

**NONLINEAR ANALYSIS OF VARIABLE STIFFNESS
COMPOSITE AND AUXETIC HONEYCOMB
SANDWICH PANELS**

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**DEPARTMENT OF APPLIED MECHANICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

ANKITA GUPTA

DEPARTMENT OF APPLIED MECHANICS

*Submitted
in fulfillment of the requirements of the degree of Doctor of Philosophy*

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2023**

***Dedicated
to
My Parents***

Certificate

This is to certify that the thesis titled “**Nonlinear Analysis of Variable Stiffness Composite and Auxetic Honeycomb Sandwich Panels**” being submitted by **Ankita Gupta** to the Indian Institute of Technology Delhi, New Delhi, India, for the award of the degree of **Doctor of Philosophy**, is a record of original, bonafide research work carried out by her under my supervision and guidance. The thesis work is my opinion, has reached the requisite standard fulfilling the requirements for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or in full, to any other University or Institute for the award of any degree or diploma.

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Abstract

Composite laminated and sandwich structures are extensively utilised as the load-bearing components in aircraft, automobile, civil and naval industries due to their high stiffness-to-weight and strength-to-weight ratios. Auxetic honeycomb cores having re-entrant cell geometry possess negative Poisson's ratio and lead to increased stiffness and density of the sandwich panel. Conventionally, laminated composites are reinforced with straight fibres which are aligned along a particular direction resulting in constant lamina properties and are known as constant stiffness composite laminates (CSCL). However, the recent advancement in manufacturing technologies like tow placement machines enables to fabricate structures with continuously varying fibre orientation, resulting in spatially varying stiffness. Such panels are named as variable stiffness composite laminates (VSCL). The use of curvilinear fibres in composite structures allows tailoring their response specific to the design requirement with additional weight reduction. The introduction of VSCL also improves the tensile and buckling response and enables an optimum control on the fundamental frequencies of the structure, and therefore, the present study explores the viability of the VSCL based auxetic sandwich panels.

This thesis presents finite element (FE) formulation based on zig-zag displacement fields to analyze linear and nonlinear static and dynamic response of variable stiffness laminated composite and auxetic honeycomb sandwich shell panels. The formulation considers third-order shear deformation theory incorporating zig-zag effects using Murakami zig-zag function and geometrical nonlinearity is included using von Kármán nonlinear strain-displacement relations. The variations of the in-plane and transverse displacements are considered according to global third- and second-order approximations along the thickness direction, respectively. A nine-noded C^0 isoparametric quadratic shell element with thirteen and eleven degrees of freedom per node is employed to study the structural response of VSCL panels. Hamilton's variational principle is used to derive the governing equations for nonlinear static and dynamic analyses. The governing equations for nonlinear static analysis are solved using the Newton-Raphson method to obtain the displacements and stress distribution curves of VSCL panels. The governing equations are further solved for eigenvalue solutions to obtain natural frequencies, and by using Newmark's time integration method for forced vibrational analysis.

The present work establishes the accuracy of the formulation by comparing the results obtained from the present structural models with those from the three-dimensional and two-dimensional benchmark FE solutions available in the literature. The numerical results are

obtained based on an appropriate mesh size determined using convergence studies. A thorough numerical study is presented in this thesis including the effects of curvilinear fibre path angles, lamination configuration, thickness ratio, curvature ratio, geometrical parameters of the honeycomb unit cell, and boundary conditions on the linear and nonlinear static and dynamic response of variable stiffness composite and auxetic honeycomb sandwich panels. New results are presented for the nonlinear static as well as free and forced vibration response of VSCL panels and auxetic structures.

The thesis also presents a finite element (FE) model based on a homogenization procedure and unit cell method to calculate the effective elastic properties of auxetic honeycomb core made up of composite CFRP material. In the absence of analytical expressions for the effective elastic properties of honeycomb core made up of composite material in the literature, the present FE model can prove to be quite useful. Using the obtained properties, the nonlinear static and dynamic behaviour of the sandwich shell panels with VSCL facesheets and CFRP auxetic core is studied. The present thesis also demonstrates the effect of curvilinear fibre angle and geometric parameters of the core on the linear and nonlinear behaviour of the VSCL panels with composite honeycomb core.

सारांश

कंपोजिट लैमिनेटेड और सैंडविच संरचनाएं उच्च कठोरता-वजन अनुपात और सख्ती-वजन अनुपात के कारण हवाई जहाज, ऑटोमोबाइल, सिविल और नौसेना उद्योगों में अपरिहार्य रूप से उपयोग होती हैं। रीएंट्रेट सेल ज्यामिति वाली ऑक्सेटिक हनीकॉब कोर में नकारात्मक पॉइसन अनुपात होता है और सैंडविच पैनल की कठोरता और घनत्व में वृद्धि होती है। पारंपरिक रूप से, लैमिनेटेड कॉम्पोजिट को सीधे रेटांकित रेशेज से मजबूत बनाया जाता है जो किसी विशेष दिशा के साथ संरेखित होते हैं, जिसके परिणामस्वरूप लेमिना गुणों में स्थिरता होती है और इन्हें स्थिर कठोरता वाले कॉम्पोजिट लैमिनेट्स (सीएससीएल) के रूप में जाना जाता है। हालांकि, टो प्लेसमेंट मशीन्स जैसी हाल की प्रौद्योगिकियों की प्रगति ने यह संभव बनाया है कि निरंतर बदलते रेशे आवयवी अवस्था वाली संरचनाएं बनाई जाएं, जिससे स्थानिक रूप से बदलती कठोरता होती है। ऐसे पैनल को परिवर्तनशील कठोरता वाले कॉम्पोजिट लैमिनेट्स (वीएससीएल) कहा जाता है। कॉम्पोजिट संरचनाओं में कर्वीलिनियर रेशेज का उपयोग करने से इनकी प्रतिक्रिया को डिज़ाइन आवश्यकता के अनुरूप तैयार किया जा सकता है और अतिरिक्त वजन कम करने की सुविधा भी होती है। वीएससीएल के होने से टेंशन और बकलिंग प्रतिक्रिया में सुधार होता है और संरचना के मूल आवृत्तियों पर आवश्यक नियंत्रण संभव हो पाता है, इसलिए वर्तमान अध्ययन में वीएससीएल आधारित ऑक्सेटिक सैंडविच पैनल की संभावना का पता लगाया गया है।

यह थीसिस परिवर्तनशील कठोरता वाले लैमिनेटेड कॉम्पोजिट और ऑक्सेटिक हनीकॉब सैंडविच शैल पैनलों की लीनियर और नॉनलीनियर स्थिर और गतिशील प्रतिक्रिया का विश्लेषण करने के लिए ज़िग-ज़ैग विस्थापन क्षेत्रों पर आधारित फाइनाइट एलिमेंट (एफई) सूत्रीकरण प्रस्तुत करती है। यह सूत्रीकरण तृतीयकारी शीयर डीफॉर्मेशन सिद्धांत को मानता है और मुराकामी ज़िग-ज़ैग फ़ंक्शन का उपयोग करके ज़िग-ज़ैग प्रभावों को शामिल करता है और वॉन कर्मान नॉनलीनियर तनाव-विस्थापन संबंधों का उपयोग करके ज्यामितिक नॉनलीनियरीटी को शामिल किया गया है। तलमध्य और पार्श्विक विस्थापनों की विभिन्नताएं मुख्य तृतीयकारी और द्वितीयकारी अनुमानों के अनुसार परिग्रहित की जाती हैं। स्ट्रक्चरल प्रतिक्रिया का अध्ययन करने के लिए नौ नोड के सी 0 आयसोपैरामेट्रिक क्वाड्रेटिक शैल तत्व का उपयोग किया गया है जिसमें प्रति नोड त्रयोदश और ग्यारह स्वतंत्रता गुणों का उपयोग किया गया है। नॉनलीनियर स्थिर और गतिशील विश्लेषणों के लिए हैमिल्टन के परिवर्तनीय सिद्धांत का उपयोग किया गया है। नॉनलीनियर स्थिरता विश्लेषण के लिए न्यूटन-राफ़सन विधि का उपयोग करके गणितीय समाधान द्वारा वीएससीएल पैनलों के विस्थापन और प्रतिबल वितरण के लिए शासकीय समीकरणों को हल किया गया है। शासकीय समीकरणों को अधिक उपयुक्त मानों के लिए निजमूल मान समाधान के लिए हल किया गया है जिससे प्राकृतिक आवृत्तियाँ प्राप्त हुई हैं, और बल प्रेरित वाइब्रेशन विश्लेषण के लिए न्यूमार्क के समय संकलन विधि का उपयोग किया गया है।

वर्तमान कार्य द्वारा सूत्रीकरण की सटीकता स्थापित की गयी है जिसके लिए वर्तमान संरचनात्मक मॉडल से प्राप्त परिणामों की तुलना साहित्य में उपलब्ध त्रिआयामी और द्विआयामी मानक एफई समाधानों से की गयी है। संख्यात्मक परिणामों को संरचनात्मक अध्ययनों का उपयुक्त मेश आकार के आधार पर प्राप्त किया गया है जो अभिसरण अध्ययन का उपयोग करके निर्धारित किया गया है। इस थीसिस में एक संपूर्ण संख्यात्मक अध्ययन प्रस्तुत किया गया है जिसमें कर्वीलिनियर रेशे पथ के कोण, लेमिनेशन कॉन्फिगरेशन, मोटाई अनुपात, क्षैतिज अनुपात, हनीकॉब यूनिट सेल के ज्यामितीय पैरामीटर, और सीमांकन शर्तें इत्यादि के परिवर्तनशील कठोरता वाले कॉम्पोजिट और ऑक्सेटिक हनीकॉब सैंडविच पैनलों के लीनियर और नॉनलीनियर स्थिर और गतिशील प्रतिक्रियाओं का अध्ययन किया गया है। वीएससीएल पैनलों और ऑक्सेटिक संरचनाओं की नॉनलीनियर स्थिर, एवं स्वतंत्र और बल प्रेरित वाइब्रेशन प्रतिक्रिया के लिए नए परिणाम प्रस्तुत किए गए हैं।

यह थीसिस एक होमोजनीकरण प्रक्रिया और यूनिट सेल विधि पर आधारित एक फाइनाइट एलिमेंट (एफई) मॉडल भी प्रस्तुत करती है, जिसके द्वारा संयुक्त सीएफआरपी सामग्री से बने ऑक्सेटिक हनीकॉब कोर की प्रभावी लचीली गुणांकता की गणना की गयी है। साहित्य में कम्पोजिट सामग्री से बने हनीकॉब कोर की प्रभावी लचीली गुणांकता के लिए विश्लेषणात्मक संचार के अभाव में, वर्तमान एफई मॉडल बहुत उपयोगी साबित हो सकता है। प्राप्त गुणों का उपयोग करके, वीएससीएल फेसशीट और सीएफआरपी ऑक्सेटिक कोर के सैंडविच शैल पैनल की नॉनलीनियर स्थिर और गतिशील व्यवहार का अध्ययन किया गया है। वर्तमान थीसिस ने यह भी प्रदर्शित किया है कि कर्वीलिनियर रेशे कोण और कोर के ज्यामितीय पैरामीटरों का कॉम्पोजिट हनीकॉब कोर युक्त वीएससीएल पैनलों के लीनियर और नॉनलीनियर व्यवहार पर क्या प्रभाव होता है।

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Organization of the Thesis

The thesis consists of nine chapters. Chapters 1 and 2 provide the introduction and review of the literature related to the present study. Based on the observations made, the scope and objectives of the present work are given in Chapter 3. Chapter 4 explains the mathematical formulation employed to perform the linear and nonlinear analyses of VSCL and sandwich shell panels having curvilinear fibres. The mathematical formulation is based on the third-order shear deformation theory including Murakami zig-zag function. Based on this formulation, the linear and nonlinear static and dynamic analyses of the VSCL shell panels are performed and the results are shown in Chapter 5. Chapter 6 presents the static, free and forced vibration response of the VSCL sandwich shell panels having curvilinear and parabolic fibres. Chapter 7 highlights the static and dynamic behaviour of the sandwich shell panels having auxetic honeycomb core and curvilinear fibre reinforced facesheets using the formulation explained in Chapter 4. Next, the effective properties are calculated for the conventional and re-entrant honeycomb core made up of isotropic as well as composite material using ABAQUS. The results of the static and dynamic analyses of the sandwich shell panels having VSCL facesheets and composite honeycomb core are discussed in Chapter 8. Chapter 9 lists major conclusions drawn from the present study and scope of the future work. Lastly, the references used for the present study are listed.