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Studies on Preform Properties of Multilayer Interlocked Woven Structures Using Fabric Geometrical Factors

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ABSTRACT: Structure property correlation is a critical textile research area explored by various researchers and many factors have been proposed over the years to predict/compare/design the woven fabrics. Cross-over firmness factor (CFF) and floating yarn factor (FYF) have been recently proposed as parameters to understand weave effect on fabric properties (Morino, H., Matsudaira, M. and Furutani, M. (2005). Predicting Mechanical Properties and Hand Values from the Parameters of Weave Structures, *Textile Research Journal*, **75**(3): 252–257). Redefined CFF and FYF factors using fabric fields in terms of interlacement index (I) and float index (F), respectively have been proposed in this article. This new approach provides better understanding of the interlacements and floats in the woven structure and further they are applied on multilayer interlocked fabrics to quantify the structural influence on the properties. Multilayer interlocked woven fabrics with different interlacement patterns have been developed. Influence of fabric structure on preform properties relevant for resin transfer molding composite manufacture, such as compression, permeability, and tensile behavior were studied

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with respect to the interlacement and float indices. Tensile and compression tests were conducted on universal testing machine. Liquid permeability of these structures was evaluated based on horizontal wicking and contact angle wettability tests. Results show that influence of structural factor is greater on tensile and permeability properties than the compression properties of these multilayer fabrics.

KEY WORDS: multilayer interlocked structures, firmness factor, CFF, interlacement index, float index, compression properties, permeability.

INTRODUCTION

TEXTILE PREFORMS HAVE been applied as prime reinforcement for composite applications due to its versatile design potential through structural complexity, easy handling, and contourability to fit the net shape [1]. As the composite design properties like strength/stiffness, fracture toughness, formability of preforms into complex shapes, material requirements and cost of production vary considerably, preform engineering has an important part to play in design of composites, through optimization of the design elements, which has received widespread attention among researchers in the recent times [2]. Woven fabrics are the key reinforcement type used for composites and most of the composites are made by stacking layers of woven fabrics one over the other, which lead to prominent delamination failure in the composites under performance [3]. Sewing and 3D weaving are the promising technologies, which address the shortcomings of the stack-reinforced composites. Multilayer interlocked fabrics are quite distinctive class of 3D textile structures manufactured by interlocking of fabric layers during the weaving stage.

Multilayer interlocked fabrics have long been applied for industrial textile applications, but have been scantily explored for composite reinforcement applications. Multilayer fabrics provide the advantage of cost effective preform manufacture with control over binding point density based on weave variations. Even stuffer yarns could be inserted between the layers during weaving to improve the tensile properties in particular direction of the preform. Multilayer interlocked fabrics are composed of several series of warp and weft yarns that form distinct layers and these layers are bound by interlacing warp ends [4]. Based on the type of interlacements, the multilayer fabrics are categorized into angle interlocked and layer interlocked structures. In angle-interlock structures, warp yarns of each layer interlace with the weft yarns of the adjacent layers, while in layer-interlock structures warp yarns interlace the top and bottom layer of the fabric.

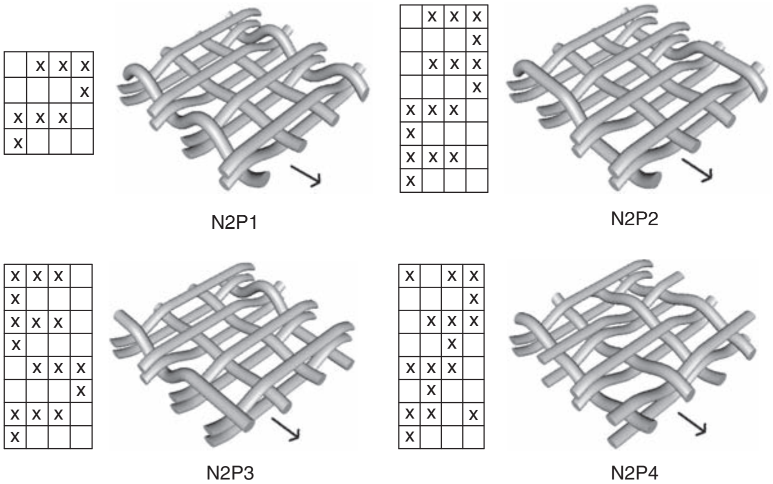
Among the few studies reported on multilayer interlocked fabrics for composite applications, an angle-interlocked four-layer 3D fabric has been manufactured using E-glass yarn through on-machine interlocking technique on a shuttle loom fitted with dobby. The properties were compared with the plain-woven 2D fabric after impregnating with Epoxy resin to prepare the composite materials. The mechanical properties (tensile, flexural, and impact) of the multilayer reinforced composites were found to be better than those of the 2D reinforced composites [4]. In another study T joints and I joints were prepared with angle-interlocked multilayer glass reinforcements and compared with 2D laminates reinforced with epoxy resin matrix. Although tensile properties were lesser than the laminated composites, multilayer reinforced composites displayed higher shearing strength [5]. Comparative studies on composites reinforced with the following structures were reported: (a) orthogonally woven 3D fabric, (b) orthogonal structure with layer-to-layer binding, (c) multilayer angle-interlocked, and (d) modified angle-interlocked structures. Tensile strength of orthogonal 3D and modified angle-interlocked reinforced composites were better than the layer-to-layer bound orthogonal and angle-interlock reinforced composites [6].

Although these very few attempts have been carried out to apply multilayer fabrics as composite reinforcement, systematic studies on influence of interlacement and floats of multilayer structure on the preform and composite properties are yet to be ventured. In this study, it is attempted to analyse the influence of interlacements in two-layer and three-layer interlocked multilayered structures on the important preform properties from resin transfer molding (RTM) composite manufacture point of view. The two-layer and three-layer interlocked structures with varying interlacements considered for the present studies are illustrated in Figures 1 and 2. 3D structures have been developed using Texgen software (freeware developed by University of Nottingham) and along with the 3D illustration, weave designs of the structures are also presented.

Fabric Structure and Geometrical Factors

Woven fabrics have two sets of yarns perpendicular to each other interlaced by weaving process. Tensile, bending, and permeability properties in either direction of the woven reinforcement is primarily a function of the yarn property, but is also influenced by the fabric weave [7]. A generalization of the woven structure by an integrated factor would give suitable basis of comparison for any such experimental investigation [8].

Kumpikaite and Milašius [9] and Seyam and El-Shiekh [10] have done a study of various fabric structural factors used and their application. They have observed that the fabric structural factors correlate well with the fabric properties. Newton [11] has aptly classified the various fabric tightness factors into two groups, one based on Peirce equations [8] and the other based on maximum set equations derived empirically. First group of factors based on Peirce theory, propose a factor as a ratio of a surface covered by warp/weft or both yarns with the whole fabric area, such as Peirce's cover factor [8],



	x	x	x
			x
x	x	x	
x			

	x	x	x
			x
	x	x	x
			x
x	x	x	
x			
x	x	x	
x			

x	x	x	
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x	x	x	
x			
	x	x	x
			x
x	x	x	
x			

x		x	x
			x
	x	x	x
		x	
x	x	x	
	x		
x	x		x
x			

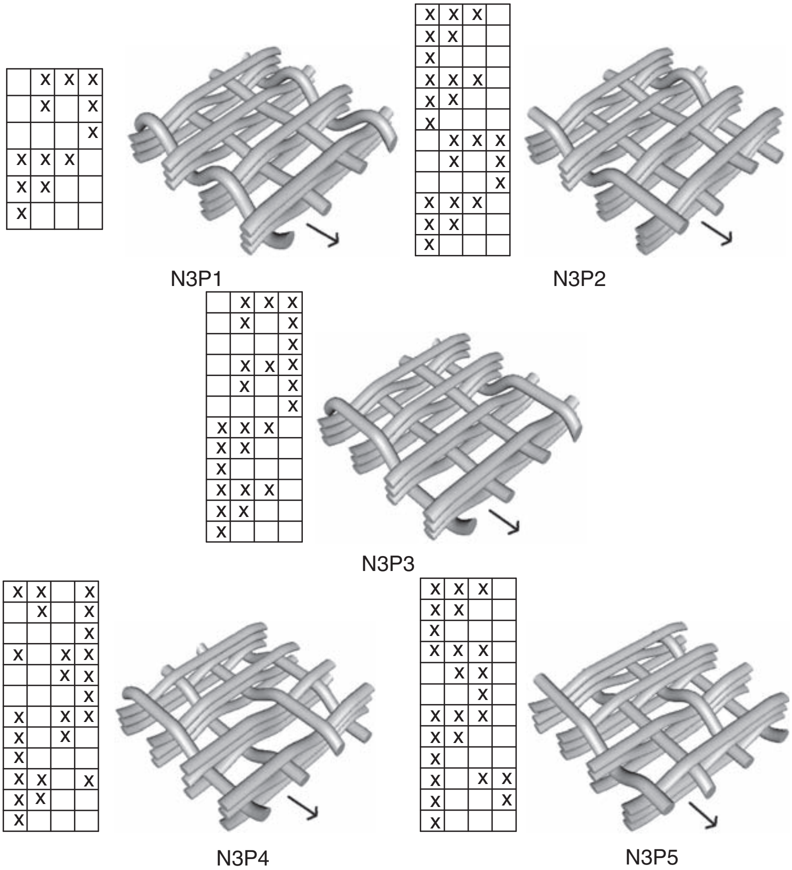
FIGURE 1. Two-layer interlocked woven structures.

Love's tightness [12], and Hamilton's tightness factor [13]. The second group factors are formulated as a ratio of the setting of 'square' analog of the given fabric with the setting of the standard woven fabric. Fabric tightness factors proposed by Brierley [14,15], Russell [16] and Galuszynski [17] are categorized in this second group. Most of these factors considered seven parameters of the fabric structure i.e., type of fiber (in warp and weft), yarn linear density (warp and weft), setting of these yarns and the weave, in which influence of fabric weave is very minimal or negligible. To consider the weave effects, Skliannikov proposed the Weave Tenseness factor (C), based on the fabric fields (Figure 3) to relate woven structure with fabric properties [18].

Fabric fields are division of weave area in three types of fields, namely contact (c), interlacing (i), and float fields (f) as represented by Figure 3 [18]. Contact field is defined as the projected region occupied by both thread systems (warp and weft). Interlacement is the region of cross-over of warp yarn from one plane to another, around a weft yarn, and vice versa. In the same case, when the yarn does not shift from one plane to another between two contact fields, then it can be termed as float.

$$C = \frac{6R_1R_2 - (2n_f + \sum_{i=1}^{6} K_i\, n_f i)}{6R_1R_2} \tag{1}$$

where R_1 and R_2 are the warp and weft repeat of the weave, respectively, n_f is the number of free fields defined in the woven structure between the yarns,



N3P1

	X	X	X
	X		X
			X
X	X	X	
X	X		
X			

N3P2

X	X	X	
X	X		
X			
X	X	X	
X	X		
X			
	X	X	X
	X		X
			X
X	X	X	
X	X		
X			

N3P3

	X	X	X
	X		X
			X
	X	X	X
	X		X
			X
X	X	X	
X	X		
X			
X	X	X	
X	X		
X			

N3P4

X	X		X
	X		X
			X
X		X	X
		X	X
			X
X		X	X
X		X	
X			
X	X		X
X	X		
X			

N3P5

X	X	X	
X	X		
X			
X	X	X	
	X	X	
		X	
X	X	X	
X	X		
X			
X		X	X
X			X
X			

FIGURE 2. Three-layer interlocked woven structures.

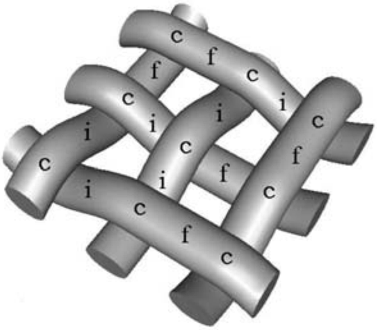


FIGURE 3. Fabric fields.

n_{fi} the number of free fields belonging to group i (all free fields are distributed into six groups), K_i is the elimination factor of group i, and subscripts 1 and 2 denote warp and weft, respectively.

Further using similar methodology, Milasius suggested a new factor called as weave firmness factor (P) derived from the weave tenseness factor and Brierley fabric tightness factor [18].

$$P_{1(2)} = \sqrt{\frac{3R_1R_2}{3R_1R_2 - \left(2n_{f1(2)} + \sum_{i=1}^{6} K_i n_{fi} 1(2)\right)}} \tag{2}$$

These factors evaluate not only a single thread float but an interlacing of adjacent threads as well and can be calculated for all the types of the weaves. Further a most convenient form of structural factor called firmness factor (φ) has been proposed by Milasius (Equation (3)), which has been demonstrated to be applicable universally [19]. This firmness factor can be used in the design of new fabrics, to evaluate their properties, estimate fabric weavability, and consider the weaving process parameters.

$$\varphi = \sqrt{\frac{12}{\pi}\frac{1}{P_1}}\sqrt{\frac{T_{av}}{\rho}}S_1^a S_2^b \tag{3}$$

where T is yarn linear density; S setting of yarns; ρ is fiber density given by Equation (4); T_{av} is given by Equation (5); a, b are given by Equation (6); and subscripts 1 and 2 denote warp and weft, respectively.

$$\rho = \frac{S_1\rho_1 + S_2\rho_2}{S_1 + S_2} \tag{4}$$

$$T_{av} = \frac{S_1T_1 + S_2T_2}{S_1 + S_2} \tag{5}$$

$$a = \frac{1}{1 + \frac{2}{3}\sqrt{\frac{T_1}{T_2}}}, \quad b = \frac{\frac{2}{3}\sqrt{\frac{T_1}{T_2}}}{1 + \frac{2}{3}\sqrt{\frac{T_1}{T_2}}} \tag{6}$$

A recent study has proposed a crossing-over firmness factor (CFF) and floating yarn factor (FYF) as parameter of weave structure based on the interlacements and floats in the structure for predicting the mechanical parameters and fabric hand values [20]. The CFF is given by Equation (7) where, crossing-over line is defined as the place at which interlacing point changes, for example, the warp yarn changes from over to under the weft yarn, or vice versa for weft in the warp direction (Figure 4). Similarly FYF is calculated from the type of floats defined in ref. [20], number of floats of each type and overall interlacing points in the repeat as given by the expression (8).

$$\mathrm{CFF} = \left(\frac{\text{Number of crossing over lines in the complete repeat}}{\text{Number of interlacing points in the complete repeat}}\right) \tag{7}$$

$$\mathrm{FYF} = \left(\frac{(\text{Type}_{\mathrm{I}\sim\mathrm{IX}})\,\mathrm{X}\,(\text{Existing number of type}_{\mathrm{I}\sim\mathrm{IX}}\text{ in the complete repeat})}{\text{Number of interlacing points in the complete repeat}}\right) \tag{8}$$

These CFF and FYF are important from the point of view of fabric dynamic properties and overall behavior of composites reinforced with fabrics to events such as impact loads, as they give a warp and weft influenced single factor unlike the previously mentioned firmness factor (φ) which are emphasized in warp and weft directions of the woven structure. Milasius et al. [21] in their comment to the editor on Morino et al.'s article [20], have discussed about relevance of CFF and FYF, the shortcomings, and value recalculation for the different 2D woven structures mentioned in the article, thus indicating that the basic terminologies and calculations suggested by Morino et al. [20], were tedious to understand and arrive at by calculation. Hence, a different approach is tried to arrive at interlacement and float factors in the woven structures using the earlier mentioned fabric fields (Figure 3). These factors have been redefined as interlacement index (I) and float index (F) to represent CFF and FYF, respectively. Interlacement index is defined as the ratio of number of interlacements in the given weave repeat to that of maximum possible contact

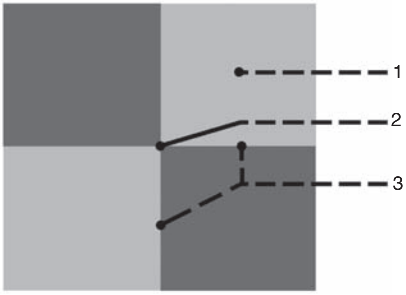


FIGURE 4. Complete repeat of plain weave 1: Interlacking point; 2: Cross-over lines; 3: Interspace of weave.

field in the design as given by the Equation (9), where i_{wp} and i_{wf} are interlacements in warp and weft, respectively. Product of warp repeat (R_1) and weft repeat (R_2) of a woven design gives the maximum possible contact fields in the woven design repeat. Highest interlacement is in plain-woven structure ($I = 2$) and non-interlaced structure would have I value of 0.

$$I = \left(\frac{i_{wp} + i_{wf}}{R_1 \cdot R_2}\right) \tag{9}$$

Complimentary to the interlacement index (I), float index (F) is defined as ratio of number of floats in the weave structure to the maximum possible floats in the weave repeat as given by the Equation (10), where f_{wp} and f_{wf} are floats in warp and weft, respectively. For a plain-woven structure, float index will be 0, as the floats are absent in it and it increases with number of floats in the structure with a maximum value of 2 for all unidirectional structure without interlacement. Both interlacement and float indices complement each other and the sum of interlacement index (I) and float index (F) is always 2 as expressed by Equation (11).

$$F = \left(\frac{f_{wp} + f_{wf}}{R_1 \cdot R_2}\right) \tag{10}$$

$$I + F = 2 \tag{11}$$

Table 1 presents the calculated values for various textile weaves used by Morino et al. [20] in terms of interlacement and float index. The values of the interlacement and float indices are found to be same as CFF and FYF, respectively [20,21], but explanation in terms of interlacement/float in the structure with respect to design repeat, is unambiguous for interlacement and float indices. Further, the interlacement and float indices are very easy to understand and to calculate.

Hewitt et.al. [20], have analyzed the preform structural variations such as weave, fabric, and yarn parameters for plain, twill, and satin structures using a fortran program [22]. The authors in this work have thus developed a single generic system to design and display any single or multilayer weave structure and generate data for a loom to weave it. However, investigation on preform properties with respect to structural factors such as interlacement index has not been reported yet. Prominent preform properties from the composite manufacturing by RTM perspective are permeability, compressibility and formability characteristics [23–25]. An attempt has been made to study the structure–property relations in preforms for composite reinforcement applications by developing nine different multilayer interlocked woven

Table 1. Interlacement index, float index of various textile structures.

	Weave repeat		Interlacement		Floats			
	R_1	R_2	Warp	Weft	Warp	Weft	I (CFF)	F (FYF)
Plain	2	2	4	4	0	0	2.0000	1.0000
2/2 twill	4	4	8	8	8	8	1.0000	1.0000
5end satin	5	5	10	10	15	15	0.8000	1.2000
Crape	8	8	44	44	20	20	1.3750	0.6250
Huck-a-back	16	16	180	172	76	84	1.3750	0.6250
Special honeycomb	16	14	102	96	122	128	0.8839	1.1161
Sponge	16	16	158	158	98	98	1.2344	0.7656
Granite	12	12	72	72	72	72	1.0000	1.0000
Dice	16	16	112	112	144	144	0.8750	1.1250
10 end satin	10	10	20	20	80	80	0.4000	1.6000

structures with varying interlacements. Present article attempts to understand the influence of woven structure (interlacement and float indices) on the tensile, compression, and permeability behavior of multilayer interlocked preforms for the composite reinforcement applications.

MATERIAL AND METHODS

Multilayer Woven Preforms

The two-layer (2-ply) and three-layer (3-ply) interlocked multilayer fabric samples were woven on 4 harness, flexible rapier automatic loom (Dornier), at 400 rpm with 24 ends/cm and 12 picks/cm setting. Five meter length of four varieties of Nylon 2-ply fabrics (N2P1-4) and five varieties of 3-ply fabrics (N3P1-5) were woven for the present studies using high tenacity Nylon-6 filament yarn (96Tex, fiber diameter 27.2 μm). The graphical representation of the woven design and 2-ply and 3-ply multilayer woven structures are represented in Figures 1 and 2. The general construction characteristics of the fabric samples made are provided in the Table 2, where s_1, s_2 denote warp/cm, weft/cm and c_1, c_2 represent warp, weft crimp % values, respectively. Multi-layer structures N2P1, N2P2, N2P3, N3P1, N3P2, and N3P3 apart from regular interlacing warp yarns, contain relatively straighter set of warp yarns in the structure, due to which, the crimp values of warp yarns in these structures are having higher variations. Table 3 presents the interlacement and float index values for the multilayered fabric samples.

Table 2. Multilayer woven interlocked perform properties.

	$s_1 \times s_2$ (cm)	c_1 (%)	c_2 (%)	Thickness (mm)	Aerial density (g/m^2)
N2P1	24 × 13	7.8 (6.4)	3.6 (2.3)	1.12	432.6 (2.8)
N2P2	23 × 11	6.9 (9.3)	3.2 (3.8)	1.18	411.4 (3.1)
N2P3	23 × 11	5.3 (8.2)	2.1 (2.9)	1.2	407.6 (5.3)
N2P4	24 × 12	4.3 (3.8)	2.6 (3.2)	1.25	412.2 (4.7)
N3P1	25 × 12	6.3 (7.6)	3.1 (3.0)	1.22	422.2 (2.9)
N3P2	24 × 12	4.4 (6.7)	2.1 (4.1)	1.34	420.1 (3.2)
N3P3	24 × 12	5.6 (7.8)	3.0 (1.9)	1.32	438.5 (2.5)
N3P4	24 × 13	6.5 (3.9)	4.0 (3.3)	1.27	436.8 (1.4)
N3P5	25 × 12	6.8 (4.8)	3.6 (4.4)	1.41	437.2 (2.9)

CV % values are given within parenthesis.

Table 3. Interlacement index, float index of multilayer structures.

	Weave repeat		Interlacement		Floats			
	R_1	R_2	Warp	Weft	Warp	Weft	I	F
N2P1	4	4	12	8	4	8	1.2500	0.7500
N2P2	4	8	20	16	12	16	1.1250	0.8750
N2P3	4	8	20	16	12	16	1.1250	0.8750
N2P4	4	8	16	16	16	16	1.0000	1.0000
N3P1	4	6	12	14	12	10	1.0833	0.9167
N3P2	4	12	20	26	28	22	0.9583	1.0417
N3P3	4	12	20	28	28	20	1.0000	1.0000
N3P4	4	12	16	28	32	20	0.9167	1.0833
N3P5	4	12	16	24	32	24	0.8333	1.1667

Testing Methods

TENSILE AND COMPRESSION TESTS

Tensile tests on the preform samples were carried out on Instron universal testing machine as per the ASTM Standards (ASTM Test Method D5035) at 15 mm/minute CRE with 200 mm gage length and 50 mm fabric strip width. Ten samples in each warp and weft direction were subjected to the uniaxial test. Compressibility is an important property of the textile preforms, which influences the porosity. It not only influences the fiber architecture but also affects the permeability through porosity variations and hence composite manufacturing process [26]. Many studies on the compaction behavior of textile preforms have been proposed, relating pressure with fiber volume fraction [27–29] and empirical relations have been expressed through curve-fitting techniques [30]. The compression behavior of these multilayer woven fabrics were conducted on Instron universal testing machine (compression head area 24.6 cm^2) at rate of 5 mm/minute Preform compression behavior as function of applied force to maximum of 9.81 N (1 kg force) was carried-out.

FABRIC PERMEABILITY

Fluid permeability through a textile fabric is by a combined process of wetting and wicking. Preform permeability for multiaxial warp knit fabrics have been studied through contact angle wettability test and horizontal wicking test [29].

Wetting is the initial process involving the fluid spreading wherein the fiber–air interface is displaced with the fiber–liquid interface. Wetting is measured in terms of contact angle, which is formed by the substrate and the tangent to the surface of the liquid droplet at the contact point. The contact angle measurement is a precise empirical tool to determine the wetting interaction between a liquid (surface tension) and a substrate (surface free energy). Contact angle test was carried on Tensiometry instrument (Kruss Model K100) though vertical wicking method for the Nylon filament. Capillary constant (C_c, a measure of average capillary size), mass-rate of liquid absorbed (M/t) by the filament yarn and maximum liquid mass absorption capacity can be measured using this tensiometric instrument interfaced with computer system.

$$M^2 = \frac{t\,C_c\,\gamma\cos\theta}{2\eta} \tag{12}$$

Initially the capillary constant of nylon yarn is found using tensiometric wicking test [31] by imparting liquid parameters in the adopted form of Lucas–Washburn Equation (12) using very low surface tension liquid, having almost zero contact angle (θ) so that $\cos\theta = 1$ (liquid used – n-hexane, density – 0.661 g/cm^3, surface tension – γ–18.4 dyne/cm, viscosity – η 0.294 cP). Again the wicking test is repeated with water (density – 1 g/cm^3, surface tension – 72 dyne/cm, viscosity – 1 cP) and contact angle is calculated with the same equation inserting the capillary constant obtained earlier.

Wicking is the capillary flow of liquid through the porous preform due to the difference in fluid pressure. Wickability of the said fabrics was obtained by measuring the water flow rate by in-plane wicking method [29] using horizontal wicking tester developed in the Department of Textile Technology, IIT-Delhi, India [29].

Video of the flow pattern during this in-plane wicking is also acquired using digital camera to measure the areal flow rate. Darcy's law for a linear and slow steady state flow through a porous media is given by the Equation (13)

$$Q = -K\frac{\Delta P}{L} \tag{13}$$

where K is a flow conductivity proportionality constant or permeability constant of the porous medium with respect to the fluid, ΔP is the net flow pressure head, and L is the length of flow in the sample. The length of fluid flow in capillary defined in Darcy's equation, L (cm), at a given time t (s) is provided by the Washburn Equation (14) as follows for horizontal capillary wicking, replacing the capillary radius with the hydraulic radius of the fiber bed [32].

$$L = \sqrt{\frac{m\gamma\cos\theta}{\eta}t} \tag{14}$$

The permeability constant K is a ratio of permeability (k) of the media to the fluid viscosity (η). ΔP, the difference in fluid pressure is the sum of the external fluid flow pressure difference and the internal capillary pressure ($P + P_c$). This capillary pressure, P_c (dyne/cm^2), is given by Equation (15), where γ is the surface tension of the fluid, θ is the wetting angle (contact angle), and m is the hydraulic radius of the fiber bed (cm) [33].

$$P_c = \frac{\gamma \cdot \cos\theta}{m} \tag{15}$$

This hydraulic radius of the fiber bed, m, is expressed in terms of capillary radius as the ratio of capillary cross-sectional area normal to the flow and its wetted perimeter, calculated by the relation (Equation (16)) as follows [33]:

$$m = f_f\frac{d_f(1 - f_v)}{4f_v} \tag{16}$$

where d_f is fiber diameter (27.2 µm for nylon filaments used for study), f_v is fiber volume fraction, and f_f is a function of fabric geometry. Approximation of this fabric geometry function (f_f) using yarn crimp values is proposed as under.

$$f_f = \frac{(n_1(1 - c_1)) + (n_2(1 - c_2))}{n_1 + n_2} \tag{17}$$

where n_1 and n_2 are warp, weft yarn density, c_1 and c_2 are warp, weft crimp, respectively. In woven fabrics, crimp is the waviness of the yarn in the fabric, if the crimp in the yarn is 0.05, it means that the yarn has 5% waviness. In terms of nonwaviness or straightness of the yarn, it can be expressed as $(1-0.05=0.95=f_f)$ as fabric geometry function. So $(1-c)$ gives the extent to which yarn is straight in the fabric, thus when crimp is zero fabric geometry function becomes 1, which is applicable to unidirectional noncrimp fabrics.

RESULTS AND DISCUSSIONS

The tensile properties of the multilayer interlocked fabrics i.e., peak strength and corresponding extension of the aforesaid samples have been provided in the Table 4. It is observed that breaking strength is influenced by the interlacement index as evident from Figure 5. Tensile strengths of the multilayer interlocked fabrics are found to be linearly increasing with the multilayer fabric structural parameter and interlacement index. Although the increase is not much, the noticeable slight increase in fabric strength with increased interlacement could be due to fabric assistance. Further the N2P4, N3P4 and N3P5 fabrics are observed to have lower strength than the rest of the fabrics in both warp and weft directions which could be due to the absence of stiffer yarns (strength enhancing yarns) in the structure.

Figure 6 illustrates the typical compression behavior of the textile preforms under investigation. The behavior can be segregated into three parts: initial, final linear trend, and mid nonlinear behavior. Initially, under the action of compression forces on fabric, the pore volume reduces rapidly to bring the fibers close to each other. This initial phase could be recognized from the figure as first linear segment, as it requires less force for compression. In the second curvy-linear stage, the fibers realign themselves and are rearranged involving fiber bending, hence this phase requires more force compared to first and the higher compression resistance could be due to bending modulus of the fibers in preform. The final stage involving compressing the fibers themselves, is represented by last linear segment of the diagram.

Exponential curve fitting technique was adopted to establish empirical relation between the Δf_v – change in fiber volume fraction resulting from reduction in the fabric thickness due to compressive force, P, where c and α are constants and applied compressive force as represented from Equation (18) [29].

The constant c signifies the slope of the initial linear region (part 1 of typical curve, Figure 6) corresponding to the increased fiber repositioning along with decrease of pores during preform compression. Constant α

Table 4. Tensile properties of the multilayer performs.

	Tensile property			
	Peak strength		Extension at peak	
	L_1 (kg)	L_2 (kg)	E_1 (%)	E_2 (%)
N2P1	446.2 (7.4)	309.8 (7.2)	38.4 (4.4)	36.2 (3.0)
N2P2	440.1 (6.4)	293.5 (8.2)	32.7 (4.9)	31.8 (3.8)
N2P3	434.8 (6.9)	302.5 (8.6)	38.7 (0.9)	29.0 (4.8)
N2P4	429.3 (5.4)	272.5 (3.5)	31.5 (4.8)	29.6 (4.4)
N3P1	446.4 (1.9)	282.4 (9.7)	36.2 (3.6)	29.6 (4.1)
N3P2	434.7 (2.8)	280.7 (5.1)	27.6 (5.1)	27.0 (4.4)
N3P3	444.0 (6.8)	276.2 (7.1)	24.9 (3.2)	29.2 (3.4)
N3P4	423.1 (5.9)	277.2 (7.0)	28.3 (3.9)	34.3 (4.1)
N3P5	411.9 (9.6)	268.1 (8.7)	27.1 (7.0)	28.2 (4.6)

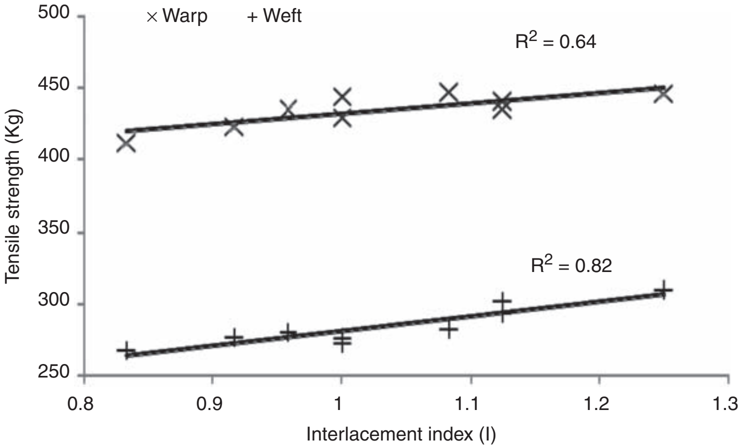


FIGURE 5. Tensile strength as a function of interlacement index.

represents the slope of the nonlinear region of the curve (part 2 of typical curve, Figure 6) corresponding to the fiber bending during compression.

$$\Delta f_v = \frac{t_i - t_p}{t_i} = \frac{\ln(P) - \ln(c)}{t_i \alpha} \tag{18}$$

where t_i is initial preform thickness to that at compressive force $P(t_p)$.

Fiber volume fraction of the preforms was calculated from fiber density (nylon 1.15 g/cc), fabric aerial weight, and fabric thickness values. The values of constants c and α and coefficient of determination (r^2) values for each type of

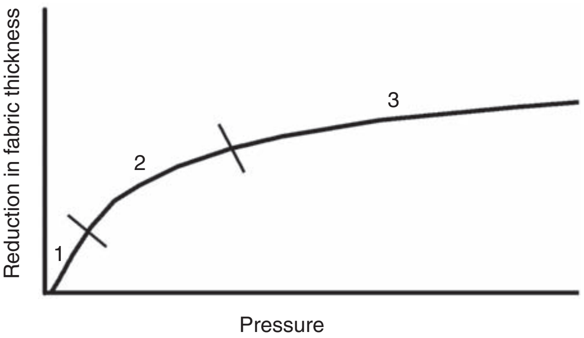


FIGURE 6. Typical compression behavior of textile fabrics.

Table 5. Compression behavior of multilayer fabrics.

Preform	Fiber volume fraction (f_v)	Preform thickness at 9.81 N (mm)	C	α	r^2
N2P1	0.34	0.70	4E−07	7.82	0.84
N2P2	0.31	0.96	3E−08	11.14	0.94
N2P3	0.30	0.57	2E−08	8.98	0.95
N2P4	0.29	0.89	5E−04	4.46	0.89
N3P1	0.30	0.84	5E−05	5.49	0.88
N3P2	0.28	0.97	1E−04	5.47	0.93
N3P3	0.29	0.99	2E−04	5.38	0.96
N3P4	0.30	0.92	5.9E−03	2.92	0.88
N3P5	0.27	1.07	3E−04	5.5	0.99

preform of empirical Equation (18) are tabulated (Table 5) after analyzing the test data. Influence and application of compression behavior with respect to fiber volume fraction has been discussed in permeability studies later in the article. Compressibility of the preform (ratio of preform initial thickness to thickness at pressure $P-9.81$ N) does not vary much with interlacement index, evident from the correlation analyses (r^2 values between 0 and 0.1), pointing towards lesser influence of the preform architecture on compression behavior.

The vertical wick test conducted on tensiometry instrument provided the average m^2/t value for the nylon 6 filament yarn with *n*-hexane ($4.93 \times 10^{-7}\,g^2/s$) and with water ($1.956 \times 10^{-7}\,g^2/s$). The capillary constant for nylon yarn and its contact angle with water was calculated to be 0.1192×10^{-7} and 76.8°, respectively. The results of the horizontal wicking test and contact angle measurement are useful to understand and arrive at permeability values for the preforms using Darcy's law, as discussed in testing section. Table 6 provides the calculated values of permeability parameters of

Table 6. Wicking and permeability properties of performs.

Preform	Flow rate at 30 seconds Q, (cm/second)	Hydraulic radius m, (μm)	Flow length at 30 seconds L, (cm)	Pressure difference ΔP, (10^3 dyne/cm^2)	Permeability k, (10^{-8} m^2)
+N2P1	0.250 (4.2)	12.43	0.0553	13.20	1.05
N2P2	0.285 (6.3)	14.55	0.0599	11.28	1.51
N2P3	0.278 (3.9)	15.34	0.0615	10.70	1.60
N2P4	0.279 (7.4)	16.08	0.0629	10.21	1.72
N3P1	0.216 (2.5)	14.78	0.0603	11.11	1.17
N3P2	0.256 (6.0)	17.28	0.0652	9.50	1.76
N3P3	0.254 (4.3)	15.75	0.0623	10.42	1.52
N3P4	0.277 (8.1)	14.85	0.0605	11.05	1.52
N3P5	0.271 (9.4)	17.15	0.0650	9.57	1.84

CV % values are given within parenthesis.

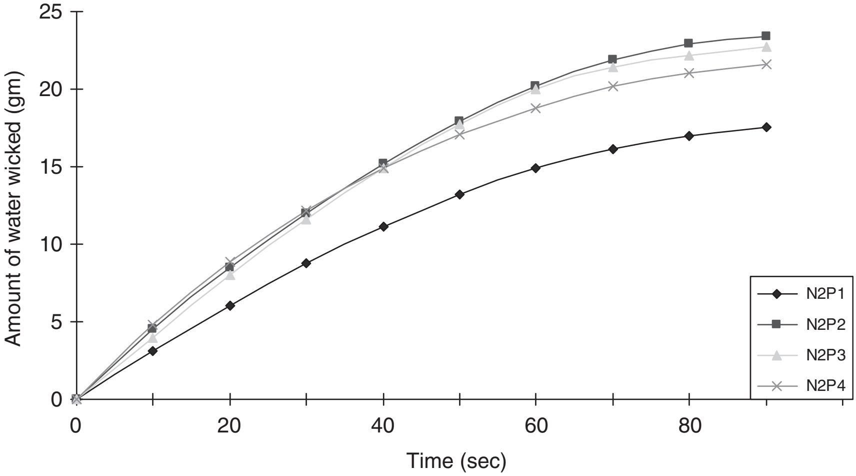


FIGURE 7. Wicking behavior of 2-ply multilayer fabrics.

multilayer preforms under consideration based on average flow rate of the areal flow data from the wicking test at 30 seconds.

The preform permeability studies with respect to water flow rate measurements by horizontal wicking test is as represented by Figures 7 and 8 for 2-ply and 3-ply multilayer fabrics, respectively. It is interesting to observe that in these multilayer structures, amount of water wicked is influenced with respect to structural parameter – interlacement index, lower in case of N2P1, N3P1 and higher for N2P4 and N3P5 fabrics, other fabrics wicking intermediately. Also a plot of multilayer fabric permeability with the structure interlacement index (Figure 9) shows that fabric permeability

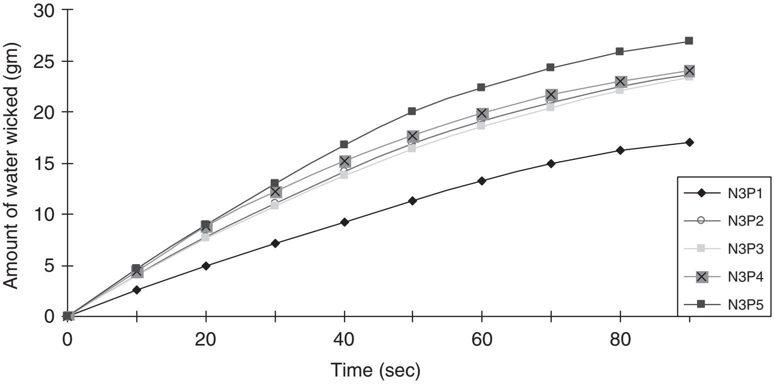


FIGURE 8. Wicking behavior of 3-ply multilayer fabrics.

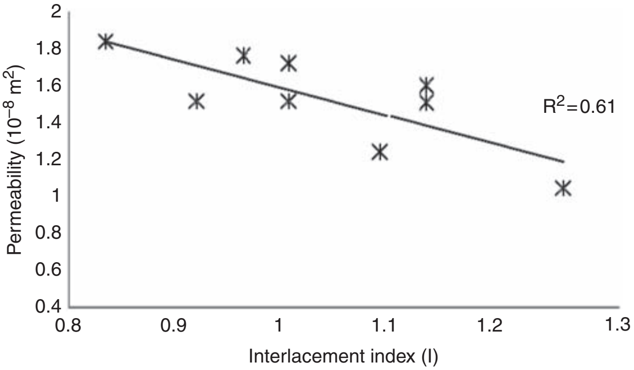


FIGURE 9. Influence of interlacement on fabric permeability.

decreases with increase in the interlacements of the multilayer interlocked fabrics. It shows that capillaries responsible for water transport are more conducive with respect to interlacement index, with lower interlacement index, flattening the yarns in the structure, hence better is the water transport through the capillaries. The permeability values obtained in this article are to be further utilized to understand and simulate the resin flow through these reinforcements during RTM composite manufacture.

CONCLUSIONS

The woven fabric geometry of multilayer interlocked structures has been expressed in terms of interlacement index and float index, by redefining the earlier proposed CFF and FYF factors. Interlacement and float indices complement each other; sum of these two factors for a given woven design is always 2. Properties of the multilayer interlocked woven preforms are influenced by the fabric structure. Structural influence (interlacement index) on tensile, compression and fabric permeability properties has been carried out. The tensile behavior of the developed multilayer woven preforms co-relate with the interlacement index. Compression behavior of these multilayer preforms are not dependent on the fabric structural geometry but are influenced by the fiber volume fraction of these preforms. Permeability measurements in terms of water wickability and permeability values can be well explained by this structural factor, straighter the yarn with least interlacements, better is the wickability. Structure property correlation of these multilayer fabrics would be further extended to analyze the composite performance based on textile reinforcement properties.

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BIOGRAPHY

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