博 士 学 位 论 文

题目：蜂窝芯弯曲过程形性演化机理与变形调控方法

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摘 要

正六边形蜂窝夹芯结构由于具有高的比刚度、比强度及良好的隔声与隔热等特性，被广泛运用于航空航天产品中的大曲率构件。夹芯结构的优良性能取决于其制造过程中蜂窝芯格能否保持原始形状。然而，在大曲率蜂窝夹芯结构制造过程中，蜂窝芯弯曲预成型不可避免地会产生芯格坍塌缺陷，导致夹芯结构力学性能降低，无法满足设计要求。因此，在保证夹芯结构力学性能的前提下，如何有效控制并消除弯曲预成型中形成的芯格坍塌，是大曲率蜂窝夹芯结构精确制造中亟待解决的工程问题。开槽处理是一种可行的工艺方法，但开槽参数与蜂窝芯变形及力学性能之间的关系尚不明确。因此，要控制芯格坍塌变形，就必须探明蜂窝芯弯曲过程中形性演化机理，这正是正六边形蜂窝芯弯曲预成型中的关键科学问题。

为此，论文针对大曲率正六边形芳纶纸蜂窝夹芯结构，围绕蜂窝芯弯曲过程中芯格变形评估、力学性能分析和变形调控开展研究，旨在揭示蜂窝芯弯曲过程芯格变形及面外压剪复合力学性能演化机理，并发展弯曲诱导的芯格变形精确控制工艺方法，促使大曲率正六边形蜂窝夹芯结构制造工艺过程由部分定量、基于经验的试错模式向定量调控模式转变，主要研究工作包括：

（1）建立了不均匀胞元参数的蜂窝芯面内等效弹性性能计算模型。在不规则六边形胞元形状方面，量化了表征六边形蜂窝芯形状不规则的胞壁长度及角度参数，并通过相关性分析确定了独立的胞壁长度及角度参数；建立了基于快速傅里叶变换的大尺寸不规则蜂窝芯面内等效弹性性能计算方法，阐明了形状参数不确定性至面内等效弹性性能的传播过程。在胞元参数不均匀方面，使用 Micro-CT 扫描技术对蜂窝芯制备过程产生的不均匀胞元参数进行识别、表征与量化，包括：六边形形状不规则、壁厚不均、斜壁弯曲及节点粘接树脂富集；提出了图像驱动的快速傅里叶变换蜂窝芯面内等效弹性性能计算方法，可考虑蜂窝芯实际制备过程产生的不均匀胞元参数的影响，胞元形状不规则参数对蜂窝芯面内等效弹性性能具有主要影响，与试验结果对比，最大偏差为 4.7%，提高了传统模型的计算精度，可用于弯曲载荷作用下蜂窝芯变形响应分析。

（2）揭示了蜂窝芯弯曲过程芯格屈曲变形演化机理。提出了一种蜂窝芯弯曲过程芯格变形定量化评估方法，采用 Harris 角点检测算法识别沿 W 方向弯曲后蜂窝芯上表面轮廓芯格角点并重构蜂窝芯格，通过构造六边形芯格单元形函数，以单元面积变化率 J 及最小主伸长量 $\min(\lambda)$表征芯格变形；归纳了不同构件参数组合下蜂窝芯坍塌模式，包括：沿 W 方向坍塌及与 W 方向成±60°的倾斜坍塌；分析了蜂窝芯弯曲变形对构件参数和胞元参数的敏感性和响应规律，坍塌模式对蜂窝芯胞壁厚度及弯曲半径较为敏感，芯格宽度、弯曲半径越小以及蜂窝芯厚度越大对应的芯格变形越大；基于计算得到的三种不同规格蜂窝芯面内等效弹性性能进一步揭示了结构参数对芯格变形量的影响规律；

利用非线性后屈曲理论描述了蜂窝芯弯曲过程中芯格屈曲起始及演化过程。

（3）揭示了弯曲蜂窝芯面外压剪复合加载力学性能演化机理。通过设计弯曲蜂窝芯面外压剪复合加载专用 Arcan 夹具，开展了不同弯曲半径、加载角度的面外压剪复合加载试验，基于获取的力学响应和胞壁变形模式验证了弯曲蜂窝芯面外压剪复合加载有限元分析模型的有效性；分析了构件参数对蜂窝芯面外峰值强度的影响规律，其中弯曲半径对峰值强度有重要影响，相对于平板蜂窝芯，100 mm 弯曲半径的蜂窝芯峰值应力最大减小量为 16.20%，进一步明确了蜂窝芯弯曲变形量与峰值强度的关系；利用有限元分析模型分离的弯曲蜂窝芯面外法向和切向峰值强度数据，建立了考虑弯曲半径、面内取向角及厚度的弯曲蜂窝芯峰值应力宏观强度准则，并提出了基于半圆形弯曲蜂窝芯面外单轴压缩响应的准则参数反演识别方法，实现了该准则修正系数及指数系数的快速、准确识别。

（4）提出了一种蜂窝芯弯曲过程芯格变形调控方法，通过对蜂窝芯内型面开槽处理去除多余的材料以消除弯曲诱导的胞壁坍塌缺陷。开展了连续 V 型槽蜂窝芯弯曲试验，分析了开槽间距对蜂窝芯弯曲变形量及面外压缩强度的影响规律，通过设置 90%面外压缩强度容限建立开槽间距确定准则，结合高斯过程机器学习算法，建立了等曲率外形的开槽间距预测及变曲率外形的开槽轨迹设计方法；利用弯曲前后槽口几何关系确定了开槽角度计算方法。以某飞机蜂窝夹芯整流罩零件为例，详细描述了零件的开槽参数计算过程及开槽工艺设计结果，并进行了弯曲成形验证，结果表明：弯曲后蜂窝芯格形状保持完好，未发生坍塌，同时开槽区域槽口完全闭合，验证了蜂窝芯弯曲过程芯格变形调控方法的有效性。

关键词：蜂窝芯，弯曲成形，等效弹性性能，形性演化，变形评估，强度准则，变形调控

Abstract

Hexagonal honeycomb sandwich structure has been extensively used in large curvature sandwich components in the aeronautical and astronautics industries as its low density, high stiffness, excellent strength-to-weight ratio, sound, and thermal insulation properties. The outstanding performances of the sandwich structure strongly rely on whether the original hexagonal shape of the cells can be maintained during the manufacturing process. Unfortunately, the collapse defects in honeycomb cells inevitably arise during bending preform, which can significantly affect the mechanical properties of sandwich structures and render it unsuitable for design requirements. Thus, how to effectively control and eliminate the collapse of honeycomb during bending preform while ensuring the mechanical properties are met is an urgent engineering problem to be solved in the accurate manufacturing of large curvature sandwich structures. One such method is the grooving-based process, but the relationship between grooving parameters and honeycomb deformation and mechanical properties is still unclear. As a result, it is necessary to explore the shape-property evolution mechanism for hexagonal honeycomb during bending to control the collapse deformation, which is a critical scientific problem in the bending preform of hexagonal honeycombs.

This paper focuses on the deformation assessment, mechanical properties analysis, and deformation control of aramid paper hexagonal honeycombs during bending, to reveal the evolution mechanism of honeycomb deformation and out-of-plane combined compression-shear mechanical properties of honeycomb, and to develop a process method to eliminate the bending-induced collapse, so as to promote the transformation of the manufacturing process of hexagonal honeycomb sandwich structure from a partially quantitative, trial-and-error mode to a quantitative control mode. The main work includes the following aspects:

(1) A model for calculating the effective in-plane elastic properties of honeycomb with uneven cell parameters is established. In the aspect of cell irregular hexagonal shape, the cell wall length and angle parameters that characterize irregular shape of honeycomb are quantified. Independent cell wall length and angle parameters are determined by correlation analysis. The Fast Fourier Transform based method for calculating the effective in-plane elastic properties of large-scale irregular honeycomb is established, and the propagation process of shape parameters uncertainty to the effective in-plane elastic properties is clarified. In the aspect of global uneven cell parameters, the uneven geometric parameters inside the honeycomb are identified and quantified using Micro-CT scanning technology, including the irregularity of

hexagonal shape, variation in cell wall thickness, curved cell walls, and node bond fillets. A geometric topology-driven fast Fourier transform method for calculating the effective in-plane elastic properties of honeycomb is proposed, which can consider the influence of the uneven cell parameters. The cell irregular shape has a primary effect on the effective in-plane elastic properties. The maximum deviation is 4.7% compared with the experimental results, which improves the calculation accuracy of the classical model and can be used to analyze the deformation response of honeycomb during bending.

(2) The evolution mechanism of honeycomb cell buckling deformation during bending is revealed. A quantitative deformation assessment method for honeycomb cells during bending is proposed. The Harris detector is used to recognize each cell wall's two vertexes on the upper surface of the honeycomb after bending in the W-direction, and the honeycomb cells are reconstructed by connecting these recognized vertexes with straight lines. The area ratio, J, and the minimum principal stretch, $\min(\lambda_i)$, are presented to characterize the deformation of honeycombs by constructing the shape function of cell element. The collapse modes of honeycomb with different combinations of component parameters are summarized, including horizontal collapse band along the W-direction and inclined collapse band at an angle of $\pm 60°$ with respect to the W-direction. The sensitivity and response of honeycomb bending deformation to component and cell parameters are analyzed. The collapse mode is more sensitive to the cell wall thickness and bending radius, and the smaller the cell size and bending radius, the larger the honeycomb thickness lead to larger cell deformation. Furthermore, the influence law of the component parameters on the honeycomb deformation is revealed based on the calculated effective in-plane elastic properties. A snap-through buckling mechanism is proposed for describing the cell collapse onset and evolution during bending.

(3) The evolution mechanism of out-of-plane combined compression-shear mechanical properties of curved honeycomb is revealed. The out-of-plane combined compression-shear experiments of curved honeycomb with different bending radii and loading angles are conducted using a specially designed Arcan set-up. Then, a detailed finite element model is validated based on the obtained mechanical responses and deformation modes. The influence of component parameters on the out-of-plane peak strength of honeycomb is analyzed. It is found that the curvature had a significant effect on the peak strength. As the curvature increased from 0 mm to 100 mm, the peak stress is reduced by 16.20%. Furthermore, the relationship between the deformation level of honeycomb and the peak strength is clarified. A phenomenological strength criterion about the peak stress of curved honeycomb is proposed considering the bending radius, R, in-plane orientation angle, β, and honeycomb thickness T,

using the separated normal and shear strengths. In addition, a criterion parameter inversion identification method for curved honeycombs is proposed based on the uniaxial compression response of semicircularly curved honeycomb to achieve rapid and accurate identification of the correction and exponential coefficients.

(4) A deformation control method for hexagonal honeycombs during bending is proposed by grooving to remove redundant material on the inner surface, and further eliminate the collapse of honeycomb. The continuous V-shaped grooved honeycomb bending experiments are carried out, and the effect of grooving spacing on honeycomb deformation level and out-of-plane compression strength are analyzed. Then, a criterion for determining the grooving spacing is proposed by setting a 90% tolerance of the out-of-plane compression strength. Furthermore, the methods of predicting grooving spacing for equal curvature profile and designing grooving trace for variable curvature profile are established by combining the Gaussian Process algorithm. The calculation method of grooving angle is determined using the geometric relationship of the groove before and after bending. Finally, the grooving parameters calculation, process design and forming verification of a aircraft honeycomb sandwich fairing part are conducted. The results show that the local collapse of the honeycomb cell walls is not observed, and the grooves are fully closed, which verifies the effectiveness of the deformation control method for hexagonal honeycombs during bending.

Key words: Honeycomb structures; Bending forming; Effective elastic properties; Shape-property evolution; Deformation assessment; Strength criterion; Deformation control