the isotropic materials. In addition, the method is extended to the hybrid stress elements for the anisotropic materials. The curves of similarity of all sub-modes with respect to the ply orientations are calculated, considering the composite materials with carbon fiber and glass fiber which are popular in engineering. The results show that, although the similarity with respect to the ply orientations is different from one sub-mode to another, the sub-modes corresponding to the largest similarity are independent of the ply orientations. So, the optimal stress modes for hybrid elements of composite materials are equivalent to the isotropic materials. Several popular numerical examples are calculated using the present hybrid elements of isotropic material as well as the composite materials. Their comparisons with other elements indicate the advantage of our method as well as the resulting hybrid stress elements.

Key words: composite thick tube; pure bending; equivalent flexture stiffness; 0° or 90° winding angle; unified-parameter method; hybrid stress element; basic stress modes; material-weighted inner product; quantitative selection method; optimal assumed stress field; similarity degree

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