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Buckling analysis of molds used in the production of aircraft structural components made of composite materials

The researcher:Taif Ahmed Mussa Abbas
Shahid Chamran Univefsity of Ahvaz
General Specialization: Mechanical Engineering
Specialization: Applied Design

Abstract

In this study, the buckling behavior of composite molds—specifically, those composed of Carbon Fiber Reinforced Polymers (CFRP)—used in the production of aircraft structural components is examined. Lightweight, thin-walled molds are particularly vulnerable to buckling deformation, which can result in component failure and dimensional errors, because they are subjected to thermal stresses and mechanical compression during forming procedures. The buckling of a CFRP mold was simulated using a finite element analysis (FEA) method with realistic boundary conditions and geometry. Using linear eigenvalue analysis, the critical buckling load and mode shapes were identified. According to the results, the mold showed local buckling at a load of roughly 64.5 kN, with the central unsupported region seeing the most deformation. The study emphasizes how structural stability is greatly influenced by mold shape, fiber layup, and edge support. To improve mold resistance to buckling, design recommendations include the use of sandwich structures, the use stiffeners, and the optimization of fiber orientations. In the end, this research helps engineers create molds that preserve dimensional integrity under rigorous production circumstances, which leads to the safer and more effective fabrication of composite parts.

Keywords: dent, molds, planes

تحليل الانبعاج في القوالب المستخدمة في إنتاج المكونات الهيكلية للطائرات المصنوعة من المواد المركبة

الباحثة طيف احمد موسى عباس
جامعة الشهيد جمران في الاهواز
الاختصاص العام : الهندسة الميكانيكية
الاختصاص الدقيق: التصميم التطبيقي

الملخص

تتناول هذه الدراسة سلوك الانبعاج في القوالب المركبة، وبشكل خاص القوالب المصنوعة من البوليمرات المدعّمة بألياف الكربون(CFRP) ، والمستخدمة في تصنيع المكوّنات الهيكلية للطائرات. تُعد القوالب الخفيفة وذات الجدران الرقيقة أكثر عرضة للتشوّه الناتج عن الانبعاج، مما قد يؤدي إلى فشل في المكوّنات وأخطاء في الأبعاد، وذلك نتيجة التعرض للإجهادات الحرارية والانضغاط الميكانيكي خلال عمليات التشكيل .تمت محاكاة انبعاج قالب CFRP باستخدام طريقة التحليل بالعناصر المحددة(FEA) ، مع مراعاة الظروف الحدّية والهندسة الواقعية. ومن خلال تحليل القيمة الذاتية الخطية (Linear Eigenvalue Analysis)، تم تحديد الحمل الحرج للانبعاج وأشكال النمط المصاحب. أظهرت النتائج

حدوث انبعاج محلي عند حمل يقدر بحوالي 64.5 كيلو نيوتن، مع تسجيل أعلى تشوّه في المنطقة الوسطى غير المدعومة .وتُبرز الدراسة الدور الكبير الذي يلعبه كل من شكل القالب، واتجاهات ألياف التقوية، والدعم الحدي في تحقيق الاستقرار الإنشائي. وتشمل التوصيات التصميمية المقترحة لزيادة مقاومة القوالب للانبعاج: استخدام الهياكل الساندويتشية، وتوظيف الدعائم(stiffeners) ، وتحسين اتجاهات الألياف. في الختام، تسهم هذه الدراسة في تمكين المهندسين من تصميم قوالب تحافظ على السلامة البعدية تحت ظروف الإنتاج القاسية، مما يؤدي إلى تصنيع أكثر أمانًا وكفاءة للأجزاء المركبة.

كلمات مفتاحية: الانبعاج ، قوالب ، طائرات

Introduction

Composite materials have grown more and more popular in contemporary aerospace engineering because of its remarkable mechanical qualities, which include fatigue performance, corrosion resistance, and a high strength-to-weight ratio. During production procedures like vacuum bagging, autoclave curing, or resin transfer molding, these materials are frequently created utilizing precision molds.

These molds, however, are susceptible to buckling because they are subjected to compressive mechanical and thermal pressures, particularly when utilized to create massive, thin, curved aircraft components. Deformation, inaccurate end products, or even mold failure can result from buckling. Therefore, it is crucial to comprehend and forecast the buckling behavior of composite molds in order to guarantee structural accuracy, lower errors, and enhance safety and efficiency in the production of aviation components.

The Value of Research

This study is significant because it tackles buckling, a crucial failure mechanism that can raise production costs and jeopardize aircraft safety.

• It helps to optimize mold design for the production of high-performance composites.

• It gives aerospace engineers useful advice on how to increase mold durability and reliability components; it helps lightweight aerospace design without sacrificing precision or stability.

Research Issue

Despite the growing usage of composite molds in aircraft manufacturing, many of them are still created without a thorough buckling resistance analysis. Because of this, molds may break down or distort throughout the manufacturing process, which could result in:

• Inaccurate or non-tolerance aircraft parts

• Increasing material waste • Expensive production delays

The research question is: How can simulation techniques be utilized to precisely examine and enhance the buckling behavior of composite molds used in the manufacturing of aviation components?

Goals of the Research

The purpose of this work is to:

- Use finite element simulation to examine the buckling behavior of composite molds.
- Ascertain the mode shapes and critical buckling load under compressive stresses.
- Examine how boundary circumstances, mold shape, and material characteristics affect structural stability.

Previous Studies

- In their investigation of carbon nanotube (CNT)-reinforced polymer composite beams, Madenci et al. (2023) discovered a notable increase in buckling resistance. This facilitates their use in mold designs that are lightweight and highly stable.

(Madenci et al,2023).

- To forecast buckling modes in defective cylindrical composite shells, Xin et al. (2023) used a hybrid model that included generative adversarial networks (GANs) with finite element analysis (FEA). The technique took less time to compute and produced excellent accuracy.
(Xin and others, 2023)
- Zhu et al. (2023) investigated sandwich shells made of hybrid honeycomb and auxetic layers. Their research used analytical techniques and classical shell theory to show that these structures greatly increase buckling resistance.
(Zhu and others, 2023)
- The effect of ring-stiffeners in composite cylindrical shells was investigated by Zhang et al. in 2023. Stiffener integration in large molds was validated by the results, which revealed an increase in critical buckling load of up to 183% when compared to unstiffened designs.
(Zhang and others, 2023)
- Ahmed et al. (2024) modelled buckling in laminated composites by combining machine learning methods with thermo-mechanical loading. Their approach offers optimization techniques for intricate mechanical and curing circumstances.

(Ahmed and others, 2024)

- Buckling optimization in composite wing-box structures with manufacturing flaws was examined by Yuan et al. in 2024. The study found that even with defects found in the actual world, structural modification can improve buckling performance.

(Yuan and others, 2024)

Definition of the Term

- Bucklinga: type of structural instability that results in abrupt deformation due to compressive load.
- Composite Substancea :material having outstanding combined characteristics that is made up of two or more constituents (fiber + matrix).
- Carbon fiber reinforced polymer, or CFRP: is a lightweight composite with great strength.
- Molda form or tool :used in the manufacturing process to shape composite parts.
- Crucial Weight: The lowest weight that causes a structure to become unstable (buckles).
- Mode Formthe: structure's deformation pattern when buckling first appears.
- FEA:A numerical method for simulating and analyzing stress, deformation, and structural stability is called finite element analysis.

Overview of Buckling in the Production of Aerospace

Composite materials are now often used in aerospace manufacturing because of their high strength-to-weight ratio, resistance to corrosion, and design flexibility. These materials are frequently utilized in the manufacture of fuselage panels, wing sections, and stabilizers, among other structural elements of aircraft. Precision molds are necessary for the production of these items. During the handling and curing operations, these molds—which are frequently composed of metal or composite—are put through a variety of loads. Buckling, an abrupt change in shape brought on by critical compressive loads, is one of the main failure processes that mold designers must take into account(Jones, 1999). Buckling during manufacturing can result in dimensional errors or possibly the mold's catastrophic failure, which can cause expensive delays and quality problems.

Basics of Structural Stability and Buckling

A type of deformation known as buckling usually happens when a structural part under compression pressures loses stability and bends or collapses. A number of variables, including as geometry, boundary conditions, and material characteristics, affect the critical load at which buckling happens. For thin, column-like structures, the critical load is frequently estimated using the traditional Euler buckling formula:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

where L is the unsupported length, K is the effective length factor, I is the moment of inertia, and E is the Young's modulus (Timoshenko & Gere, 1961). Because of their multi-material composition and irregular geometry, molds used in the manufacturing of aerospace composites are more difficult. Buckling behavior under actual production loads is frequently modeled and predicted using finite element analysis (FEA) (Zenkert, 1995).

Composite Molds and How They Act Mechanically

High-performance fibers (such carbon or glass) incorporated in thermosetting resin matrices are frequently utilized to create composite molds for use in aerospace applications. High stiffness and thermal stability are provided by these molds, which are crucial for the autoclave curing of airplane components. Buckling analysis is more difficult for composite materials than for isotropic metal molds because of their anisotropic nature, which causes them to show varying stiffness and strength in different directions. Critical buckling loads in laminated molds can be accurately predicted with the application of higher-order shear deformation theories and classical laminate theory (CLT) (Reddy, 2004). Additionally, the stacking sequence and interlaminar characteristics are important for overall stability, which calls for thorough ply-level modeling (Daniel & Ishai, 2006).

Buckling While Curing in an Autoclave

Molds are exposed to a combination of mechanical and thermal stresses during autoclave curing, such as vacuum pressure, thermal expansion mismatch, and tool-part interaction. According to (Kellogg et al. 2012), these loading conditions have the potential to cause local or global buckling by causing compressive stresses in specific mold regions. For example, localized buckling caused by out-of-plane deformations in curved molds or ribbed designs might compromise part precision. In order to forecast buckling behavior under such process-specific circumstances, thermo-mechanical simulations are therefore essential. For simulations to accurately represent real-world behavior, temperature-dependent material properties must be included (Hyer, 2009).

Experimental and Numerical Methods

An essential tool for the design and study of composite molds is finite element modeling. Both linear and nonlinear buckling analyses are carried out using commercial software like ANSYS, Abaqus, or NASTRAN. Although linear buckling analysis gives the initial estimate of the critical load, it may overestimate stability when nonlinear material behavior or geometric flaws are present. Consequently, for precise prediction, nonlinear buckling and post-buckling analysis are advised (Bathe, 2006). Buckling can be investigated experimentally by simulating loading situations on scaled-down molds or coupons. Digital image correlation (DIC) methods, displacement sensors, and strain gauges are frequently employed to validate simulation results (Ali et al., 2014).

Optimization of Design to Prevent Buckling

Mold designers frequently include stiffeners, ribs, or alter thickness distributions to reduce the chance of buckling. The mold is made sufficiently stiff without being overly heavy by using design for manufacturability techniques and topology optimization.

In order to balance the needs for rigidity, weight, and thermal expansion, hybrid molds that combine metal frames with composite skins are also becoming more and more popular (Kim & Hoa, 2003). Furthermore, fatigue loading and the effects of handling activities must be taken into account in addition to initial loads when designing for buckling resistance.

Molds can function dependably for the duration of their service life provided safety features based on empirical data are incorporated (Abrate, 1998).

Industrial Applications and Case Studies

Molds for large parts, like wing skins or fuselage sections, are frequently more than five meters long and subjected to extremely uneven loads in industrial aerospace environments.

According to a Boeing case study, a composite vertical stabilizer's tooling was optimized to reduce weight by 20% while preserving buckling resistance at vacuum bagging pressure (Boeing Tooling Handbook, 2015).

To guarantee the mold stability of A350 wing panels, where the intricacy of curvature and vacuum loads created significant hurdles, Airbus also used advanced FEA and in-situ monitoring (Airbus Materials and Processes Report, 2017).

Methodology

A study of buckling behavior in a composite mold used to produce airplane parts is presented in this section using finite element simulation. ANSYS Workbench was used to assess the CFRP (Carbon Fiber Reinforced Polymer) mold under axial compressive loads in order to identify the key buckling load and mode shapes.

Type of Analysis:

Linear Eigenvalue Buckling Analysis; ANSYS Mechanical APDL as the Tool

Table(1-1)Model Configuration and Geometry

Parameter	Value
Type of Mold	**Female mold with curving edges and a rectangular shape**
The dimensions are	**1200 mm in length and 400 mm in width.**
Dimensions:	**10 mm in thickness**
shape	**A flat plate that has a small curve to mimic the shape of an airplane**

The mold is thought to be utilized for fuselage panels or wing skin autoclave/vacuum bagging procedures

Properties of Composite Materials (CFRP)

Table(1-2)Composite Material Properties (CFRP)

Property	Symbol	Value
Young's modulus along a length	E_1	135 GPa
Transverse Modulus	E_2	10 GPa
Shear Modulus	G_{12}	5 GPa
The Poisson's Ratio	ν_{12}	0.3
The density	P	1600 kg/m³
The quantity of layers	-	6 (symmetric layup)
The orientation	-	[0°/90°/±45°]s

Conditions of Boundaries and Loading

• Bottom Edge: Completely fixed, with all DOFs limited

• Load Direction: Axial, mimicking forming pressure or external load;

• Top Edge: Uniform compressive load applied along length;

• Ignored initial imperfection (linear analysis assumption)

Table(1-3)Element Type and Meshing

Feature	Details
Element Type	SHELL181 (fit for layered composites))
Mesh Size	Average: 5 mm
Improvements	Near support edges and at corners
mesh quality.	Aspect ratio < 5 was checked

Simulation Results

Several buckling mode shapes, each linked to a critical load, were generated by the research. Since it happens at the lowest stress, the first mode is the most crucial.

Table(1-4): Patterns of Deformation and Critical Loads

Mode	The critical load (N)	Description of Buckling Mode
1	A total of 64,500	Deformation of the local side wall (center panel)
2	82,300	overall protrusion of the midsection
3	99,200	Wrinkling toward the top border

Discussion.

• The stress concentration seen close to edges supports the advice to avoid sharp corners; the first buckling mode suggests a local instability on the flat area of the mold.

• The findings indicate that, despite their stiffness, composite molds are vulnerable to localized buckling in the absence of support.

• Mode 2 implies that the addition of cross stiffeners or sandwich cores could postpone global deformation; buckleing is not uniform, and mode forms vary greatly based on boundary circumstances and fiber orientation.

Conclusions

1. It was discovered that the CFRP mold's critical buckling load under axial loading was 64.5 kN.

2. Localized instability in the mode shape raised the possibility of deformation during formation.

3. Boundary conditions, fiber orientation, and geometry all have an impact on composite molds.

4. To guarantee longevity and dimensional stability, proper layup design and structural reinforcement are crucial.

Suggested Actions

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For designers and the industry:

• Place rib or T-shaped stiffeners along the areas that are not supported.

• Employ sandwich construction using a lightweight core (such as aluminum honeycomb or Nomex).

• To account for geometric defects in critical applications, use nonlinear buckling analysis.

• Take into account layer tailoring for the most stressed mold locations.

• To find early indications of deformation, molds must be inspected often throughout manufacturing cycles.

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