

STUDIES ON STRETCHABLE STRAIN SENSING MATERIALS FOR MEMBRANE STRUCTURES

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**DEPARTMENT OF TEXTILE AND FIBRE ENGINEERING
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STUDIES ON STRETCHABLE STRAIN SENSING MATERIALS FOR MEMBRANE STRUCTURES

by

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Department of Textile and Fibre Engineering

Submitted

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to the



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Dedication

I dedicate this thesis to my beloved father, whose memory continues to inspire and guide me every day.

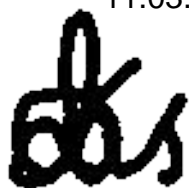
CERTIFICATE

This is to certify that the thesis entitled "**Studies on Stretchable Strain Sensing Materials for Membrane Structures**", being submitted by **Mr. Amit Kumar Mandal**, to the **Indian Institute of Technology, Delhi**, for the award of the degree of **Doctor of Philosophy** in the Department of Textile and Fibre Engineering, is a record of bonafide research work carried out by him. Mr. Amit Kumar Mandal has worked under our guidance and supervision and fulfilled the requirements for the submission of the thesis, which, to our knowledge, aligns with the requisite standards for a Ph.D. degree from this Institute.

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

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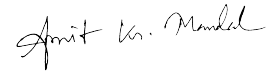
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A handwritten signature in black ink, reading "Amit Kumar Mandal". The signature is written in a cursive style with a prominent initial 'A'.

(Amit Kumar Mandal)

ABSTRACT

In contemporary engineering practice, membrane structures are extensively utilized across various applications, including inflatable space habitats, aerostats, and tunnel sealing, primarily due to their lightweight characteristics and ease of deployment. However, significant challenges persist in managing stress accumulation and conducting structural health monitoring, as these structures are subject to substantial deformations.

The primary objective of this research is to develop finite element models of diverse membrane structures incorporating cable stiffeners to mitigate stress buildup. Additionally, this study aims to develop and characterize strain-sensing materials tailored for these structures and to perform finite element simulations of the proposed strain-sensing materials.

In the finite element modeling of membrane structures reinforced with cable stiffeners, the updated Lagrangian method was employed. For inflatable membrane structures, it was observed that the incorporation of cable stiffeners effectively regulates the inflation process and consequently mitigates the accumulation of stress.

A novel coating method, referred to as the bar coating technique, was employed to fabricate textile-based strain sensing materials composed of polyester knitted fabric, carbon nanotubes, and polydimethylsiloxane. In this composite, the polyester fabric served as the base material, carbon nanotubes functioned as conductive fillers, and polydimethylsiloxane acted as the matrix material.

Various piezoresistive characterization methods were applied to evaluate the performance of the developed strain sensing materials. The characterization results revealed that the selected textile material inadvertently increased the stiffness of the strain sensing composite, which is undesirable for strain sensing applications. Additionally, the electrical response of the material was observed to be non-instantaneous. Initially, the time-dependent electrical response of these strain-sensing materials was attributed to the presence of time-dependent electrical

components, such as capacitors and inductors, inherent within their nanostructures. However, subsequent investigations involving both numerical simulations and experimental analyses revealed that the viscoelastic properties of the material play a more significant role in governing the time-dependent electrical behavior.

Building upon our findings, finite element simulations were conducted on strain-sensing materials wherein the base material (knitted fabric) was omitted. The simulations incorporated the viscoelastic behavior in both electrical and structural domains under conditions of large deformation, utilizing a total Lagrangian formulation. The analysis revealed that these strain-sensing materials were capable of detecting instantaneous responses at very low strain rates, specifically below 1 % strain per minute.

सारांश

वर्तमान अभियांत्रिकी प्रचलन में मेम्ब्रेन स्ट्रक्चर्स का व्यापक रूप से विभिन्न अनुप्रयोगों में उपयोग किया जा रहा है, जैसे इन्फ्लेटेबल स्पेस हैबिटैट्स, एयरोस्टैट्स, तथा सुरंग सीलिंग प्रणालियाँ, जिसका मुख्य कारण इनका हल्का होना तथा आसानी से स्थापित किया जाना है। हालांकि, इन संरचनाओं में तनाव के संचय को नियंत्रित करना तथा संरचनात्मक स्वास्थ्य निगरानी करना अभी भी एक महत्वपूर्ण चुनौती बना हुआ है, क्योंकि ये संरचनाएँ बड़े स्तर के विरूपण के अधीन होती हैं।

इस शोध का मुख्य उद्देश्य विभिन्न प्रकार की मेम्ब्रेन स्ट्रक्चर्स के लिए फाइनाइट एलिमेंट मॉडल्स विकसित करना है, जिनमें केबल स्टिफनर्स को सम्मिलित करके तनाव संचय को कम किया जा सके। इसके अतिरिक्त, इस अध्ययन का उद्देश्य इन संरचनाओं के लिए उपयुक्त स्ट्रेन-सेंसिंग सामग्री का विकास एवं उनका विश्लेषण करना तथा प्रस्तावित स्ट्रेन-सेंसिंग सामग्री के लिए फाइनाइट एलिमेंट सिमुलेशन्स करना भी है।

केबल स्टिफनर्स से सुदृढ़ की गई मेम्ब्रेन स्ट्रक्चर्स के फाइनाइट एलिमेंट मॉडल्स के विकास में अपडेटेड लग्रांजियन मेथड का उपयोग किया गया। इन्फ्लेटेबल मेम्ब्रेन स्ट्रक्चर्स के अध्ययन में यह पाया गया कि केबल स्टिफनर्स का उपयोग इन्फ्लेशन प्रक्रिया को प्रभावी रूप से नियंत्रित करता है और परिणामस्वरूप तनाव संचय को कम करता है।

वस्तु आधारित स्ट्रेन सेंसिंग सामग्री के निर्माण के लिए एक नई कोटिंग विधि, जिसे बार कोटिंग टेक्नीक कहा जाता है, का उपयोग किया गया। इस समग्र पदार्थ में पॉलीएस्टर निटेड फैब्रिक, कार्बन नैनोट्यूब्स, तथा पॉलीडाइमेथिलसिलॉक्सेन का उपयोग किया गया। इस समग्र में पॉलीएस्टर फैब्रिक बेस सामग्री आधार सामग्री के रूप में कार्य करता है, कार्बन नैनोट्यूब्स कंडक्टिव फिलर्स के रूप में कार्य करते हैं तथा पॉलीडाइमेथिलसिलॉक्सेन सामग्री मैट्रिक्स के रूप में कार्य करता है।

विकसित स्ट्रेन सेंसिंग सामग्री के प्रदर्शन का मूल्यांकन करने के लिए विभिन्न पाइजोरेसिस्टिव विश्लेषण विधियाँ का उपयोग किया गया। विश्लेषण के परिणामों से यह पाया गया कि चयनित वस्तु सामग्री ने अनजाने में स्ट्रेन सेंसिंग कॉम्पोजिट की कठोरता बढ़ा दी, जो स्ट्रेन सेंसिंग एप्लिकेशन्स के लिए उपयुक्त नहीं है। इसके अतिरिक्त, सामग्री की विद्युत प्रतिक्रिया तात्कालिक नहीं पाई गई। प्रारंभ में इन स्ट्रेन-सेंसिंग मटेरियल्स की समय-निर्भर विद्युत प्रतिक्रिया को उनकी नैनोस्ट्रक्चर्स में उपस्थित समय-निर्भर विद्युत अवयवों, जैसे कैपेसिटर्स और इंडक्टर्स, की उपस्थिति से जोड़ा गया था। हालांकि, बाद में किए गए संख्यात्मक अनुकरण और प्रायोगिक विश्लेषणों से यह स्पष्ट हुआ कि इस समय-निर्भर विद्युत व्यवहार को नियंत्रित करने में सामग्री के विस्कोइलास्टिक गुण अधिक महत्वपूर्ण भूमिका निभाते हैं।

इन निष्कर्षों के आधार पर, स्ट्रेन-सेंसिंग सामग्री पर आगे फाइनाइट एलिमेंट सिमुलेशन्स किए गए, जिनमें आधार सामग्री (निटेड फैब्रिक) को हटाया गया। इन अनुकरणों में बड़े विरूपण की स्थिति में विद्युत तथा संरचनात्मक दोनों क्षेत्रों में विस्कोइलास्टिक व्यवहार को सम्मिलित किया गया तथा इसके लिए टोटल लॉग्रैजियन फॉर्मूलेशन का उपयोग किया गया। विश्लेषण से यह ज्ञात हुआ कि ये स्ट्रेन-सेंसिंग मटेरियल्स अत्यंत कम स्ट्रेन रेट, विशेष रूप से प्रति मिनट १ प्रतिशत से कम, पर भी तात्कालिक प्रतिक्रिया को पहचानने में सक्षम हैं।

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