

MODELING AND CHARACTERIZATION OF 3D WOVEN SOLID STRUCTURES AND THEIR COMPOSITES

BIBHU PRASAD DASH



**DEPARTMENT OF TEXTILE TECHNOLOGY
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MODELING AND CHARACTERIZATION OF 3D WOVEN SOLID STRUCTURES AND THEIR COMPOSITES

by

BIBHU PRASAD DASH

Department of Textile Technology

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Dedicated to

Almighty

Certificate

I am satisfied that the thesis entitled “Modeling and Characterization of 3D Woven Solid Structures and their Composites” presented by Mr. Bibhu Prasad Dash is worthy of consideration for the award of the Degree of **Doctor of Philosophy** and is a record of the original bonafide research work carried out by him under my guidance and supervision and that the results contained in it have not been submitted in part or full to any other University or Institute for award of any degree/diploma.

I certify that he has pursued the prescribed course of research.

Date: October 2013

(Prof. B. K. Behera)

Department of Textile Technology

Indian Institute of Technology Delhi

New Delhi – 110016

India

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ABSTRACT

The eminence of composite material produced using textile reinforcement depends largely on architecture of the fibrous assemblies. To ensure the production of high quality textile reinforced structural composites and to minimise the cost in designing such composites, it is necessary to develop methods to predict the physical and mechanical properties of the reinforcements. The thesis presents a comprehensive review of previous research into geometrical modeling of three dimensional (3D) woven fabrics and finite element (FE) modeling of their composites. A review of micromechanical models for predicting the properties of 3D woven composites is also presented. From this review, gaps and challenges are identified in the prediction of geometrical parameters of various 3D woven constructions and current understanding of the mechanical properties of 3D woven composites, which form the basis of the research presented in this thesis. This thesis employs a modeling approach in predicting geometrical and mechanical properties of 3D textile structures. New and existing algorithms are combined together to form a consistent modeling approach.

The research begins with an original study into the geometrical modeling of 3D textile structures. Modeling the internal geometry of 3D woven structures is important because a geometric model is necessary as an input to many computational models like modeling the mechanical properties of fabrics for determining forming behavior, predicting the fiber volume fraction of fabrics for processing of composites, modeling the mechanical properties of composite parts and their damage behavior for use in engineering applications. The permutations in the design of 3D woven structures are very large. However, one factor that is common to all designs is that of the repeating pattern or the unit cell. The unit cell represents the smallest repeat unit of the weave architecture. The

unit cell describes the whole reinforcing fabric. It is established that the predicted behaviour of the unit cell is representative of the 3D fabric as a whole. The modeling approach taken here for the unit cell of 3D solid structures, overcomes the deficiencies of adopting an idealized tow cross section that is often assumed as rectangular or circular. The first objective of this research is to model various 3D solid constructions in order to quantify and characterize the effect of various constructional parameters on internal geometry of 3D woven fabrics.

Subsequently, this research work presents an experimental investigation into the tensile, bending, compression, low velocity impact, and knife penetration, of three-dimensional (3D) woven fabrics, having through-thickness (z-binder) tow. The investigation begins with the study of the damage caused to the in-plane yarns and z-binder during the weaving process used to manufacture 3D composite preforms. It is found that 3D weaving degraded the tensile strength of the yarns and z-binders. The strength reduction is attributed to ultra-small scratches on the brittle fibres which are generated by abrasion of the fibres during weaving. Choice of loom accessories with a low-friction material is recommended to reduce the amount of fibre damage caused by 3D weaving that will result in a composite product with higher tensile strength. With proper choice of loom accessories different 3D structures are developed using the sample weaving machine from high performance fiber like glass, basalt, Kevlar and zylon. In addition two dimensional (2D) and unidirectional (UD) structures are developed to compare properties of laminated composites with 3D counterparts. To study the effect of fiber hybridization on the mechanical properties of reinforcement, glass- Kevlar and glass-zylon 3D fabrics have also been developed. The fabrics had comparable thicknesses, close total fiber

volume fractions and similar total fiber amount distributions between the warp and fill directions.

After studying the effect of fiber architecture, fiber type, hybridization of the reinforcement structure in z direction and constructional parameters on the mechanical properties of the 3D solid structures, the research focuses on the mechanical performance of the composite material. The quality of composite materials depends on material composition and manufacturing condition variables such as resin %, hardener %, and curing pressure, time and temperature. When multiple variables are involved, it becomes difficult to study the system using the common approach of varying only one factor at a time, while holding the others constant. A more efficient way to investigate these systems is to develop a mathematical model describing the relationship between the response and independent variables, in which the significance of individual factors and multifactor interactions can be determined. A Box-Behnken Design (BBD) is a versatile method to statistically model and optimize response variables that are affected by multiple independent factors. In this study, the effects of resin %, hardener % and curing pressure on the impact properties of the resulting panels are evaluated using BBD using Design Expert software, Design-Expert 8.0.7.1 to statistically model the system. Impact resistance properties studied included total energy absorbed and peak force, which are key parameters for assessing composite quality. Numerical optimization is performed to determine the best conditions for the manufacture of 3D fabric reinforced composite. LY556 Epoxy resin has been used as a matrix component and is applied by hand layup technique. The principal advantage of compression molding is its ability to produce parts of complex geometry in short periods of time.

Glass fiber Reinforced composites are translucent when properly consolidated. Hence, damaged regions of impacted samples become opaque, and internal damage can be visually identified. This investigation examines how the variation of fabric architecture in composite systems with comparable areal densities affects perforation resistance, strength in both tensile and compressive manner, flexural resistance, stab resistance and dynamic mechanical analysis of glass fibre reinforced plastic (GFRP) composite panels. Five woven preforms such as UD, 2D plain-woven laminates, three different 3D woven solid structures are used to prepare compression moulded composites and examined in this study.

It is found that tensile strength of fibre reinforced composite (FRC) is a reflection of number of load bearing tows available in the loading direction. Results of the comparative study of tensile properties, showed that, among three 3D composites, the angle interlock fabric reinforced composite possesses highest stress which is followed by warp interlock and orthogonal. However plain 2D and unidirectional fabric reinforced composites possess higher strength than any 3D counterpart in warp direction for comparable fibre volume fraction (FVF). The ultimate tensile load and stress observed the similar trend as those of their fiber modulus, respectively, glass being the lowest and zylon being the highest. Compression properties of composites reinforced with different tow architecture almost followed the similar trend to those of tensile properties. However while comparing the composites made up of different type of fiber it is observed that kevlar and zylon show markedly poor compression properties as compared to tensile. Compressive properties of hybrid composites are found to reduced due to introduction of fibers like Kevlar and zylon in through the thickness direction. Flexural properties of composites reinforced with different tow architecture almost followed the similar trend

to those of tensile properties. In 3 point bending test the type of breakage is almost due to the tensile failure. Hybridisation of reinforcing fiber architecture does not show up any decisive conclusion. 2D composite samples did undergo delamination near the point of loading. 3D composites show better impact resistance when measured in terms of total energy, absorbed, peak energy absorbed and peak resistance offered as compared to 2D and UD structures. Impact resistance properties of composites reinforced with 3D fabric, produced from different type of high performance fiber depicts that zylon is best suitable for this followed by Kevlar, basalt and glass. The effect of fiber hybridisation in Z direction is found to be slightly beneficial when compared with the parent glass fabric. Owing to the higher values of work at peak and load at peak in knife penetration test, it is revealed that 3D fabrics offer better protection than 2D and UD structures. Resistance to knife penetration through the composites reinforced with 3D fabric made from various high performance fibers as well as their hybrids with glass follow similar trend to as those of low velocity impact resistance mentioned earlier. Composites with the 3D woven fabrics as reinforcement show higher values of storage modulus. Higher is the tensile modulus of the reinforcing fiber higher is the storage modulus and lower is the tan delta values. Storage modulus of 3D composites reinforced with basalt, kevlar and zylon are found to have reflection of their tensile modulus in them. Effect of hybridisation of Kevlar and zylon fiber tow in Z direction is observed to have positive effect on storage modulus of 3D woven composites.

In the last part of the research a novel FE modeling of the 3D textile structure and of course composites made their of has been developed, using the solid modeler SOLIDWORKS and ANSYS, a modeling package for numerically solving a wide variety of mechanical problems. Meso-scale FE modeling of textiles and textile

composites is a powerful tool for the homogenisation of mechanical properties, study of stress-strain fields inside the unit cell, determination of damage initiation conditions and sites and simulation of damage development and associated deterioration of the homogenised mechanical properties of the composite. The present work focuses on modeling, dealing with issues of building FE models of textile structures (geometry, meshing and boundary conditions), of interpretation of the results and of verification of the models. The FE solution is broken into three stages: defining key points/lines/areas/volumes, defining element type and material/geometric properties, defining mesh lines/areas/volumes as required. This is the basic guideline that can be used for setting up any Finite element analysis (FEA). This modeling technique is suitable not only for academic research and illustration of principles, but also for serious treatment of practically important textile composites with complex architecture, and allowing rapid variation of the reinforcement structural parameters and mechanical properties of the constituents, using user friendly interface. The experimental procedure provided the qualitative as well as quantitative knowledge about the ultimate load and stress of both 3D fabrics and their composites. In order to understand the stress behavior the FE simulation has been carried out which deals with unit cell computational model. These modeling approaches are validated, by comparing the predictions with the experimental results. The values of coefficient of determination (R^2), root mean square error (RMSE) and Error % are found to be well within the limit.

A significant database of material properties has been generated through this study, providing a platform for further investigation on properties of 3D composites and their modeling work.

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