

MECHANICAL PERFORMANCE OF 3D WOVEN SOLID STRUCTURES AND THEIR COMPOSITES

ASHWINI KUMAR DASH



**DEPARTMENT OF TEXTILE TECHNOLOGY
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MECHANICAL PERFORMANCE OF 3D WOVEN SOLID STRUCTURES AND THEIR COMPOSITES

by

ASHWINI KUMAR DASH

Department of Textile Technology

Submitted

in fulfilment of the requirement of the degree of Doctor of Philosophy

to the



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Dedicated to Almighty and

and my family

CERTIFICATE

This is to certify that the thesis entitled “**Mechanical performance of 3D woven solid structures and their composites**” being submitted by **Mr.Ashwini Kumar Dash** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. Mr. Ashwini Kumar Dash has worked under my guidance and supervision and fulfilled the requirements for submission of the thesis. The results contained in thesis have not been submitted, in part or full, to any other university for the award of any degree or diploma.

Prof. B. K. Behera
Department of Textile Technology
Indian Institute of Technology Delhi,
New Delhi- 110016.

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Ashwini Kumar Dash

New Delhi

ABSTRACT

In this research, 3D fabrics were investigated for their possibility of numerous structural variations using weaving technology, adaptability of these 3D preforms to form a particular geometry, characterization of these preforms as well as their composites and finally theoretical analysis of tensile behavior of basic orthogonal and interlock structures by Solidworks and Ansys software with experimental validation.

The first module of this research work was aimed to study the mechanical performance of preforms. From the results of the preform tests conducted, it was undoubtedly evidenced that stuffer tows were mainly responsible for warp way tensile applications. Fabric cross over points had a dominating role in deciding the impact performance. Knife penetration characteristics were more influenced by tow linear densities and number of tows per unit width of the fabric than the influence of fabric cross over points as noticed in case of impact analysis of the fabrics. In a generalized way, it is concluded that thickness of the preforms must be sufficiently higher in order to avoid binder extension during tensile applications.

Another important characteristics of the preforms in terms of formability was studied with these samples in the next module. Scientists defined formability as the ability of a preform to attain complex 3D shapes, particularly for composite applications. For comparison purpose, forming energy was chosen as measuring index which was obtained from the area of the load-deformation curve. In this work, all the eighteen different types of 3D fabrics (six of different weave designs, six of different stuffer layers, and six of different FVFs of orthogonal and interlock designs) were tested for the determination of forming energy. A special attachment was fabricated and mounted on INSTRON 3365 tensile testing machine and the preforms were

tested in compression mode upto a fixed deformation level. Fabric cross over points were found to be the dominating parameter for the results of forming energy. It is established that bending rigidity can provide the most relevant information to assess the formability of preforms related to a representative process of pressing a flat fabric into a hemispherical form. This work was done with different weave designs of 2D preforms made up of graphite fibres. Hence in this work, exploration of 3D fabrics of various weave designs were attempted for necessary correlation with the bending rigidity results. Excellent correlation was observed in these two properties like the earlier work. As it was found that fabric cross over points had a major role to determine the forming energy, the former one i.e. the fabric cross over points were correlated with bending rigidity as well as forming energy. Reasonably good correlations were obtained in both the cases. However, correlation was higher between the cross over points with the bending rigidity in comparison to the other one.

As the end use of the 3D preforms are supposed to be into composites, these prepared fabric samples were subjected to composite preparation with epoxy resin and tested for tensile, bending and impact analysis in the next module. The interlacement patterns of binder tows facilitated different resin rich regions as well as different cross sectional shapes of weft tows as observed from microscopic images. Due to some larger resin rich regions, some composites resulted non-uniform failure during tensile testing. During flexural testing, the more angular movement of the binder tows eased them to act like a truss and improved bending properties. Coarser binder tows probably required more energy to bend. The impact properties of composites resulted same as that of the results of preform analysis. Considerable gain in impact energy was there in case of all weave designs, stuffer layers, and FVFs in the composite stage in comparison to their preform stage. However, in case of higher stuffer layers (4 and 6) and

FVFs (50% and 60%), the reverse is the trend. Also there was substantial gain in ultimate tensile strength in composite stage to their preform stage in case of all weave designs, stuffer layers, and FVFs.

The final module was concentrated for the theoretical analysis of tensile behavior of two basic designs of orthogonal and interlock fabrics. Finite element analysis was carried out as it is a powerful and established tool to predict the mechanical properties of materials. Hence two basic models were prepared in Solidworks 2015 software as per the specifications of the geometrical modeling and imported to Ansys workbench 16.2 for simulation. It was observed that the simulated results were comparatively more than the corresponding experimental results. This was probably because of the peculiar characteristics of textile structures like yarn crimp, exact cross section, and correct contact area of constituent yarns. Further, the micro structure of 3D fabrics is really very complex. Hence FE methods need to be further improved incorporating these features of textile structures and then experimentally validated.

सार

इस शोध में, 3 डी कपड़ों की बुनाई तकनीक का उपयोग करके कई संरचनात्मक विविधताओं की उनकी संभावना के लिए जांच की गई थी, इन 3 डी preforms की अनुकूलनशीलता एक विशेष ज्यामिति बनाने के लिए, इन preforms के लक्षण वर्णन के साथ ही उनके कंपोजिट और अंत में मूल ओर्थोगोनल के दसियों व्यवहार का सैद्धांतिक विश्लेषण और प्रायोगिक सत्यापन के साथ सॉलिडवर्क्स और Ansys सॉफ्टवेयर द्वारा इंटरलॉक संरचनाएं।

इस शोध कार्य का पहला मॉड्यूल पूर्वरूपों के यांत्रिक प्रदर्शन का अध्ययन करना था। आयोजित प्रीफॉर्म परीक्षणों के परिणामों से, यह निस्संदेह सबूत था कि सामान टो मुख्य रूप से ताना तन्य अनुप्रयोगों के लिए जिम्मेदार थे। प्रभाव के प्रदर्शन को तय करने में फैब्रिक क्रॉस ओवर पॉइंट्स की प्रमुख भूमिका थी। कपड़े के प्रभाव विश्लेषण के मामले में देखे गए बिंदुओं पर फैब्रिक क्रॉस के प्रभाव की तुलना में चाकू की प्रवेश विशेषताएँ कपड़े के प्रति यूनिट चौड़ाई में टो रैखिक घनत्व और संख्या से अधिक टो से प्रभावित थीं। सामान्यीकृत तरीके से, यह निष्कर्ष निकाला गया है कि दसियों अनुप्रयोगों के दौरान बांधने की मशीन विस्तार से बचने के लिए पूर्वरूपों की मोटाई पर्याप्त रूप से अधिक होनी चाहिए।

सूत्रीकरण के संदर्भ में पूर्वसूचनाओं की एक अन्य महत्वपूर्ण विशेषता अगले नमूने में इन नमूनों के साथ अध्ययन की गई थी। वैज्ञानिकों ने फॉर्मैबिलिटी को जटिल 3 डी आकृतियों को प्राप्त करने की क्षमता के रूप में परिभाषित किया, विशेष रूप से समग्र अनुप्रयोगों के लिए। तुलनात्मक उद्देश्य के लिए, ऊर्जा को मापने के सूचकांक के रूप में चुना गया था जो लोड-विरूपण वक्र के क्षेत्र से प्राप्त किया गया था। इस काम में, सभी अठारह अलग-अलग प्रकार के 3 डी फैब्रिक्स (छह अलग-अलग बुनाई के डिजाइन, छह अलग-अलग सामान की परतें, और ऑर्थोगोनल और इंटरलॉक डिजाइन के अलग-अलग एफवीएफ के छह) का गठन ऊर्जा के निर्धारण के लिए किया गया। एक विशेष लगाव निर्मित किया गया था और INSTRON 3365 तन्यता परीक्षण मशीन पर लगाया गया था और एक निश्चित विरूपण स्तर तक संपीड़न मोड में प्रीफॉर्म का परीक्षण किया गया था। ऊर्जा बनाने के परिणामों के लिए फैब्रिक क्रॉस ओवर पॉइंट्स को वर्चस्व वाला पैरामीटर पाया गया। यह स्थापित किया गया है कि झुकने की कठोरता एक प्लैट कपड़े को एक गोलार्ध में दबाने की प्रतिनिधि प्रक्रिया से संबंधित पूर्वरूपों की संगतता का आकलन करने के लिए सबसे अधिक प्रासंगिक जानकारी प्रदान कर सकती है। यह काम ग्रेफाइट फाइबर से बने 2 डी प्रीफॉर्म के विभिन्न बुनाई डिजाइनों के साथ किया गया था। इसलिए इस काम में, विभिन्न बुनाई डिजाइनों के 3 डी कपड़ों की खोज को झुकाने वाली कठोरता परिणामों के साथ आवश्यक सहसंबंध के लिए प्रयास किया गया था। पहले के काम

की तरह इन दोनों गुणों में उत्कृष्ट सहसंबंध देखा गया था। जैसा कि यह पाया गया कि गठन ऊर्जा को निर्धारित करने के लिए फैब्रिक क्रॉस ओवर पॉइंट्स की एक प्रमुख भूमिका थी, पूर्व में यानी पॉइंट्स पर फैब्रिक क्रॉस को झुकने वाली कठोरता के साथ-साथ ऊर्जा बनाने से संबंधित किया गया था। दोनों मामलों में उचित रूप से अच्छे संबंध थे। हालांकि, अन्य एक की तुलना में झुकने कठोरता के साथ क्रॉस ओवर पॉइंट के बीच सहसंबंध अधिक था।

के रूप में 3 डी preforms के अंत का उपयोग कंपोजिट में माना जाता है, इन तैयार कपड़े के नमूने epoxy राल के साथ समग्र तैयारी के अधीन थे और अगले मॉड्यूल में तन्य, झुकने और प्रभाव विश्लेषण के लिए परीक्षण किया गया था। बाइंडर टो के इंटरलेसमेंट पैटर्न ने अलग-अलग राल समृद्ध क्षेत्रों के साथ-साथ सूक्ष्म चित्रों से देखे गए तौलिए के अलग-अलग क्रॉस सेक्शनल आकार को सुविधाजनक बनाया। कुछ बड़े राल समृद्ध क्षेत्रों के कारण, कुछ कंपोजिट में तन्य परीक्षण के दौरान गैर-समान विफलता हुई। फ्लेक्सुरल परीक्षण के दौरान, बांधने की मशीन के टावरों के अधिक कोणीय आंदोलन ने उन्हें एक पुलिंदा की तरह काम करने और झुकने वाले गुणों में सुधार करने में आसानी हुई। मोटे रबड़ के टावरों को झुकने के लिए संभवतः अधिक ऊर्जा की आवश्यकता होती है। कंपोजिट्स के प्रभाव गुण पूर्ववर्ती विश्लेषण के परिणामों के समान थे। प्रभाव ऊर्जा में उल्लेखनीय लाभ सभी पूर्वनिर्मित चरण की तुलना में सभी बुनाई डिजाइनों, सामान परतों और समग्र चरण में FVFs के मामले में था। हालांकि, उच्च सामान परतों (4 और 6) और एफवीएफ (50% और 60%) के मामले में, रिवर्स प्रवृत्ति है। इसके अलावा सभी बुनाई के डिजाइन, सामान की परतों, और FVFs के मामले में उनके प्रारंभिक चरण के लिए समग्र चरण में अंतिम तन्य शक्ति में पर्याप्त लाभ था।

अंतिम मॉड्यूल ऑर्थोगोनल और इंटरलॉक कपड़ों के दो बुनियादी डिजाइनों के तन्य व्यवहार के सैद्धांतिक विश्लेषण के लिए केंद्रित था। परिमित तत्व विश्लेषण किया गया क्योंकि यह सामग्री के यांत्रिक गुणों की भविष्यवाणी करने के लिए एक शक्तिशाली और स्थापित उपकरण है। इसलिए दो बुनियादी मॉडल सॉलिडवर्क्स 2015 सॉफ्टवेयर में ज्यामितीय मॉडलिंग की विशिष्टताओं के अनुसार तैयार किए गए थे और अनुकार के लिए Ansys कार्यक्षेत्र 16.2 पर आयात किया गया था। यह देखा गया कि सिम्युलेटेड परिणाम तुलनात्मक रूप से संबंधित प्रयोगात्मक परिणामों की तुलना में अधिक थे। यह संभवतः यार्न समेटना, सटीक क्रॉस सेक्शन और घटक यार्न के सही संपर्क क्षेत्र जैसी कपड़ा संरचनाओं की अजीब विशेषताओं के कारण था। इसके अलावा, 3 डी कपड़ों की सूक्ष्म संरचना वास्तव में बहुत जटिल है। इसलिए एफई तरीकों को कपड़ा संरचनाओं की इन विशेषताओं को शामिल करते हुए और बेहतर बनाने की आवश्यकता है और फिर प्रयोगात्मक रूप से मान्य किया गया है।

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ABBREVIATIONS

Abbreviations	Description
W-1	Orthogonal 1×1 plain weave design
W-2	Orthogonal 4×4 matt weave design
W-3	Orthogonal 4×4 twill weave design
W-4	Interlock 1×1 plain weave design
W-5	Interlock 1×1 plain weave design without stuffer
W-6	Interlock 4×4 twill weave design
OS2	Orthogonal fabrics with two stuffer layers
OS4	Orthogonal fabrics with four stuffer layers
OS6	Orthogonal fabrics with six stuffer layers
IS2	Interlock fabrics with two stuffer layers
IS4	Interlock fabrics with four stuffer layers
IS6	Interlock fabrics with six stuffer layers
OFVF40	Orthogonal fabrics with fibre volume fraction % of 40
OFVF50	Orthogonal fabrics with fibre volume fraction % of 50
OFVF60	Orthogonal fabrics with fibre volume fraction % of 60
IFVF40	Interlock fabrics with fibre volume fraction % of 40
IFVF50	Interlock fabrics with fibre volume fraction % of 50
IFVF60	Interlock fabrics with fibre volume fraction % of 60
FVF	Fibre volume fraction
TSC	Textile structural composites
UD	Unidimensional

2D	Two dimensional
3D	Three dimensional
epi	Ends per inch
ppi	Picks per inch
GSM	Grams per square meter
CV%	Coefficient of variation %
R^2	Coefficient of determination
MPa	Mega pascal