

**DESIGN AND DEVELOPMENT OF 3D WOVEN
COMPLEX HOLLOW STRUCTURES AND THEIR
COMPOSITES FOR ENERGY ABSORBENT
STRUCTURES**

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**DEPARTMENT OF TEXTILE TECHNOLOGY
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

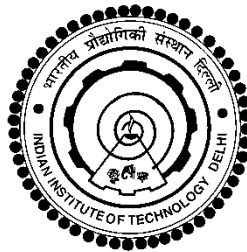
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Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

FEBRUARY 2019

DEDICATED TO

MY

PARENTS AND ALMIGHTY

CERTIFICATE

This is to certify that the thesis entitled “**DESIGN AND DEVELOPMENT OF 3D WOVEN COMPLEX HOLLOW STRUCTURES AND THEIR COMPOSITES FOR ENERGY ABSORBENT STRUCTURES**” being submitted by **Mr. MANJUNATH R N** to Indian Institute of Technology Delhi for the award of the degree of “**DOCTOR OF PHILOSOPHY**” is a record of the authentic research work carried out by him under our supervision and guidance. He has fulfilled all the requirements for submission of this thesis, which to the best of our knowledge has reached the required standard.

The material contained in this thesis has not been submitted in part or full to any other University or Institute for the award of any other degree.

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Abstract

The need for significant improvements in intra- and inter-laminar strength, damage resistance and the large scale economical manufacturing of structural composites resulted in the emergence of textile structural composites. In this work, the problems associated with delamination in three different areas of the composite applications are identified and an attempt is made to provide an integrated solution through 3D woven reinforcements that can enhance their performance and service life. To overcome the issues concerned with handling brittle fibers like glass and carbon during weaving, in this work all preform manufacturing trials were carried out using polyester yarns as a reinforcing material. This thesis work is divided into four research modules in which the first module is aimed at studying material properties and the rest three modules are focussed on structural integration and to study the aspects of preform geometry in designing composites for various structural applications.

The first module of this research work is aimed at exploring the possibilities of using polyester as a reinforcement material in substitute to glass fibers (which is most commonly used material to develop preforms). High tenacity fully drawn polyester yarns and E-glass yarns, both of 300 Tex linear densities were selected and their mechanical properties were subsequently analysed in raw form and in unidirectional reinforced epoxy based composite form. Tensile tests reveals that the fiber and matrix under tensile loads in both the specimen cases, work as a single unit and fail altogether with fiber breakages more prominently sighted in both the cases. Flexural test reveals that the polyester-epoxy material combination can encompass excellent toughness (residual strength) properties which were in contrast to the typical brittle behaviour of glass-epoxy composites. Izod Impact tests interestingly revealed that, the polyester-epoxy showed better energy absorption than the glass-epoxy composites due to its ductile properties which dominantly assisted in plastic deformation of the specimen

prior to fracture. It was evident that the polyester-epoxy material combination exhibited the ability to perform well even in the presence of fractures and damages.

The next module of this research was aimed at developing woven fabrics with integrated stiffener sections of four different configurations namely Flat T bar, Split Tube, Inverted Channel and Hull channel were produced using modified face to face weaving principle. The fabric samples were resin impregnated to consolidate them into to composites using a standard hand lay-up technique. The geometrical parameters like thickness, unit mass and fiber volume fraction (FVF) were formulated hypothetically through meso-mechanical based modelling approach. Flexural analysis of the composite structures showed a very good flexural stability with the flexural load being increased in the range of 150 – 250% in comparison to unstiffened 2D structures. The fracture morphology observations indicate that the damage patterns of the structure vary with the dimensions of the stiffener sections and hollowness within the structure. These structures can be used as structural load bearing elements in resisting out of plane bending loads along with maintaining structural integrity.

The next module is aimed towards the modification of conventional weave architecture to produce 3D woven spacer fabrics with three different configurations of vertical connecting walls. Following weaving process, the fabric samples were converted to composites through a standard hand lay-up technique. To corroborate the structural appropriateness of the developed structures, their mechanical properties were investigated through flat-wise compression and three-point bending tests. The experimental results from these tests point out that the spacer structures with augmented cores demonstrated a significant increase in their compressional and flexural performances in comparison to sandwich composites made from spacer structures with single connecting wall.

The next module is aimed at the development of integrated single piece woven preforms for reinforcement in designing composite wing structures free from assembly components. The proposed fabric structures are designed and woven in the shape of an aerodynamic wing profile which consists of two outer skin sections integrally connected together by shear webs sections to form a single piece wing structure. The fabric preforms were further converted to composites followed by a smooth surface finish using NC putty and painted to get the final single piece wing prototype. The developed wing prototypes were taken for lab scale Wind-tunnel testing to determine their aerodynamic characteristics. Further, t-peel test was performed to study the junction strength and delamination resistance of the structure. The findings from the T-peel test indicate that the junction of the structures is peel resistant due to structurally integrated skin and core fabric sections thereby, preventing delamination prone failures. It was evident that the proposed integrated wing structure is attributed to zero chances of failures due to delamination unlike traditional laminates and enhanced structural homogeneity without the presence of assembly materials.

Undoubtedly, the test results related to mechanical performance and fracture morphological studies of the composites have proved that the 3D woven fabric preforms which are built to near net shape perform significantly well under design loads. Unlike brittle failures in glass reinforced composites, the ductile behaviour of polyester- material combination has proved that the structures can exhibit load bearing capability even in presence of a fracture. Furthermore, polyester can be acquired from the recycling of scrapped plastics which is abundantly dumped in the landfills causing environmental imbalance. This research work focused on promoting polyester as a reinforcing material can be an experimental database for most of the manufacturing companies that uses recycled products as their raw material in order to leverage the growing quantity of hazardous wastes.

सार

अंतर- और अंतर-लामिना शक्ति, क्षति प्रतिरोध और संरचनात्मक कंपोजिट के बड़े पैमाने पर किफायती विनिर्माण में महत्वपूर्ण सुधार की आवश्यकता के परिणामस्वरूप टेक्सटाइल संरचनात्मक कंपोजिट का उदय हुआ। इस काम में, समग्र अनुप्रयोगों के तीन अलग-अलग क्षेत्रों में प्रदूषण से जुड़ी समस्याओं की पहचान की जाती है और 3 डी बुने हुए सुदृढीकरण के माध्यम से एक एकीकृत समाधान प्रदान करने का प्रयास किया जाता है जो उनके प्रदर्शन और सेवा जीवन को बढ़ा सकते हैं। बुनाई के दौरान कांच और कार्बन जैसे भंगुर तंतुओं को संभालने से संबंधित मुद्दों पर काबू पाने के लिए, इस कार्य में सभी प्रबल निर्माण परीक्षण पॉलिएस्टर यार्न का उपयोग करके एक मजबूत सामग्री के रूप में किया गया था। यह थीसिस कार्य चार अनुसंधान मॉड्यूल में विभाजित किया गया है जिसमें पहला मॉड्यूल भौतिक गुणों का अध्ययन करना है और बाकी तीन मॉड्यूल संरचनात्मक एकीकरण पर केंद्रित हैं और विभिन्न संरचनात्मक अनुप्रयोगों के लिए कंपोजिट डिजाइन करने में प्रीफॉर्म ज्यामिति के पहलुओं का अध्ययन करना है।

इस शोध कार्य का पहला मॉड्यूल ग्लास फाइबर के विकल्प में एक सुदृढीकरण सामग्री के रूप में पॉलिएस्टर का उपयोग करने की संभावनाओं की खोज करना है (जो कि आमतौर पर पहले से उपयोग की जाने वाली सामग्री का उपयोग किया जाता है)। उच्च तपस्या पूरी तरह से पॉलिएस्टर यार्न और ई-ग्लास यार्न, दोनों 300 टेक्स रैखिक घनत्वों का चयन किया गया था और उनके यांत्रिक गुणों का बाद में कच्चे रूप में और यूनिडायरेक्शनल प्रबलित एपॉक्सी आधारित समग्र रूप में विश्लेषण किया गया था। तन्य परीक्षणों से पता चलता है कि दोनों नमूना मामलों में तन्य भार के तहत फाइबर और मैट्रिक्स, एक ही इकाई के रूप में काम करते हैं और दोनों मामलों में फाइबर के टूटने के साथ पूरी तरह से विफल हो जाते हैं। लचीले परीक्षण से पता चलता है कि पॉलिएस्टर-एपॉक्सी सामग्री संयोजन उत्कृष्ट क्रूरता (अवशिष्ट शक्ति) गुणों को शामिल कर सकता है जो ग्लास-एपॉक्सी कंपोजिट के विशिष्ट भंगुर व्यवहार के विपरीत थे। इज़ॉड इम्पेक्ट परीक्षणों ने दिलचस्प रूप से खुलासा किया कि, पॉलिएस्टर-एपॉक्सी ने अपने नमनीय गुणों के कारण ग्लास-एपॉक्सी कंपोजिट से बेहतर ऊर्जा अवशोषण दिखाया, जो फ्रैक्चर से पहले नमूना के प्लास्टिक विरूपण में मुख्य रूप से सहायता करता था। यह स्पष्ट था कि पॉलिएस्टर-एपॉक्सी सामग्री संयोजन ने फ्रैक्चर और नुकसान की उपस्थिति में भी अच्छा प्रदर्शन करने की क्षमता का प्रदर्शन किया।

इस शोध के अगले मॉड्यूल का उद्देश्य चार अलग-अलग विन्यासों जैसे फ्लैट टी बार, स्प्लिट ट्यूब, इनवर्टेड चैनल और हल चैनल के एकीकृत स्ट्रैजिन वर्गों के साथ बुने हुए कपड़ों को विकसित करना था। कपड़े के नमूने एक मानक हाथ ले-अप तकनीक का उपयोग करके उन्हें कंपोजिट में समेकित करने के लिए राल लगाए गए थे। मोटाई, इकाई द्रव्यमान और फाइबर मात्रा अंश (FVF) जैसे ज्यामितीय मापदंडों को मेसो-मैकेनिकल मॉडलिंग मॉडलिंग दृष्टिकोण के माध्यम से काल्पनिक रूप से तैयार किया गया था। संयुक्त संरचनाओं के लचीले विश्लेषण से पता चलता है कि अस्थिर 2 डी संरचनाओं की तुलना में प्लेक्सुरल लोड 150 - 250% की सीमा में बढ़ रहा है। अस्थिभंग आकृति विज्ञान टिप्पणियों से संकेत मिलता है कि संरचना के नुकसान पैटर्न संरचना के भीतर स्टर्जन वर्गों और खोखलेपन के आयामों के साथ भिन्न होते हैं। इन संरचनाओं का उपयोग संरचनात्मक भार वहन करने वाले तत्वों के रूप में किया जा

सकता है जो संरचनात्मक अखंडता को बनाए रखने के साथ-साथ विमान के झुकने वाले भार से निपटने में सक्षम होते हैं।

अगले मॉड्यूल ऊर्ध्वाधर बुनाई की दीवारों के तीन अलग-अलग विन्यासों के साथ 3 डी बुना हुआ स्पेसर कपड़े बनाने के लिए पारंपरिक बुनाई वास्तुकला के संशोधन की ओर लक्षित है। बुनाई की प्रक्रिया के बाद, कपड़े के नमूनों को मानक हाथ ले-अप तकनीक के माध्यम से कंपोजिट में बदल दिया गया था। विकसित संरचनाओं की संरचनात्मक उपयुक्तता की पुष्टि करने के लिए, उनके यांत्रिक गुणों की जांच फ्लैट-वार संपीड़न और तीन-बिंदु झुकने परीक्षणों के माध्यम से की गई थी। इन परीक्षणों के प्रयोगात्मक परिणाम बताते हैं कि संवर्धित कोर के साथ स्पेसर संरचनाओं ने एकल कनेक्टिंग दीवार के साथ स्पेसर संरचनाओं से बने सैंडविच कंपोजिट की तुलना में उनके कम्प्रेसेशनल और फ्लेक्सुरल प्रदर्शन में उल्लेखनीय वृद्धि का प्रदर्शन किया।

अगला मॉड्यूल असेंबली घटकों से मुक्त समग्र विंग संरचनाओं को डिजाइन करने में सुदृढीकरण के लिए एकीकृत एकल टुकड़ा बुना पहिले के विकास के उद्देश्य से है। प्रस्तावित कपड़े संरचनाओं को एक एरोडायनामिक विंग प्रोफाइल के आकार में डिज़ाइन और बुना जाता है जिसमें दो बाहरी त्वचा के खंड होते हैं जो कतरनी जाले वर्गों द्वारा एक साथ मिलकर एक एकल विंग विंग संरचना बनाते हैं। कपड़े के पहनावे को आगे कंपोजिट में बदल दिया गया, इसके बाद नेक पुट्टी का उपयोग करके एक चिकनी सतह खत्म की गई और अंतिम सिंगल पीस विंग प्रोटोटाइप प्राप्त करने के लिए पेंट किया गया। विकसित विंग प्रोटोटाइप को उनकी वायुगतिकीय विशेषताओं को निर्धारित करने के लिए लैब स्केल विंड-टनल परीक्षण के लिए लिया गया था। इसके अलावा, संरचना की जंक्शन शक्ति और प्रदूषण प्रतिरोध का अध्ययन करने के लिए टी-छील परीक्षण किया गया था। टी-छील परीक्षण के निष्कर्षों से संकेत मिलता है कि संरचनाओं का जंक्शन छील फिर से है

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List of abbreviations

μ_e, μ_p	: Linear density of warp (ends) and weft (pick) tows (kg/m)
ρ	: Density of warp and weft tows (kg/m ³)
C_e, C_p	: warp crimp and weft crimp in the fabric
EPI, PPI	: Thread Density
W	: Width of the fabric (inches)
FVF	: Fiber volume fraction of the unit cell.
PET	: Poly-ethylene terephthalate
$HDPE$: High density poly-ethylene
UD	: Uni-directional
SFI	: Stiffener section facing the indenter
BFI	: Base section facing the indenter

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