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Behavioral Studies on Multi-Directionally Reinforced 4-D Orthogonal Composites on Various Preform Configurations

Sriram Venkatesh, V. Murali Mohan, T. V. Karthikeyan

Abstract**—**The main advantage of multidirectionally reinforced composites is the freedom to orient selected fiber types and hence derives the benefits of varying fibre volume fractions and there by accommodate the design loads of the final structure of composites. This technology provides the means to produce tailored composites with desired properties. Due to the high level of fibre integrity with through thickness reinforcement those composites are expected to exhibit superior load bearing characteristics with capability to carry load even after noticeable and apparent fracture. However, a survey of published literature indicates inadequacy in the design and test data base for the complete characterization of the multidirectional composites. In this paper the research objective is focused on the development and testing of 4-D orthogonal composites with different preform configurations and resin systems. A preform is the skeleton 4D reinforced composite other than the matrix. In 4-D performs fibre bundles are oriented in three directions at 120^0 with respect to each other and they are on orthogonal plane with the fibre in 4^{th} direction. This paper addresses the various types of 4-D composite manufacturing processes and the mechanical test methods followed for the material characterization. A composite analysis is also made, experiments on course and fine woven preforms are conducted and the findings of test results are discussed in this paper. The interpretations of the test results reveal several useful and interesting features. This should pave the way for more widespread use of the perform configurations for allied applications.

Keywords**—**Multidirectionally Reinforced Composites, 4-D Orthogonal Preform, Course weave, Fine weave.

I. Introduction

THE advanced composite manufacturing technologies are capable of generating highly engineered fibre architectures with novel features distinct from classical laminated constructions. The Multi-directionally reinforced preform with the high performance fibrous reinforcements in resin, metal or ceramic matrix enhance the range of composite product applications in aerospace, industrial, automobile and biomedical fields. The composites made with the advanced manufacturing technologies like multidirectional weaving, braiding with through thickness provides high degree of damage tolerance, interlaminar shear strength, fatigue resistance with distinct advantage of manufacturability in near-net shapes resulting in adequate structural integrity and directional properties [1]. Multidirectional composites are specially designed for the fabrication of products to withstand severe aero-thermo-mechanical stresses. Among these multidirectional fibre architectures which can be used as reinforcement for composites of this type 4D preform appears at the present time as most promising. The simplest form of multidirectional structure is a 3D preform consists of fibre bundles positioned on their Cartesian co-ordinates [2]. 4D orthogonal structure is another type of preform where fibre bundles are oriented in four directions. In 4-D preforms fibre bundles are oriented in three directions at 120^0 with respect to each other and they are on orthogonal plane with the fibre in 4^{th} direction. A 4D preform structure with U, V, W directions of reinforcement perpendicular the Z direction is shown in Fig. 1.

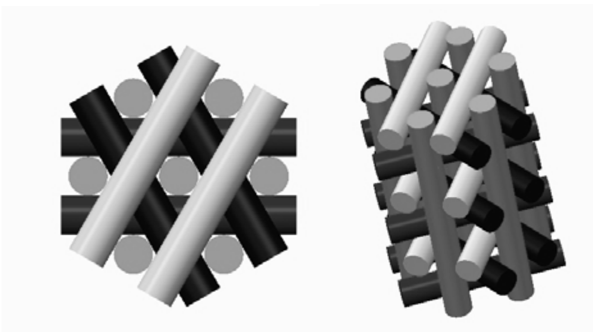

Fig. 1 4-D Preform construction

Being more isotropic than the 3-d structure, a 4-D structure presents another distinct advantage offering great interest for the manufacture of carbon-epoxy, Carbon-Carbon, carbon-phenolic, Silica-silica composites. Its porosity is formed by a widely open and intercommunicating void network which can be easily infiltrated by the subsequent matrix forms.

A. Preform Design and Configuration

The nominal 4-D preform texture is formed by the placement of fibre bundles in four directions in orthogonal planes. Fig. 2 shows the 4D unit cell and the word unit cell represents the preform configuration and the characteristics [3].

Sriram Venkatesh is Professor Head of the Department of Mechanical Engineering, University College of Engineering, Osmania University, Hyderbad, India (e-mail: venkatmech@yahool.com).

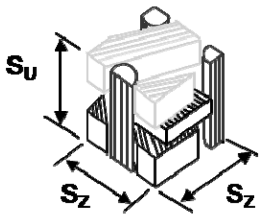

Fig. 2 4-D unit cell

It also shows the terminology for preform spacing where Su, Sv, Sw, Sz are the fibre bundle center to center spacing of U, V, W, Z sites respectively. Nu, Nv, Nw, Nz are the fibre reinforcement fractions in all the four directions. Fineness of preform can be qualified by a parameter "unit cell volume" i.e. Vuc = Sx Sz Sz. When a preform woven with 6k fibre and laid one bundle in all four directions it is called as balanced weave and preform weave is noted as 1,1,1,1 configuration. In 1,1,1,2 configuration two 6k fibre bundles are laid in the z direction and it is called unbalanced weave. The type of fibre and the number of fibre bundles can be varied in all directions. The preform characteristics are calculated for various constructions from the fibre density, diameter and fibre packing efficiency. Here simple preform calculations are given in the Table I for better understanding. T300 6k fibre bundles with 7 microns filament diameter are used to make the preforms. Carbon fibre rods of dia 0.6 and 1.0 mm pultruded rods are used to fabricate those preforms.

TABLE I
SIMPLE PERFORM CALCULATIONS

Preform	Unit cell size mm			Unit cell volume	Reinforcement filaments/ sq.mm		Fibre volume fraction		Total fibre
	Sz_1	Sz_2	Su	mm	Nz	Nu	Vfz	Vfu	content Vft %
1,1,1,1	1.2	1.38	1.8	2.98	3623	2415	13,94	9.29	41.61
3,3,3,3	2.0	2.38	3.00	27.71	3878	3000	15.00	11.54	49.63

II. PREFORM MANUFACTURING METHODS

Various manufacturing techniques have been used to make the 4-D preforms. One of the most versatile and widely used 4-d preforming approaches is dry weaving process. In the process initially all the 'Z' fiber bundles are positioned through the loom plates and held between the hooks. Fibres layers in U, V, W directions are laid between corridors of the Z spacing. Figs. 3 and 4 show the 4-D weaving process and the 4-D carbon fibre perform.

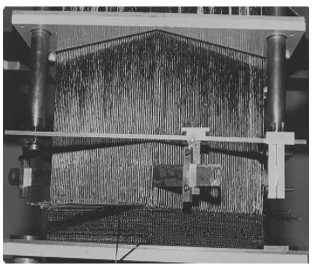

Fig. 3 4-D Weaving loom

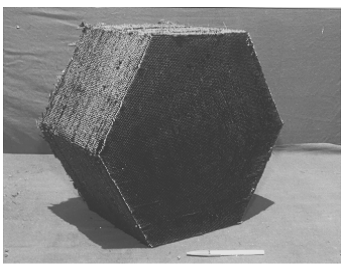

Fig. 4 4-D woven preform

Another preforming process the pultruded fibre rods are assembled into desired directions and bonded with a binder [4]. Fig. 5 demonstrates 4-D preform made of carbon fibre rods. Epoxy resin systems are used to infiltrate some of these preforms through resin transfer molding and some are densified through carbon matrix system [5]. 4-D carbon-carbon block is shown in Fig. 6.

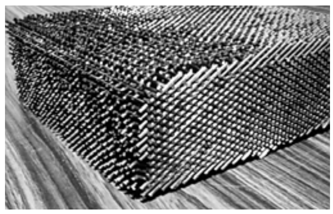

Fig. 5 4-D rods assembly

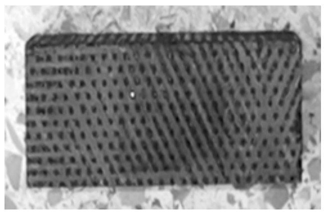

Fig. 6 4-D carbon-carbon

III. EVALUATION OF MECHANICAL PROPERTIES

Based on the unit cell dimensions preform packing efficiencies in-terms of volume fractions are derived. Test samples are prepared as per ASTM standards and using Instron universal testing machine tensile, flexural, compressive, and ILSS properties are tested [6]. Fig. 7 shows the sample testing by Instron machine.

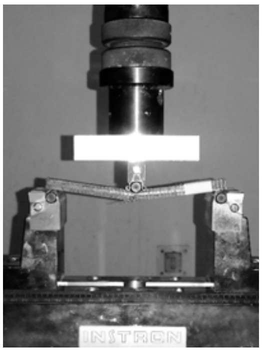

Fig. 7 Flexural testing of 4-d carbon-carbon sample

Table II shows the mechanical properties of the 4-D Composites.

TABLE II
MECHANICAL PROPERTIES OF 4-D COMPOSITES

Property	**4D 3,3,3,3** Carbon-Carbon	**4D 6,6,6,8** Carbon-Carbon	**4D 6,6,6,6** Carbon-Epoxy
Fibre packing Vfz	15.0	13.58	13.51
Fibre packing Vfu ,v,w	11.54	8.0	9.10
Fibre packing Vft	49.63	37.57	40.84
Tensile strength in Z Mpa	80	115	95
Tensile modulus in Z Gpa	62	47	17
Ultimate failure strain in Z	1400	2794	4500
Tensile strength in U Mpa	88	89	95
Tensile modulus in U Gpa	45	19	17
Ultimate failure strain in U	1600	4400	4500
Compressive strength in Z in Mpa	70.21	64.45	73.8
ILSS in Z Mpa	89	103	12
ILSS in U Mpa	67	78	12
Flexural strength in Z Mpa	95	130	116
Flexural modulus in Z Gpa	34.84	3.4	10
Flexural strength in U Mpa	130	48	116
Flexural modulus in U Gpa	25.79	8.7	10
Density gm/cc	1.8	1.78	1.03

Figs. 9-11 illustrate the tensile, flexural and compressive behavior of 4D composites. Fig. 12 shows the interlaminar shear strength comparative properties of 4- D composites.

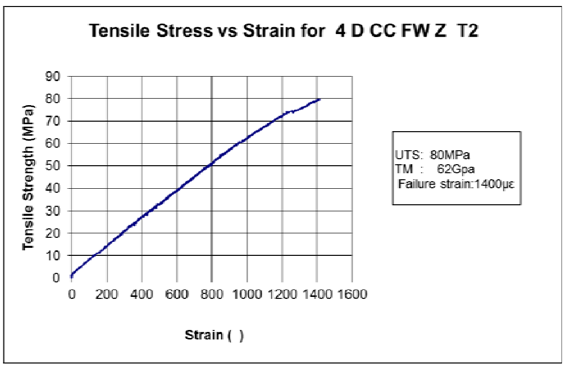

Fig. 9 Tensile behavior of 4-D 3,3,3,3 C/C

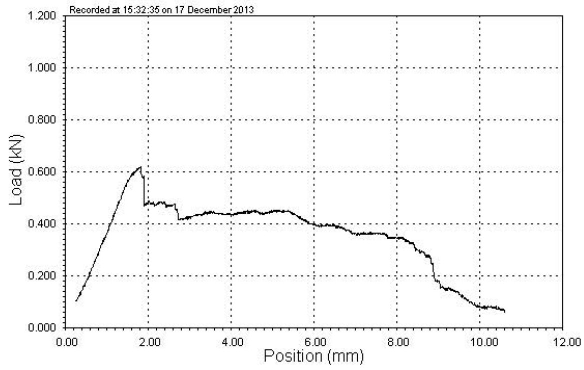

Fig. 10 Flexural behavior of 4-D 6,6,6,8 C/C

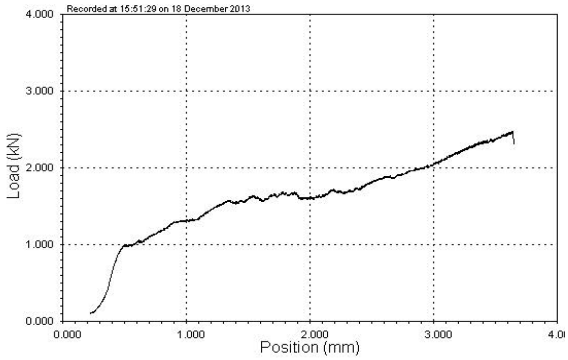

Fig. 11 Compressive strength of 3,3,3,3 C/C

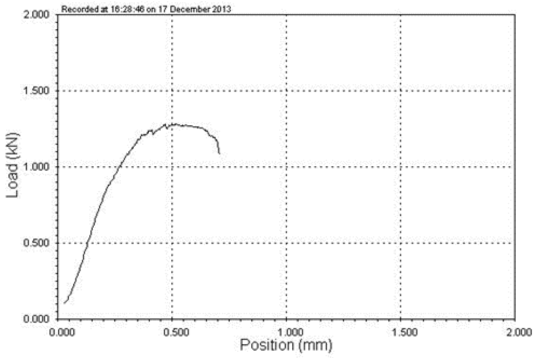

Fig. 12 ILSS of 3,3,3,3 Carbon-Carbon

IV. CONCLUSIONS

Two different 4-D preform manufacturing processes are developed and explained. Realization of preforms through rods assembly is taking short production time when compared with the dry weaving technique. During preform development it is observed that the preform characteristics are controlled by the raw material form available and the tooling used to fabricate the preform. An important preform parameter is the size and the distribution of void pockets. Small and well dispersed void cells in fine woven preforms are easier to fill with the resin and approach the grain size of the carbon and fibre packing efficiency is high in fine weaves. In 4-D voids are communicating and form a spiral around the Z fibres unlike in 3D. The advantages of 4-D over 3-D are the structure is more isotropic, easy to infiltrate the matrix. Evaluation of mechanical properties is carried for the different 4-D preforms and it is observed that in high pressure environments, fine weave play a substantial role in ablation, minimal mechanical erosion and enhanced thermal stress resistance. Future work is planned on complete characterization of various fine and course weaves infiltrated with different matrix systems.

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Sriram Venkatesh is currently working as Professor and Head of the Department of Mechanical Engineering, University College of Engineering, Osmania University, Hyderabad, INDIA. He did his Ph.D in the area of bulk solids flow problems from Osmania University, Hyderabad and M.E course in Tribology and Maintenance Engineering from Devi Ahilya Viswavidyalaya (SGSITS), Indore, M.P. He has more than 19 years of experience in teaching and research. He has been awarded "Career Award for Young Teachers" by All India Council for Technical Education, New Delhi, for his research contribution in the area of bulk solids flow problems. He is coordinator for various R&D and consultancy projects and executed projects worth Rs. 50 Lakhs. Published over 65 papers in national & international journal and conferences. He is member of many academic and professional bodies in India. He has visited Australia, USA, Germany, Thailand and Singapore for presenting papers.

V. Murali Mohan is the Research Student in Mechanical Engineering Department, Ousmania University, Hyderabad. He received National Research Development Corporation Award in the year 1993 on Multidirectional Composites. He has been granted a Indian Patent on Multidirectional reinforced composites in the year 2004. He has published 15 papers at national level and 8 international papers on Aerospace Composites.

Dr. T. V. Karthikeyan is the Research Guide in Mechanical Engineering Department, Ousmania University, Hyderabad. He has published 32 National level papers and 10 international papers on Thermal Batteries and Composites.