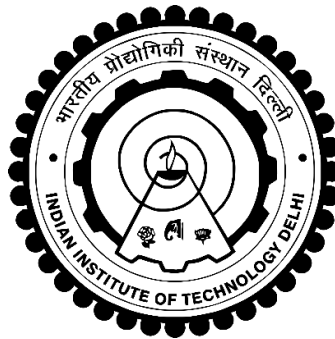


**AN EXPERIMENTAL AND NUMERICAL STUDY
ON KEVLAR-POLYPROPYLENE HYBRID
NONWOVENS AND FIBERWEB COMPOSITES**

GARGI JAISWAL



**DEPARTMENT OF APPLIED MECHANICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JUNE 2021**

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by

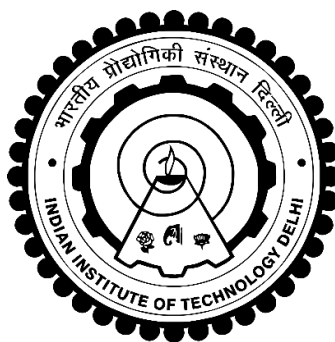
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Submitted

in fulfilment of requirements for the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2021

Dedicated to

My father Late Mr. Harinarayan Prasad Jaiswal

&

My husband Sanjeev Kumar

CERTIFICATE

This is to certify that the thesis titled " **An Experimental and Numerical study on Kevlar-Polypropylene Hybrid Nonwovens and Fiberweb Composites**" being submitted by **Ms. Gargi Jaiswal** to the **Indian Institute of Technology, Delhi** for the award of degree of **Doctor of Philosophy** is the record of bonafide research work carried out by her under our supervision. In our opinion, the thesis has reached the standards fulfilling the requirements in accordance with the regulations of the institute and the student is worthy of consideration.

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

Date: June, 2021

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Acknowledgement

Strength does not come from winning. Your struggles develop your strength.

When you go through hardships and decide not to surrender, that is strength.

-Mahatma Gandhi

This Ph.D. has been a truly life-changing experience for me and it's just not a degree to me but almost life. My Ph.D. journey would not have been possible to do without the support and guidance that I received from many people. First and foremost, I would like to **thank almighty God** for giving me the opportunity, strength, and determination to complete this research study satisfactorily.

As they say, the best teachers don't give you the answer, they spark within you the desire to find the answer yourself. For me, my advisor, **Prof. M.K. Singha** ignited the spark inside me and gave the wings to fly. **Prof. Dipayan Das** valuable experiment related suggestions always helped to make the right decision and move ahead. I would like to acknowledge both for their patient guidance, advice, and encouragement throughout my Ph.D. This work would not have been possible without their continuous support and guidance.

I am highly grateful to all my **SRC (Student Research Committee)** members, **Prof. B.P. Patel, Dr. Vikrant Tiwari, Dr. Samrat Mukhopadhyay** (Textile Department) for their insightful comments and encouragement. I am also thankful to each of them for extending their every possible support not only from providing lab facilities but also giving their precious time to discuss experiment related queries. Thank you all for your co-operation and guidance.

I would like to acknowledge the **National Physical Laboratory (NPL)**, Delhi, and **Central Institute of Plastics Engineering and Technology (CIPET)**, Murthal for allowing me to conduct specimen testing in their respective labs. I am indebted towards the **Council of Scientific and Industrial Research (CSIR)**, Pusa for their financial assistance in the initial two years of my Ph.D.

Experiments are an integral part of my thesis and many laboratory staff has given their silent contribution in shaping the experiment section of my work. I would like to thank the lab staff of the Textile Department, **Mr. Vikas Khatkar, Mr. Kundu, Mr. Kuldeep, Mr. Subhash, Mr. Amarjeet, Mr. Kala, Mr. Khattar, and Mr. Biswal**. A special thanks to **Mr. Madan** and **Mr. Rishi** for their help in conducting experiments at the workshop and strength of materials in the Applied Mechanics department. I would like to acknowledge my juniors (M.Tech) **Alok, Rishabh, and Pulkhit** for their help in fiber opening process. I am thankful to my Impact lab juniors, **Purnashis, Anoop, and Kuldeep** for setting up DIC to conduct testing of composites.

Happiness is having colleagues who understand and support you. Computation Lab has been the best lab I have ever worked with. I would like to thank my seniors, **Dr. Aswani, Dr. Amit, Dr. Gaurav Watts, Dr. Emrati, Dr. Mehnaz, Dr. Mohit, Dr. Shreya, and Dr. Jeetendra** for their valuable advice and energetic support. I am thankful to my wonderful friends, **Adnan, Anurag, Mayank, Ankita, Yadwinder, Rishabh, Babu, Sriram, Satendra, Bashir, Hasan, Sajjan, Raushan, Prakhar** for keeping a healthy environment in the lab. I would like to acknowledge my campus friends **Anasuya, Chandrajeet, Prachi, Richa, Sapna, Neha, Ravita and Saket, Upma, and Anu** for their moral support. Special thanks to my dear friends, **Anusurti, Amit sir, Vikas, Rashmi** and **Taruna mam** for their emotional support in the most difficult phase of my Ph.D. and helped to maintain a positive mindset.

I have no words to describe the love and emotional support of my beloved **parents**, **brothers**, and **sisters** who believed in me and stood like a pillar in my all ups and downs. Thank you, **papa**, for shaping my career and making me a strong and independent woman. It was your dream for me to become a doctorate, though last year you left me alone in this journey but your smiling face and motivating lines,” hard work pays off so have patience” made me to finish this and make you proud.

I owe a depth of gratitude to the biggest pillar of my life, my husband **Mr. Sanjeev Kumar** for his continued and unfailing love, and support during the pursuit of my Ph.D. that made the completion of the thesis possible. I salute to his level of understanding and patience. Though living in long-distance from starting, at times I thought it is impossible to continue but his beliefs in me made this journey possible.

Gargi Jaiswal

Abstract

The short-fibre based "*nonwoven fabrics*" are recently being used in transportation and infrastructural industries in addition to various products of decorative, filtration, insulation and disposable nature. The needle-punching is one of the high-speed and low-cost processes for the mechanical interlocking of the random mixture (without any specific pattern) of curved short fibres in this type of textile fabrics. Research on the mechanics of "*needle-punched nonwoven*" is a subject of ongoing research to explore its potential towards durable and high strength application areas (e.g., ground stabilization, protective clothing, military helmets, geo-synthetic etc). Similarly, the short-fiber reinforced composites are attracting the attention of civil and transport industries, as they have reasonable strength, stiffness and impact resistance with a lower fabrication cost and higher production rate, as compared to the continuous fiber reinforced composites. An attempt is made in this thesis to improve the understanding of the mechanics of "*needle-punched nonwoven*" and short-fibre based "*fiberweb composites*" by a combined experimental and theoretical / numerical approach.

First part of the thesis is focussed on the tensile stiffness and strength of "*needle-punched nonwoven*", prepared from short fibres. At the beginning, extensive experimental investigation is conducted to investigate the effect of process parameters (areal weight, punch density and depth of penetration) on the physical and tensile properties of polypropylene nonwoven fabrics under uni-axial and bi-axial loads. Thereafter, high strength aramid fibres are mixed (homogeneous and layer-wise pattern) with the ductile polypropylene fibres to prepare hybrid nonwovens using the

carding and needle-punching techniques to explore their competence in important application areas demanding both strength and ductility. The realistic fibre orientation distribution and fibre-to-fibre slippage is used to correlate the tensile strength of nonwovens with the tensile strength of individual fibres using the Hearle's theory of nonwovens.

Next, an attempt is made to develop a finite element model of the needle-punched nonwovens using an idealized fiber network. The randomly placed (entangled or non-entangled) curved polypropylene fibers are assumed to be hyperbolic (cosine or sine) within the representative area element (RAE). The orientation of individual fibers is randomly fixed, while, the fiber interlocking is deterministically defined in the indigenously prepared MATLAB code. A two-node fiber element is employed to simulate the tension only behavior of individual fibers in the presence of frictional forces from the surrounding fibers. The present finite element model of representative 50 randomly oriented hyperbolic fibers predicts the tensile behavior of nonwoven qualitatively and quantitatively.

The second section of the thesis deals with the Kevlar-polypropylene fiberweb composites. Kevlar and polypropylene fibres of 51 mm cut-length are mixed together to prepare a hybrid nonwoven and compression moulding technique is employed to prepare the hybrid nonwoven. These fiberweb reinforced composites are tested for physical properties such as density, volume fraction, void fraction and the fiber orientation. Thereafter, extensive experimental investigation is carried out to determine the stiffness, strength and failure mechanism of fiberweb composites under tension, compression, shear, bending, and impact loads. An effort is also made to discuss experimental results in the light of theoretical models. A modified rule of mixture that considers the tensile strength of fiber and matrix, realistic fiber orientation factor and

void content predicted the tensile properties quite satisfactorily. The flexural behavior was correlated well with the distinct material response under tension and compression.

सार

शॉर्ट-फाइबर आधारित "नॉनवॉवन फैब्रिक्स" का उपयोग हाल ही में सजावटी, निस्पंदन, इन्सुलेशन और डिस्पोजेबल प्रकृति के विभिन्न उत्पादों के अतिरिक्त परिवहन और अवसंरचनात्मक उद्योगों में किया जा रहा है। सुई-छिद्रण उच्च गति और कम लागत वाली प्रक्रियाओं में से एक है। इस तरह के वस्तुओं में घुमावदार छोटे फाइबर के यादृच्छिक मिश्रण अर्थात् किसी विशिष्ट पैटर्न के बिना यांत्रिक इंटरलॉकिंग के द्वारा किया जाता है। "सुई-छिद्रित नॉनवॉवन" के यांत्रिकी अनुसंधान दृढ़ और उच्च शक्ति अनुप्रयोग क्षेत्रों (जैसे, जमीन स्थिरीकरण, सुरक्षात्मक कपड़े, सैन्य हेलमेट, भू-सिंथेटिक आदि) की दिशा में संक्षेप में अपनी क्षमता का पता लगाने के लिए चल रहे शोध का विषय है। फाइबर प्रबलित कंपोजिट्स नागरिक तथा परिवहन उद्योगों का ध्यान आकर्षित कर रहे हैं। क्योंकि निरंतर प्रबलित कंपोजिट फाइबर की तुलना में उनके पास लगातार कम फाइबर लागत और उच्च उत्पादन दर के साथ उचित मजबूती, कठोरता आदि प्रभावों का प्रतिरोध है। इसलिए इस थीसिस में प्रयास किया गया है कि एक संयुक्त प्रयोगात्मक और सैद्धांतिक / संख्यात्मक दृष्टिकोण द्वारा "सुई-छिद्रित नॉनवॉवन" और शॉर्ट-फाइबर आधारित "फाइबरवेब कंपोजिट" के यांत्रिकीकरण की में सुधार लाया जाये।

थीसिस के पहले भाग को तंतुमय कठोरता और "सुई-छिद्रित नॉनवॉवन" की ताकत पर फोकस किया गया है, जो छोटे तंतुओं से तैयार किया गया है। शुरुआत में, प्रक्रिया मापदंडों (क्षेत्र भार, पंच घनत्व और गहराई) के प्रभाव की जांच के लिए व्यापक प्रयोगात्मक जांच की जाती है। यूनी-अक्षीय और द्वि-अक्षीय भार के तहत पॉलीप्रोपाइलीन नॉनवॉवन कपड़ों के भौतिक और तन्यता गुणों पर पैठ। इसके बाद, उच्च शक्ति वाले आर्मी फाइबर को मिश्रित (सजातीय और परत-वार पैटर्न) नमनीय पॉलीप्रोपाइलीन फाइबर के साथ हाइब्रिड नॉनवॉवन तैयार करने के लिए उपयोग किया जाता है। कार्डिंग और सुई-छिद्रण तकनीक दोनों महत्वपूर्ण शक्ति क्षेत्रों में अपनी क्षमता

का पता लगाने के लिए ताकत और लचीलापन दोनों की मांग करते हैं। हालें का सिद्धांत नॉनवॉर्वेस यथार्थवादी फाइबर अभिविन्यास वितरण और फाइबर-टू-फाइबर स्लिपेज का उपयोग व्यक्तिगत फाइबर के दसियों की ताकत के साथ गैर-तन्वी की तन्यता ताकत को सहसंबंधित करने के लिए किया जाता है।

आगामी, एक आदर्श फाइबर नेटवर्क का उपयोग करके सुई-छिद्रित नॉनवॉर्वेस का एक परिमित तत्व मॉडल विकसित करने का प्रयास किया जा रहा है। प्रतिनिधि क्षेत्र तत्व (RAE) के भीतर बेतरतीब ढंग से रखा (उलझा हुआ या गैर-उलझा हुआ) घुमावदार पॉलीप्रोपाइलीन फाइबर हाइपरबोलिक (कोसाइन या साइन) माना जाता है। व्यक्तिगत फाइबर का अभिविन्यास बेतरतीब ढंग से तय किया जाता है, जबकि, फाइबर इंटरलॉकिंग का निर्धारण स्वदेशी रूप से तैयार MATLAB कोड में किया जाता है। तंतु दो-नोड फाइबर तत्व को तनाव का अनुकरण करने के लिए नियोजित किया जाता है, जो केवल आसपास से घर्षण बलों की उपस्थिति में व्यक्तिगत फाइबर के व्यवहार को दर्शाता है। प्रतिनिधि का वर्तमान परिमित तत्व मॉडल 50 अनियमित रूप से उन्मुख हाइपरबोलिक फाइबर गुणात्मक और मात्रात्मक रूप से गैर-बुना हुआ तन्यता व्यवहार की भविष्यवाणी करता है।

थीसिस का दूसरा खंड केवलर-पॉलीप्रोपाइलीन फाइबरवेब कंपोजिट से संबंधित है। हाइब्रिड नॉनवॉर्वेन तैयार करने के लिए 51 मिमी कट-लेंथ के केवलर और पॉलीप्रोपाइलीन फाइबर को एक साथ मिलाया जाता है और हाइब्रिड नॉनवॉर्वेन तैयार करने के लिए कम्प्रेशन मोल्डिंग तकनीक को काम में लिया जाता है। इन फ़ाइब्रेब प्रबलित कंपोजिट का परीक्षण भौतिक गुणों जैसे घनत्व, वॉल्यूम अंश, शून्य अंश और फाइबर अभिविन्यास के लिए किया जाता है। इसके बाद, तनाव, संपीड़न, कतरनी, झुकने और प्रभाव भार के तहत फाइबरवे कंपोजिट की कठोरता, शक्ति और विफलता तंत्र को निर्धारित करने के लिए व्यापक प्रयोगात्मक जांच की जाती है।

सैद्धांतिक मॉडल के प्रकाश में प्रयोगात्मक परिणामों पर चर्चा करने का प्रयास भी किया जाता है। मिश्रण का एक संशोधित नियम जो फाइबर और मैट्रिक्स की तन्यता ताकत पर विचार करता है, यथार्थवादी फाइबर अभिविन्यास कारक और शून्य सामग्री ने तन्यता गुणों की काफी संतोषजनक भविष्यवाणी की है। तथा लचीले व्यवहार को तनाव और संपीड़न के तहत अलग-अलग सामग्री प्रतिक्रिया के साथ अच्छी तरह से सहसंबद्ध किया गया था। शॉर्ट-फाइबर आधारित "नॉनवॉवन फैब्रिक्स" का उपयोग हाल ही में सजावटी, निस्पंदन, इन्सुलेशन और डिस्पोजेबल प्रकृति के विभिन्न उत्पादों के अलावा परिवहन और अवसंरचनात्मक उद्योगों में किया जा रहा है। सुई-छिद्रण उच्च गति और कम लागत वाली प्रक्रियाओं में से एक है। इस तरह के वस्त्रों में घुमावदार छोटे फाइबर के यादृच्छिक मिश्रण अर्थात् किसी विशिष्ट पैटर्न के बिना यांत्रिक इंटरलॉकिंग के द्वारा किया जाता है। "सुई-छिद्रित नॉनवॉवन" के यांत्रिकी अनुसंधान दृढ़ और उच्च शक्ति अनुप्रयोग क्षेत्रों (जैसे, जमीन स्थिरीकरण, सुरक्षात्मक कपड़े, सैन्य हेलमेट, भू-सिंथेटिक आदि) की दिशा में संक्षेप में अपनी क्षमता का पता लगाने के लिए चल रहे शोध का विषय है। फाइबर प्रबलित कंपोजिट्स नागरिक और परिवहन उद्योगों का ध्यान आकर्षित कर रहे हैं। क्योंकि निरंतर प्रबलित कंपोजिट फाइबर की तुलना में उनके पास लगातार कम फाइबर लागत और उच्च उत्पादन दर के साथ उचित मजबूती, कठोरता आदि प्रभावों का प्रतिरोध है। इसलिए इस थीसिस में प्रयास किया गया है कि एक संयुक्त प्रयोगात्मक और सैद्धांतिक / संख्यात्मक दृष्टिकोण द्वारा "सुई-छिद्रित नॉनवॉवन" और शॉर्ट-फाइबर आधारित "फाइबरवेब कंपोजिट" के यांत्रिकीकरण की में सुधार लाया जाये।

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LIST OF SYMBOLS

E	Young's modulus
σ	Stress
A	Area of cross-section
$\{\delta\}$	Displacement vector
$\{F\}$	Force vector
$[K_G]$	Global stiffness matrix
$[K_T]$	Tangent stiffness matrix
$[K_\sigma]$	Initial stress matrix
$\{F_\sigma\}$	Pre-stressing force
$F_n(\varepsilon)$	Tensile force acting on a nonwoven material
$F_f(\varepsilon)$	Fiber force factor
$\zeta_f(\varepsilon)$	Fiber orientation factor
$\lambda_f(\varepsilon)$	Fiber slippage factor
F'_f	Fiber breaking force
W_n	Basis weight of nonwoven
t_f	Fiber fineness
ε'_f	Breaking elongation of fiber
α	Angle of inclination of fibers from the longitudinal axis of nonwoven
B_n	Width of nonwoven

μ_f	Coefficient of friction between fiber
c_f	Radius of fiber curvature,
l_f	Fiber length,
α	Modal angle
d_f	Fiber diameter
ρ	Density
$f(\psi)$	Probability density function of angle ψ
H	Preferential intensity of fiber orientation along the modal direction
V	Volume fraction
EI	Equivalent flexural rigidity of a bi-modulus beam
κ	Shear correction factor