

ABSTRACT

INCE, MEHMET ERDEM. Performance of Composites from 3D Orthogonal Woven Preforms in terms of Architecture and Sample Location during Resin Infusion. (Under the direction of Dr. Abdel-Fattah M. Seyam and Dr. Mansour H. Mohamed).

Woven preforms are different than laminates due to their complex internal structure such as yarn interlacing, yarn spacing, yarn size, yarn cross-sectional shape, etc. that change the architecture greatly. Another distinguished property of woven preforms is “weave repeat” also called “representative unit cell” which reflects the overall properties of the structure.

3D woven preforms are superior to 2D woven laminates due to presence of through-thickness elements (z-yarn components) that suppress delamination and improve interlaminar properties. The geometry and relative amount of z-yarn is critical to manipulate in-plane and out-of-plane performance. The increase in the z-yarn content leads to improvement in the out-of-plane performance of composite at the expense of in-plane properties.

Geometric modeling of woven preforms is a useful tool to predict preform thickness, preform areal density and fiber volume fraction (FVF) of constituent yarns. Previous geometrical models of 3D orthogonal woven preforms, which are extensively reviewed in Chapter 2, were limited to plain weave interlacing pattern in jammed case. In this study, generalized geometric models in terms of weave design (represented by a numerical value termed “weave factor”) were developed. The models cover both jammed and non-jammed cases, consider circular, racetrack, and rectangular yarn cross-sectional shapes. The models predict thickness, constituent yarn weights, and FVFs of 3D orthogonal woven preforms. The models illustrated fabric architecture potential of 3D orthogonal woven preforms. Numerical results for hypothetical structures showed how to control through the thickness components of the z-yarn and total FVF, that have direct effect on the in-plane and out-of-plane properties, with interlacing pattern (weave factor) and z-yarn linear density. The models were demonstrated as an essential design tool that may be used to develop composites with predicted level of structural parameters and performance.

Broad range of 3D orthogonal woven preforms from glass fibers with different architectures were woven and consolidated by vacuum infusion process (VIP) with different z-yarn interlacing pattern, number of y-yarn layers, and x-yarn spacing to verify the model for filament yarns.

Dry preform thickness and weight of in-plane yarns predicted by the geometric model for filament yarns correlated well with experimental results. Z-yarn weight of dry preform was 24.3% overestimated by the model due to shortening of z-yarn at cross overs in real preforms due to the flattening of x-yarns caused by the tension of z-yarns. Total FVF of actual dry preform was 0.4% greater than model prediction. However, total FVF of composite was 5.4% overestimated by the model, which is within the experimental error.

In VIP, presence of flexible vacuum bag on one side of the molding and pressure gradient from resin inlet to flow front change the compaction pressure on unsaturated preform that results in thickness and FVF variation in cured composite. Previous work on composite using VIP dealt with resin flow modeling to predict thickness, FVF, and resin pressure profiles. However, the effect of these profiles on mechanical properties was not investigated. In this study, specimens from composite panels were tracked in terms of their positions relative to resin inlet. Analytical (thickness, FVF, and void content) and mechanical (tensile, three-point flexure, and impact) properties of the specimens were measured to investigate the effect of specimen location on composite dimension and performance. Additionally, vacuum (75 and 100 kPa levels) was considered as variable to investigate its effect on composite formation and performance. Effect of fabric architecture on resin infusion performance was demonstrated by faster mold filling times of preforms with plain and basket weaves due to their straight, uniform, and wide resin flow channels compared to tortuous channels in preforms with twill weaves. Analytical properties of 3D orthogonal woven glass fiber composites showed parallel result with previous VIP researches such as thickness decreased, FVF increased and void content fluctuated from resin inlet to outlet.

Slight increase from resin inlet to outlet was observed for the tensile properties in x- and y-directions. Due to their higher FVF compared to the composites with other two weaves, composites with twill weaves resulted in better mechanical properties. Increase in x-yarn density caused increase in tensile stress in x-direction, whereas it resulted in reduction in tensile properties in y-direction. Increase in vacuum pressure slightly improved tensile stress in both directions.

Peak tensile stress in y-direction of three layers, 5.48 x-yarns/layer/cm balanced (defined as identical total denier in x- and y-directions/unit sample width) composites manufactured at 100 kPa vacuums was 15.24% greater than peak tensile stress in x-direction due to more uniform placement of y-yarn than x-yarn.

Flexural stress was affected by the independent variables (number of y-yarn layers, weave, x-yarn density, and vacuum pressure) the same as tensile stress was affected; however, the variation in flexural stress was greater than tensile stress due to more sensitivity of flexural stress to thickness variation than tensile stress. Peak impact load of composites slightly decreased from resin inlet to outlet. Composites with twill weaves having higher total FVF than composites with plain and basket weaves indicated better peak impact load and total penetration energy than composites with plain and basket weaves. Composites manufactured at 75 kPa vacuums resulted in lower total FVF and high void content than composites manufactured at 100 kPa vacuums; however, they demonstrated better peak impact load and total penetration energy than composites infused at 100 kPa (full) vacuums.

Performance of Composites from 3D Orthogonal Woven Preforms in terms of Architecture
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by
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DEDICATION

Dedicated to my family.



BIOGRAPHY

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1. INTRODUCTION

Materials are generally grouped into three different categories such as metals, ceramics, and polymers, and each category has its own unique properties. Metals are preferred for strength and toughness, ceramics for strength and transparency, polymers for lightweight and ductility. However, each material group has its drawback, such as metals are heavy, ceramics are brittle, and polymers are low strength.

Today, it is difficult to provide needs for modern technologies (such as aerospace, transportation, and marine) with a single type of material. For example, aerospace industry demands lightweight, strong, stiff, abrasive-corrosive-impact resistant materials. However, it is difficult to produce a product having all these properties by using only one group of materials, because, strong materials are generally heavy and increasing strength of any material results in ductility decrease [1].

The fourth material group to meet the requirement of modern technologies is composites that contain two or more material types without any change in chemical properties of the constituents. The main idea in composites is to combine useful and desired properties of the main materials. A typical example for composite is fiberglass in which short glass fibers are embedded in polymeric matrix. As short glass fibers provide strength and stiffness; polymeric matrix increases ductility and lowers density of the whole structure. Composite phenomena may also be summarized as “moving together” that means the phases of composite respond together to an external (physical, mechanical, environmental) effect [2] [3].

Many composite materials consist of two phases. Continuous form is known as matrix or binder phase, which surrounds other phase. The other phase is known as dispersant. Figure 1.1 shows dispersed-phase based classification of composites [1].

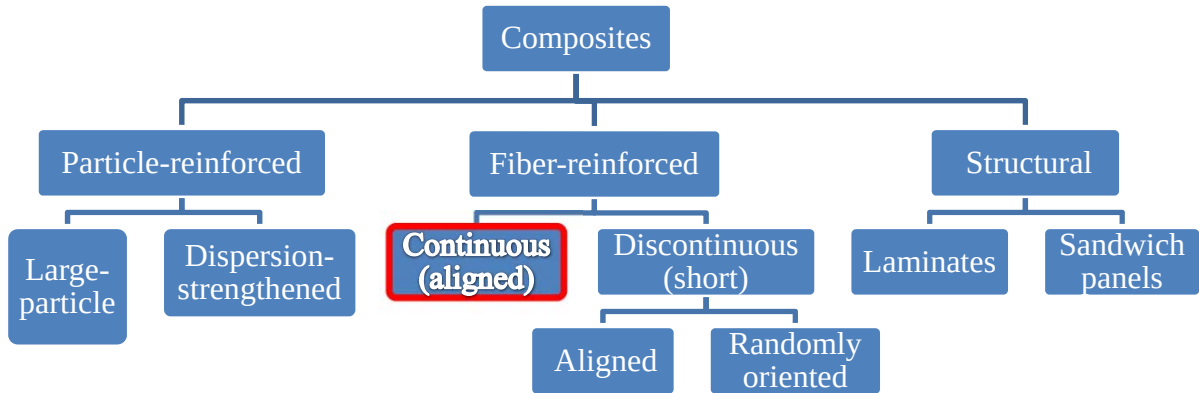


Figure 1.1. Dispersed-phase based classification of composites

Classification of composites shows that composite science is very broad. The research area of this thesis falls into “Fiber Reinforced Composites” and subcategory of “Continuous (aligned) Fibers”. Composites can also be classified according to matrix type. Figure 1.2 depicts the classification of composites based on type of matrix material.

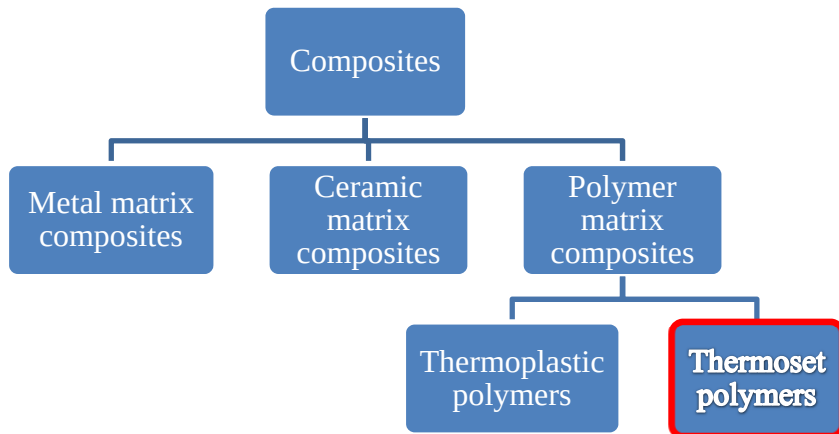


Figure 1.2. Matrix-based classification of composites

Polymer matrix composites are the most popular one in this classification. They are classified as thermosets and thermoplastics according to type of interaction between polymer molecules. Polymers having intermolecular bonds as strong as covalent bonds in the

backbone of polymer are called thermoset polymers. These strong bonds are named crosslinks. If bonds between polymer molecules are weak secondary bonding, then this type of polymers are called thermoplastics [3].

The research area of this thesis falls into “Polymer Matrix Composites” and subcategory of “Thermoset Polymers”. Thermoset polymers are generally liquid or easy to melt at room temperature. They may take any shape or be manipulated with reinforcement material in liquid form. In contrast to thermoplastics, which solidify by cooling, thermosets cure (crosslink) and take solid form as result of chemical reaction. Curing process, which is solidification of thermosets, is formation of crosslinks between polymer molecules. Crosslinks between polymer molecules create a unique, interconnected, three-dimensional network structures. Molecular weight of this network structure is dramatically high, which increases melting temperature to a point higher than the degradation temperature. Therefore, thermoset polymers do not melt at high temperature. They char at high temperature. Crosslinking increases not only melting point but also glass transition temperature of polymers.

Main target in the design of “Fiber-reinforced Polymer Matrix Composites” is to get high strength and stiffness by keeping in mind the weight of product. Therefore, for composites, specific strength, which is ratio between strength and density of composite, is an important property. Similarly, for stiffness-based design, specific stiffness that is ratio between stiffness and density of composite is considered. Fiber reinforced polymer matrix composites include low-density fiber and resin; therefore they have high specific-strength and specific-stiffness [1] [3].

1.1. Reinforcement forms (preforms)

Two important factors affecting properties of composite are the nature (form) of reinforcement (fiber, mat, fabric, etc.) and manufacturing (processing) technique. The reinforcement form itself also dictates composite manufacturing technique. Therefore, having sound knowledge about the structure of reinforcement is important to understand and predict

processing and mechanical performance of composites.

Numerous fiber reinforcement forms are available in the market. Fiber itself may be a reinforcement form or it can be converted into different type of sheet forms such as mat and fabric. Textile manufacturing techniques are widely used to produce reinforcement fabric for composite industry [4].

Between 1985 and 1997, woven, braided and knitted textile structures were widely investigated at Langley Research Center under NASA Advanced Composites Technology (ACT) Program. The main aim was to produce main structural parts (such as wing and fuselage) of passenger aircrafts from textile composites. NASA contractors; universities and companies conducted comprehensive research on textile composites especially due to their damage tolerant internal structures as compared to tape laminates (prepregs) [5] [6].

Handling ease is one of the most important advantages of textiles for composites. Due to interlacement between yarns in a textile fabric, it can easily be taken from weaving loom and transported to consolidation area with minimum distortion. Textile technology processes can create preform that has the similar shape of final composite product, therefore; not only part assembly process is eliminated but also more strong joints (bonding) are created compared to other joint types (bolted, adhesive bonded) [7].

3D woven fabrics

The most significant contribution of textile technologies to composite manufacturing is 3D textile structures. Two-dimensional (2D) fiber reinforced composites are very weak against out-of-plane loads, because only weak polymer matrix material resists against out-of-plane loads. Therefore, loads including complex components should not be applied to 2D composites, because separation of layers, which is called delamination, may occur because of out-of-plane forces. In order to suppress weakness of 2D composites against complex out-of-plane loads, three-dimensional reinforcement materials were developed [2].

Composite material itself is 3D. However, composites are produced by combination of one or

two-dimensional reinforcements. It is critically important to achieve desired thickness and other dimensions during lay-up process. One of the reasons to eliminate potential dimensional variation of composites is to use direct three-dimensional reinforcements instead of combination of 2D structures. Namely, another advantage of 3D reinforcement is direct preform manufacturing. 3D weaving process forms preform fabrics on volumetric basis, whereas 2D weaving process forms fabrics on areal basis [3] [8].

Fibers placed in thickness direction are called z-yarn, warp weaver, or binder yarn for 3D woven fabrics. More than one layer of fabric is woven at the same time, and z-yarn interlaces warp and weft yarns of different layers during the process. At the end of the weaving process, an integrated 3D woven structure, which has a moderate thickness, is produced. Formability potential of 3D woven fabric is higher than 2D fabrics. 3D fabric has highly porous structure, which decreases resin infusion time compared to stacked 2D woven structures. 3D woven fabrics have also lower or no yarn crimp than 2D woven fabric; therefore, mechanical properties of fibers are almost fully utilized in 3D woven structures. Another advantage of 3D woven structure is being easy to optimize properties for specific directions by strategically placing different fibers in different directions, which is called hybridization [9].

Reinforcement forms having fibers in their thickness direction are stronger against impact and (interlaminar) shear forces between layers. However, placing fibers in thickness direction lowers the amount of fibers available in x-y plane. Therefore, in-plane properties are deteriorated in the presence of through-thickness fibers. If the purpose is just to increase handle ability of preform, then 1% - 2% z-yarn is good enough. In case of great amount of out-of-plane loads, then 33% z-yarn content may be used in through-thickness direction. In final case, a preform having equal load carrying capability in x-, y-, and z-directions is manufactured [2] [3].

Classification of 3D woven fabrics

Today, there is more than one type of 3D woven fabric in composite market. Figure 1.3 shows the classification of 3D woven fabrics based on weaving technique [10].

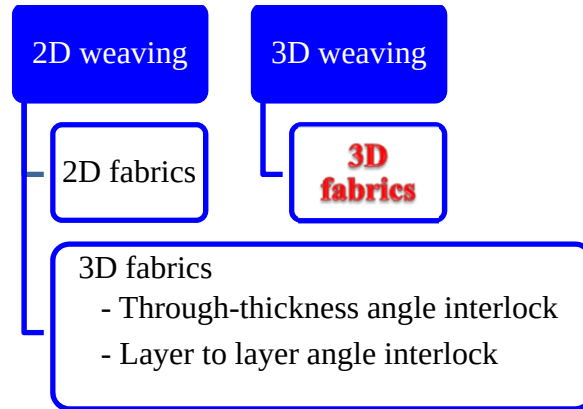


Figure 1.3. Classification of 3D fabrics by Khokar

Classification shows that it is possible, using proper weave design techniques, to manufacture 3D woven fabrics using the traditional weaving process (in which one shed is formed at a time; single phase weaving) for manufacturing 2D fabrics.

Figure 1.4 illustrates manufacturing of 2D (a) and 3D fabric (b) on conventional 2D weaving machine. One type of 3D fabrics woven on 2D conventional weaving machine is 3D angle interlock fabric. Weaver or z-yarn in 3D angle interlock fabrics might go through all the thickness of fabric or layer to layer.

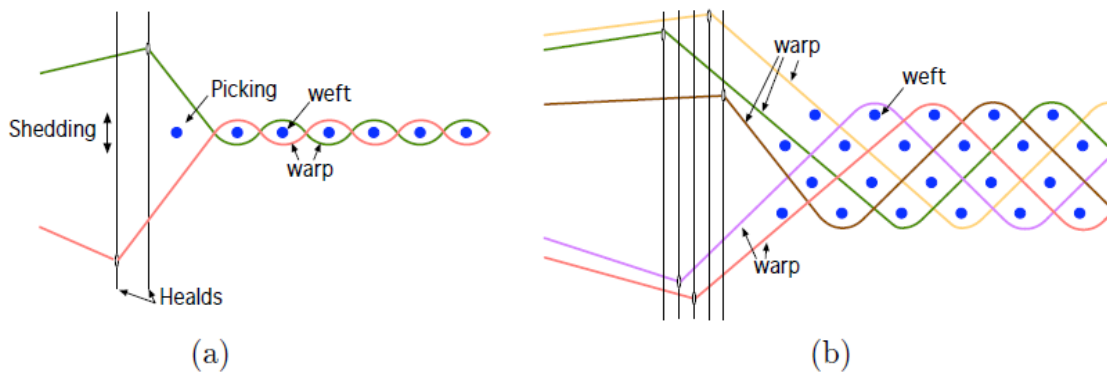


Figure 1.4. Illustration of conventional 2D weaving principle
(a) 2D fabric, (b) 3D angle interlacing fabric [11]

Figure 1.5 shows a through-thickness angle interlock 3D weave with warp stuffer (y-) yarns

(blue) seen from its three principles planes and in an isometric view. Warp weaver (z-) yarns are green and weft (x-) yarns are red in the figures.

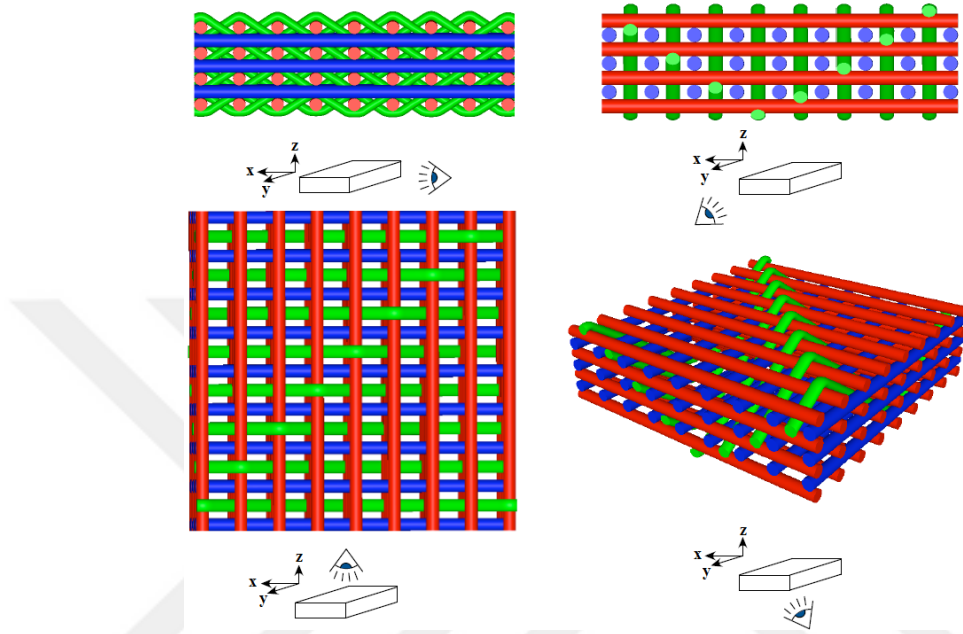


Figure 1.5. Through-thickness angle interlock 3D weave [11]

Figure 1.6 shows a 3D orthogonal fabric seen from its three principle planes and from an isometric view. Warp weaver (or binder, z-) yarns are in green, warp stuffer (y-) yarns are blue, and filler (x-) yarns are red in the illustrations [12] [13].

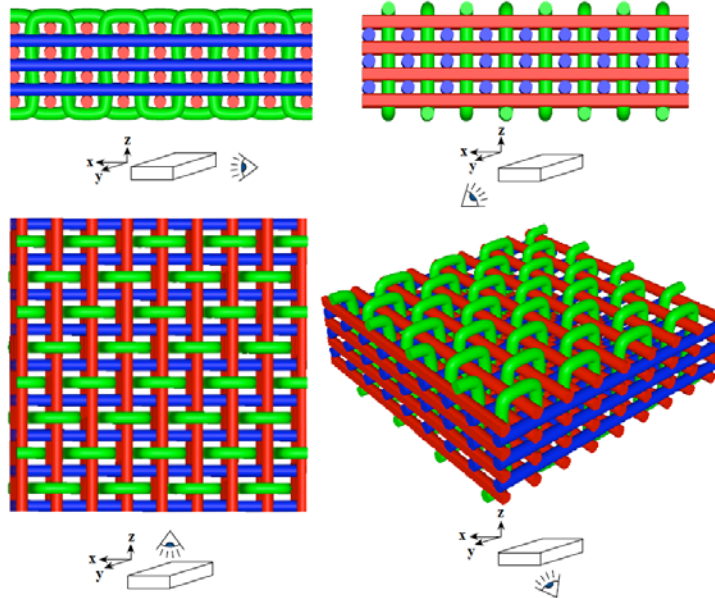


Figure 1.6. 3D orthogonal woven fabric [11]

This new class of fabric is called 3D orthogonal woven fabric and the process to form such fabric was patented by Mohamed and Zhang [14]. The architecture of 3D orthogonal woven fabric consists of three different sets of yarns; warp yarns (y-yarn), weft yarns (x-yarn), and z-yarn. Z-yarn is placed through-thickness of the preform as shown in Figure 1.7.

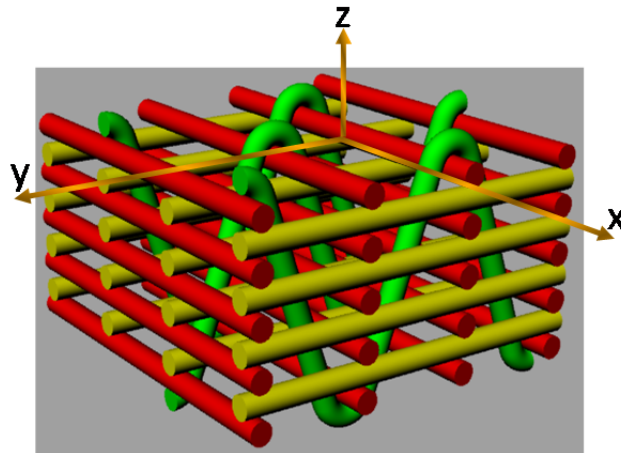


Figure 1.7. Architecture of 3D orthogonal woven fabric

There is no interlacing between warp and weft yarns and they are straight and perpendicular to each other. On the other hand, z-yarns combine the warp and the weft layers by interlacing (moving up and down) along the y-direction over the weft yarn. Interlacing occurs on the top and the bottom surface of the fabric. The straight configuration of warp and weft yarns enables to benefit from the maximum load carrying capacity of high performance fibers in these directions.



2. LITERATURE REVIEW

The current research deals with fiber-reinforced composites from 3D orthogonal woven structures and thermoset resin. It encompasses geometric modeling of 3D orthogonal preforms from spun as well as continuous filament yarns, effect of fabric architecture on physical and mechanical properties of the final composites, and the effect of sample location from the resin inlet on the physical and mechanical performance. This chapter addresses the relevant previous research in these areas.

2.1. Geometric modeling of 3D woven preforms

Mohamed et al. [15] defined unit cell consisting of one y-yarn, one x-yarns and one z-yarn with different cross section geometry (Figures 2.1 and 2.2, note that Figure 2.1 includes one x-yarn, however maximum fiber volume calculations were based on two x-yarns in unit cell). The reason for considering two x-yarns is the use of continuous x-yarn that dictated the double insertion for each shed. The geometry indicates that the z-yarn forms plain weave (considering each two picks as one) or 2x2-warp rib (considering two picks per shed). Additionally, their geometry neglected the z-yarn crowns. They calculated maximum total fiber volume fractions for different yarn cross-sectional shapes. Table 2.1 shows the calculated maximum total and constituent yarns fiber volume fractions. They assumed yarn packing factor of unity, which is not realistic assumption. Same yarn (or yarn diameter) for all directions was used to define the unit cells. Therefore, the effect of different yarns (yarn diameters) in different directions was neglected. Geometry of other than plain weave (or 2x2-warp rib) was neglected, and only jammed construction in which adjacent yarns are in contact was adopted.

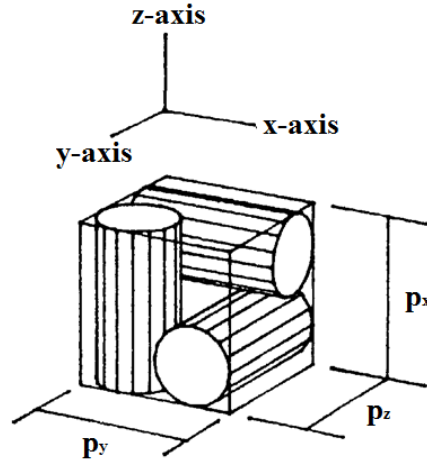


Figure 2.1. Unit cell of 3D orthogonal weave
(note that the unit cell shows only one x-yarn, but maximum total fiber volume fraction calculations in Table 2.1 were based on double x-yarns in unit cell) [15]

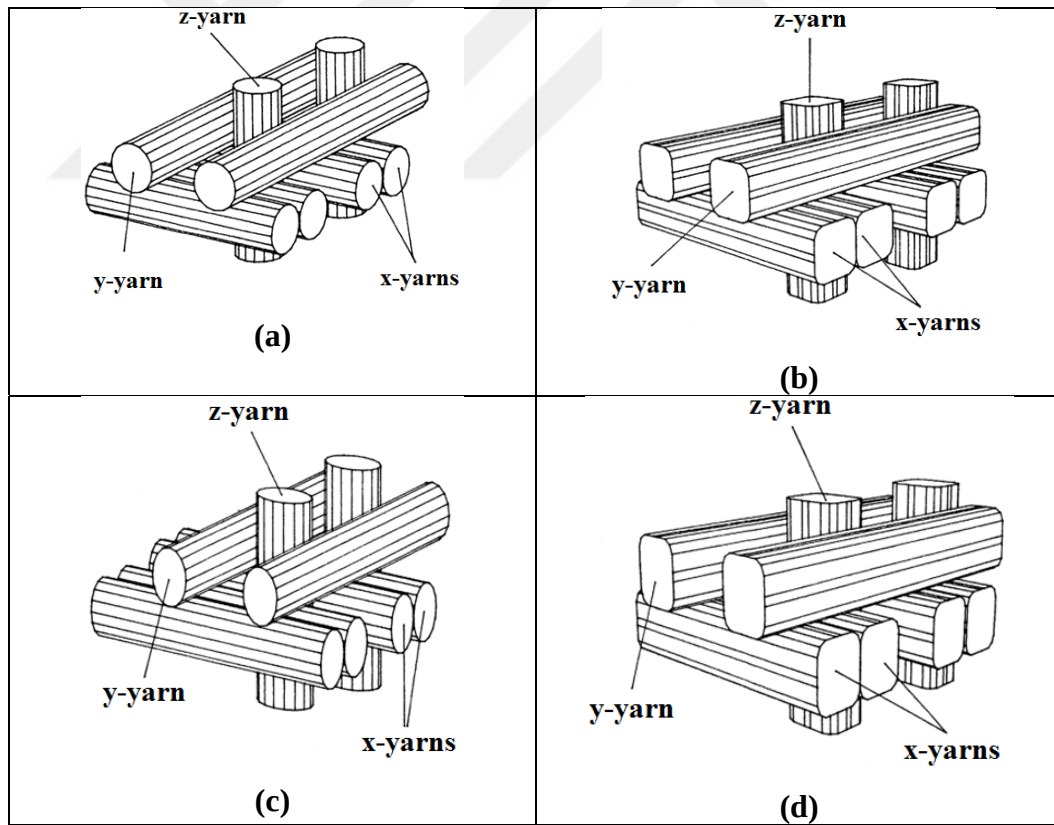


Figure 2.2. Structures of 3D orthogonal weave in jammed case
(a) circular, (b) square, (c) ellipse, (d) rectangular cross section [15]

Table 2.1. Maximum fiber volume fractions for different yarn cross sections

Cross-sectional shape	AR*	Maximum fiber volume fractions			
		F_{fx} (%)	F_{fy} (%)	F_{fz} (%)	$F_{fxyz}(\%)^{**}$
Circular	1.0	26.18	19.63	13.09	58.90
Elliptical	0.6	26.18	14.73	16.36	57.27
Elliptical	0.3	26.18	9.06	20.14	55.38
Square	1.0	33.33	25.00	16.67	75.00
Rectangular	0.6	33.33	18.75	20.83	72.92
Rectangular	0.3	33.33	11.54	25.64	70.51

Note: Maximum total fiber volume fraction (F_{fxyz}) for elliptical cross-sectional shape with 0.3 aspect ratio was miscalculated as 37.6% in related publication [15]. The model assumes ellipses and rectangles are in perpendicular (longer dimension of yarn cross section is perpendicular to x-y plane) position.

* AR: Aspect ratio (the ratio between short and long dimension of shape)

** Reported in [15]

where F_{fx} , F_{fy} , F_{fz} in Table 2.1 are the volume fractions of the fiber in x-, y-, and z-yarn respectively, and F_{fxyz} is the total fiber volume fraction, calculated from;

$$F_{fxyz} = F_{fx} + F_{fy} + F_{fz} \quad (2.1.)$$

Later Mohamed et al. [16] derived equations for their geometric model to calculate basic dimensions of the unit cell. Schematic unit cell and its dimensions for rectangular yarn cross section are given in Figure 2.3.

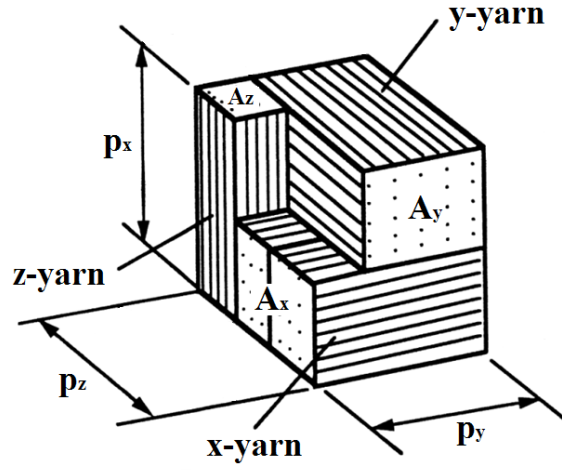


Figure 2.3. Internal unit cell of 3D orthogonal woven preform [16]

Overall fiber volume fraction; F_{fxyz} is defined in equation (2) as:

$$F_{fxyz} = \frac{\text{Total volume of fibers in internal unit cell}}{\text{The volume of internal unit cell}} \quad (2.2.)$$

$$F_{fxyz} = \frac{A_x p_y + A_y p_z + A_z p_x}{p_x p_y p_z} \quad (2.3.)$$

$$F_{fxyz} = \frac{A_x}{p_x p_z} + \frac{A_y}{p_x p_y} + \frac{A_z}{p_y p_z} = F_{fx} + F_{fy} + F_{fz} \quad (2.4.)$$

where

A_x = cross section area sum of fibers in x-yarn (cm^2);

A_y = cross section area sum of fibers in y-yarn (cm^2);

A_z = cross section area sum of fibers in z-yarn (cm^2);

p_x = x-yarn spacing (height of unit cell) (cm);

p_y = y- yarn spacing (width of unit cell) (cm);

p_z = z-yarn spacing (length of unit cell) (cm);

$$A = \frac{N}{9000 * 100 * \rho_v} \quad (2.5.)$$

N (g/9km) is the linear density of related yarn, and ρ_v (g/cm³) is the volumetric density of fiber composing the yarn. They derived equations to calculate unit cell dimensions for a given set of yarns and constituent yarns' fiber volume fractions those are lower than the calculated maximum fiber volume fractions given in Table 2.1.

$$p_x = \sqrt{\frac{A_x A_y F_{fz}}{F_{fx} F_{fy} A_z}} \quad (2.6.)$$

$$p_y = \sqrt{\frac{A_y A_z F_{fx}}{F_{fy} F_{fz} A_x}} \quad (2.7.)$$

$$p_z = \sqrt{\frac{A_x A_z F_{fy}}{F_{fx} F_{fz} A_y}} \quad (2.8.)$$

Unit cell dimensions were used to compute number of y-yarn layers for a given preform thickness, reed density (one y-, and one z-yarn for each reed dent), x-yarn density, number of y-yarns in one layer for a given preform width, and fabric take-up rate during weaving.

Gu [17] modified Mohamed et al.'s model by considering all warp and filling layers in unit cell and incorporating yarn packing factor assumption of 0.65 for all sets of yarns. While this is more realistic assumption, such low yarn packing factor is more suitable for spun yarns woven tightly in 2D fabrics per Peirce [18]. The structure of 3D orthogonal woven fabric described by Gu is given in Figure 2.4.

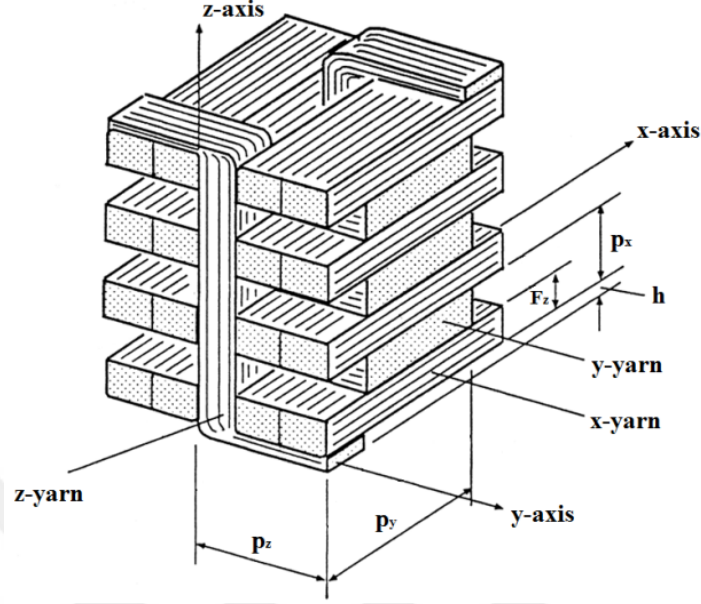


Figure 2.4. Structure of 3D orthogonal woven fabric [17]

Instead of p_x (x-yarn spacing, also height of internal unit cell in previous model); Gu used total thickness t of the fabric which is expressed as;

$$t = np_x + F_z + 2h \quad (2.9.)$$

where n is the number of y-yarn layers, F_z is the thickness of x-yarn, and h is the thickness of z-yarn.

Gu also predicted aspect ratio of each yarn set for a given reed density, reed blade width, and filling (x-) yarn density ($1/x$ -yarn spacing). He achieved good agreement between measured and calculated structural parameters of the unit cell. However, the agreement between measured and calculated values decreased as the size of z-yarn is increased. Gu's model was limited to jammed plain weave construction; it was not generalized and not including the open weaves. Realizing the limitation of his geometry, Gu recognized the need for a general geometrical model, which can cover wider range of structures, which is one of the objectives of the current work.

Ko and Du [19] [20] defined a unit cell for 3D orthogonal fabric, which is shown in Figure 2.5.

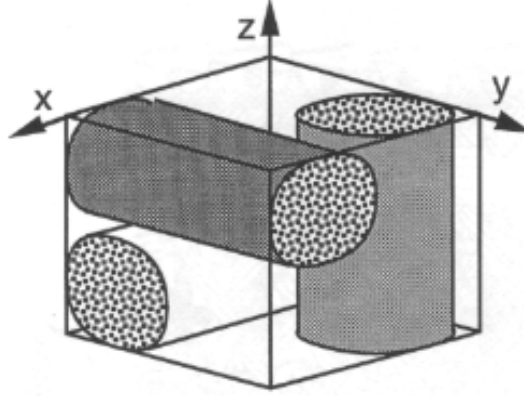


Figure 2.5. Unit cell for 3D orthogonal fabrics [19]

They calculated fiber volume fraction based on this unit cell geometry as shown in equation 2.10;

$$V_f = \frac{\pi}{4} \kappa \frac{d_x^2(d_y + d_z) + d_y^2(d_x + d_z) + d_z^2(d_x + d_y)}{(d_x + d_y)(d_x + d_z)(d_y + d_z)} \quad (2.10.)$$

where d_x , d_y , and d_z are diameters of the yarns in x-, y-, and z-direction, respectively; and κ is the yarn packing factor of the yarns. Figure 2.6 shows total fiber volume fraction versus d_y/d_x ratios, assuming yarn packing factor of 0.8. The graph was drawn based on three different d_z/d_x ratios (0.01, 1, and 100). For all d_z/d_x ratios, total fiber volume fraction firstly decreases with the increase in d_y/d_x ratio, reaches a minimum, and then increases. With this geometry, achievable maximum total fiber volume fraction is 0.63, and minimum is 0.47 in case of same yarn diameter for all x-, y-, and z-directions. Unit cell developed by Ko and Du considered only jammed orthogonal structures in which three set of yarns are perpendicular to each other, and unit cell is not generalized in terms of z-yarn weave pattern. The unit cell is also internal (not representing the whole structure by ignoring the effect of

number of layers), and does not include z-yarn cross-over arcs (crowns) on the top and bottom surfaces of the preform. Only circular yarn cross section, which is valid for spun yarns and not valid for filament yarns, was considered.

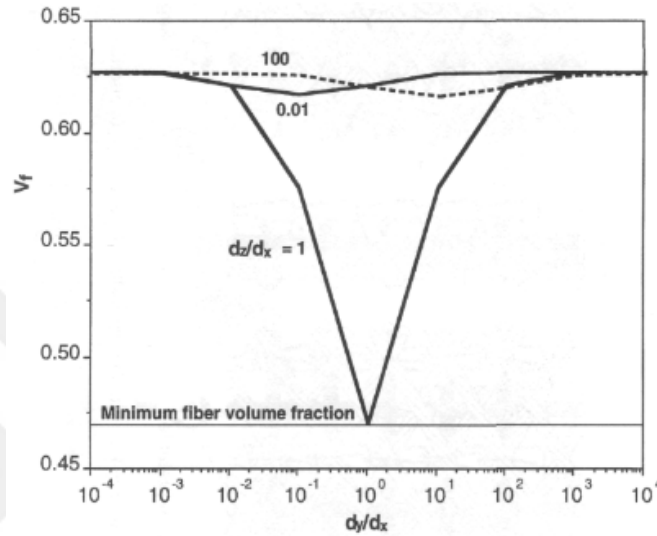


Figure 2.6. Process window of fiber volume fraction for 3D orthogonal fabric [19]

Cox and Dadkhah [21] investigated the elastic properties of 3D woven composites. They tried to predict both in-plane and out-of-plane elastic properties. They computed volume fractions of different constituent (x-, y-, and z-) yarns for dry preform in terms of structure specifications (number of yarn layers, yarn spacing, yarn count, and measured crimp factor for each yarn set) as input parameters. Their volume fraction of a given yarn is defined as the ratio of the fiber volume of the yarn to the total volume of all fibers. They measured total fiber volume fraction (by acid digestion method) and composite thickness and used them with volume fractions of constituent yarns to calculate macroscopic elastic properties of composite. Figure 2.7 shows schematic of 3D orthogonal weave architecture in their study. They assumed the z-yarns are straight and perpendicular to in-plane (x- and y-) yarns. The weave pattern was limited to plain weave and calculation was based on 1mm x 1mm dimensions, which does not necessarily provide complete repeats of the weave structure.

They calculated the thickness of individual x- and y-yarn layers in terms of yarn count, yarn spacing, number of layers for each yarn set, and measured composite thickness. However, they did not consider the contribution of z-yarn to overall thickness, yarn cross-sectional shape and its dimensions including yarn packing factor. The experimental results for in-plane properties correlated well with the predicted ones. However, the errors in predicting through-thickness properties were attributed to the difficulty in quantifying the irregularity in through-thickness (z-) yarns.

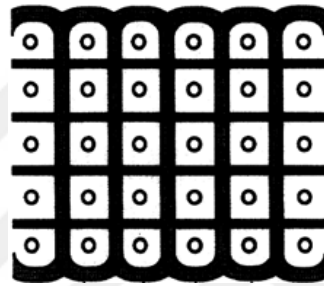


Figure 2.7. Schematic of 3D orthogonal weave architecture [21]

Cox and Flanagan [6] compiled a NASA contractor report titled “Handbook of Analytical Methods for Textile Composites”. They defined 3D orthogonal woven preform as shown in Figure 2.8.

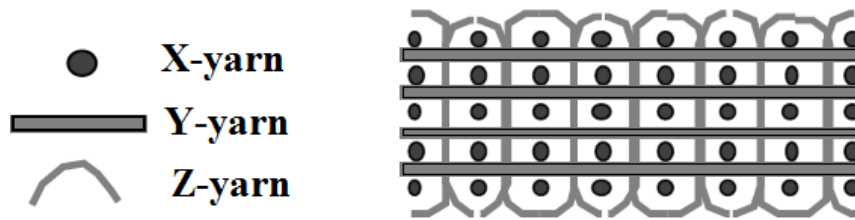


Figure 2.8. 3D orthogonal weave pattern [6]

As seen from Figure 2.8, 3D orthogonal woven preform was defined by plain weave z-yarn interlacing pattern in jammed (orthogonal) construction. They derived three equations to

predict fiber volume fraction of yarns in different directions. They showed that in a composite of thickness t with n_y layers of y-yarns alternating with n_x layers of x-yarns, the volume fractions of y- and x-yarns are simply defined by equations 2.11 and 2.12;

$$V_y = \frac{en_y}{[y_y \rho_f t]} \quad (2.11.)$$

and

$$V_x = \frac{pn_x}{[y_x \rho_f t]} \quad (2.12.)$$

Where e is the number of ends (y-yarns) per unit length in the x-yarn direction and p is the number of x-yarns per unit length in y-yarn direction; y_x and y_y are the yields (yield is defined as yards/liber) of the x-yarn and y-yarn; ρ_f is the fiber density. The volume fraction of z-yarn can be written as:

$$V_z = \frac{en_z c_z}{[y_z \rho_f t]} \quad (2.13.)$$

Where n_z is the number of z-yarns between successive columns of y-yarns, y_z is the yield of z-yarn, and c_z is a crimp factor. Cox and Flanagan mentioned that z-yarn crimp factor is difficult to predict as a priori, and requires experimental measurement such as; 1.1 and 1.3 for layer-to-layer angle interlock weaves, near 1.5 for through-thickness angle interlock weaves, and between 2 and 5 for orthogonal interlock weaves [6]. The model developed by Cox and Flanagan is limited to jammed structure, plain weave and requires the experimental measurement of crimp factor for z-yarn. Their calculation was based on dimensions of the unit length (1 cm or 1 inch) which may not represent the complete weave repeat for different weaves. The model did not consider yarn cross-sectional shape, and its dimensions including yarn packing factor. The model also did not consider the thickness computation, and used cured composite thickness as input.

Hill and McIlhagger [22] developed a geometric model for 3D orthogonal woven fabrics to calculate total areal weight, and weight percentage of different constituent (x-, y-, and z-) yarns for a given value of the total fiber volume fraction. The model adopted fiber type (volumetric density), yarn count (linear density), yarn spacing, number of layers for each yarn set, limited number of weave patterns for z-yarn, and planned total fiber volume fraction as input parameters. They simplified 3D orthogonal woven structure shown in Figure 2.9 (a) and obtained the simplified geometrical model depicted in Figure 2.9 (b). The model assumed z-yarn path of segmented straight parts and only jammed (maximum construction) case. Their weave interlacing model incorporated different two-harness weaves but did not allow for generalization in terms of weave structure. They did not consider the yarn cross-sectional shape and its dimension including yarn packing factor; therefore, measured cured composite thickness was used in calculations.

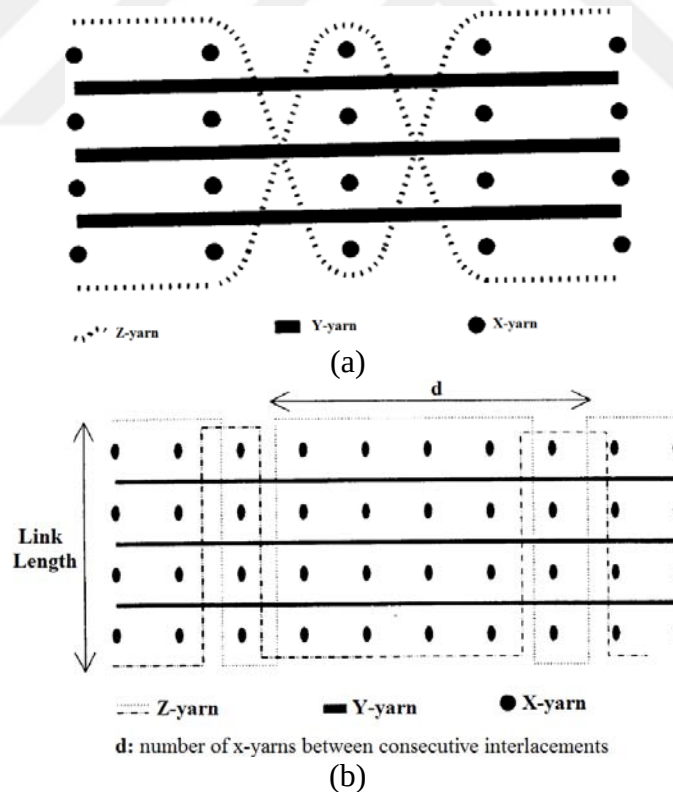


Figure 2.9. 3D orthogonal woven structure
(a) defined structure, (b) idealized structure [22]

Brown and Wu [23] [24] developed a geometric model to predict volume proportions of yarn in x-, y-, and z-directions for 3D orthogonal woven fabric. The model also included overall fiber volume fraction and preform areal density calculation. The length of the unit cell is fixed to 1 cm as shown in Figure 2.10 (b). Similar to the work by Hill and McIlhagger [22], their weave structure model is based on connected straight segments of the z-yarn path. They considered different weave structures as shown in Figure 2.11; however, their model is restricted to two-harness weaves of equal float length for a given weave; therefore, it is not a generalized model. They considered different yarn cross-sectional shapes (circular, elliptical, rectangular) and considered rectangular and hexagonal fiber packing. They also took into account the contribution of z-yarn to overall thickness. Brown and Wu used the constituent material properties of Cox and Dadkhah's study [21] to validate their model. Their predicted overall fiber volume fraction and thickness from the geometric modeling matched the measurements of Cox and Dadkhah very well. In another experiment, they achieved well correlation between predicted and measured thicknesses.

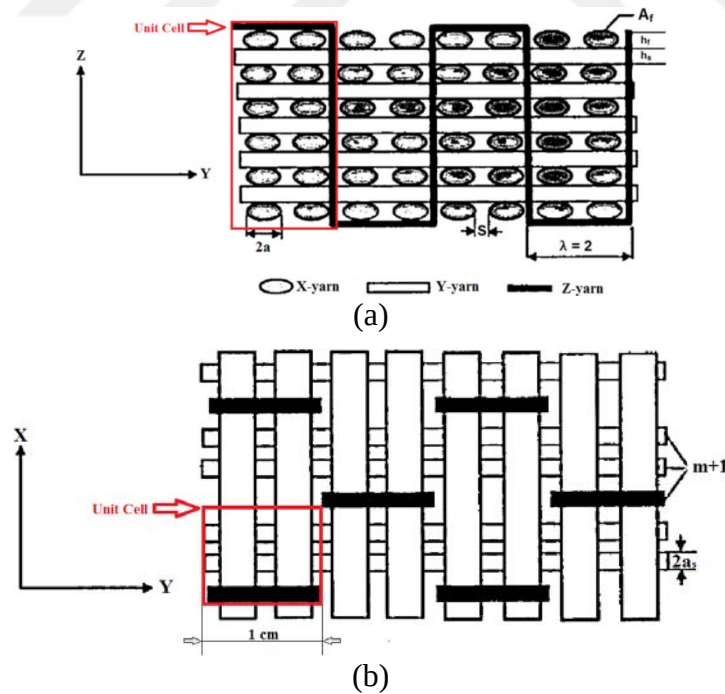


Figure 2.10. Geometric design of 3D orthogonal woven fabric
(a) x-yarn cross section, (b) z-yarn cross section [23]

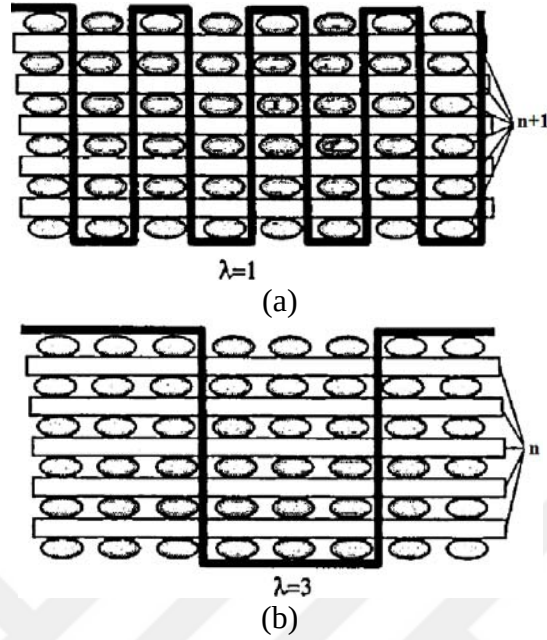


Figure 2.11. Different weave patterns for 3D orthogonal woven fabrics [23]

Brown and Wu [25] used their geometric model to predict stiffness and Poisson's ratio. They compared their study with the theoretical and experimental results of Cox and Dadkhah [21]. The results showed that the mechanical properties predicted by their model are more close to experimental results than Cox and Dadkhah's theoretical results. However, there are still discrepancies between their predicted mechanical properties and experimental results. Brown and Wu also indicated the deficiency of their model is related to the unrealistic geometry in which z-yarns were assumed as connected parts of straight segments.

Quinn et al. [26] developed computer based fabric design software to predict areal density and fiber volume proportions for the yarns in x-, y-, and z-direction of 3D orthogonal woven fabric. The lenticular (two arcs of two circles of equal diameter forming the shape of an eye) tow cross section was adopted in their study. The predicted results for areal density were very close to experimental values; however, fiber volume proportion prediction in z-direction was higher than the experimentally measured value. This difference was attributed to the

assumption that z-yarns are formed from connected straight segments for jammed construction with all yarn systems orthogonal as shown in Figure 2.12.

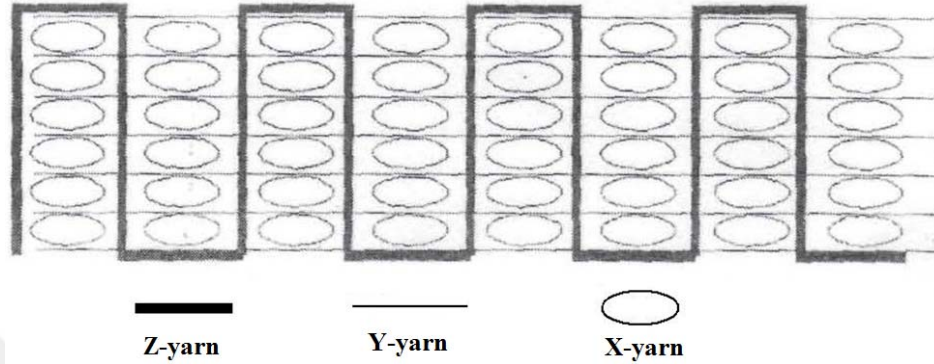


Figure 2.12. Idealized yarn path of 3D orthogonal woven fabric structure (note that unbounded y-yarn layers on the top and bottom surfaces of the preform) [26]

Quinn et al. [27] modified their previous model in regards to the path of z-yarns to predict fabric thickness, areal density and fiber volume percentage of z-yarn more accurately. They challenged the assumption that the z-yarn is formed from connected straight segments. They considered z-yarn geometry that is not perpendicular to the x- and y-yarns, and z-yarn consists of tilted straight part and arc parts at the crossover areas with the x-yarn. Figure 2.13 shows the yarn path representation of their geometry. They computed the dimensions of lenticular shape considering yarn count and yarn packing factor. Their experimental results well correlated with the theoretical model especially for z-yarn volume percentage. However, they did not generalize the theory in terms weave design. While their publication indicates they considered different weaves (4-, 6-, and 8-harness satin weaves), their derived geometric relationship does not show a generalized model for generalized weave structure.

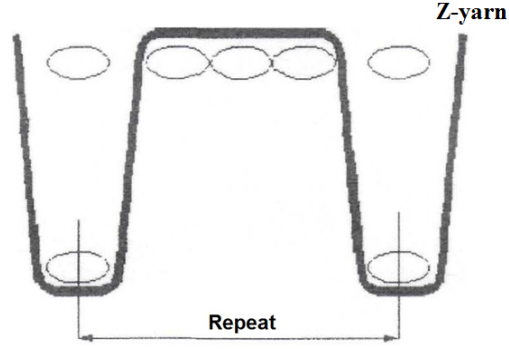


Figure 2.13. Lenticular yarn path representation [27]

Buchanan et al. [28] developed and experimentally validated a geometric model for a specific 3D angle interlock woven fabric structure in which the z-yarn forms staircase path. Figure 2.14 depicts the adopted weave architecture in their model study. The model considered the weave repeat and its dimensions. Ellipsoidal cross-sectional shape was adopted. The error between the calculated and experimental results (length and fiber volume fraction) for z-yarn (binder tow) was attributed to assumption of the staircase shape of the z-yarn. The model was also not generalized to include all possible weave patterns of z-yarn.

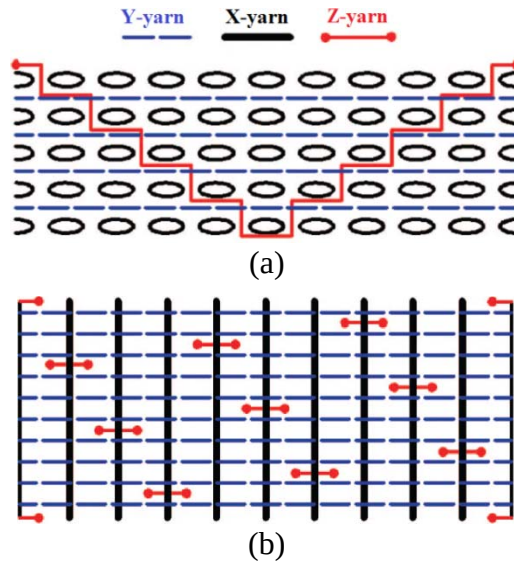


Figure 2.14. 3D angle interlock weave architecture (a): x-yarn cross section, (b): z-yarn cross section [28]

Byun and Chou [29] developed a model to predict fiber volume fraction and elastic constants of three-dimensional angle-interlock fabric composites. They investigated the architecture by identifying the structural and geometric parameters. The structural parameters were total number of weft threads in the preform and the number of weft threads interlocked by warp threads in the thickness directions. A lenticular geometry was assumed for warp and weft threads cross sections in order to represent thread flattening. They determined elastic constants by using the averaging method and tensor transformation to examine the effects of various structural and geometrical parameters on the elastic properties of the composites. They concluded cross-sectional shape of warp/weft threads and the distance between warp threads in the weft direction of the preform are the key parameters that affect the elastic properties of 3D angle interlock woven composites. They stated that as warp threads interlock more layers in the thickness direction, the thread volume fraction increases and thus improve the composite modulus. The model developed by Byun and Chou is only valid for 3D angle-interlock preform and is not generalized for other weaves.

Bogdanovich and Mohamed [30] published a comprehensive literature review for a range of 3D reinforcements including structures with stitching, z-pinned, and woven reinforcements. They provided comprehensive comparison indicating the advantages and shortcomings of each technique in view of in-plane and out-of-plane mechanical properties. They adopted Gu's [17] geometric model and indicated the relationship between in-plane and out-of-plane properties. They theoretically investigated the effect of changing size of z-yarn on fiber volume fraction and mechanical properties of 3D orthogonal woven preforms. It was mentioned that increase in the z-yarn size causes decrease in in-plane fiber volume fraction and formation of large interstitial resin rich areas. Geometries of different z-yarn size are given in Figure 2.15, which clearly shows that the size of interstitial pockets and spacing of in-plane yarns decrease as the z-yarn size decreases.

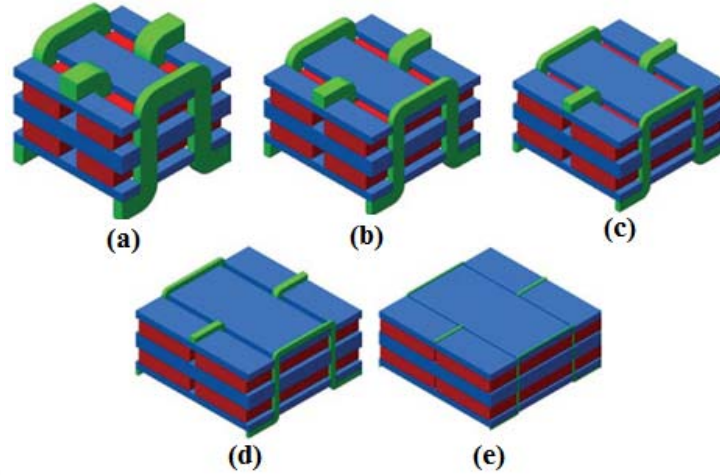


Figure 2.15. Geometric models of 3WEAVE[®] fabrics
[with 12K warp, 12K weft and different size z-yarns: (a) 12K, (b) 6K, (c) 3K, (d) 1K, and (e) 0.1K] [30]

Effect of z-yarn size over fiber-resin volume fractions and modulus in principal directions are given in Figure 2.16. The authors concluded that total fiber volume fraction in composite and in-plane elastic moduli of the composite could be significantly increased by reducing the size of z-yarn. Similarly, the volume of interstitial matrix block (resin rich areas) greatly reduced that enhances in-plane mechanical properties. However, their modeling is limited to 3D orthogonal plain weave. Optimum z-yarn content, minimum volume of resin rich areas, and minimum distortion to in-plane (especially x-) yarns can be achieved by using weave pattern that has more float on the preform surface and less interlacing through-thickness of the preform compared to plain weave.

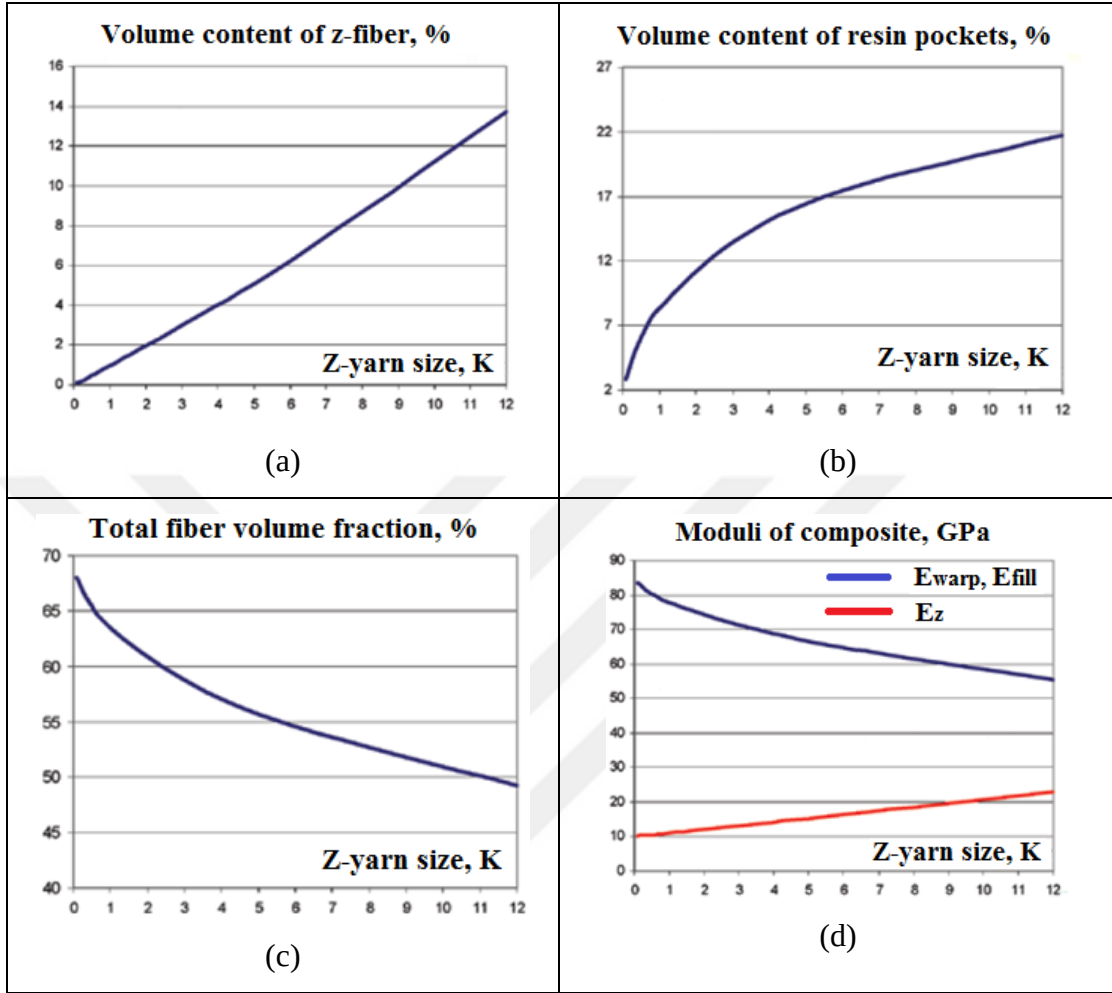


Figure 2.16. Effect of changing size of z-yarn
 [Theoretically predicted variations of z-yarn volume content (a), total volume content of resin pockets (b), total fiber volume fraction in a carbon fiber composite (c) and its elastic moduli in warp-, weft-, and z-directions (d) as functions of z-yarn size] [30]

2.2. Effect of fabric architecture on composite formation and performance

Pearce et al. [31] investigated the effects of preform fabric architecture on the processing (composite manufacturing) performance and ILSS (Interlaminar Shear Strength) of fiber reinforced composites produced by resin transfer molding. They used 2D layered woven fabrics with different weave architectures such as; 2x2 twill, 5-harness satin, and 5-harness satin with flow enhanced tow woven at intervals. Figure 2.17 shows the schematics of the weaves and the micrographs of the final composites. All three fabrics had the same areal density (290 g/m^2), and were woven from the same batch of fiber. The permeability ranking between the fabrics is in the order: twill > satin with flow enhanced tow > satin. The order for ILSS values is; satin > satin with flow enhanced tow > twill. They stated that variations in permeability and ILSS property can be related to fabric architecture and the presence of flow enhancement tow (change in pore space distribution). Flow enhancement tow in satin weave increased pore space area that resulted in more resin rich areas, void content and decrease in ILSS value as compared to regular satin weave. Twill weave, due to its crimped architecture, impeded nesting between layers that increased the pore space area, and permeability, however resulted in minimum ILSS value. Another important result of their study is that fabrics having higher permeability (larger pore space between tows) value resulted in more void content, which is related to resin flow rate difference between tows (channel flow) and inside the tows (capillary flow). They also stated, “There is no discernible relationship between void content and specimen location with respect to the injection ports. Therefore, there is no reason to suspect any influence on measured ILSS values due to specimen location”.

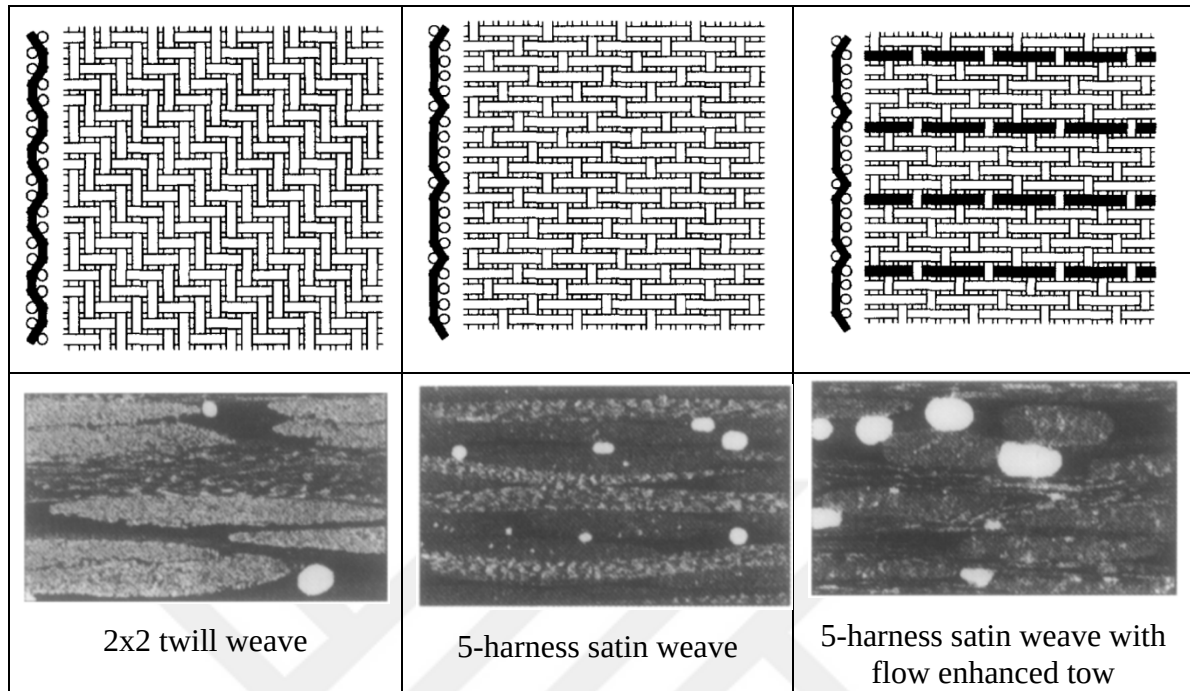


Figure 2.17. 2D woven structures and corresponding micrographs [31]

Thomas [32] used ultrasonic imaging to measure the effect of fabric architecture on through-thickness flow rates during impregnation of an epoxy resin film. He alternately combined ten layers of 2D woven carbon fabrics and epoxy films, which are resin film infusion precursors and manufactured laminates by using vacuum bagging technique. The architecture of woven fabrics is shown in Figure 2.18. Ultrasonic C-scan imaging was performed on the laminates during infusion in a heated water tank (65°C) to be able to monitor reflected intensity, which is proportional to resin front flow through the thickness direction, since resin front flow could not be seen when processing carbon fibers. Figure 2.19 shows reflected intensities versus time for all weave architectures. The shortest impregnation time, which was attributed to ideal tow nesting, was achieved for plain weave, whereas 4x4-twill weave showed the longest infusion time. Infusion rate showed strong dependence on fabric architecture. Fabrics having same areal density were infused with different resin flow rates. Thomas concluded

that impregnation rates were directly affected by inter-tow spacing and tow nesting, which are characteristics of fabric architecture, and were indirectly affected by areal densities.

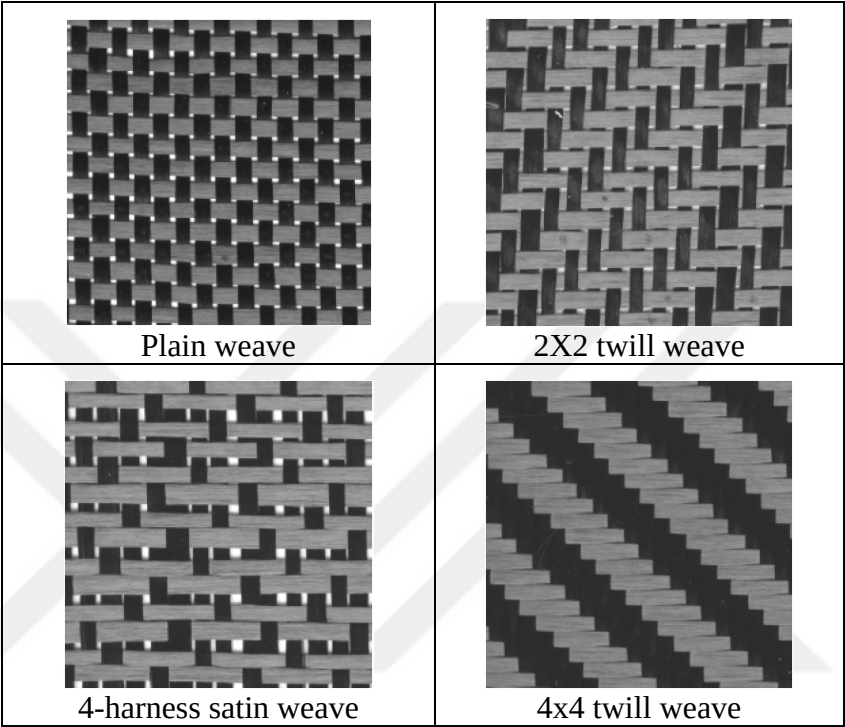


Figure 2.18. 2D fabric architectures
[32]

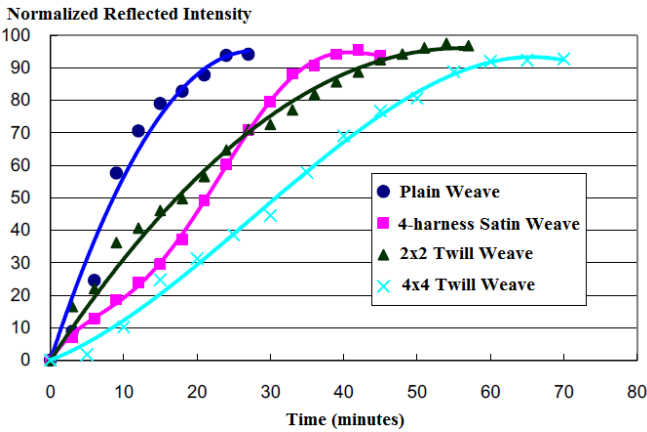


Figure 2.19. Reflected intensities results
[32]

Brandt et al. [33] compared the mechanical performance of 3D orthogonal woven carbon-epoxy composites with 2D laminates and other traditional 3D angle interlock woven composites. They found that the 3D orthogonal weaving process invented by Mohamed and Zhang [14] manufactures preforms, which have superior mechanical properties compared to other conventional preforms. 3D orthogonally woven composites have higher impact energy absorption capacity, and compression after impact properties than 2D laminates and 3D angle interlock woven composites. 3D orthogonal woven reinforcement greatly impeded the delamination such as; compression strength after impact test (at a 6.7 J/mm impact energy level) of 3D orthogonal fabric reinforced composites was 60% higher than the equivalent 2D laminates as shown in Figure 2.20.

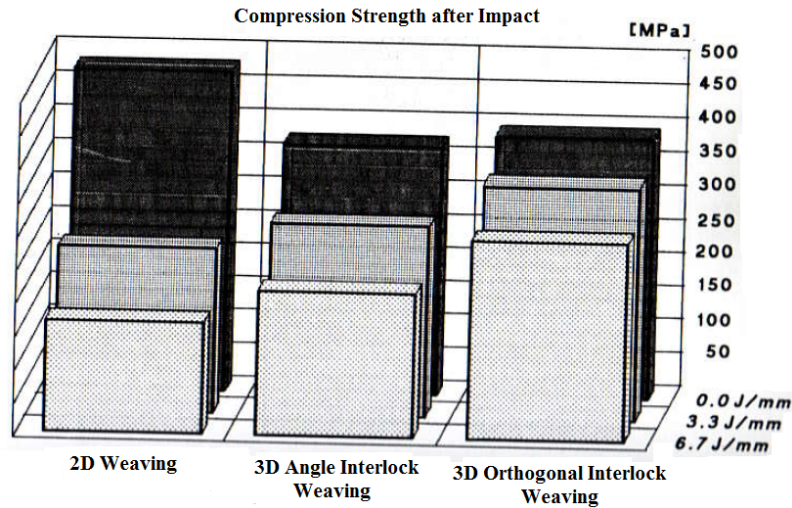


Figure 2.20. Compression strength after impact test [33]

Chou et al. [34] investigated the effect of weave architecture on mechanical (tensile and impact) properties of 3D orthogonal structures from carbon fiber in which z-yarns were introduced by rod replacement method. Figure 2.21 shows axial (0° and 90°) and off-axis ($\pm 45^\circ$) yarn placement in 3D orthogonal weaving process. Variables in Chou's 3D specimens were z-yarn spacing, and reinforcement addition in $\pm 45^\circ$ directions. They compared these

structures with a traditional 2D composite. Tensile strength results of the 2D composite were higher than the 3D composites. 3D composites showed stepwise fracture, and were more deformable (having high strain to failure) than 2D composites. In drop-weight impact tests, 3D structures performed better as compared to 2D structures in terms of maximum load, crack initiation, and propagation energies, which were attributed to presence of z-yarn and off-axis yarns in 3D structures. Bogdanovich and Mohamed [30] indicated 3D orthogonal woven composites produced by 3D weaving machine show better or comparable tensile properties to equivalent 2D laminates that shows the advantages of the 3D weaving technique over rod replacement technique in terms of tensile properties.

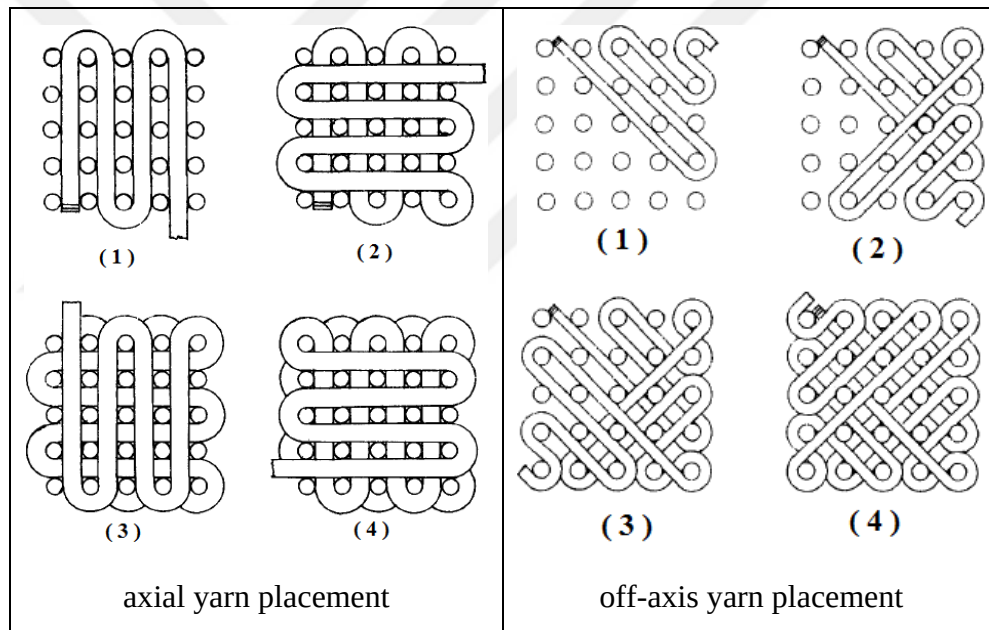


Figure 2.21. Weaving process of 3D orthogonal fabric (z-yarn cross sections) [34]

Portanova [35] investigated impact damage resistance and damage tolerance of three different textile composites. These were stitched and unstitched uniweaves, 2D braids, and 3D weaves. Illustration of the 3D weaves in Portanova's study is given in Figure 2.22. Description of the 3D interlock woven materials in Portanova's study is given in Table 2.2.

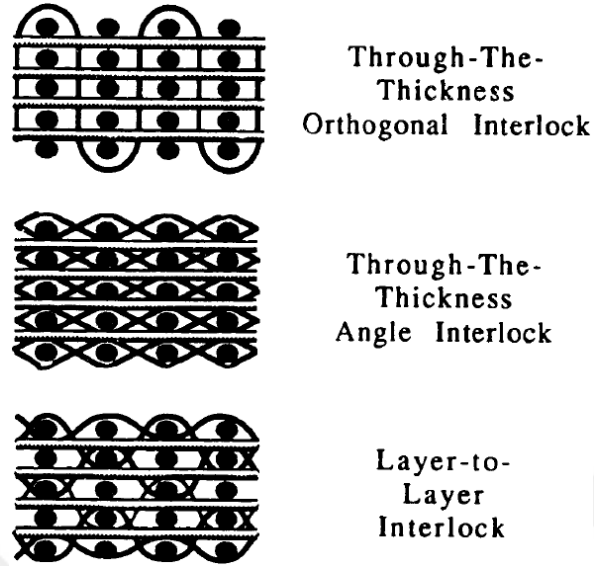


Figure 2.22. Illustration of 3D interlocking materials
(note that the other set of z-yarns of 3D orthogonal preform is not shown) [35]

Table 2.2. 3D interlock woven materials

Name	Description	Warp tow	Weft tow	Weaver (binder) tow
OS-1	Through-thickness orthogonal interlock	24 K (59%)	12 K (33%)	6 K (7.4%)
OS-2		12 K (58%)	6 K (37%)	3 K (6.1%)
TS-1	Through-thickness angle interlock	24 K (57%)	12 K (33%)	6 K (9.8%)
TS-2		12 K (56%)	6 K (38%)	3 K (5.8%)
LS-1	Layer-to-layer interlock	24 K (58%)	12 K (34%)	6 K (6.8%)
LS-2		12 K (57%)	6 K (36%)	3 K (5.9%)

[35]

Thickness was same for all 3D fabrics; therefore, impact response should be an effect of fabric architecture and tow size. It is obvious that thickness of preform decreases as tow size is decreased for a given number of layers. Preform thickness decrease was probably balanced by increasing the number of layers, which was not mentioned in the publication. Impact response of material might be different for different energy levels (strain rate), therefore;

three different impact energy levels were used to get a given indent depth for each level, such as; “Barely Visible Impact Damage Level (20.9 J.)”, “Mean Impact Energy Level (53 J.)”, and “Visible Impact Energy Level (85 J.)”. For each 3D weave fabric class in itself, only the effect of tow size on impact response was investigated. The fabric architecture for each class in itself was not changed, which is plain weave for orthogonal fabrics.

Portanova’s study concluded that all 3D woven materials demonstrated comparable damage resistance at the low impact energy level (Barely Visible Impact Damage). OS-1 material had the worst resistance of the 3D weaves with 53% more damage area than best performing TS-1 at the severe impact level (85 J). 3D weaves showed better damage tolerance in tension than in compression. At low energy impact level (20.9 J.) the OS-2 retained 90% of its unimpacted strength in tension but only 65% in compression. All weaves showed moderate compression performance after impact. In tension after impact tests, TS2 and OS2 showed the best results. 3D weaves with larger tow sizes typically had less damage area. For damage tolerance, large fiber bundles resulted in an increase in post-impact strength but a reduction in the percentage of strength reduction. Specifically, the OS-2 material had highest strength in compression, while the TS-2 sample had the lowest percentage of compression strength retention.

Baucom and Zikry [36] investigated the effect of reinforcement geometry on the progression of impact damage and ultimate perforation failure performance at quasi-static crosshead speeds (10 - 80 $\mu\text{m/s}$) for 2D plain-woven laminates, 3D orthogonal woven laminates, and 3D orthogonal woven monolithic composites. They used S2 glass fiber and Derakane[®] 8084 rubber-toughened epoxy / vinyl ester resin. Vacuum infusion process was used to produce composites. Figure 2.23 shows the composite systems of different architectures with comparable areal density and thickness. Results showed that 3D orthogonal woven laminates had greater damage tolerance than 2D laminates and 3D orthogonal monolithic composites. They indicated damage mechanism of 3D orthogonal woven composites in which extensive straining of the z-reinforcement was frequently observed. They claimed that manipulation

and control of relative properties of the in-plane and z-reinforcements can enable the control of crack initiation, propagation and energy absorption for 3D orthogonal woven preforms.

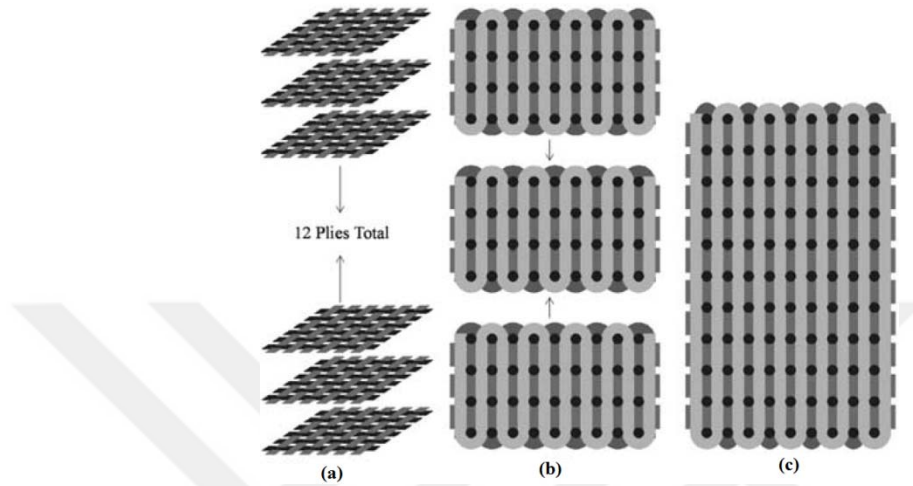


Figure 2.23. Thick composite systems with different architectures
(a) 2D plain-woven laminate, (b) 3D orthogonal woven laminates, and (c) 3D orthogonal woven monolithic composites [36]

Baucom and Zikry [37] investigated the effect of porosity (void content) on three point bending and ballistic impact performance of 3D orthogonal woven composites. Voids were induced by nitrogen gas pressurization. They stated that porous 3D orthogonal composites resulted in weight reduction, while ballistic impact and bending resistance are maintained. They showed that void sites might behave as points where failure surface are deflected and mitigated in bending test. Porous composites showed gradual failure in three point bending which means failure can be controlled in the porous structures compared to nonporous composites where brittle (sudden, abrupt) rupture impedes the failure control. Absorbed energy results were normalized by areal density of composites and referred to as “absorbed specific energy”. The results showed that highly porous composites absorbed more energy than the nonporous ones. The advantage of porous composites in bending and ballistic impact is explained that transverse cracks are deflected by pores, therefore impeding and spreading failure over larger radial areas.

Baucom and Zikry [38] carried out experimental study to gain understanding of the effects of reinforcement geometry on damage progression in woven composites under repeated drop-weight impact loading conditions. Specimens were 2D plain-woven laminate, 3D orthogonal woven structure, and biaxial reinforced warp knit. The energy level was 18 J (at impact velocity of 2 m/s). 3D composites showed greatest resistance to penetration and absorbed more total energy than the other structures. This unique energy absorption and damage spreading capability was attributed to the presence of through-thickness z-yarn. They stated that straining and fracture of z-yarns acted as additional means of energy absorption. 3D composites spread the energy over wider area, which was attributed to in-plane straight warp and weft yarn placement as compared to greatly undulated yarn placement in 2D woven laminate.

Baucom et al. [39] compared impact performance of 2D woven laminates and 3D orthogonal woven composites. They performed repeated drop weight impact test over specimens at an energy level of 44 J. Damage areas and absorbed (dissipated) energy values of 3D woven composites were greater than 2D woven laminates. Higher damage resistance was attributed to unique fabric architecture of 3D orthogonal woven composites, which incorporate crimped portion of z-yarns in their preform structure. At the conclusion part of the study, they stated that modification of the properties of z-yarn should significantly influence the perforation (puncture) resistance and overall behavior of 3D composite systems.

Desplentere et al. [40] explored the potential of X-ray microcomputer tomography to characterize micro-structural variation of 3D orthogonal woven preforms. They measured yarn thickness, width, and spacing through X-ray micro CT images, and compared them with the results obtained from surface and cross section images taken by conventional optical microscope. This comparison indicated that the difference between the two techniques is not statistically significant at a certainty level of 95%. All preforms used in their study were limited to plain weave z-yarn interlacing pattern.

Padaki et al. [41] investigated the influence of preform interlacement on the low velocity impact behavior of multilayer textile composites. They used structure parameter termed interlacement index “I”, which is defined as number of interlacements in warp and weft divided by the maximum possible contact fields (number of crossover points), to determine structure-impact property relationship. They used high tenacity Nylon-6 filament yarn (96 tex) to manufacture multilayer woven preforms using 4-harness, flexible rapier automatic loom. Woven structures shown in Figure 2.24 were 3D preforms woven on 2D machine. They used hand lay-up technique, unsaturated polyester, and ambient temperature to produce composite structures. In view of impact performance the sequence is 3D orthogonal interlock weave > 3D through-thickness angle interlock weave > 3D layer-to-layer angle interlock weave. They concluded that higher interlacement index of reinforcement results in better impact strength. They also developed impact damage area maps to understand the contribution of different damage mechanisms. Figure 2.25 shows the damage area map adopted to classify different impact failure mechanisms. They showed that increase in interlacement decreases fiber failure area (Figure 2.25) and increases interface failure area. The increase in interface failure area indicates that load (transfer) dissipation capability of composite is increased by interlacement.

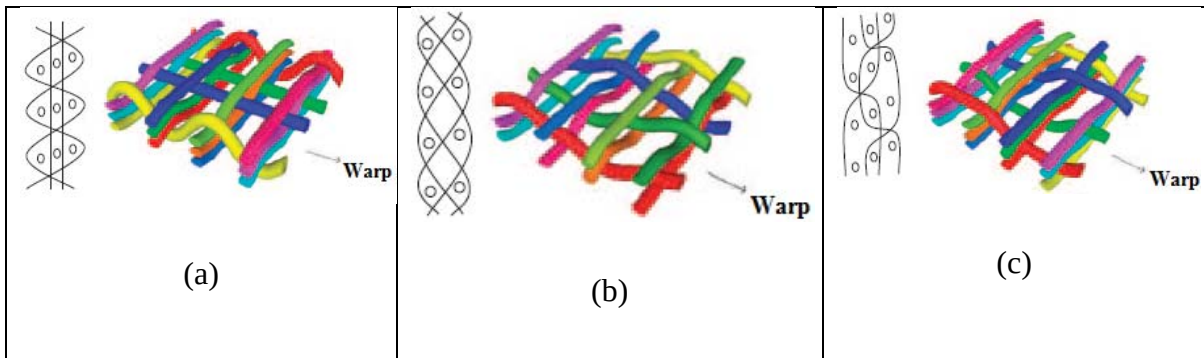


Figure 2.24. Multilayer woven structures
(a) 3D orthogonal interlock weave, (b) 3D through-thickness angle interlock weave,
(c) 3D layer to layer angle interlock weave [41]

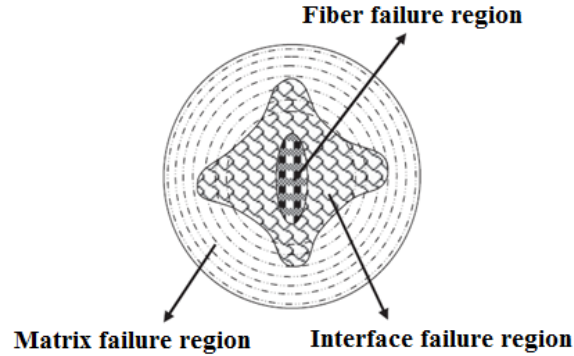


Figure 2.25. Damage area map of impacted specimen [41]

King et al. [42] investigated the influence of z-yarn count on fiber volume fraction, yarn crimp, and damage tolerance on 3D orthogonally 5-harness woven composites. They performed dry preform compression testing to predict FVF by using power law relationship between fiber volume fraction and applied pressure. Their FVF prediction from compression tests and FVF values from density buoyancy tests correlated well for 1 bar and 2 bar process pressure values. They stated that a high degree crimp for z-yarn is required to reduce the amount and size of resin rich areas arising from presence of the z-yarn through-thickness direction. It should be mentioned here that crimp of the z-yarn was controlled by the x-yarn spacing and compaction pressure. The higher the x-yarn spacing is ($1/x\text{-yarn density}$), the lower the z-yarn crimp.

Salem [43] studied bending and shear behavior of 3D orthogonal plain woven composites (3D OPWC). In order to improve bending and shear properties of 3D OPWC, he combined 3D woven preforms with 2D braid preforms (on both surfaces of 3D woven preforms) by using braiding machine. He changed braid yarn size (6K, 9K, 12K), and braid yarn angle (ranging from 30 to 64 degrees) as structural parameters. He did not change any structural parameters of 3D woven preforms. He used hot press (compression molding) to produce composites from single (monolithic) 3D, and 3D woven plus 2D braid combined preforms. He picked two different consolidation pressures (572 and 848 kPa). In addition, he investigated the effect of preform heating just before the infusion process. He used short

beam shear and bending (flexural) tests to measure interlaminar (transverse) shear properties, and Iosipescu's shear test to measure in-plane shear properties. Preform heating and increasing consolidation pressure increased bending and shear resistance. He showed that bending and shear properties of 3D orthogonal woven preforms can be improved by adding uniformly covered, thin layer 2D braid to both surfaces of the 3D preform before consolidation. He achieved the highest in-plane shear properties in the case of 45 degree braid angle. He did not measure any impact properties. However, adding 2D braid layer on both surfaces of 3D woven preforms may affect impact behavior, such as crack initiation and propagation profiles are expected to be affected by the presence of off-axis yarns on the surface such as initiated crack may be constricted or spread over a wider area by 2D braid layer.

Gu [17] produced 3D woven composites with different size of z-yarn (3K, 6K, 9K, and 12K) for analytical and mechanical performance tests. As z-yarn size is increased, in-plane fiber volume fractions and correspondingly in-plane mechanical properties decreased. He also did low velocity impact test and mentioned that z-yarn size has negligible effect on impact and post impact performance. However, his impact test device was non-instrumented, and he did not get puncture at the end of impact test by increasing the energy level. In order to evaluate complete energy absorption capability of composite specimen, a full puncture on specimen, and zero force detection on striker are required at the end of the impact test. He also mentioned that more tests such as bending, in-plane shear, and interlaminar shear tests are required to evaluate the effect of z-yarn size on composite mechanical performance.

Bogdanovich and Mohamed [30] indicated through-thickness reinforcement advantage of 3D orthogonal woven preforms over stitching and z-pinning by referencing Figure 2.26. In contrast to stitching and z-pining, z-yarn placement in 3D woven orthogonal preforms does not significantly distort fabric architecture and damage in-plane yarns (breaks and/or splits into two parts). However, it still decreases in-plane fiber volume fraction, and creates resin rich areas, which are very susceptible to cracks formation-coalescence-propagation. In order to decrease in-plane yarn distortion and formation of resin rich areas, weave patterns other

than plain weave, which incorporates less interlacing or through-thickness penetration per unit area of preform, should be used in composite production. However, all design options of their study shown in Figure 2.15 consist of plain weave pattern.

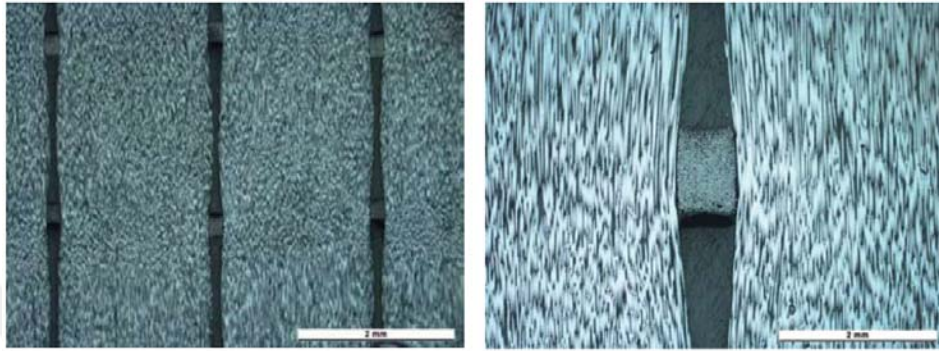


Figure 2.26. Z-yarn cross section of 3D orthogonal plain woven composite [30]

The main aim to introduce through-thickness reinforcement is to be able to combat undesirable failure mechanisms in 2D laminates. 3D structures behave similar to 2D laminates in elastic regime, however, in plastic regime where stress is redistributed, and damage accumulation occurs, 3D structures respond quite differently compared to 2D laminates due to presence of through-thickness reinforcement. Therefore, amount and geometry of through-thickness reinforcement element should be thoroughly investigated for designs requiring analysis beyond yield (proportional) limit. Previous studies were limited to jammed plain woven 3D orthogonal preforms. Limiting z-yarn interlacing pattern to plain weave in jammed configuration does not allow investigating fabric architecture potential of 3D orthogonal woven preforms. Infusion performance (measured by resin flow front) of preforms with architectures of different z-yarn interlacing pattern and resultant composites' mechanical performance beyond yield point in which through-thickness reinforcement plays a great role should be investigated. Additionally, impact damage resistance, post impact tensile and compression strengths, in-plane and interlaminar shear resistance properties should be investigated for different z-yarn interlacing patterns. The current study addresses limitation of previous studies, which are mainly focused on plain weave. This study is

designed to reveal architecture potential of 3D orthogonal woven preforms that may lead to better understanding of relationship between the weave designs of z-yarn, which control the amount of through-thickness reinforcement. Plain weaves have the highest amount of z-yarns in the thickness direction, which causes reduction of in-plane fiber volume fraction that leads to deterioration of in-plane properties. Reduction of z-yarn interlacing using other than plain weave may enhance the in-plane properties without reduction in the other performance (interlaminar) properties.



2.3. Effect of composite manufacturing technique on thickness variability

It is critically important to select a manufacturing technique, which is suitable to produce a composite product that has required performance characteristics for a specific application. In this study, vacuum infusion process (VIP), which is a subclass of the resin infusion techniques, was used to manufacture composites.

2.3.1. Resin infusion techniques

There are many varieties of resin infusion techniques used by composite industry. Common steps for all resin infusion techniques are; placement of dry preform into mold cavity, closing of mold, injection of liquid resin, and complete wetting of dry preform with liquid resin. After full wetting, resin cures and mold is opened and solid composite structure is taken out [44]. Generally, resin infusion technologies are divided into two main groups namely pressurized injection (resin injected by an injection pump), and vacuum-assisted injection.

Resin transfer molding (RTM, pressurized injection)

Resin transfer molding for composites is the same process that is being used in plastic industry for plastic molding. Resin is transferred into the two-sided closed molding by means of pressure. Therefore, it is possible to get smooth surfaces for both faces of composite. Thickness of composites can be adjusted by changing the distance between two rigid surfaces of mold. Injection pressure is generally less than 100 psi or 689 kPa (generally 30 psi or 207 kPa). It is important that mold should be rigid enough not to be distorted by injection pressure. High injection pressure also distorts nature of reinforcement, which is called fiber wash.

Hayward and Harris [45] investigated the effects of process variables (vacuum assistance, injection pressure, mold temperature, and viscosity) on the quality of RTM. They concluded that high level of reproducibility is possible, and vacuum assistance improves mechanical properties by decreasing void content. Quality of moldings was not affected by variations in resin injection. It was found that mechanical properties of high volume percent glass/polyester and carbon/epoxy composites made by RTM are almost equal to hot pressed

(compression molded) composites. Resin transfer molding is more controllable as compared to VIP, which was described in the following section [46].

Vacuum infusion process (VIP)

Application of pressure in VIP is different than RTM. Pressure is applied into the evacuated mold cavity by atmosphere itself. A vent is opened where last part of dry preform is desired to be wetted. Atmospheric pressure (14.7 psi or 101 kPa) is used for resin flow. There is no need to use two-sided rigid tooling in VIP. One side of tooling is rigid, and other side is flexible vacuum bag. Therefore, tooling cost is lower compared to RTM. VIP is very eligible for large composite parts manufacture. However, surface of composite, which is in contact with vacuum bag, is not smooth. When mold cavity is evacuated, vacuum bag collapses over preform surface and take shape of dry preform surface contour. Therefore, part thickness variation in VIP is higher than RTM [47].

Presence of flexible vacuum bag on one side of the molding in VIP totally changes the nature of the process compared to conventional RTM. In VIP, the thickness of the preform changes during the process, which directly affect resin filling time and permeability of the preform. Resin pressure, which is the driving force for the flow, changes locally as the resin flow front propagates. Change in resin pressure results in change in compaction of preform (Figure 2.27), therefore, the permeability and porosity of the preform change which leads to change in the final composite thickness due to more resin toward the inlet than toward the outlet [48] [49]. For example, any increase in resin pressure inside the mold cavity decreases the compaction force on the preform, which results in change in local fiber volume fraction and permeability [50]. Hence, the performance of the composite is expected to vary from part to another in the same panel.

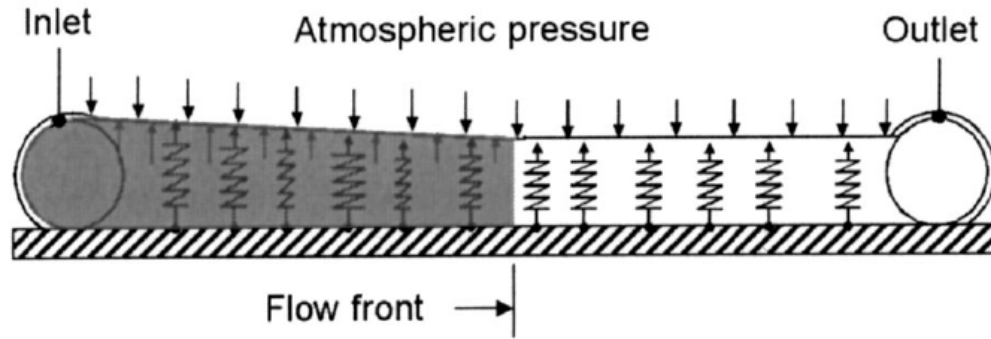


Figure 2.27. Effect of fluid pressure on compaction in vacuum infusion [48]

Before unclamping of the resin inlet at the beginning of the process, while preform is under vacuum, pressure inside the mold cavity is equal to vacuum pump pressure, and compaction stress on the preform is the difference between atmospheric pressure and vacuum pressure. Once the inlet is unclamped, the resin pressure inside the mold cavity increases which leads to decrease in compaction stress over the preform. Decrease in compaction stress results in change in preform thickness depending on the local resin pressure. Once the mold is filled (resin flow front reaches to outlet), the inlet is clamped, and this section of the process is called post-filling (bleeding). During post-filling, the vacuum pump is still running, and the resin pressure inside the mold cavity both decreases and equilibrates. Therefore, compaction stress over the preform is increased and preform thickness is decreased [50].

Figure 2.28 shows composite thickness (h) is a function of time (t) in vacuum infusion, whereas thickness is independent from the time for RTM during infusion. Figure 2.29 shows the effect of fluid pressure on preform compaction in vacuum infusion.

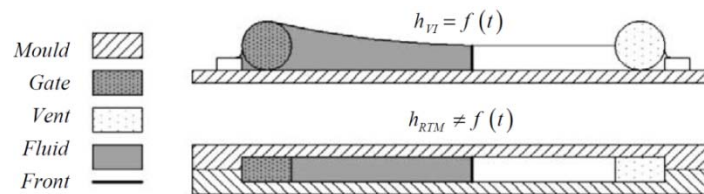


Figure 2.28. Thickness distribution in vacuum infusion (top) and RTM (bottom) [51]

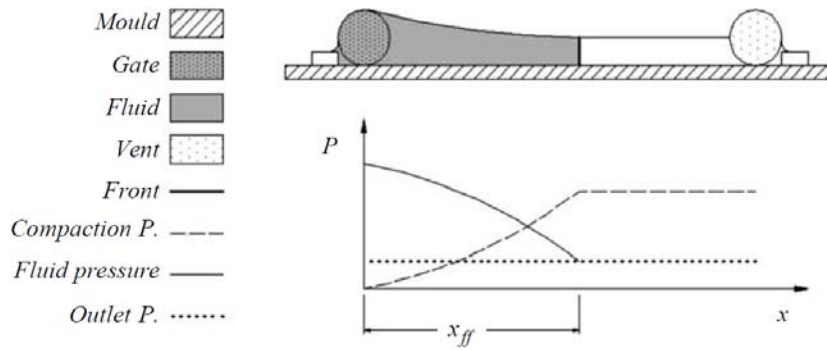


Figure 2.29. Schematic of effect of fluid pressure on compaction in vacuum infusion [51]

Govignon et al. [50] monitored thickness and resin pressure change along the length of preform during filling and post-filling of vacuum infusion process. They used biaxial stitched fabric and continuous filament mat as preform. Great changes both in thickness and resin pressure were observed during both in filling and post-filling section as shown in Figure 2.30. Changes of the parameters in post-filling process occurred on a larger period. They also investigated the effect of distribution media, which resulted in shorter fill time. Continuous filament mat resulted in reduced fill time and significantly higher flow rate compared to biaxial stitched fabric. Govignon and his co-workers concluded that there is a large difference between filling and post filling duration in view of thickness and pressure distribution, and the part reaches its final shape and quality during post-filling process. Therefore, it is important to control that part of the process.

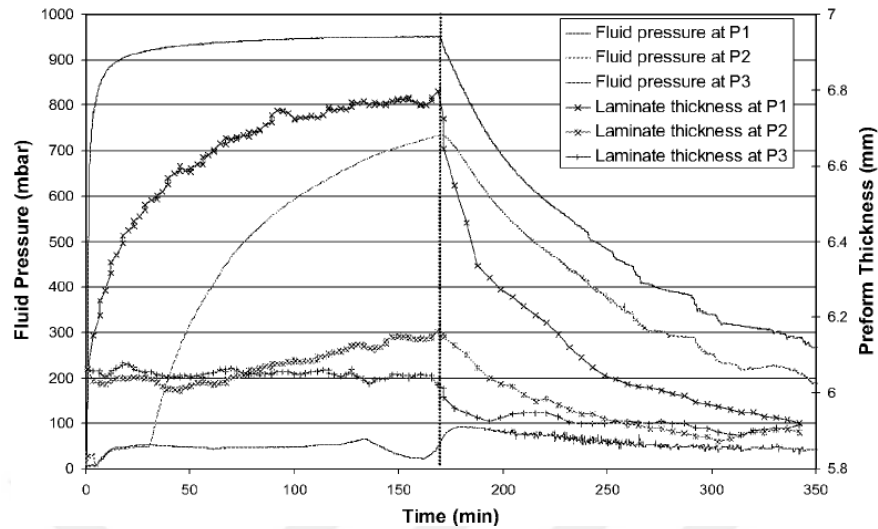


Figure 2.30. Evolution of pressure and laminate thickness during vacuum infusion [50]

Rigas et al. [52] investigated effect of processing conditions on vacuum assisted resin transfer molding process (VARTM). They concluded that thickness variation can be significant, and to some degree, random; in addition, pre-compaction of the preform significantly influences the amount of consolidation pressure needed during infusion. They also stated that dimensional variations due to gradients in the pressure distribution of the vacuum affect permeability (and hence resin flow), as well as dimensional tolerances in manufactured parts. They concluded that VIP is satisfactory for lower fiber volume fraction, thin composites those are used in non-structural/non-ballistic applications, however for thick and high fiber volume applications; the process must be optimized.

Anderson et al. [53] applied digital speckle photography to measure thickness variation in the vacuum infusion process. They used non-crimp fabric stack and a continuous strand mat on top of the fabric stack in order to enhance the flow. Polyester resin penetrated from center of the preform stack with radial flow. Resin inlet was clamped as complete saturation of the stack was achieved. Vacuum was kept at the outlet until curing of the resin. They observed a reduction in thickness in all directions starting from the origin and moving toward the sample

edges. Figure 2.31 shows the thickness variation during the infusion process. The overall decrease in thickness was found rather large, about 10% of the total final thickness.

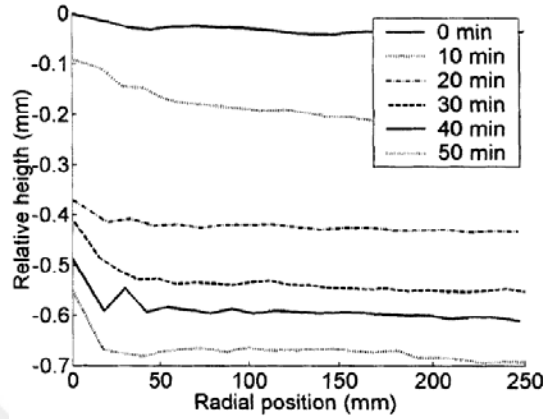


Figure 2.31. Thickness variation before, during, and after injection (zero-height represents the initial thickness and taken as reference) [53]

Bayldon and Daniel [54] modeled the flow in vacuum infusion process. They also compared their model with experimental study including 2D plain weave fabric (16 plies) and continuous filament random mat (4 plies) and silicone oil as resin. The thickness changes were measured using moiré system. Pressure profile of vacuum infusion of 2D plain weave stack predicted by the model is given in Figure 2.32. Similar pressure profile was also predicted for continuous filament random mat.

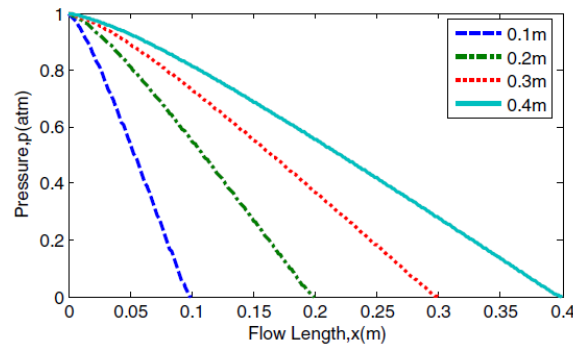


Figure 2.32. Predicted pressure profiles for resin flow in plain weave fabric [54]

The results show that as flow progresses the pressure gradient at the inlet end becomes very small. They stated that the effect is observed in actual molded components, where the inlet end of the infusion becomes ‘baggy’ and the inlet flow rate becomes very low, even though the flow front is still moving. Figure 2.33 shows the change in thickness profile for the plain weave material. They obtained good thickness profile agreement between model and experiment for saturated region in contrast to unsaturated flow front region, which controls the minimum thickness.

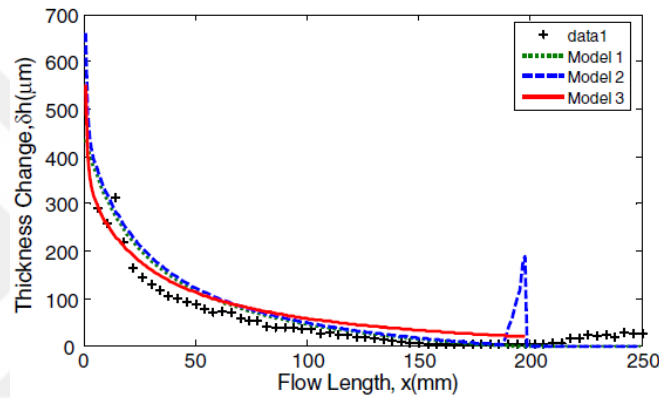


Figure 2.33. Predicted and measured thickness profiles for plain weave glass fabric [54]

Correia et al. [51] measured thickness variation in vacuum infusion. They used 12 layers of chopped strand mat as preform, and polyester resin using a line injection. After curing, the panel thickness was measured at 26 points. Final thickness profile is given in Figure 2.34. It was shown that the thickness is clearly dependent on position. Higher local fluid pressure at the inlet reduces compaction pressure on the preform and increases thickness. It was reported that the total difference in thickness was 2.2 mm, which corresponds to 22% of the average thickness of the panel.

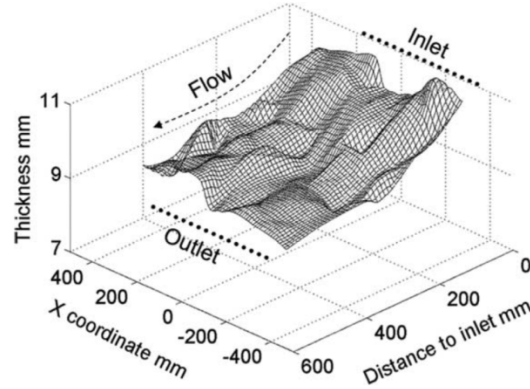


Figure 2.34. Final thickness of a vacuum infused continuous strand mat panel [51]

Correia et al. [51] developed a flow model for vacuum infusion. The model included pressure field prediction and preform compaction. They used the model results to determine distribution of fiber volume fraction and thickness at any point of time including curing time corresponding to final composite. Figure 2.35 shows the model predictions for fiber volume fraction and thickness of six layer stitched bidirectional fabric. They indicated that the thickness data could be used to predict resin consumption. Further, they speculated that the data could be used to predict the local mechanical properties. However, predicting such properties in terms of thickness alone is oversimplified since other parameters such as fiber volume fraction and voids are also varied in terms of sample location.

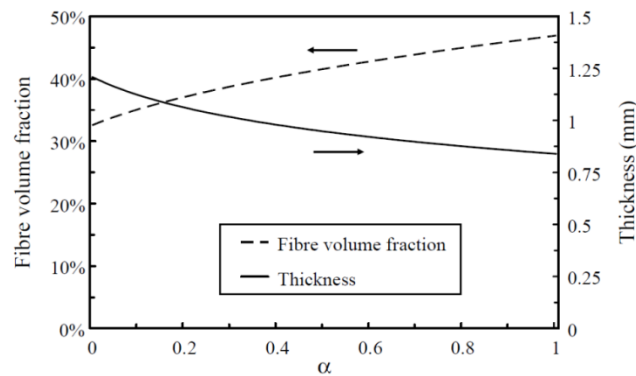


Figure 2.35. Thickness and fiber volume fraction as a function of location (for stitched biaxial fabric stack with a surface density of 1 kg/m^2) [51]

Hae Park et al. [55] proposed analytical flow model and closed form solutions of vacuum infusion process. They obtained resin pressure profile and fabric compaction stress distribution in closed form solutions. By using fabric compaction stress distribution, they analyzed thickness and fiber volume fraction variation during vacuum infusion process. They used the same input properties of the preform used in Correia et al. [51] work. Fiber volume fraction and thickness profile of Hae Park et al. study are given in Figure 2.36.

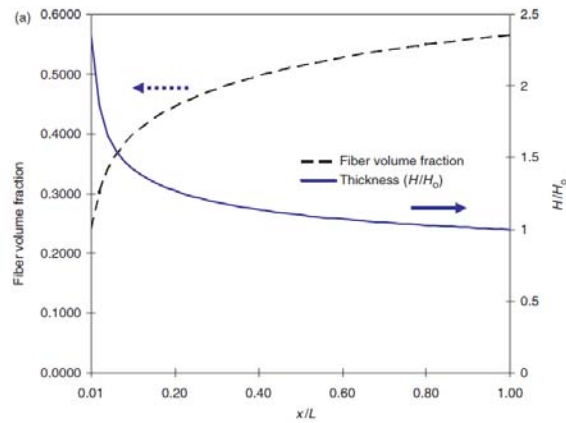


Figure 2.36. Variation of fiber volume fraction and fabric thickness in vacuum infusion [55]

Resin flow and absorption of the resin by preform must be evaluated thoroughly in order to produce nonporous, void-free composites by vacuum infusion. Resin flow within preform occurs in two scales such as; macro and micro flow. Macro resin flow that occurs between tows may be visually tracked by using transparent molding. Resin flow between tows is faster than the resin flow within tows between individual fibers. Resin absorption rate is directly affected by inter-tow spacing, which is dictated by fabric architecture. However, areal density indirectly affects the resin infusion rate. Overall, resin infusion rate is affected by fabric architecture, which incorporates macro (inter-tow spacing) and micro porosity (configuration of fibers inside the tow) of fabric, and flow direction [32] [47].

Any preform fabric architecture cannot provide all desired mechanical properties as converted into composite. Similarly, there is no one composite manufacturing technique that

provides all desired properties to final composite. Therefore, a systematic study to investigate effect of preform architecture and manufacturing technique on analytical and mechanical properties of composites is required for a given preform type and a given composite manufacturing technique [15].

The literature review on the effect of composite manufacturing technique on composite thickness variability showed that the focus of research was on the variation of resin pressure, composite thickness, fiber volume fraction, and there was no research found that address the impact of such variability on the mechanical performance of the final composite in terms of sample location. Additionally, none of the previous research dealt with 3D orthogonal woven composites.

In this work, 3D orthogonal woven preforms with different fabric architectures were woven and converted into composites by VIP. The effect of VIP on performance properties of sample in terms of sample location with respect to the resin inlet was investigated.

3. OBJECTIVES

Weaving process converts yarns into well-oriented and regular structures to meet performance requirements that cannot be matched with other processes. The yarn spacing in each (warp and weft) set may be tuned exactly as desired. The process is also very versatile such as, by changing only one construction (structural) parameter, numerous woven structures with different properties can be attained. Any change in yarn count, yarn spacing, or weave (interlacing) pattern results in a new “Fabric Architecture”. The extents and configuration of both channels between adjacent tows (yarns) and capillary channels between individual fibers within a yarn in woven structure are determined by fabric architecture. When a woven fabric is used as preform for composite manufacturing, resin flow within the fabric is directly affected by the dimension and configuration of the channels or fabric architecture. Because resin flow front and its characteristics determine the cost and composite part quality and has an effective role on manufacturing of void free composite, fabric architecture strongly affects composite quality. Fabric architecture is also directly related to the permeability, which determines the infusion time known as cycle time in composite manufacturing process.

Understanding the fabric architecture of preform and its effects on resin infusion is crucial to produce a composite in a short time with target mechanical properties. Because of these reasons, and due to lack of research mentioned in previous studies, the main objectives of the present study are addressed below.

One of the objectives of the present work is to investigate the effect of fabric architecture on resin flow time for a range of 3D orthogonally woven preforms. For this purpose, 3D woven preforms with different fabric architectures were produced by changing the z-yarn interlacing pattern, number of layers, weft yarn density, and vacuum (–ve pressure) level. It is possible to produce preforms with same areal density but different fabric architecture by changing the z-yarn interlacing pattern. Previous works on the area of 3D orthogonally woven fabric were generally limited to plain weave. In this study, in addition to preforms with plain weave

pattern (considered as control), preforms with basket and twill weave patterns were produced with same areal densities and their resin flow front profiles and infusion times were compared. The industry is generally using 100 kPa (full) vacuum pressure to increase productivity. The question that was answered in this study is the quality of composites produced by lower vacuum level compared to full vacuum composites. Two different vacuum levels (75 and 100 kPa) were chosen for this purpose. It may also be thought that 75 kPa vacuum levels simulates one quarter of vacuum leakage. On the other hand, lower resin flow front speed in 75 kPa may result in better wetting and saturation of dry preform by decreasing the rate difference between hydrodynamic (inter tow) and capillary (intra tow) flow. The analytical and mechanical properties of the composite panels produced with different vacuum levels were compared to decide the compromise between production speed (vacuum level) and the quality of the composite.

The second objective is to investigate the performance of range of 3D woven composites as impacted by fabric architecture (number of y-yarn layers, x-yarn density, and weave pattern) and pressure used during VIP. Additional significant parameter considered here is the effect of sample location on the performance of the composite. The effect of location on analytical (thickness, fiber volume fraction, void content) and mechanical (tensile, flexure, impact) properties of the composite are also considered. The specimens were tracked according to their position relative to resin inlet. The change of each property from inlet to outlet was investigated for each panel. The independent parameters considered in objective one are considered here as well. One of the drawbacks of composite structures is their variable thickness, which may result from variability of resin volume fraction due to infusion time. Relating the variation of the performance of composites with sample location in terms of composite architecture and VIP parameters and cycle time may reveal the best blend of parameters that provide uniform composite structure.

The third objective of the present study is to develop a generalized geometric model to predict thickness, areal density, and fiber volume fraction of 3D orthogonally woven preforms in terms of yarns and preform construction parameters including weave. Input

parameters of the model are yarn material volumetric density, yarn packing factor, yarn cross-sectional shape (circular, racetrack, and rectangular), yarn linear density, yarn spacing, number of layers and interlacing pattern of z-yarn. The model is generalized that considers predicting parameters mentioned earlier for any weave pattern for orthogonal (jammed) and non-orthogonal structures. The model revealed fabric architecture potential of 3D orthogonal woven preforms, and show how to control z-yarn reinforcement content by means of interlacing pattern (weave) change. Z-yarn fiber volume fraction predictions of newly developed model for weave designs other than plain weave will enable to produce preforms with targeted in-plane and out-of-plane properties. The model will also help to predict mechanical properties accurately since these are tightly related to the fiber volume fraction, areal density, amount of through-thickness z-yarn segments. The model was verified experimentally for broad range of experimental fabrics.

4. GENERALIZED GEOMETRIC MODELS OF 3D ORTHOGONAL WOVEN PREFORMS

This chapter was dedicated to develop the theory for generalized geometric models of 3D orthogonal preforms from single ply spun and flat filament yarns.

4.1. Generalized geometric model of 3D orthogonal woven preforms from spun yarns

Most of composite products are generally produced from epoxy resin and tows of continuous flat filaments that are manufactured from petroleum precursors. Much of the published research addressed such composites. The decrease in petroleum reserves and negative impact on the environment prompted the composite producers to seek alternatives to reduce the need for petroleum-based products. The most promising solution is “green composites” from natural fibers and resins [56] [57]. Yarns spun from natural fibers are twisted and thus possess different geometry (tend to form circular cross section) and structure compared to continuous filament yarns. Therefore, 3D woven preform construction parameters, and resultant geometry from natural staple fibers are totally different than the preforms from filament yarns.

The lack of research in developing generalized model, which are extensively reviewed in Chapter 2.1, prompted us to undertake this research. Our objective is to develop a generalized model for non-jammed and jammed 3D orthogonal woven preforms predicting preform thickness, preform areal density, FVF of structure constituents and minimum thread (x-, y-, and z-yarn) spacing to achieve jammed construction in terms of weave factor, number of layers, yarn cross-sectional shape (circular in case of spun yarns covered in this section), and constituents' variables (yarn arrangement, linear density, packing factor, and fiber volumetric density).

A consistent system of nomenclature capable of representing the preform structural parameters is given in Appendix A.

4.1.1. Assumptions and generalized modeling strategy

To simplify derivation of geometrical relationships, the following assumptions are set considering spun (or twisted) yarns:

1. x-, y-, and z-yarns are uniform cylinders
2. x-, y-, and z-yarns are completely flexible, inextensible, and incompressible
3. x- and y-yarn spacing is uniform in case of non-jammed structures
4. Following assumptions in regards to jammed structures are considered:
 - i. x-, y-, and z-yarns are uniform cylinders
 - ii. x-yarns under weave float form single racetrack shape with height identical to the original yarn diameter
 - iii. y-yarns between z-yarns assume racetrack shape with height identical to the original yarn diameter

While a spun yarn is not uniform cylinder, assumption 1, originally assumed by Peirce and Womersley [18], has been proven to be reasonable and easy to calculate from yarn linear density, fiber density, and packing factor. Yarns from natural staple fibers such as cotton, wool, jute, hemp, sisal, kenaf, and flax (which established themselves in composite applications due to their sustainability and friendliness to the environment [56] [57]) must be twisted to increase the coherence between the fibers. Therefore, the cross-sectional shape of spun yarns tends to be circular due to lateral forces caused by twist. This section of study focuses on modeling preforms from spun yarns.

Yarn diameter (cm), is calculated according to generalized formula [58] given below.

$$d_k = \frac{1}{280.2} * \sqrt{\frac{\rho_{\ell k}}{\Phi_k \rho_{vk}}} \quad (4.1.)$$

While yarns are not completely flexible, assumption 2 in the context of this research is close enough for the purpose of predicting the parameters of interest. The thread spacing is uniform for both non-jammed and jammed plain woven preforms. However, the thread spacing for

other weaves in case of non-jammed structure shows in reality larger thread spacing at a weave interlacing compared to the spacing under a float. Again, this difference is not predictable since it depends on numerous parameters and cause complexity in modeling if the difference is considered. It has been shown that assumption 3 is reasonable for prediction of geometrical relationship in 2D woven structures [59].

The assumption of racetrack shape of yarns under float has been proven to be reasonable as indicated by Love [60] and Seyam and El-Sheik [59]. The racetrack cross-sectional shape indicates the average thread spacing is smaller than yarn diameter and provides preforms with higher FVF. The yarns tend to form close shape to racetrack by thread spacing that can be controlled by beat-up force, warping and reed of the weaving machine that maintains the spacing during weaving. Figures 4.1 – 4.4 show 3D orthogonal woven structures that fit the assumptions of the cases considered.

4.1.2. Generalized model for non-jammed structures with circular yarns

Figure 4.1 shows the isometric view (a) and one repeat (b) of 3D orthogonal plain woven preform along with its dimension (c). The structure is formed of several layers of y-yarn, several layers of x-yarn (which exceeds y-yarn layers by 1), and two sets of z-yarn that are woven oppositely.

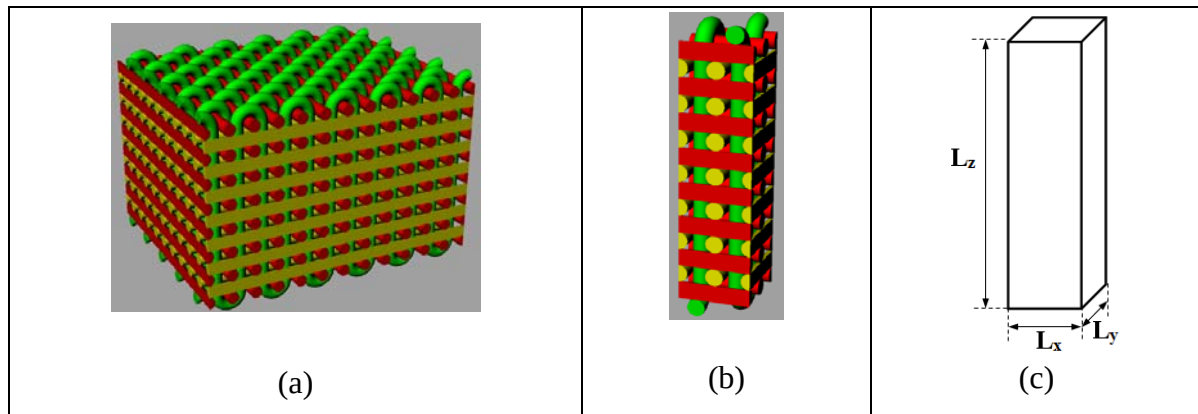


Figure 4.1. 3D orthogonal woven fabric (jammed plain weave)
(a) isometric view, (b) weave repeat, (c) dimensions of the weave repeat
● y-yarn, ● x-yarn, ● z-yarn

Regardless of weave pattern, the preform thickness L_z is a function of diameters of constituent yarns and number of layers and can be written as

$$L_z = n_y d_y + n_x d_x + 2d_z \quad (4.2.)$$

For any weave, preform volume per weave repeat is given by

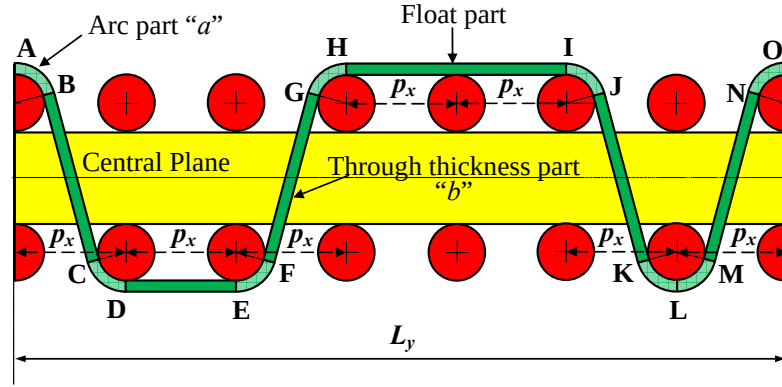
$$V_{repeat} = L_x L_y L_z \quad (4.3.)$$

Figure 4.2 shows a generalized non-jammed weave structure with circular yarn cross section in which x-yarn spacing (p_x) and y-yarn spacing (p_y) are uniform. Weave repeat length (L_y) for non-jammed weave structure is

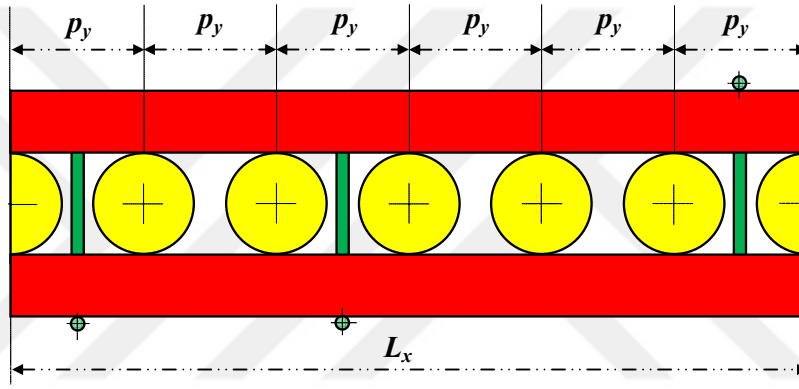
$$L_y = N_x p_x \quad (4.4.)$$

Weave repeat width (L_x) for non-jammed structures is given by

$$L_x = N_y p_y \quad (4.5.)$$



a



b

Figure 4.2. Generalized non-jammed structure with circular yarn cross section
a: x-yarn cross section, b: y-yarn cross section (x-yarn in red, y-yarn in yellow, and z-yarn in green)

4.1.3. Generalized model for jammed structures with circular yarns

Figure 4.3 shows the maximum construction for the circular yarn cross section case. For jammed case, in contrast to unique x-yarn spacing (p_x) in non-jammed structure, there are two different spacing; one at interlacing and another under the z-yarn float. The spacing at interlacing (p_{xi}) is equal to the sum of the x- and z-yarn diameters ($d_x + d_z$). On the other hand, the spacing under the float (p_{xf}), where two successive x-yarns touch without compression, is equal to x-yarn diameter (d_x).

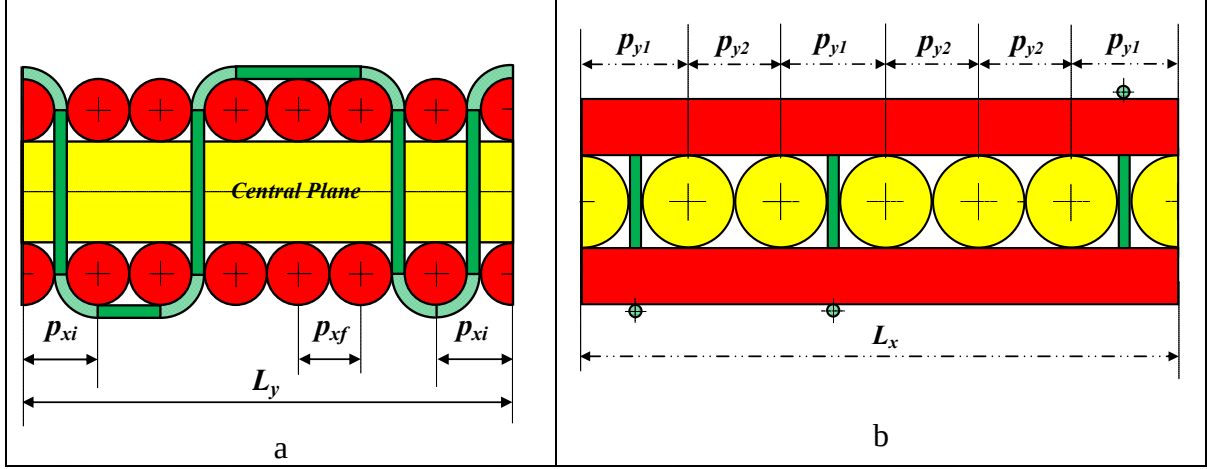


Figure 4.3. Generalized jammed structure with circular yarn cross section
a: x-yarn cross section, b: y-yarn cross section

For the maximum construction shown in Figure 4.3.a, the repeat length is given by

$$L_y = N_x \bar{p}_x \quad (4.6.)$$

Average x-yarn spacing ($\bar{p}_x$) in terms of M_z is given by

$$\bar{p}_x = \frac{M_z d_x + d_z}{M_z} \quad (4.7.)$$

Equation 4.7 provides average x-yarn spacing ($\bar{p}_x$) for any weave, which is the minimum average spacing required to obtain jammed structures with circular yarns. This is a design parameter required to obtain jammed structures with circular yarns. The weaving machines can be pre-programmed to set the $\bar{p}_x$ to desired value that is controlled by the take-up mechanism and beat-up force.

Similarly, there are two y-yarn spacing ($p_{y1} = d_y + d_z$ and $p_{y2} = d_y$) as it can be seen from Figure 4.3.b.

Following equation shows the weave repeat width (L_x)

$$L_x = N_y \bar{p}_y \quad (4.8.)$$

The $\bar{p}_y$ is calculated from

$$\bar{p}_y = \frac{N_y d_y + N_z d_z}{N_y} \quad (4.9.)$$

The warp spacing ($\bar{p}_y$) is a design parameter which is controlled by the y-yarn density during warping and maintained by the reed of the weaving machine. This is the average minimum spacing required to achieve jammed constructions with circular yarns.

4.1.4. Generalized model for jammed structures with racetrack yarn cross section

Figure 4.4 shows generalized maximum construction for racetrack shape. For this case, there are two types of x-yarn spacing; one at the interlacing ($p_{xi} = d_x + d_z$), and one under the z-yarn float [$p_{xf} = (\pi/4) d_x$].

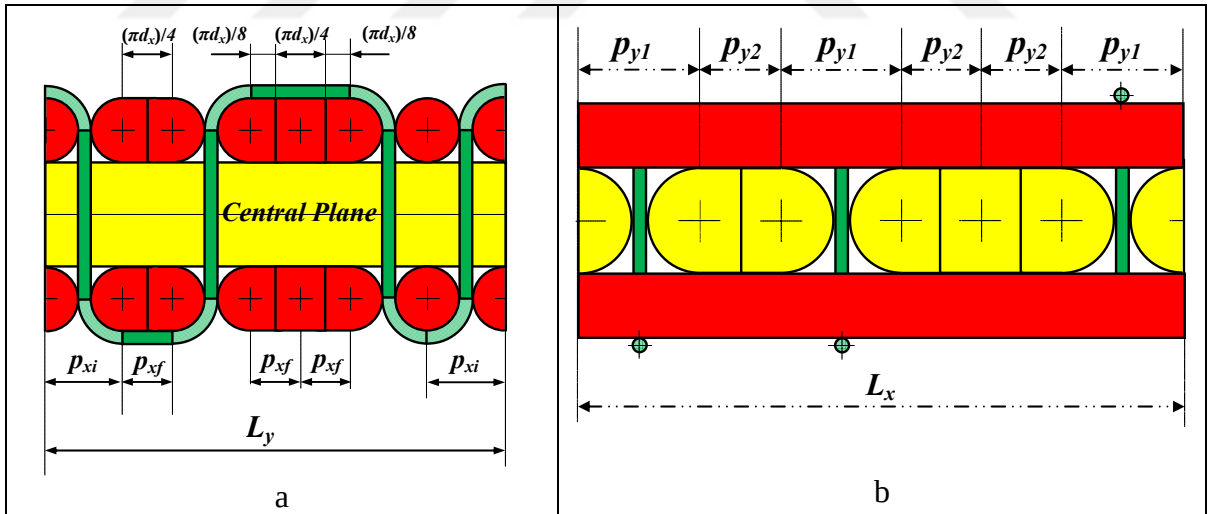


Figure 4.4. Generalized jammed structure with racetrack yarn cross section
a: x-yarn cross section, b: y-yarn cross section

The weave repeat length (L_y) for jammed structures with yarns of racetrack cross-sectional shape can be calculated from

$$L_y = N_x \bar{p}_x \quad (4.10.)$$

The average x-yarn spacing (minimum spacing), which is key design parameters needed for formation of such jammed structures with racetrack cross section, is expressed as

$$\bar{p}_x = \frac{\frac{\pi}{4} M_z d_x + \left(1 - \frac{\pi}{4}\right) d_x + d_z}{M_z} \quad (4.11.)$$

There are two different y-yarn spacing [$p_{y1} = d_y + d_z$, and $p_{y2} = (\pi/4) d_y$] and, weave repeat width for jammed structure with racetrack cross-sectional shape is;

$$L_x = N_y \bar{p}_y \quad (4.12.)$$

The average y-yarn spacing, which is the minimum spacing required to weave such jammed structures with racetrack yarn cross section, can be calculated from the repeat size and number of spacing per repeat as

$$\bar{p}_y = \frac{N_z(d_y + d_z) + (N_y - N_z) \frac{\pi}{4} d_y}{N_y} \quad (4.13.)$$

4.1.5. Fiber volume fractions (FVFs) of x- and y-yarns

The y- and x-yarns are laid straight and therefore, their lengths in weave repeat can be calculated from the generalized unit repeat dimensions.

Total x-yarn length within the weave repeat (ℓ_x) is the product of one x-yarn length (L_x), number of x-yarns per layer per weave repeat (N_x), and number of x-yarn layers (n_x) as

$$\ell_x = L_x N_x n_x \quad (4.14.)$$

Similarly; total y-yarn length within the weave repeat (ℓ_y) is

$$\ell_y = L_y N_y n_y \quad (4.15.)$$

Fiber volume of a yarn in weave repeat (V_{fk}) is

$$V_{fk} = \frac{\ell_k \rho_{\ell k}}{\rho_{vk} 10^5} \quad (4.16.)$$

FVF of a yarn (F_{fk}) is the ratio of the fiber volume of the yarn in weave repeat (V_{fk}) to total weave repeat volume (V_{repeat}) and is expressed in % as

$$F_{fk} = \frac{V_{fk}}{V_{repeat}} 100 = \frac{\frac{\ell_k \rho_{\ell k}}{\rho_{vk} 10^3}}{L_x L_y L_z} \quad (4.17.)$$

Substituting equations 4.2, 4.4, 4.5, and 4.14 into equation 4.17 results in x-yarn FVF equation for non-jammed structures with circular yarns,

$$F_{fx} = \frac{\frac{n_x \rho_{\ell x}}{\rho_{vx} 10^3}}{p_x (n_y d_y + n_x d_x + 2d_z)} \quad (4.18.)$$

Substituting equations 4.2, 4.6, 4.7, 4.8, 4.9, and 4.14 into equation 4.17, we get x-yarn FVF equation for jammed structures with circular yarns,

$$F_{fx} = \frac{\frac{n_x \rho_{\ell x}}{\rho_{vx} 10^3}}{\left[\frac{d_z}{M_z} + d_x \right] (n_y d_y + n_x d_x + 2d_z)} \quad (4.19.)$$

Substituting equations 4.2, 4.10, 4.11, 4.12, 4.13, and 4.14 into equation 4.17, we get x-yarn FVF equation for jammed structures with racetrack yarns,

$$F_{fx} = \frac{\frac{n_x \rho_{\ell x}}{\rho_{vx} 10^3}}{\frac{1}{N_x} \left[\frac{(d_x + d_z)}{M_z} + \left(1 - \frac{1}{M_z} \right) \frac{\pi}{4} d_x \right] (n_y d_y + n_x d_x + 2d_z)} \quad (4.20.)$$

Substituting equations 4.2, 4.4, 4.5, and 4.15 into equation 4.17 results in y-yarn FVF equation for non-jammed structures with circular yarns,

$$F_{fy} = \frac{\frac{n_y \rho_{\ell y}}{\rho_{vy} 10^3}}{p_y(n_y d_y + n_x d_x + 2d_z)} \quad (4.21.)$$

Substituting equations 4.2, 4.6, 4.7, 4.8, 4.9, and 4.15 into equation 4.17, we get y-yarn FVF equation for jammed structures with circular yarns,

$$F_{fy} = \frac{\frac{N_y n_y \rho_{\ell y}}{\rho_{vy} 10^3}}{[N_z(d_y + d_z) + (N_y - N_z)d_y](n_y d_y + n_x d_x + 2d_z)} \quad (4.22.)$$

Substituting equations 4.2, 4.10, 4.11, 4.12, 4.13, and 4.15 into equation 4.17, we get y-yarn FVF equation for jammed structures with racetrack yarns,

$$F_{fy} = \frac{\frac{N_y n_y \rho_{\ell y}}{\rho_{vy} 10^5}}{[N_z(d_y + d_z) + (N_y - N_z)\frac{\pi}{4}d_y][n_y d_y + n_x d_x + 2d_z]} \quad (4.23.)$$

4.1.6. FVF of z-yarn

Z-yarn within the weave repeat consists of horizontal straight parts (floats) on top or on the bottom surface of the preform, arcs at cross-overs, and through-thickness tilted (in non-jammed structure) or through-thickness vertical parts (in jammed structure).

For non-jammed structures, the weave angle (θ) is

$$\theta = \tan^{-1} \left(\frac{2p_x \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) + \sqrt{\left(-2p_x \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) \right)^2 - 4(p_x^2 - (d_x + d_z)^2) \left(\left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right)^2 - (d_x + d_z)^2 \right)}}{2(p_x^2 - (d_x + d_z)^2)} \right) \quad (4.24.)$$

Derivation of the weave angle (θ) is given in Appendix B.

The arc length of the z-yarn for non-jammed and jammed structures

$$a = \left(\frac{d_x}{2} + \frac{d_z}{2} \right) \theta \quad (4.25.)$$

Through-thickness tilted part length (b) of z-yarn for non-jammed structure can be calculated by using equations 4.26.

$$b = \frac{p_x - 2 \left(\left(\frac{d_x + d_z}{2} \right) \sin \theta \right)}{\cos \theta} \quad (4.26.)$$

For jammed structures with circular or racetrack yarns, through-thickness vertical part is calculated by the equation defined below;

$$b = n_y d_y + (n_x - 1) d_x \quad (4.27.)$$

The total z-yarn length (ℓ_z) in weave repeat consists of through-thickness parts, arc portions, and floats (straight horizontal parts). Float length is calculated through x-yarn spacing (p_x). However, the length of each arc and through-thickness tilted part are related to the maximum angle of the z-yarn axis to the plane of the cloth (θ , radians).

Each interlacing consists of two arc parts and one through-thickness tilted part (Figure B.1 in Appendix B), where $\widehat{AB} = \widehat{CD}$ is arc length (a), and $\overline{BC}$ is through-thickness part length (b).

In Figure 4.2.a, the length of one z-yarn per weave repeat is the sum of arc parts, through-thickness tilted parts, and float parts as described below;

$$= \widehat{AB} + \overline{BC} + \widehat{CD} + \overline{DE} + \widehat{EF} + \overline{FG} + \widehat{GH} + \overline{HI} + \widehat{IJ} + \overline{JK} + \widehat{KL} + \overline{LM} + \widehat{MN} + \overline{NO}$$

where

$$a = \widehat{AB} = \widehat{CD} = \widehat{EF} = \widehat{GH} = \widehat{IJ} = \widehat{KL} = \widehat{LM} = \widehat{NO}$$

$$b = \overline{BC} = \overline{FG} = \overline{JK} = \overline{MN}$$

The sum of the arc parts' length = $2ai_z$

The sum of the through-thickness tilted parts' length = bi_z

The sum of float parts' length = $(N_x - i_z)p_x$

For open structure p_x is equal to itself.

For circular jammed structure; $p_x = d_x$

For racetrack jammed structure; $p_x = \frac{\pi}{4} d_x$

Total length of z yarns per weave repeat for non-jammed structure is;

$$\ell_z = [2ai_z + bi_z + (N_x - i_z)p_x]N_z \quad (4.28.)$$

If a flattening parameter e , which is equal to unity for jammed structure with circular yarns and $\pi/4$ for jammed structure with racetrack cross section, is defined; then total length of z yarns per weave repeat for jammed structures is;

$$\ell_z = [2ai_z + bi_z + (N_x - i_z)ed_x]N_z \quad (4.29.)$$

Substituting M_z , and equations 4.2, 4.4, 4.5, and 4.28 into equation 4.17 results in z-yarn FVF equation for non-jammed structures with circular yarns,

$$F_{fz} = \frac{\left[\frac{2a}{M_z} + \frac{b}{M_z} + \left(1 - \frac{1}{M_z} \right) p_x \right] N_z \rho_{\ell z}}{\rho_{vz} 10^3} \quad (4.30.)$$

Substituting equations 4.2, 4.6, 4.7, 4.8, 4.9, and 4.29 (with flattening factor of unity) into equation 4.17, we get z-yarn FVF equation for jammed structures with circular yarns,

$$F_{fz} = \frac{\frac{[2a + b + (M_z - 1)d_x]N_z\rho_{\ell z}}{\rho_{vz}10^3}}{[N_z(d_y + d_z) + (N_y - N_z)d_y][d_z + M_z d_x][n_y d_y + n_x d_x + 2d_z]} \quad (4.31.)$$

Substituting equations 4.2, 4.10, 4.11, 4.12, 4.13, and 4.29 (with flattening factor of $\pi/4$) into equation 4.17, we get z-yarn FVF equation for jammed structures with racetrack yarns,

$$F_{fz} = \frac{\frac{[2a + b + (M_z - 1)\frac{\pi}{4}d_x]N_z\rho_{\ell z}}{\rho_{vz}10^3}}{[N_z(d_y + d_z) + (N_y - N_z)\frac{\pi}{4}d_y][d_x + d_z + (M_z - 1)\frac{\pi}{4}d_x][n_y d_y + n_x d_x + 2d_z]} \quad (4.32.)$$

The total FVF in the weave repeat (F_{fxyz}) is the sum of FVFs of x-, y- and z-yarn.

$$F_{fxyz} = F_{fx} + F_{fy} + F_{fz} \quad (4.33.)$$

Substituting equations 4.18, 4.21, 4.30 into equation 4.33 results in total FVF for non-jammed structures with circular yarns,

$$F_{fxyz} = \frac{\frac{n_x\rho_{\ell x}}{\rho_{vx}10^3}}{p_x(n_y d_y + n_x d_x + 2d_z)} + \frac{\frac{n_y\rho_{\ell y}}{\rho_{vy}10^3}}{p_y(n_y d_y + n_x d_x + 2d_z)} + \frac{\frac{[2a + b + (M_z - 1)\frac{\pi}{4}d_x]N_z\rho_{\ell z}}{\rho_{vz}10^3}}{N_y p_y p_x (n_y d_y + n_x d_x + 2d_z)} \quad (4.34.)$$

Substituting equations 4.19, 4.22, 4.31 into equation 4.33 results in total FVF for jammed structures with circular yarns

F_{fxyz}

$$\begin{aligned}
&= \frac{\frac{n_x \rho_{\ell x}}{\rho_{vx} 10^3}}{\left[\frac{d_z}{M_z} + d_x \right] (n_y d_y + n_x d_x + 2d_z)} + \frac{\frac{N_y n_y \rho_{\ell y}}{\rho_{vy} 10^3}}{\left[N_z (d_y + d_z) + (N_y - N_z) d_y \right] (n_y d_y + n_x d_x + 2d_z)} \\
&+ \frac{\frac{[2a + b + (M_z - 1) d_x] N_z \rho_{\ell z}}{\rho_{vz} 10^3}}{\left[N_z (d_y + d_z) + (N_y - N_z) d_y \right] [d_z + M_z d_x] [n_y d_y + n_x d_x + 2d_z]} \quad (4.35.)
\end{aligned}$$

Substituting equations 4.20, 4.23, 4.32 into equation 4.33, we get total FVF for jammed structures with racetrack yarns

F_{fxyz}

$$\begin{aligned}
&= \frac{\frac{n_x \rho_{\ell x}}{\rho_{vx} 10^3}}{\frac{1}{N_x} \left[\frac{(d_x + d_z)}{M_z} + \left(1 - \frac{1}{M_z} \right) \frac{\pi}{4} d_x \right] (n_y d_y + n_x d_x + 2d_z)} \\
&+ \frac{\frac{N_y n_y \rho_{\ell y}}{\rho_{vy} 10^3}}{\left[N_z (d_y + d_z) + (N_y - N_z) \frac{\pi}{4} d_y \right] [n_y d_y + n_x d_x + 2d_z]} \\
&+ \frac{\frac{[2a + b + (M_z - 1) \frac{\pi}{4} d_x] N_z \rho_{\ell z}}{\rho_{vz} 10^3}}{\left[N_z (d_y + d_z) + (N_y - N_z) \frac{\pi}{4} d_y \right] \left[d_x + d_z + (M_z - 1) \frac{\pi}{4} d_x \right] [n_y d_y + n_x d_x + 2d_z]} \quad (4.36.)
\end{aligned}$$

4.1.7. Total weight of dry preform

Total weight of dry preform is calculated by;

$$W_{xyz} = \frac{[\ell_x \rho_{\ell x} + \ell_y \rho_{\ell y} + \ell_z \rho_{\ell z}]}{10 L_x L_y} \quad (4.37.)$$

Substituting M_z , equations 4.4, 4.5, 4.14, 4.15, and 4.27 into equation 4.37 results in total weight of dry preform for non-jammed structures with circular yarns

$$W_{xyz} = \frac{\left[N_y p_y n_x \rho_{\ell x} + p_x N_y n_y \rho_{\ell y} + \left[\frac{2a}{M_z} + \frac{b}{M_z} + \left(1 - \frac{1}{M_z} \right) p_x \right] N_z \rho_{\ell z} \right]}{10 N_y p_y p_x} \quad (4.38.)$$

Substituting equations 4.6, 4.7, 4.8, 4.9, 4.14, 4.15, and 4.28 (with flattening parameter of unity) into equation 4.37 results in total weight of dry preform for jammed structures with circular yarns

$$W_{xyz} = \frac{[N_z(d_y + d_z) + (N_y - N_z)d_y] M_z n_x \rho_{\ell x} + [d_z + M_z d_x] N_y n_y \rho_{\ell y} + [2a + b + (M_z - 1)d_x] N_z \rho_{\ell z}}{10[N_z(d_y + d_z) + (N_y - N_z)d_y][d_z + M_z d_x]} \quad (4.39.)$$

Substituting equations 4.10, 4.11, 4.12, 4.13, 4.14, 4.15, and 4.28 (with flattening parameter of $\pi/4$) into equation 4.37 results in total weight of dry preform for jammed structures with racetrack yarns

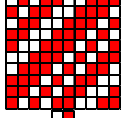
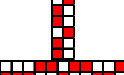
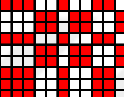
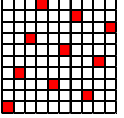
$$W_{xyz} = \frac{\left[[N_z(d_y + d_z) + (N_y - N_z)\frac{\pi}{4}d_y] M_z n_x \rho_{\ell x} + [d_x + d_z + (M_z - 1)\frac{\pi}{4}d_x] N_y n_y \rho_{\ell y} + [2a + b + (M_z - 1)\frac{\pi}{4}d_x] N_z \rho_{\ell z} \right]}{10 \left[N_z(d_y + d_z) + (N_y - N_z)\frac{\pi}{4}d_y \right] \left[d_x + d_z + (M_z - 1)\frac{\pi}{4}d_x \right]} \quad (4.40.)$$

4.1.8. Numerical results and discussion

This section is devoted to presenting numerical results calculated from the derived geometrical relationships for hypothetical structures. The impacts of weave and z-yarn linear density on 3D woven preform structural parameters namely constituents and total FVF, thickness, and dry preform areal density are presented graphically.

Table 4.1 shows range of weaves, considering numerous weave designs not previously considered, used to investigate the effect of weave. The weaves are represented graphically and numerically by the weave factor M_z that ranges from 1 to 5. The weave factor is a representative of the number of through the thickness z-components. To study the influence of z-yarn size, three levels of z-yarn linear density were considered. These are 500, 1000, 2000 (g/km or tex).

Table 4.1. Weaves considered for the numerical results

Weave	N_x	i_z	M_z	Weave design
Plain or any filling rib weave	2	2	1.00	
2x1 warp rib	3	2	1.50	
3x2, 2x1, 1x1 twill (multiple)	10	6	1.67	
2x1, 2x2 warp rib	7	4	1.75	
3x2, 1x2, 2x1 basket	11	6	1.83	
2x2 warp rib	4	2	2.00	
3x3, 2x1 warp rib	9	4	2.25	
3x2 warp rib	5	2	2.50	
3x3 warp rib	6	2	3.00	
4x3 warp rib	7	2	3.50	
4x4 warp rib	8	2	4.00	
10-H. sateen	10	2	5.00	

Numerical results for non-jammed structures with circular yarns

Table 4.2 shows input parameters, which were kept unchanged, along with their values used for non-jammed structures.

Table 4.2. Constant input parameters for non-jammed structures with spun yarns

ρ_{vk}	$\rho_{\ell x} = \rho_{\ell y}$	Φ_k	n_y	y-yarn/layer : z-yarn	p_x	p_y
1.5 g/cm ³	2000 tex	0.65	7	1:1	0.46 cm	0.46 cm

Figure 4.5, which was generated from equations 4.18, 4.21, 4.30, 4.34, shows the effect of weave represented by weave factor and z-yarn linear density on constituents and total FVF for non-jammed structures with circular yarns. For a given weave factor, increasing z-yarn linear density resulted in increase in z-yarn and total FVF, and decrease in x- and y-yarn fiber volume fractions. The effect of z-yarn linear density on z-yarn and total fiber volume fraction is more pronounced for low weave factors due to high number of through-thickness components in such weaves. For a given z-yarn linear density, the weave affects the fiber volume fraction of z-yarn, whereas it has no effect on fiber volume fractions of x-, and y-yarns. Decreasing number of interlacing of z-yarn (increasing weave factor) resulted in decrease in z-yarn and total FVF due to decrease in through-thickness components of z-yarn.

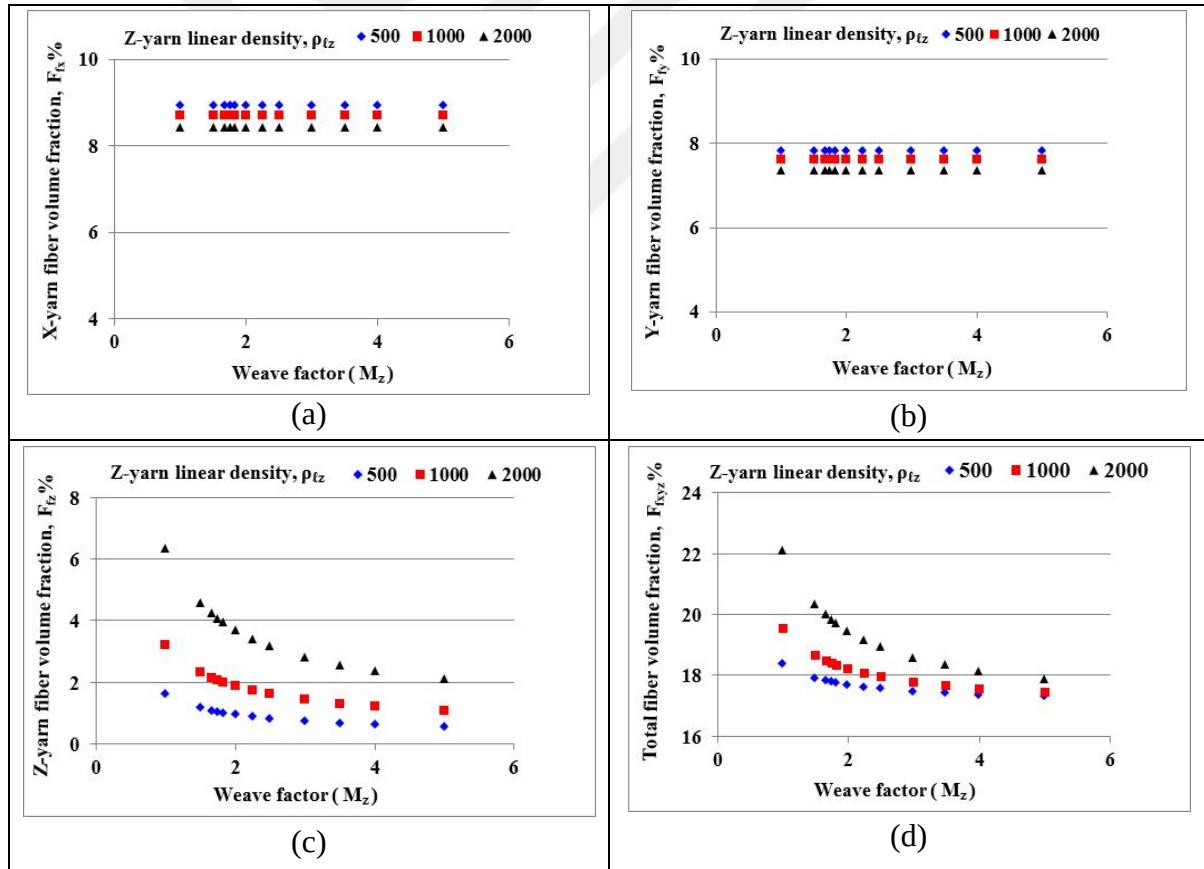


Figure 4.5. Effect of weave factor and z-yarn linear density on constituents and total FVF for non-jammed structure with circular yarn cross section
(a) x-yarn FVF, (b) y-yarn FVF, (c) z-yarn FVF, (d) total FVF

The results of Figure 4.5 can be explained from the results of the effect of weave and z-yarn linear density on preforms thickness and areal density shown graphically in Figure 4.6 (data generated from equations 4.2 and 4.38). Weave pattern has no effect on preform thickness. However, increasing z-yarn linear density caused an increase in preform thickness. The total areal density decreased with weave factor due to decrease in the amount of through the thickness components of the z-yarn. The increase in areal density as a result of increase in z-yarn linear density is more significant for preforms with low weave factor than those with long float.

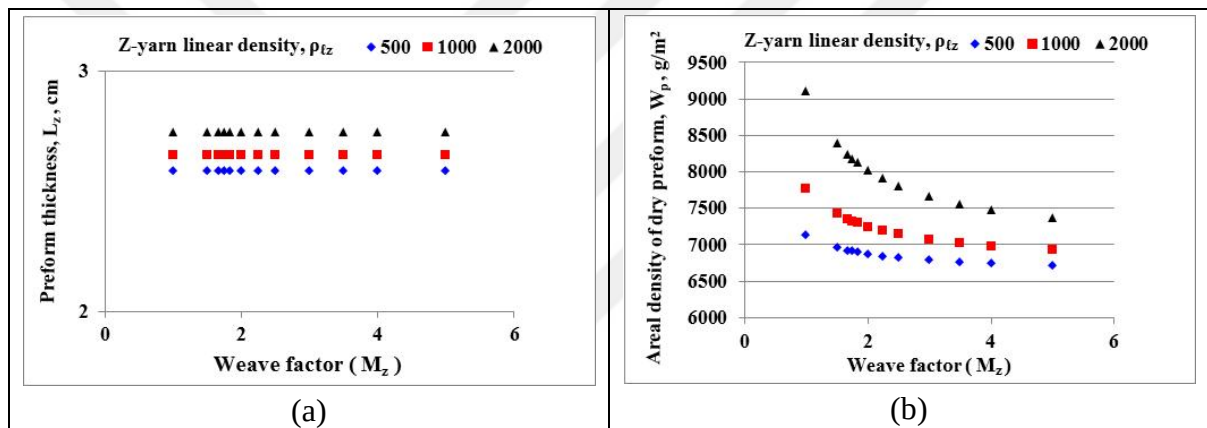


Figure 4.6. Effect of weave factor and z-yarn linear density on preform thickness (a), and areal density (b) for non-jammed structures with circular yarns

Numerical results for jammed structures with circular cross section

Table 4.3 shows the constant input variables to calculate preform parameters for jammed structure with circular yarns.

Table 4.3. Constant input variables for jammed structures with spun yarns

ρ_{vk}	$\rho_{\ell x} = \rho_{\ell y}$	Φ_k	n_y	y-yarn/layer : z-yarn
1.5 g/cm ³	2000 tex	0.65	7	1:1

Figure 4.7 shows the effect of weave factor and z-yarn linear density on constituents and total

FVF for jammed structures with circular yarns. Equations 4.19, 4.22, 4.31, and 4.35 were used to generate data of Figure 4.7. For a given weave, increase in z-yarn linear density caused increase in the z-yarn fiber volume fraction and decrease in the x- and y-yarn fiber volume fractions. The decrease in x- and y-yarn FVF is higher compared to the increase in z-yarn FVF and hence as z-yarn linear density gets higher the total FVF gets lower. The effect of z-yarn linear density on z-yarn FVF for preforms with low weave factor is more pronounced compared to those with high weave factor. Changing weave type from plain to 10-harness satin weave for a given z-yarn linear density, decreased z-yarn FVF due to decrease in through-thickness components of z-yarn, increased x-yarn fiber volume fraction due to accommodation of more x-yarns under z-yarn float, and has no effect on y-yarn fiber volume fraction. The increase in x-yarn FVF is more than the decrease in z-yarn volume fraction and hence the total FVF increased with weave factor.

While the effect of z-yarn linear density on the z-yarn FVF is similar to the non-jammed structures in that the influence is more pronounced for the structures with low weave factor, the effect on the total FVF is more significant for preforms with weaves of long floats (or high value of weave factor).

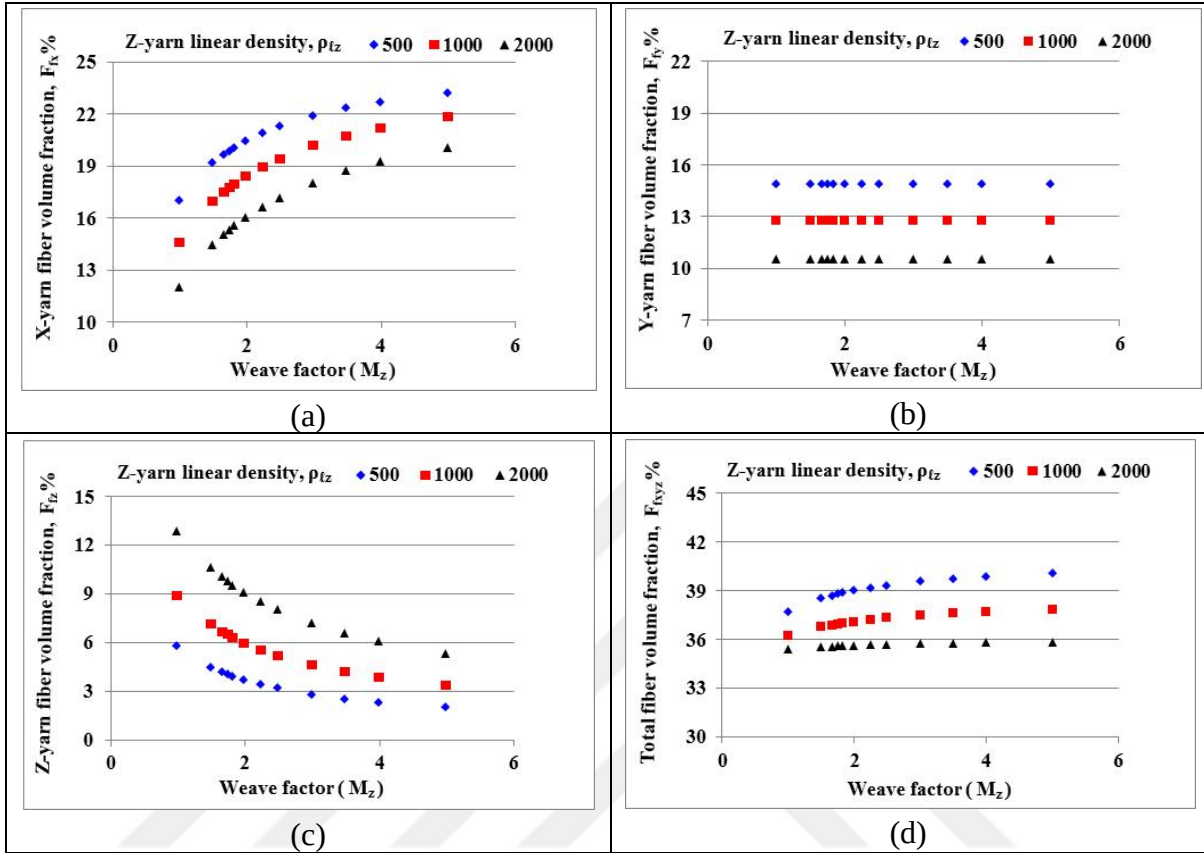


Figure 4.7. Effect of weave factor and z-yarn linear density on constituents and total FVF for jammed structures with circular yarn cross section

The reason for the trends seen in Figure 4.7 can be explained by the results of preform thickness and areal density depicted in Figure 4.8, generated from equations 4.2 and 4.39. In contrast to non-jammed structures, as weave factor is increased the total areal density of preform gets higher and the effect of z-yarn linear density on preform areal density is more significant for high weave factors.

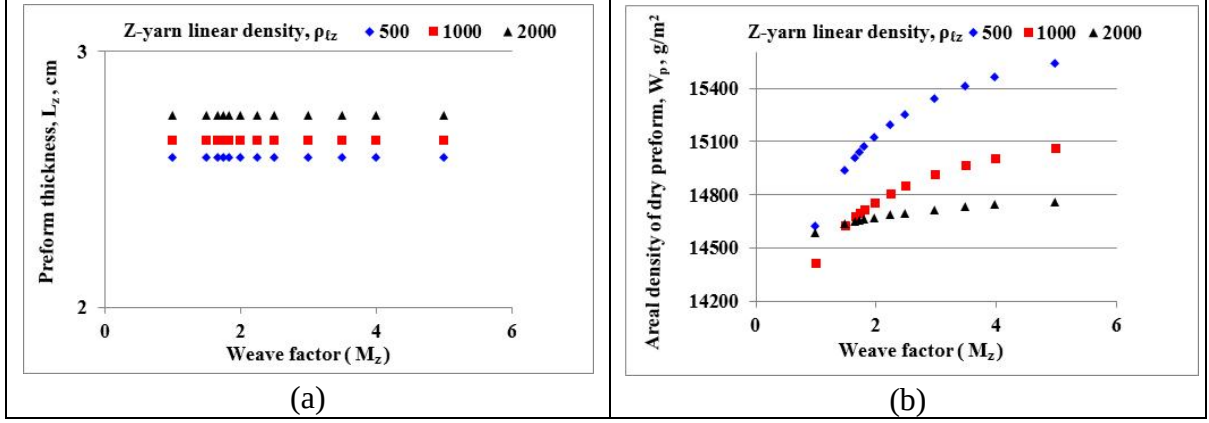


Figure 4.8. Effect of weave factor and z-yarn linear density on preform thickness (a), and areal density (b) for jammed structures with circular yarns

Numerical results for jammed structures with racetrack cross section

For this case, constant input parameters are the same as the case of jammed structures with circular yarns (Tables 4.3). Figure 4.9 shows the numerical results (generated from equations 4.20, 4.23, 4.32, and 4.36) of constituents and total FVF of jammed structures with racetrack yarns in terms of weave factor and z-yarn linear density. For plain weave, z-yarn fiber volume fraction results are the same for racetrack and circular yarns since there is only one x-yarn under (or over) each riser (or sinker) of z-yarn. While the trend is the same for jammed structures with racetrack cross section and jammed structures with circular cross section, the z- and x-yarn FVFs in racetrack model are higher compared to the structure with circular yarns excluding plain weave.

As z-yarn linear density is increased for a constant weave factor, z-yarn FVF increased, x- and y-yarn fiber volume fractions decreased. Again, the decrease in x- and y-yarn FVF is higher than the increase in z-yarn FVF, therefore total FVF decreased. Similar to circular yarns, x-yarn FVF increased and z-yarn FVF decreased with weave factor. Due to greater increase in x-yarn FVF compared to decrease in z-yarn FVF, the total FVF increased with weave factor for a given z-yarn linear density. Effect of z-yarn linear density on total FVF is more significant for high weave factor, whereas its effect on z-yarn FVF is more pronounced for low weave factors.

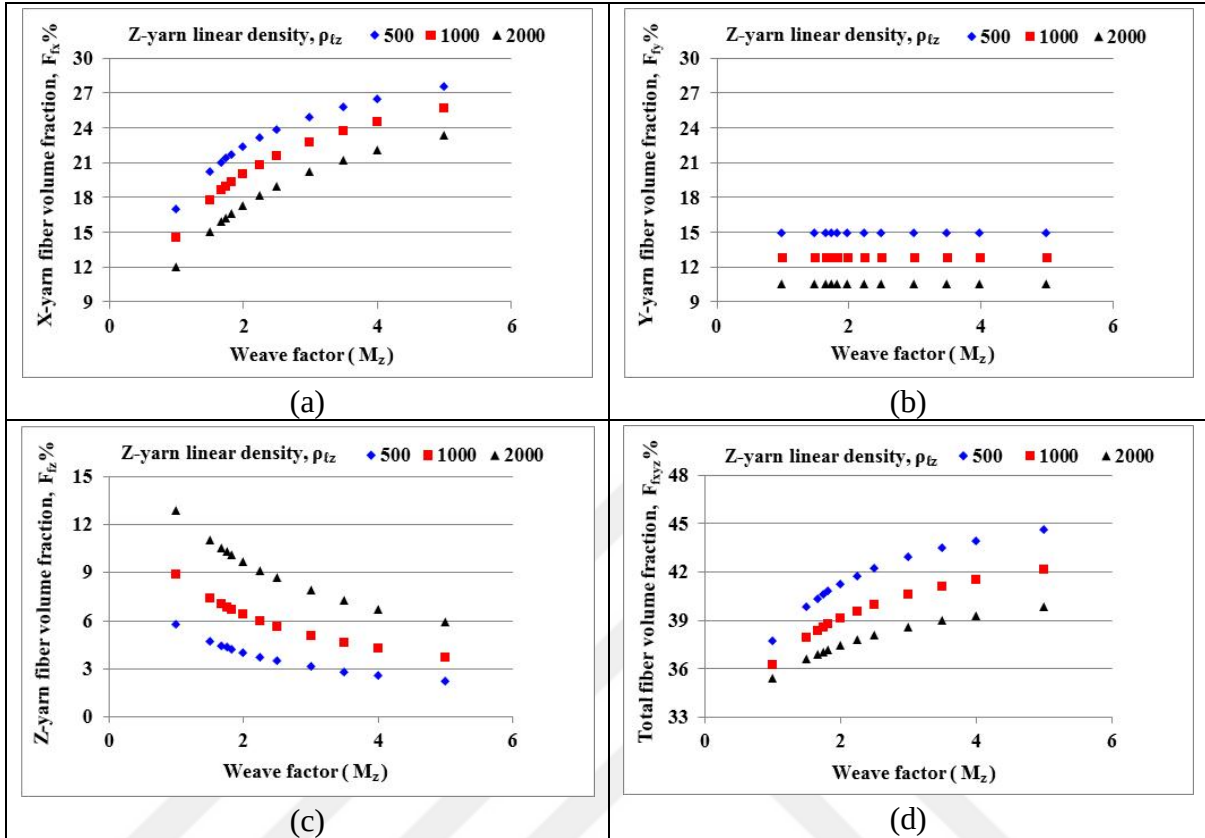


Figure 4.9. Effect of weave factor and z-yarn linear density on constituents and total fiber volume fractions for jammed structures with racetrack yarn cross section

Figure 4.10 (generated from equation 4.2 and 4.40) shows the influence of weave factor and z-yarn linear density on preform thickness and total areal density for jammed structures with racetrack yarns. The trend is similar to jammed structures with circular cross section. The effect of z-yarn linear density on preform areal density is highly significant for high weave factor; however the effect is decreased at low weave factors.

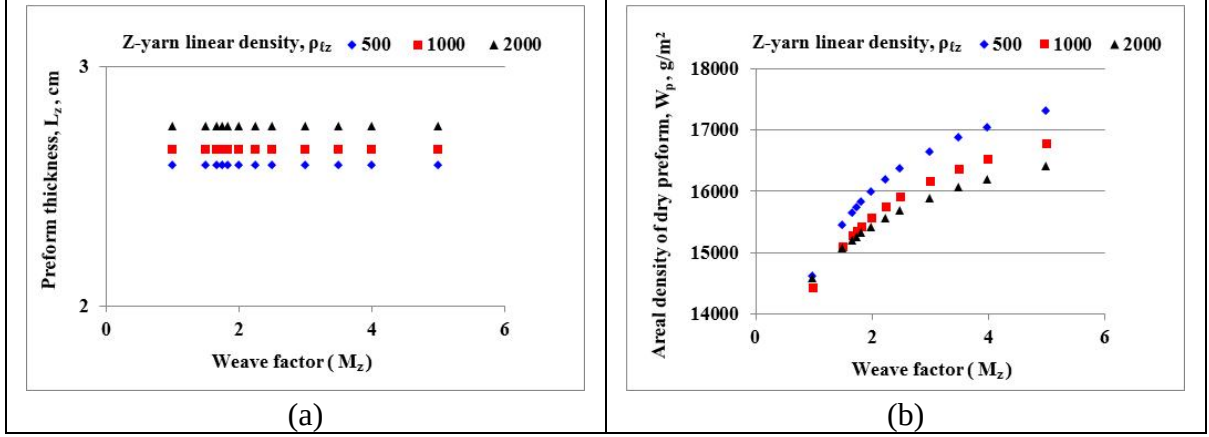


Figure 4.10. Effect of weave factor and z-yarn linear density on preform thickness (a), and areal density of dry preform (b) for jammed structures with racetrack yarns

4.1.9. Conclusion

A generalized geometric model was developed predicting thickness, areal density and fiber volume fraction of 3D orthogonally woven preforms in terms of weave structure of z-yarn represented by numerical value termed as weave factor, yarn material volumetric density, yarn packing factor, yarn size, yarn linear density, yarn spacing, and number of y-yarn layers. The model considers circular yarn cross section for non-jammed and jammed structures as well as racetrack cross-sectional shape for jammed constructions for x-yarns under z-yarn float and y-yarns between successive z-yarns. The model provides the minimum spacing of x-yarn and y-yarn that allow the manufacture of jammed structures with circular yarns and racetrack yarn cross section.

The model reveals fabric architecture potential of 3D orthogonal woven preforms, and shows how to control z-yarn reinforcement content by changing the interlacing pattern (weave factor). The geometrical relationships developed were used to generate numerical solutions for hypothetical preforms to demonstrate the capability of the model. Numerical results unveiled that the x-yarn, z-yarn and total fiber volume fraction, which determine the in-plane and out-of-plane performance, broadly varied with weave factor and z-yarn linear density keeping the other construction parameters unchanged. Out of the numerous parameters of the relationships, only two parameters were changed for demonstration that implies the endless

potential of structures that the model could be used to generate.

The developed geometrical relationships from the model could serve in simulation of the geometry of 3D orthogonal preforms including the shape of the yarn interstices and hence resin flow time could be predicted and optimized. Additionally, the geometry could be used to predict composite performance for generalized cases. This will allow the design of composite structures to meet required performance without the need for lengthy trial and error.

4.2. Generalized geometric model of 3D orthogonal woven preforms from filament yarns

Currently, composite industry is dominated by continuous filament yarns, and the most suitable yarn cross-sectional shape for them is rectangle or lenticular [28] [30]. Literature review indicated that geometric models for filament yarn are limited to plain weave in jammed case. The lack of research in developing generalized model prompted us to initiate this research. Our objective is to develop a generalized model for non-jammed and jammed 3D orthogonal woven preforms predicting FVF of structure constituents, preform thickness, preform areal density, and minimum thread spacing (x- and y-yarn spacing) to achieve jammed construction in terms of weave factor, number of layers, yarn cross-sectional shape (rectangular in case of filament yarns covered in this section), and constituents' variables (yarn arrangement, linear densities, packing factor, and fiber volumetric density).

A consistent system of nomenclature capable of representing the preform structural parameters is given in Appendix A.

4.2.1. Assumptions and generalized modeling strategy

To simplify derivation of geometrical relationships, the following assumptions are set considering filament (or untwisted) yarns:

1. x-, y-, and z-yarns are uniform along their length
 - yarn cross sections are uniform rectangle

- the yarns have uniform packing factor
2. x-, y-, and z-yarns are completely flexible, inextensible, and incompressible
 3. x- and y-yarn spacing is uniform in case of non-jammed structures

Filament yarn which is composed of numerous of individual continuous fibers, is normally twist free, and may easily take any cross-sectional shape depending on the forces applied during the preform formation (weaving), relaxation, and resin infusion process. Filament yarns generally take rectangular, lenticular, or elliptical cross-sectional shape during the fabric manufacturing process.

In this study, rectangular yarn cross section was adopted. Yarn width (w_k) and yarn thickness (t_k) are calculated according to the following formulas,

$$w_k = \sqrt{\frac{\rho_{\ell k} A R_k}{\Phi_k \rho_{vk} 10^5}} \quad (4.41.)$$

$$t_k = \sqrt{\frac{\rho_{\ell k}}{\Phi_k \rho_{vk} A R_k 10^5}} \quad (4.42.)$$

Following figures show 3D orthogonal woven structures that fit these assumptions.

4.2.2. Generalized model for non-jammed structures with rectangular yarns

Similar to 2D woven fabrics, 3D woven fabrics have weave repeat concept in which boundaries are defined by z-yarn interlacing pattern, yarn spacing, number of y-yarn layers, and number of yarns per weave repeat. Figure 4.11 shows generalized non-jammed structure for 3D orthogonal woven preforms with rectangular yarn cross section.

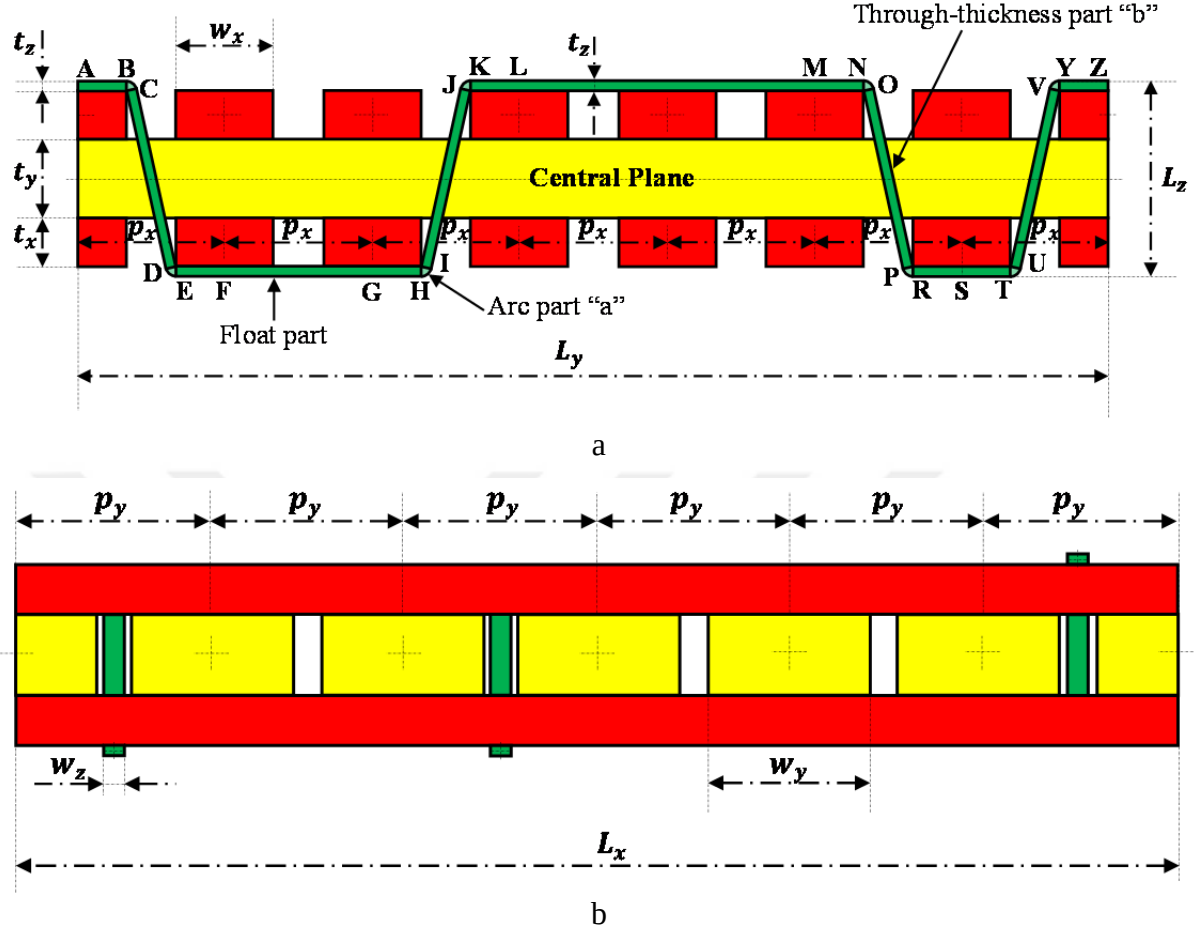


Figure 4.11. Generalized non-jammed structure with rectangular yarn cross section
a: x-yarn cross section, b: y-yarn cross section (x-yarn in red, y-yarn in yellow, and z-yarn in green)

All yarns (x-, y-, and z-yarn) contribute to thickness, therefore; preform thickness (L_z);

$$L_z = n_x t_x + n_y t_y + 2 t_z \quad (4.43)$$

Preform volume per weave repeat (V_{repeat}) is the product of weave repeat width (L_x), weave repeat length (L_y), and preform thickness (L_z).

$$V_{repeat} = L_x L_y L_z \quad (4.44.)$$

Figure 4.11 shows that x-yarn spacing (p_x) and y-yarn spacing (p_y) are uniformly distributed

along and across the preform, respectively. For non-jammed structure, x-yarn spacing is unique (spacing at weave intersection is equal to spacing under the float) and greater than the sum of x-yarn width and z-yarn thickness ($p_x > w_x + t_z$). Weave repeat length (L_y) for generalized non-jammed weave structure is;

$$L_y = N_x p_x \quad (4.45.)$$

In y-yarn cross section of non-jammed structures, the spacing of y-yarn (p_y), which is unique and equally distributed, is greater than the sum of the widths of y-, and z-yarn ($p_y > w_y + w_z$). Therefore, weave repeat width (L_x) for non-jammed structures is given as;

$$L_x = N_y p_y \quad (4.46.)$$

4.2.3. Generalized model for jammed structures with rectangular yarn cross section

In jammed structures, yarns touch each other. Figure 4.12 shows the maximum (jammed) construction for rectangular yarn cross section.

For jammed case, in contrast to unique x-yarn spacing (p_x) in non-jammed structure, there are two different spacings; one at interlacing, one under the float. The spacing at interlacing is longer than the spacing under the float. The spacing at interlacing (p_{xi}) is equal to the sum of the x-yarn width and z-yarn thickness ($w_x + t_z$). On the other hand, the spacing under the float (p_{xf}), where two successive x-yarns touch each other without compression, is equal to x-yarn width (w_x).

For the maximum construction shown in Figure 4.12.a, the repeat length is given by;

$$L_y = N_x \bar{p}_x \quad (4.47.)$$

Average x-yarn spacing ($\bar{p}_x$) in terms of weave factor (M_z) is given by;

$$\bar{p}_x = \frac{M_z w_x + t_z}{M_z} \quad (4.48.)$$

Equation 4.48 provides average x-yarn spacing ($\bar{p}_x$) for any weave, which is the minimum average spacing required to obtain jammed structures with rectangular yarns. This is a design parameter required to obtain jammed structures with rectangular yarns. The weaving machines can be pre-programmed to set the ($\bar{p}_x$) to desired value that is controlled by the take-up mechanism and beat-up force.

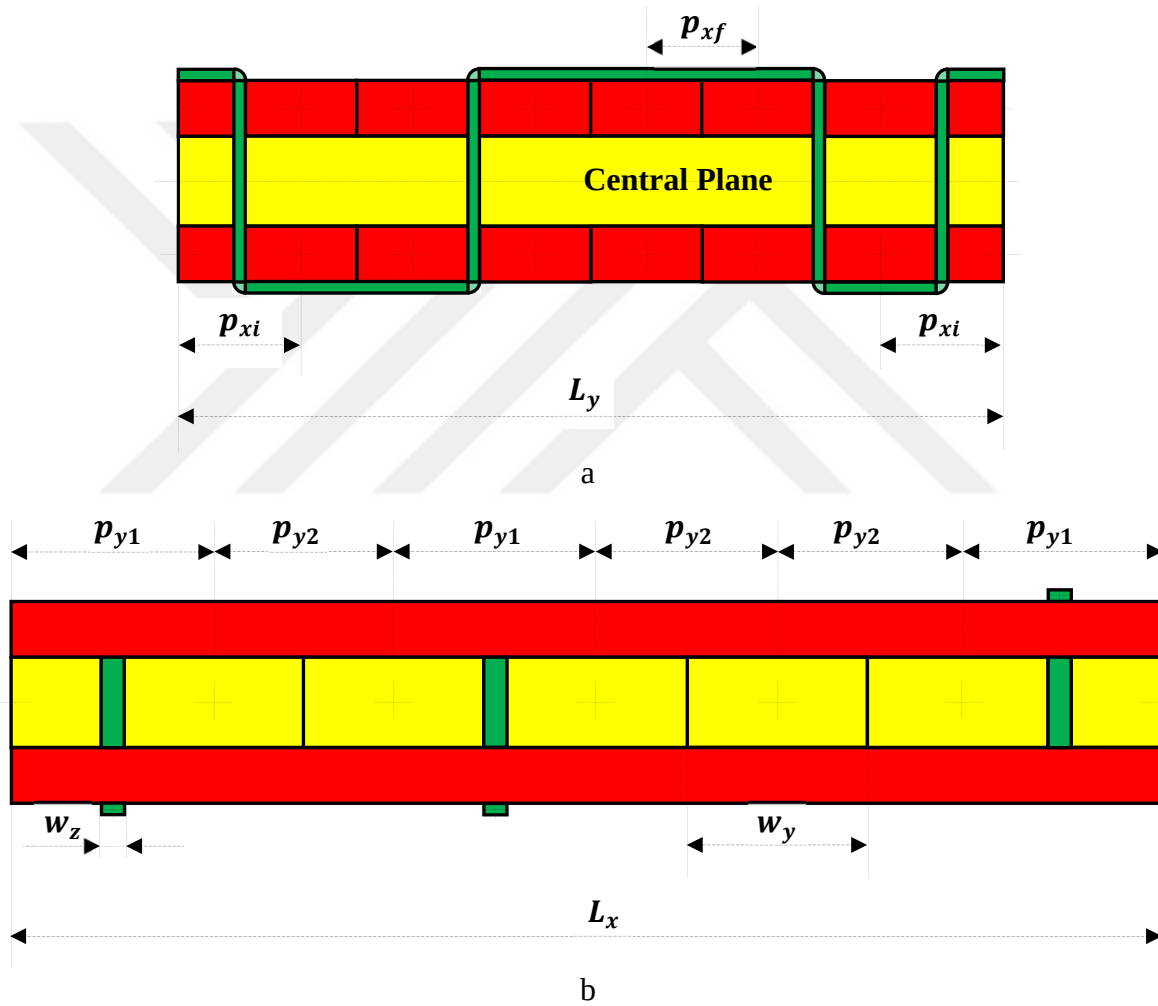


Figure 4.12. Generalized jammed structure with rectangular yarn cross section
a: x-yarn cross section, b: y-yarn cross section

Similar to x-yarn cross section, there are two y-yarn spacing ($p_{y1} = w_y + w_z$, and $p_{y2} =$

w_y) at y-yarn cross section as it can be seen from Figure 4.12.b.

Following equation shows the weave repeat width (L_x) for rectangular cross section jammed structure;

$$L_x = N_y \bar{p}_y \quad (4.49.)$$

The $\bar{p}_y$ is calculated from

$$\bar{p}_y = \frac{N_y w_y + N_z w_z}{N_y} \quad (4.50.)$$

The warp spacing ($\bar{p}_y$) is a design parameter which is controlled by the y-yarn density during warping and maintained by the reed of the weaving machine. This is the average minimum spacing required to achieve jammed constructions with rectangular yarns.

4.2.4. FVEs of x- and y-yarns

Y- and x-yarns are assumed straight within the weave repeat. Therefore, their lengths in weave repeat are calculated by weave repeat dimensions defined above.

Total x-yarn length within the weave repeat (ℓ_x) is the product of one x-yarn length (L_x), number of x-yarns per layer per weave repeat (N_x), and number of x-yarn layers (n_x).

$$\ell_x = L_x N_x n_x \quad (4.51.)$$

Similarly; total y-yarn length within the weave repeat (ℓ_y) is;

$$\ell_y = L_y N_y n_y \quad (4.52.)$$

Fiber volume of a yarn in weave repeat (V_{fk}) is;

$$V_{fk} = \frac{\ell_k \rho_{\ell k}}{\rho_{vk} 10^5} \quad (4.53.)$$

Fiber volume fraction of a yarn in weave repeat (F_{fk}) is the ratio of the fiber volume of the yarn in weave repeat (V_{fk}) and total weave repeat volume (V_{repeat});

$$F_{fk} = \frac{V_{fk}}{V_{repeat}} 100 = \frac{\frac{\ell_k \rho_{\ell k}}{\rho_{vk} 10^3}}{L_x L_y L_z} \quad (4.54)$$

Substituting equations 4.43, 4.45, 4.46, and 4.51 into equation 4.54 results in x-yarn FVF equation for non-jammed structures with rectangular yarns,

$$F_{fx} = \frac{\frac{n_x \rho_{\ell k}}{\rho_{vx} 10^3}}{p_x(n_x t_x + n_y t_y + 2t_z)} \quad (4.55.)$$

Substituting equations 4.43, 4.47, 4.48, 4.49, 4.50 and 4.51 into equation 4.54, we get x-yarn FVF equation for jammed structures with rectangular yarns,

$$F_{fx} = \frac{\frac{n_x \rho_{\ell k}}{\rho_{vx} 10^3}}{(\frac{t_z}{M_z} + w_x)(n_x t_x + n_y t_y + 2t_z)} \quad (4.56.)$$

Substituting equations 4.43, 4.45, 4.46, and 4.52 into equation 4.54 results in y-yarn FVF equation for non-jammed structures with rectangular yarns,

$$F_{fy} = \frac{\frac{n_y \rho_{\ell k}}{\rho_{vy} 10^3}}{p_y(n_x t_x + n_y t_y + 2t_z)} \quad (4.57.)$$

Substituting equations 4.43, 4.47, 4.48, 4.49, 4.50, and 4.52 into equation 4.54, we get y-yarn FVF equation for jammed structures with rectangular yarns,

$$F_{fy} = \frac{\frac{N_y n_y \rho_{\ell y}}{\rho_{vy} 10^3}}{(N_y w_y + N_z w_z)(n_x t_x + n_y t_y + 2t_z)} \quad (4.58.)$$

4.2.5. FVF of z-yarn

Z-yarn within the weave repeat consists of horizontal straight parts (floats) floating on top or on the bottom surface of the preform, x-yarn width halves, arcs at cross-overs, and through-thickness tilted (in non-jammed structure) or through-thickness vertical (in jammed structure) parts. The length of arc and through-thickness tilted parts for non-jammed structures must be calculated in terms of fabric geometry.

Figure C.1 in Appendix C shows geometry at z- yarn interlacing that consists of two x-yarn width halves ($\frac{w_x}{2}$), two arcs, and one through-thickness tilted part for non-jammed structures. The length of the arc and through-thickness tilted part depend on maximum angle (θ) of the z-yarn axis to the central plane which is related to x-yarn spacing (p_x), and the preform thickness (L_z).

Each interlacing consists of two x-yarn width halves, two arc parts, and one through-thickness tilted part, where $\widehat{BC} = \widehat{DE}$ is arc length (a), and $\overline{CD}$ is through-thickness tilted part length (b).

The total z-yarn length (ℓ_z) in weave repeat consists of x-yarn width halves ($\overline{AB}$ and $\overline{EF}$), arcs ($\widehat{BC}$ and $\widehat{DE}$) portions, through-thickness ($\overline{CD}$) parts, and floats (straight horizontal parts on preform surfaces). Float length is calculated through x-yarn spacing (p_x).

In Figure 4.11.a, the length of one z-yarn per weave repeat is the sum of x-yarn width halves, arc parts, through-thickness tilted parts, and float parts as described below;

$$= \overline{AB} + \widehat{BC} + \overline{CD} + \widehat{DE} + \overline{EF} + \overline{FG} + \overline{GH} + \widehat{HI} + \overline{IJ} + \widehat{JK} + \overline{KL} + \overline{LM} + \overline{MN} + \widehat{NO} + \overline{OP} \\ + \widehat{PR} + \overline{RS} + \overline{ST} + \widehat{TU} + \overline{UV} + \widehat{VY} + \overline{YZ}$$

where;

$$\frac{w_x}{2} = \overline{AB} = \overline{EF} = \overline{GH} = \overline{KL} = \overline{MN} = \overline{RS} = \overline{ST} = \overline{YZ}$$

$$a = \widehat{BC} = \widehat{DE} = \widehat{HI} = \widehat{JK} = \widehat{NO} = \widehat{PR} = \widehat{TU} = \widehat{VY}$$

$$b = \overline{CD} = \overline{IJ} = \overline{OP} = \overline{UV}$$

The sum of x-yarn width halves' length = $2 \frac{w_x}{2} i_z$

The sum of the arc parts' length = $2ai_z$

The sum of the through-thickness tilted parts' length = bi_z

The sum of float parts' length = $(N_x - i_z)p_x$

For non-jammed structure; p_x is equal to given value.

For jammed structure; $p_x = w_x$.

Total length of z yarns per weave repeat for non-jammed structure is;

$$\ell_z = [2ai_z + bi_z + w_x i_z + (N_x - i_z)p_x]N_z \quad (4.59.)$$

Total length of z yarns per weave repeat for jammed structure is;

$$\ell_z = [2ai_z + bi_z + w_x i_z + (N_x - i_z)w_x]N_z \quad (4.60.)$$

The length of the x and y-yarn within the weave repeat directly depends on the yarn spacing and number of layers, which are determined before the weaving process. Therefore, it is easy to calculate x and y-yarn lengths in weave repeat as mentioned previously. However, the length of the z-yarn is the result of the weaving process. The weave angle (θ) must be determined theoretically to calculate both through-thickness tilted and arcs parts length of z-yarn. The derivation of maximum angle of the z-yarn axis to the plane of the cloth (θ in radian) is given in Appendix C.

Once θ (in radians) angle is calculated, z-yarn length can be calculated. The arc length of the z-yarn for non-jammed ($\theta < \frac{\pi}{2} \text{ radians}$) and jammed structures ($\theta = \frac{\pi}{2} \text{ radians}$) is;

$$a = \widehat{BC} = \widehat{DE} = \left(\frac{t_z}{2}\right)\theta \quad (4.61.)$$

Through-thickness tilted part length (b) of z-yarn for non-jammed structure can be calculated by using equations C.1 or C.2 defined in Appendix C.

The length of the through-thickness vertical part (b) for jammed structures cannot be calculated by equations C.1 or C.2 in Appendix C. It is calculated by the equation;

$$b = n_x t_x + n_y t_y \quad (4.62.)$$

Therefore, the total z-yarn length (ℓ_z) can be calculated using equation 4.59 or 4.60. Similar to x- and y-yarn FVF, FVF of z-yarn in weave repeat (F_{fz}) is the ratio of the fiber volume of z-yarn (V_{fz}) in weave repeat to the total weave repeat volume (V_{repeat}). Substituting M_z , and equations 4.43, 4.45, 4.46, and 4.59 into equation 4.54 results in z-yarn FVF equation for non-jammed structures with rectangular yarns,

$$F_{fz} = \frac{\left[\frac{2a}{M_z} + \frac{b}{M_z} + \frac{w_x}{M_z} + \left(1 - \frac{1}{M_z}\right)p_x\right] N_z \rho_{\ell k}}{\rho_{vk} 10^3} \quad (4.63.)$$

Substituting equations 4.43, 4.47, 4.48, 4.49, 4.50, and 4.60 into equation 4.54, we get z-yarn FVF equation for jammed structures with rectangular yarns,

$$F_{fz} = \frac{\left[2a + b + w_x + (M_z - 1)w_x\right] N_z \rho_{\ell k}}{\rho_{vk} 10^3} \quad (4.64.)$$

The total fiber volume fraction in weave repeat (F_{fxyz}) is the sum of fiber volume fraction of x-, y- and z-yarn.

$$F_{fxyz} = F_{fx} + F_{fy} + F_{fz} \quad (4.65.)$$

Substituting equations 4.55, 4.57, 4.63 into equation 4.65 results in total FVF for non-

jammed structures with rectangular yarns,

$$F_{fxyz} = \frac{\frac{n_x \rho_{\ell k}}{\rho_{vx} 10^3}}{p_x(n_x t_x + n_y t_y + 2t_z)} + \frac{\frac{n_y \rho_{\ell k}}{\rho_{vy} 10^3}}{p_y(n_x t_x + n_y t_y + 2t_z)} + \frac{\left[\frac{2a}{M_z} + \frac{b}{M_z} + \frac{w_x}{M_z} + \left(1 - \frac{1}{M_z}\right) p_x \right] N_z \rho_{\ell k}}{\rho_{vk} 10^3} + \frac{N_y p_y p_x (n_x t_x + n_y t_y + 2t_z)}{N_y p_y p_x (n_x t_x + n_y t_y + 2t_z)} \quad (4.66.)$$

Substituting equations 4.56, 4.58, 4.64 into equation 4.65 results in total FVF for jammed structures with rectangular yarns

$$F_{fxyz} = \frac{\frac{n_x \rho_{\ell k}}{\rho_{vx} 10^3}}{\left(\frac{t_z}{M_z} + w_x\right)(n_x t_x + n_y t_y + 2t_z)} + \frac{\frac{N_y n_y \rho_{\ell y}}{\rho_{vy} 10^3}}{(N_y w_y + N_z w_z)(n_x t_x + n_y t_y + 2t_z)} + \frac{\left[2a + b + w_x + (M_z - 1)w_x\right] N_z \rho_{\ell k}}{\rho_{vk} 10^3} + \frac{N_y p_y p_x (n_x t_x + n_y t_y + 2t_z)}{(N_y w_y + N_z w_z)(M_z w_x + t_z)(n_x t_x + n_y t_y + 2t_z)} \quad (4.67.)$$

4.2.6. Total weight of dry preform

Total weight of dry the preform is calculated by;

$$W_{xyz} = \frac{[\ell_x \rho_{\ell x} + \ell_y \rho_{\ell y} + \ell_z \rho_{\ell z}]}{10 L_x L_y} \quad (4.68.)$$

Substituting M_z , equations 4.45, 4.46, 4.51, 4.52, and 4.59 into equation 4.68 results in total weight of dry preform for non-jammed structures with rectangular yarns

$$W_{xyz} = \frac{\left[N_y p_y n_x \rho_{\ell x} + p_x N_y n_y \rho_{\ell y} + \left[\frac{2a}{M_z} + \frac{b}{M_z} + \frac{w_x}{M_z} + \left(1 - \frac{1}{M_z}\right) p_x \right] N_z \rho_{\ell z} \right]}{10 N_y p_y p_x} \quad (4.69.)$$

Substituting equations 4.47, 4.48, 4.49, 4.50, 4.51, 4.52, and 4.60 into equation 4.68 results in total weight of dry preform for jammed structures with rectangular yarns

$$W_{xyz} = \frac{(N_y w_y + N_z w_z) M_z n_x \rho_{\ell x} + (M_z w_x + t_z) N_y n_y \rho_{\ell y} + [2a + b + w_x + (M_z - 1) w_x] N_z \rho_{\ell z}}{10(N_y w_y + N_z w_z)(M_z w_x + t_z)} \quad (4.70.)$$

4.2.7. Numerical results and discussion

In this section, numerical results obtained from the developed model will be demonstrated graphically. Effect of z-yarn interlacing pattern represented by the weave factor, and z-yarn linear density on preform thickness, areal density, constituent yarns' and total FVF will be illustrated. Table 4.1 lists broad range of weaves taken into account for the numerical results. Each weave is numerically represented by a different numeric weave factor ranging from 1 to 5. Weave factor is an indirect indication of through-thickness component of z-yarn. To investigate the effect z-yarn size, three different z-yarn linear density levels such as 500, 1000, and 2000 tex (g/km) were taken into consideration.

Numerical results for non-jammed structures

Table 4.4 shows input parameters, which were kept unchanged, along with their values used for non-jammed structures.

Table 4.4. Constant input parameters for non-jammed structures with filament yarns

ρ_{vk}	$\rho_{\ell x} = \rho_{\ell y}$	Φ_k	AR_k	n_y	y-yarn/layer : z-yarn	p_x	p_y
2.5 g/cm ³	2000 tex	0.75	2	7	1:1	0.46 cm	0.46 cm

Figure 4.13 shows the effect of weave (z-yarn interlacing pattern represented by numeric weave factor) and z-yarn linear density on x-, y-, z- and total FVFs of dry preform. Graphs in Figure 4.13 were drawn by the data from equations 4.55, 4.57, 4.63, and 4.66. Increase in z-yarn linear density for a specific weave factor resulted in decrease in x- and y-yarn FVFs, whereas it increased z-yarn and total FVFs. The increase in z-yarn and total FVFs as a result of z-yarn linear density increase is greater for low weave factors due to more through-thickness component of z-yarn in low weave factor structures. Weave factor alone has no effect on x- and y-yarn FVFs. Weave factor decreased z-yarn and total FVFs for a given z-yarn linear density due to decrease in through-thickness tilted part of z-yarn and more floats

on the surfaces of preforms.

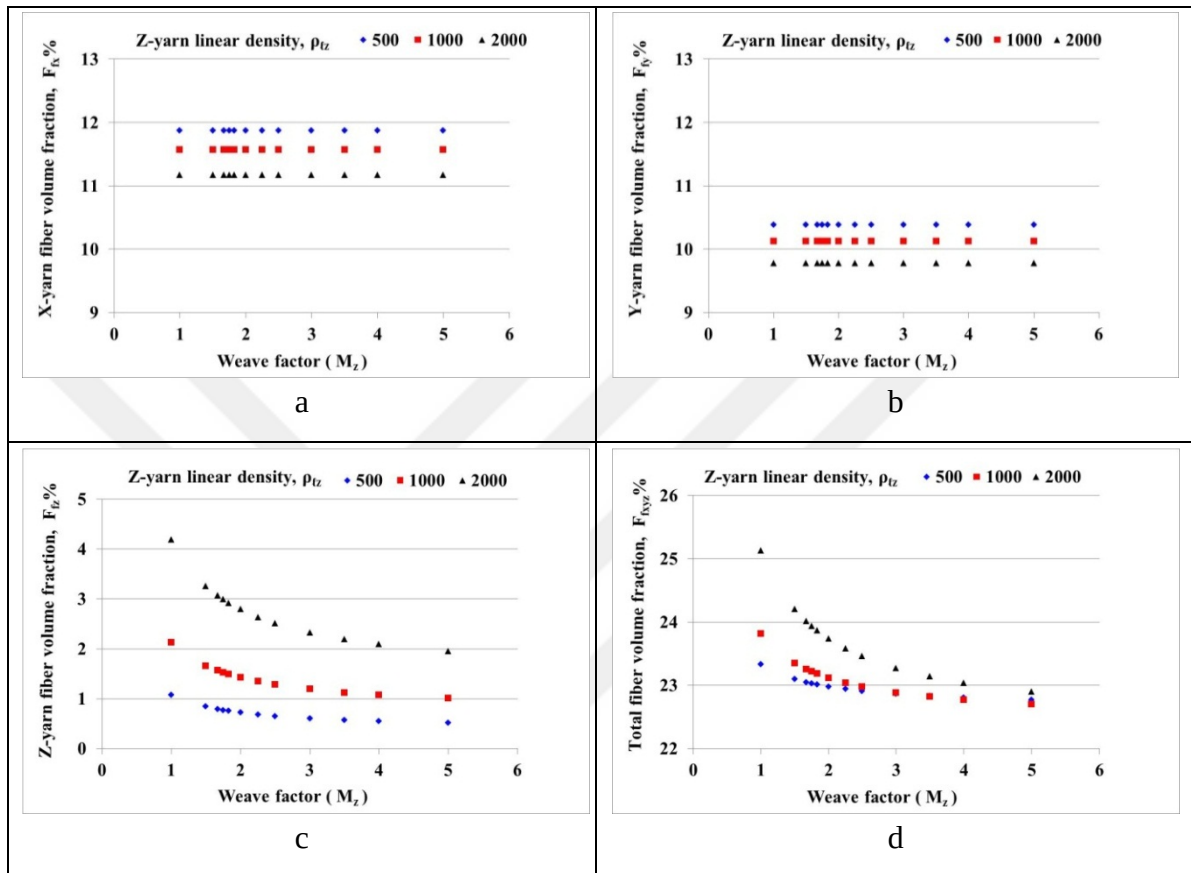


Figure 4.13. Effect of weave factor and z-yarn linear density on constituents and total FVF for non-jammed structure with rectangular yarns,
a: x-yarn FVF, b: y-yarn FVF, c: z-yarn FVF, d: total FVF

Figure 4.14 indicates the effect of variable parameters (weave factor and z-yarn linear density) on dry preform thickness and areal density. Illustrations in Figure 4.14 were generated from equations 4.43 and 4.69. Thickness was not affected by weave factor, whereas increasing linear density of z-yarn has also increased dry preform thickness. Z-yarn linear density alone increases dry preform areal density and this increase is more pronounced for low weave factor, again due to more through-thickness component of z-yarn. Increasing weave factor decreased areal density, which shows the effects of through-thickness component of z-yarn over dry preform areal density for thick preforms.

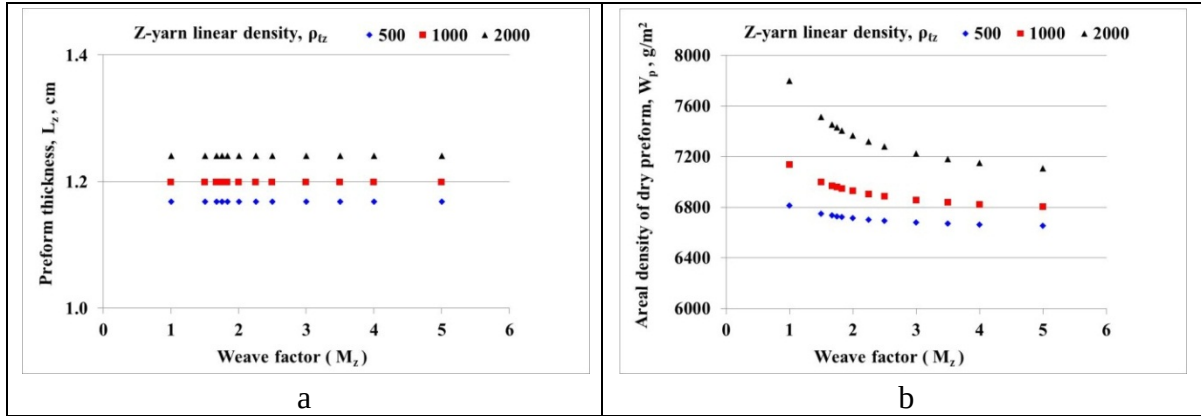


Figure 4.14. Effect of weave factor and z-yarn linear density on preform thickness (a), and areal density (b) for non-jammed structures with rectangular yarns

Numerical results for jammed structures

Table 4.5 shows the constant input parameters, to calculate preform thickness, constituent yarn FVFs, preform areal density, average x- and y-yarn spacing for jammed structures.

Table 4.5. Constant input variables for jammed structures with filament yarns

ρ_{vk}	$\rho_{Lx} = \rho_{Ly}$	Φ_k	AR_k	n_y	y-yarn/layer : z-yarn
2.5 g/cm ³	2000 tex	0.75	2	7	1:1

Figure 4.15 shows the effect of weave and z-yarn linear density on constituent yarns' and total FVFs for jammed 3D orthogonal woven preforms. Equations 4.56, 4.58, 4.64, and 4.67 were utilized to draw the graphs in Figure 4.15. For any specific weave pattern, z-yarn linear density reduces x- and y-yarn FVF, and increases z-yarn FVF. Reduction in x- and y-yarn FVFs are greater than the increase in z-yarn FVF as a result of z-yarn linear density increase, therefore higher z-yarn linear density gets lower the total FVF. Z-yarn FVF for low weave factors is increased more than for high weave factors as z-yarn yarn linear density gets higher. Increment in weave factor for a given z-yarn linear density increases x-FVF due to accommodation of more x-yarn under weave floats of high weave factors, has no effect on y-FVF, and diminishes z-FVF due to decrease in through-thickness vertical component of z-

yarn in jammed case. In contrast to non-jammed structures, weave factor alone increases total FVF for jammed structures due to compensation of z-yarn FVF reduction by x-yarn FVF rise in case of high weave factors.

Effect of z-yarn linear density on z-FVF is the same for both jammed and non-jammed structures that z-FVF is increased more in case of lower weave factors as z-yarn linear density is increased. Effect of z-yarn linear density on total FVF for jammed structures is slightly greater for high weave factors in contrast to non-jammed structures where the effect is more pronounced for low weave factors.

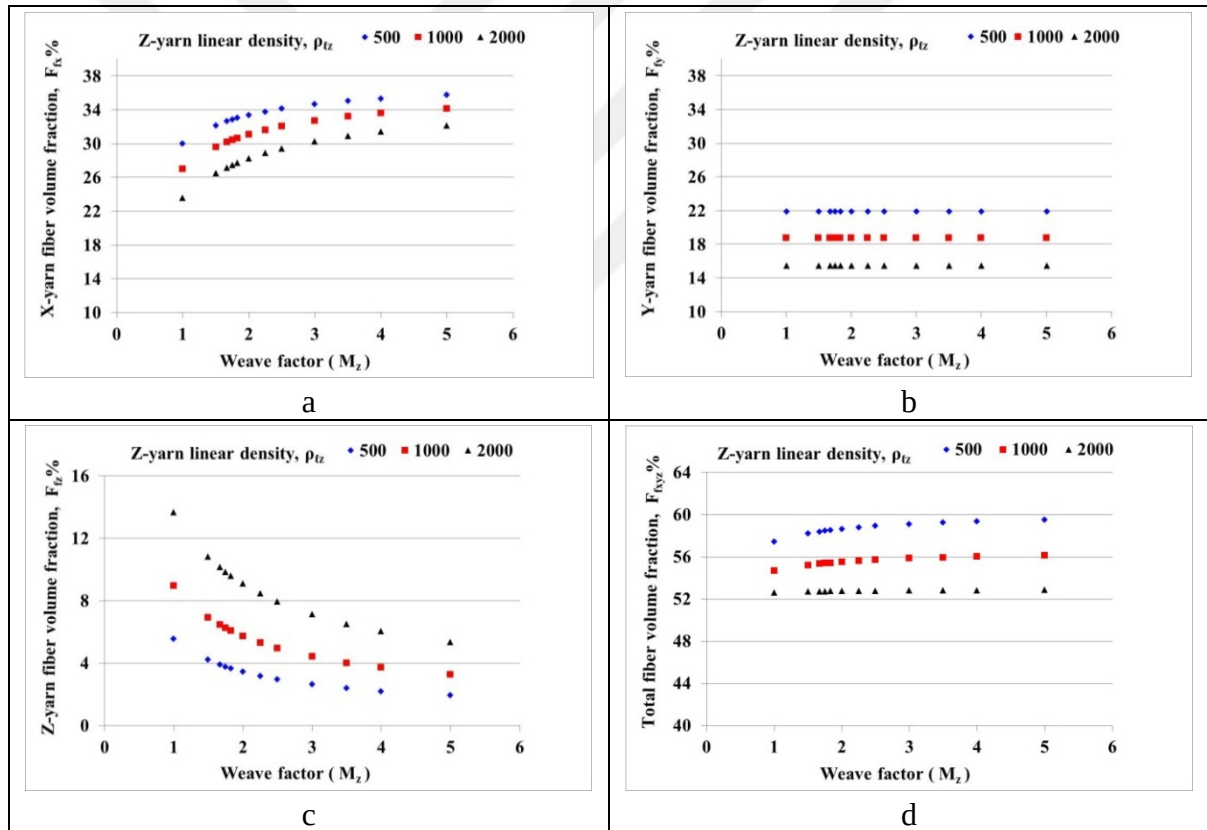


Figure 4.15. Effect of weave factor and z-yarn linear density on constituents and total FVF for jammed structures with rectangular yarns

Results indicated in Figure 4.15 can also be explained in terms of dry preform thickness and areal density predictions in Figure 4.16. Figure 4.16 were obtained from equations 4.43 and

4.70. Areal density results for jammed structures are totally opposite to non-jammed structures. For a given weave factor, z-yarn linear density reduces areal density, and this reduction is more significant for high weave factors. In contrast to non-jammed preforms, weave factor alone increases total areal density of the jammed preforms.

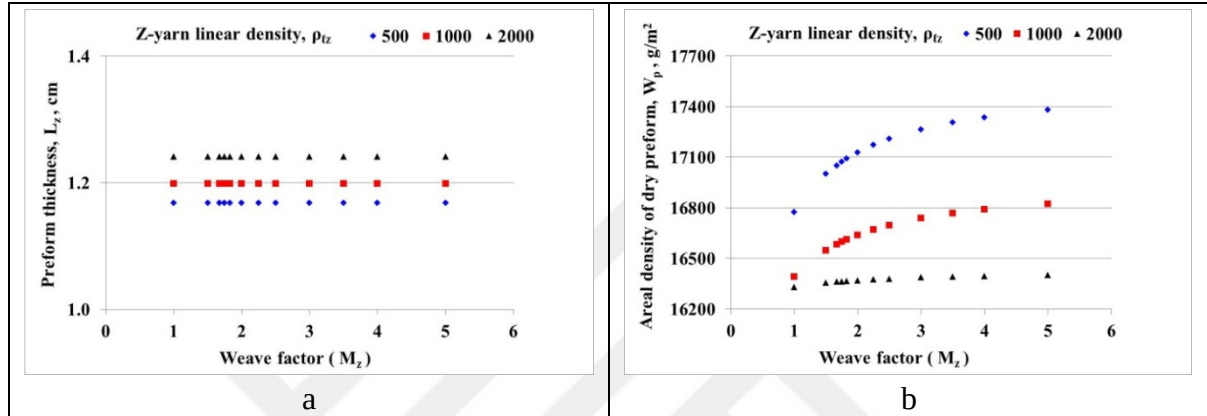


Figure 4.16. Effect of weave factor and z-yarn linear density on preform thickness (a), and areal density (b) for jammed structures with rectangular yarns

3D orthogonal woven glass fiber preforms with varying structural parameters were manufactured to verify the generalized geometric model for filament yarns, and to achieve other objectives described in Chapter 3. Following section is about verification of the model for filament yarns.

4.2.8. Experimental verification of the model

3D orthogonal woven glass fiber reinforced composites described in chapter 5 were used to verify the geometric model for rectangular cross section of filament yarns. 35.56 x 35.56 millimeters specimens on the lower half of each composite panel were sectioned in x-y, x-z, and y-z planes and mounted in 25.4 millimeters diameter plastic rings with acrylic resin (7 gram acrylic powder plus 5 gram liquid initiator). Thereafter, these rings were grinded using automatic grinding machine at PPG Industries, Shelby, NC. Table 4.6 shows grinding steps of the rings.

Table 4.6. Grinding procedure steps

Steps	Grit size	Speed rpm	Force kg-force	Duration min	Note
1	240	400	12.70	5	decrease force to 6.35 kg-force after 3 minutes
2	400	400	12.70	5	decrease force to 6.35 kg-force after 2.5 minutes
3	800	400	6.35	5	

Rings were cleansed with water after each grinding step. Once grinding steps were complete, polishing procedure was performed at 360 rpm, 9.53 kg-force for 5 minutes against micro polishing cloth at 0.3-micron alumina polishing suspension medium. Figure 4.17 shows x-yarn cross section (y-z plane) of 2 layers, plain weave, 4.87 x-yarns/layer/cm composite manufactured at 100 kPa vacuums.



Figure 4.17. X-yarn cross section of 2 layers, plain weave, 4.87 x-yarns/layer/cm composite

Micrographs revealed constituent yarns' cross-sectional shapes, z-yarn interlacing, and thickness fluctuation of composite. X-yarns on the top and bottom surfaces of the composite were affected by z-yarn interlacing that their cross-sectional shapes deviate from rectangle and their aspect ratios are lower than the aspect ratio of yarns in the middle layer. Aspect ratios for x-yarns shown in Figure 4.17 were measured as 5.27, 10.82, and 4.45 for top, middle, and bottom x-yarn layers, respectively. Additionally, z-yarn angle in Figure 4.17 was determined as 42 degree.

Figure 4.18 shows y-yarn cross section (x-z plane) of 2 layers, plain weave, 4.87 x-yarns/layer/cm composite manufactured at 100 kPa vacuums.

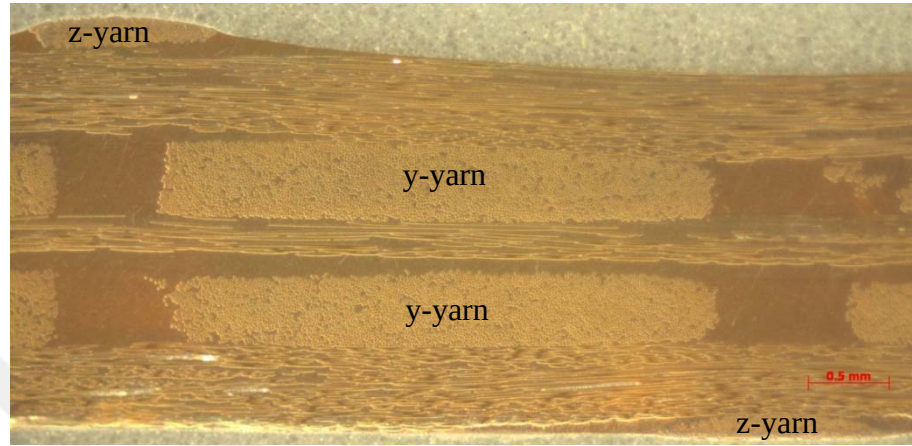


Figure 4.18. Y-yarn cross sections of 2 layers, plain weave, 4.87 x-yarns/layer/cm composite

Micrographs indicated that cross-sectional shape of y-yarns is more close to rectangle than x-yarns. Aspect ratio variation of y-yarns is lower than x-yarns'. Y-yarns in the second and first layers have aspect ratios of 7.44 and 7.37, respectively. Z-yarn cross section that is in contact with rigid mold surface at the bottom has higher aspect ratio (flatter) than the z-yarn contacting with flexible vacuum bag on the top. Z-yarn on the surface (which was in contact with vacuum bag during VIP) has aspect ratio of 6.22, and z-yarn at the bottom (which was in contact with the rigid mold during VIP) has aspect ratio of 9.83.

Aspect ratios of x-, y- and z-yarns of 2 layers, plain weave, 4.87 x-yarns/layer/cm composite manufactured at 100 kPa vacuums were measured at 9, 4 and 2 different places, respectively. The average aspect ratios reported in Table 4.7 were used as input parameters to verify the geometric model.

Table 4.7. Yarn aspect ratios

Yarn type	Average aspect ratio	CV, %
x-yarn	7.12	36.37
y-yarn	7.35	2.47
z-yarn	8.03	31.81

Another input parameter for the geometric model is yarn packing factor. Figure 4.19 shows x-yarn cross section and selected places indicated by circles to determine packing factor for 2 layers, plain weave, 4.87 x-yarns/layer/cm composite manufactured at 100 kPa vacuum. Nominal x-yarn fiber diameter is 13 microns. Diameter of the circle in Figure 4.19 is 100 microns. Diameters and numbers of fibers inside the circle were determined. Fibers on the boundary line of the circle were considered according to whether their more than half area is inside or outside of the circle. If more than half area is inside then the fiber was counted, otherwise not counted. Ratio (percentage) between area sum of fibers inside the circle, and area of the circle was calculated as yarn packing factor.

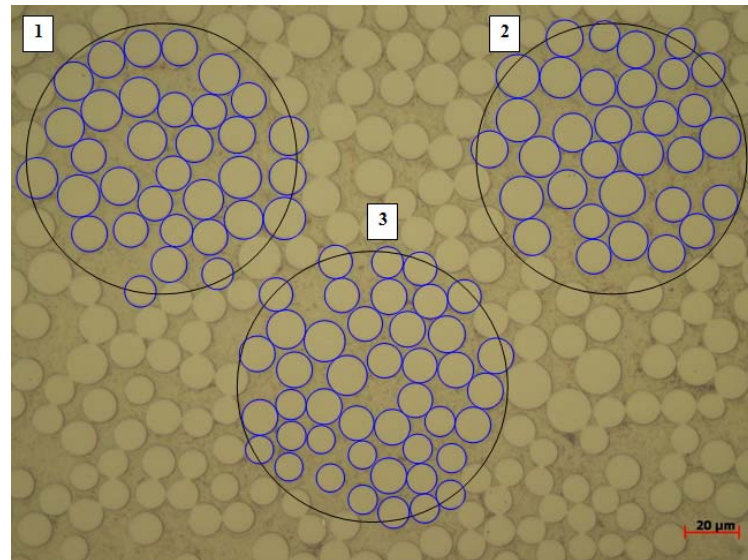


Figure 4.19. Selected spots from x-yarn to determine yarn packing factor

Packing factors for the first, second and third circles in Figure 4.19 were calculated as 0.63, 0.64 and 0.66, respectively. Similarly, y- and z-yarn packing factors for the same composite specimen were determined. Table 4.8 shows the average yarn packing factors. The average was calculated from at least six observations for each yarn type.

Table 4.8. Yarn packing factors

Yarn type	Average packing factor	CV, %
x-yarn	0.52	25.74
y-yarn	0.56	11.66
z-yarn	0.58	10.34

The measured aspect ratio, packing factor, fiber material density, and linear density for x-, y- and z-yarns reported in Tables 4.7, 4.8, 5.1, and 5.2 respectively, were plugged into the developed geometric model (Equations 4.43, 4.55, 4.57, 4.63, 4.66, and 4.69). Yarn aspect ratio and packing factor are affected by both dry preform structural parameters (yarn size, yarn spacing, number of layers, weave pattern etc.) and processing pressure (vacuum in this study) that make the prediction of these parameters difficult before manufacturing. Because of this difficulty, it was decided to measure these values from micrographs of composite. While this seems not realistic in view of modeling perspective, these measurements could be established to predict other structures for future studies.

Geometric model predicts the thickness L_z as shown in Figure 4.11.a. Therefore, both dry preform and composite thicknesses were measured by thickness-meter according to ASTM D1777 to verify the model. Thickness of composites was also calculated through volume measurement that considers the surface roughness of vacuum bag side, however volume based thickness was only used in evaluating of analytical and mechanical properties.

Table 4.9 shows prediction and measurements of thickness values. It is clear that the agreement among the predicted and measured thickness of the dry preform and composite is high. Vacuum bag on one side of the molding creates a flexible tool, and after mold was

totally filled with resin (and resin inlet was clamped), resin pressure equilibrates in the mold cavity that results in relaxation of saturated preform and slight increase in thickness.

Table 4.10 shows the predicted and measured constituent yarn weights for 2 layers, plain weave, 4.87 x-yarns/layer/cm dry preform. The difference between the predicted and measured values was expressed in percentage based on the measured values and reported as error percent in Table 4.10. Table 4.11 shows constituent yarn and total FVF results. FVFs of dry preform and composite were calculated from thickness and areal density measurements. Table 4.12 compares the predicted and experimental z-yarn angles. The experimental z-yarn angle value of composite was measured from cross section image (Figure 4.17).

Model underestimates x- and y-yarn weights, and overestimates z-yarn weight (Table 4.10). The difference between the model and measured x-, y-yarn weights is insignificant and within the experimental error. The reason for overestimating the z-yarn weight is that z-yarn is under tension during preform formation and this tension shortens its through-thickness length. Additionally, the model assumes all x-yarns have rectangular cross section that increases z-yarn weave angle (as shown in Table 4.12) and length of the through-thickness component of z-yarn compared to actual preform.

Calculated in-plane yarns' FVFs of dry preform and composite are close to model prediction (Table 4.11). However, predicted z-yarn FVF is significantly greater than dry preform and composite z-yarn FVF due to overestimation of z-yarn weight by the model. Predicted and experimental values of dry preform and composite total FVFs are in close agreement. Total FVF of actual dry preform was 0.4% greater than model prediction. However, total FVF of composite was 5.4% overestimated by the model, which is within the experimental error given the thickness variation of the composites panels as discussed earlier.

Table 4.9. Thickness results for 2 layers, plain weave, 4.87 x-yarns/layer/cm structure

Material form	Thickness, mm	Method
Model	2.44	
Dry preform	2.48 (2.1 %)	Thickness-meter (ASTM D1777)
Composite	2.62 (2.9 %)	Thickness-meter (ASTM D1777)

Vacuum is 100 kPa at composite manufacturing. Values in parenthesis are CV, percentage based on minimum three measurements.

Table 4.10. Constituent yarn weight results for 2 layers, plain weave, 4.87 x-yarns/layer/cm dry preform

Material form	X-yarn weight g/m ²	Y-yarn weight g/m ²	Z-yarn weight g/m ²	Total weight g/m ²
Model	1084.71	1078.28	89.27	2252.26
Dry preform	1142.29 (1.4%)	1081.51 (1.6%)	71.82 (0.2%)	2295.62
Error, %	-5.04 %	-0.3 %	24.3 %	-1.89 %

Table 4.11. Constituent yarn FVEs for 2 layers, plain weave, 4.87 x-yarns/layer/cm dry preform and composite

Material form	X-yarn FVF, %	Y-yarn FVF, %	Z-yarn FVF, %	Total FVF, %	Method
Model	17.80	17.08	1.46	36.34	
Dry preform	18.45 (1.78%)	16.86 (1.96%)	1.16 (0.82%)	36.47 (1.28 %)	Calculated from thickness of dry preform (ASTM D1777) and dry preform areal density
Composite	17.44	15.94	1.09	34.47	Calculated from thickness of composite (ASTM D1777) and dry preform areal density

Vacuum is 100 kPa at composite manufacturing. Values in parenthesis are CV, percentage based on minimum three measurements.

Table 4.12. Z-yarn angle comparison between model prediction and actual composite

Material form	Z-yarn angle, degree
Model	63.11
Composite	42

4.2.9. Conclusion

Generalized geometric model for 3D orthogonal woven preforms in terms of yarns and preform construction parameters including weave was developed. Input parameters of the model are yarn material density, yarn packing factor, yarn cross-sectional shape (aspect ratio of rectangular cross section), yarn linear density, yarn spacing, number of y-yarn layers and interlacing pattern of z-yarn. The model is generalized that considers predicting structural parameters for any weave pattern for orthogonal (jammed) and non-orthogonal (non-jammed) structures. The model reveals fabric architecture potential of 3D orthogonal woven preforms, and shows how to control x- and z-yarn reinforcement contents by means of interlacing (weave) pattern change. Z-yarn fiber volume fraction predictions of newly developed model for weave designs other than plain weave enable to produce preforms with targeted in-plane and out-of-plane properties. The model can also help to predict mechanical properties accurately since these are tightly related to the fiber volume fraction, areal density, amount of through-thickness z-yarn segments. For a given set of yarns and weave, the model provides prediction of minimum yarn spacing of orthogonal structures to achieve maximum fiber volume fraction. Model allows adjustment to accommodate different degree of yarn flattening (of individual yarns and yarns under the floats), which depends on yarn structural parameters.

Experimental verification of the model indicated that there is high correlation between predicted and measured dry preform thickness, in-plane (x- and y-) yarns' weights, composite thickness, in-plane (x- and y-) yarns' FVFs. However, the model over predicted weight of z-yarn in dry preform, which in turn caused overestimation of z-FVF. The main reason for the overestimation of z-FVF and z-yarn weight is the tension experienced by the z-yarns during preform formation that caused flattening of x-yarn at cross overs, and results in shortening of through-thickness component of z-yarns. In contrast to model, which assumes unique aspect ratio for x-yarns, micrographs indicated that x-yarn aspect ratio is variable (affected by the location of the x-yarn layer). Therefore, a predictive model that considers yarn-flattening (aspect ratio) at cross overs of x- and z-yarns is needed. The predictive model should also

consider the effect of pressure, which seems to be varied within the preform during VIP, on flattening of x- and z-yarns at different layers.



5. EXPERIMENTAL

This chapter is devoted for describing the materials, experimental design, and preform formation. Methods and equipment to determine physical and mechanical properties of both dry preform and composites are also given in this chapter.

5.1. Materials

5.1.1. Fiber

The material of the warp, weft, and z-yarn is Hybon® 2022 E-glass filament yarns were donated by PPG Industries. The specifications of the three yarns are shown in Table 5.1. Experimentally measured x-, y- and z-yarn linear densities (ASTM D1917) are given in Table 5.2.

Table 5.1. Specification of yarns provided by supplier

Yarn	Linear density (tex, g/km)	Number of filaments	Filament diameter (μ)	Fiber density* (g/cm ³)
Weft (x-yarn)	735	1960	13	2.50 (1.16 %)
Warp (y-yarn)	2275	3920	17	2.59 (0.74 %)
Binder (z-yarn)	276	378	13	2.51 (2.41 %)

* measured according to ASTM D792 using density kit available at the composite core facility, College of Textiles, NC State University. Values in parenthesis are CV, percentage.

Table 5.2. Measured values of x-, y-, and z-yarn linear density

Linear density, tex, g/km	Yarn type		
	x-yarn	y-yarn	z-yarn
Average	741.83	2282.36	282.71
CV, %	5.43	0.66	1.03

5.1.2. Resin system

DERAKANE[®] 8084 epoxy based vinylester resin donated by ASHLAND Inc. was used in this study. It is an elastomer-modified resin, and its typical liquid resin properties are given in Table 5.3. Peroxide type initiator, NOROX[®] MEKP-925H, was used in this study. Typical properties of the initiator are given in Table 5.4.

Table 5.3. Typical liquid resin properties of Derakane[®] 8084

Property	Value
Density, 25 °C	1.02 g/mL
Dynamic viscosity, 25 °C	360 mPa·s (cP)
Kinematic viscosity	350 cSt
Styrene content	40%
Shelf life, dark, 25 °C	6 months

Table 5.4. Typical properties of initiator (NOROX[®] MEKP-925H)

Property	Value
Active oxygen	9.0 %, max
Form	Liquid
Color	Water white
Specific gravity @ 25 ⁰ /4 ⁰ C	1.10

5.2. Experimental design and preform formation

Preforms were woven using 3D weaving machine (Figure 5.1) donated by 3TEX, Inc. that is available at the composite core facility, College of Textiles, NC State University. Experimental design variables and levels for 3D orthogonal woven preform and composite formation from glass fibers are given in Table 5.5.

The preforms were formed using 102 y-yarns/layer, and one y-yarn in a given layer was drawn in a reed dent. Similarly, total number of z-yarns was 102, and the reed plan of the z-

yarns was one yarn/reed dent. The reed density was 2.36 dents/cm (6 dents/inch). The preform width was 40 cm in-machine and remained as such after formation.

Three different x-yarn density levels were used. These specific densities were chosen to manufacture linear density balanced preforms in x- and y-direction (the total denier/unit length in x- and y-directions is equal) for each specific number of y-yarn layers level. For example, 2 y-yarn layers preforms woven with 4.87 x-yarns/layer/cm are linear density balanced in x-, and y- direction (total denier/cm is 1200 in x- and y-directions). Similarly, 3 y-yarn layers preforms with 5.48 x-yarns/layer/cm are balanced in x- and y-direction. The main reason to produce balanced preforms is to check whether they provide balanced properties in x- and y-directions.

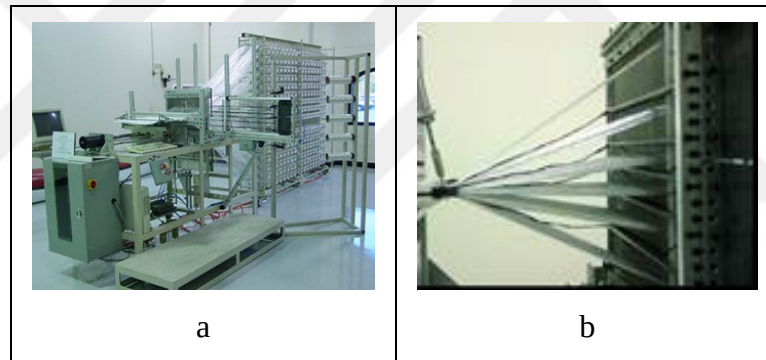


Figure 5.1. View of the 3D weaving machine (a), multi-insertion of filling yarns (b)

Table 5.5. Design of experiment

Variable	Levels
Number of y-yarn layers	2, 3, 4
X-yarn density, yarns/layer/cm	4.87, 5.48, 5.85
Weave	Plain, 2x2 Basket, 2x2 Twill
Vacuum, kPa	75, 100
Total runs	54 Samples (3x3x3x2)

The machine was upgraded to include four harnesses to be able to weave plain, 2x2 twill and

2x2 basket weaves. In basket weave, two harnesses were used to form the weave and the other two harnesses were used to form selvages from z-yarns to secure the preform edges. Software code was modified to weave 2x2 basket and 2x2 twill weave structures. Simulations of the weave structures drawn in RhinocerosTM 4.0 software are shown in Figure 5.2.

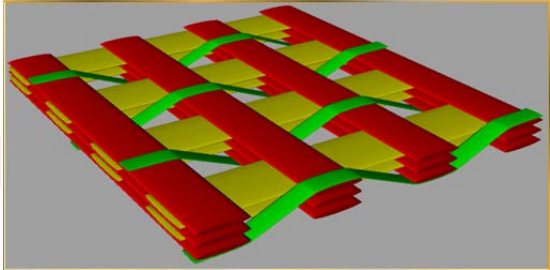
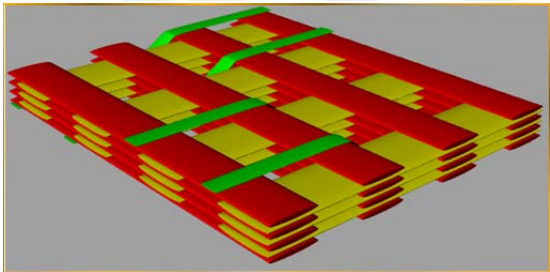
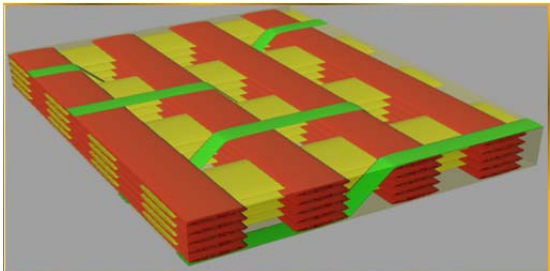
	Number of y-yarn layers: 2 Weave: Plain
	Number of y-yarn layers: 3 Weave: 2x2 Basket
	Number of y-yarn layers: 4 Weave: 2x2 Twill

Figure 5.2. Fabric architecture simulations

● x-yarn (weft), ● y-yarn (warp), ● z-yarn (binder)

In total, 27 different preforms each of which having different combination of structural parameters (fabric architectures) were woven. Surface images of all 2 layers 3D orthogonal

woven preforms are given in Figure 5.3. Figure 5.4 indicates surface images of 4 layers, 5.85 x-yarns/layer/cm 3D orthogonal woven preforms.

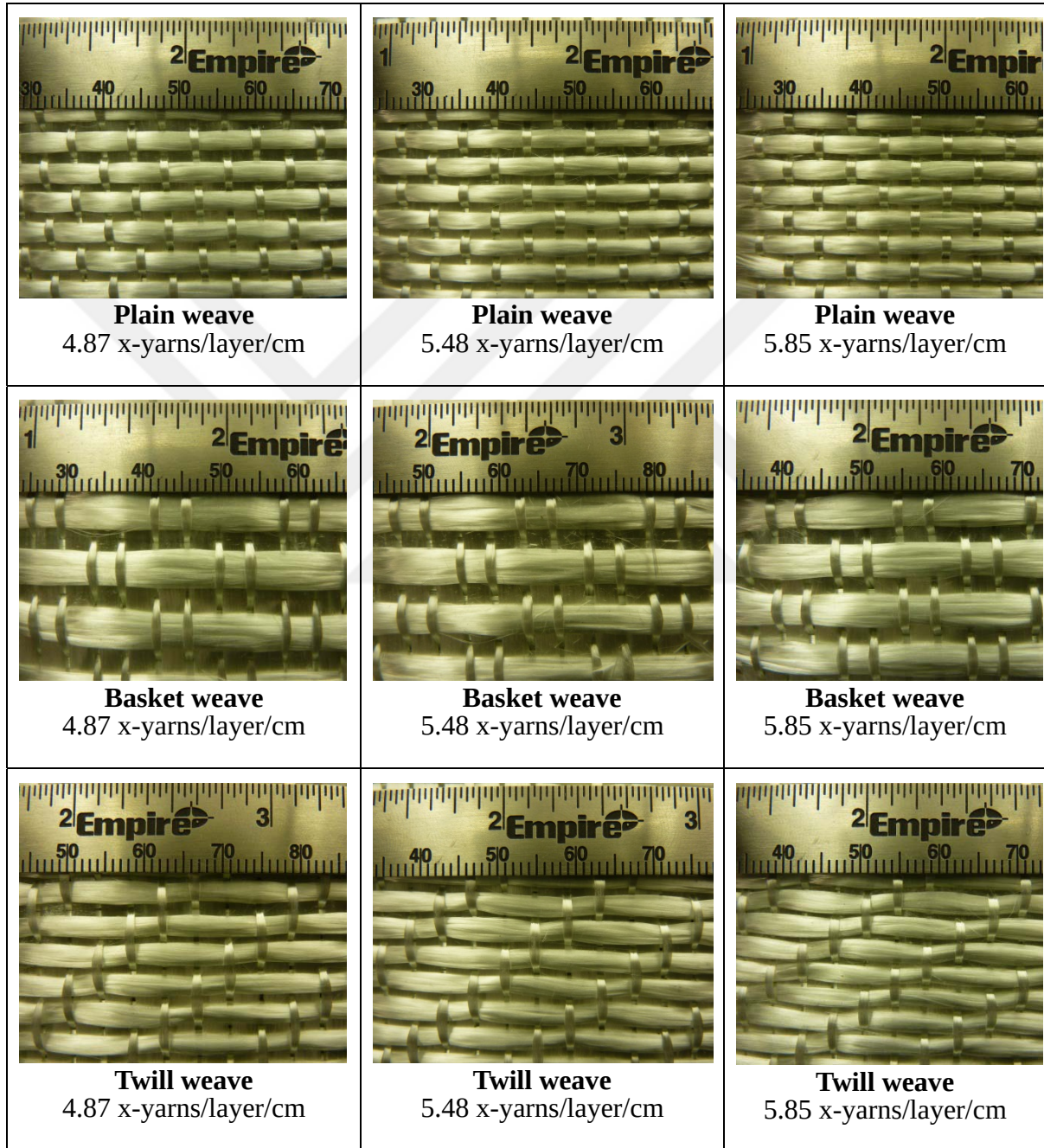


Figure 5.3. Surface images of all 2 layers 3D orthogonal woven dry preforms

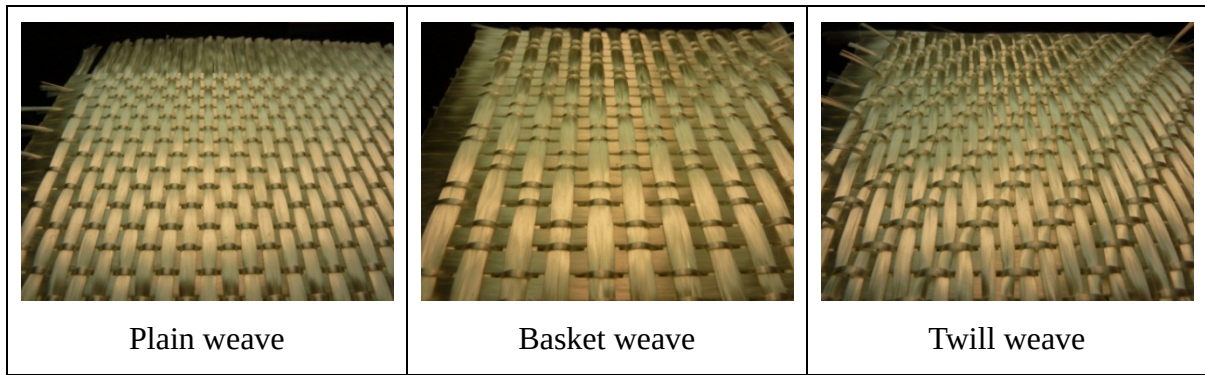


Figure 5.4. Surface images of 4 layers, 5.85 x-yarns/layer/cm dry preforms

5.3. Thickness

Three specimens (10cm x 10cm) from each 3D orthogonal woven dry preform samples were cut by using die cutter as shown in Figure 5.5 to measure preform thickness, and constituent yarn weights using raveling technique to separate x-, y-, and z-yarns.



Figure 5.5. Sampling for dry preform characterization

Dry preform thickness measurement was performed according to ASTM D1777. Pressure foot diameter and the applied pressure for thickness measurement were 28.7 mm and 4.14 kPa, respectively.

35.56 x 35.56 millimeters specimens cut from the upper half of each composite panel were used to measure composite thickness. Each upper half panel has nine analytical specimens tracked according to their location relative to resin inlet. First, eighth and ninth analytical specimens were not taken into consideration due to their close locations to resin inlet or outlet (Figures 5.10 and 5.11.a). Volume of each specimen was measured by using density kit (Figure 5.6.) available at Composite Core Facility, College of Textile, NC State University. Absolute average thickness of each analytical specimen was calculated by dividing the volume by surface area. Thickness of each analytical specimen from many different spots was also measured by hemispherical tip micrometer. It was observed that average micrometer thickness was very close to the thickness calculated in terms of volume measurements; therefore, calculated (volume-based) thickness was considered for the analysis of analytical and mechanical properties of composite.



Figure 5.6. Density kit for volume measurement of analytical specimens

Geometric model predicts the thickness L_z as indicated in Figure 4.11.a. Therefore, thickness of 2 layers, plain weave, 4.87 x-yarns/layer/cm composite infused at 100 kPa was measured by thickness meter according to ASTM D1777 to verify the model.

5.4. Constituent yarn weights

10x10 cm dry preform specimens were used to measure constituent yarns' weights according to ASTM D3776. 3D orthogonal woven dry preforms were separated into x-, y- and z-yarn components as shown in Figure 5.7. Thereafter, constituent yarns' weights were measured by three-digit electronic balance, which provided accuracy of 0.001 g.



Figure 5.7. Separation of constituent yarns of dry preform

5.5. Z-yarn crimp

Z-yarns were removed from dry preform specimen and their straight lengths were measured under a moderate tension to remove the crimp as shown in Figure 5.8. The difference between the length of the z-yarn measured under tension and the length of preform specimen was calculated. The difference between the z-yarn straight length and preform specimen length expressed in percentage based on preform specimen length was reported as z-yarn crimp.



Figure 5.8. Z-yarn crimp measurement

5.6. Resin infusion

Preforms were cut to one-meter length in preparation for resin infusion. 3D orthogonal woven dry preforms were consolidated using VacMobiles® 20/2 VARTM equipment, which is available at the composite core facility, College of Textiles, NC State University. In order to decrease the mold filling time, x-yarn direction which has shorter total flow length (40 cm) compared to y-yarn direction (100 cm) was chosen as resin flow direction.

Each dry preform (100 cm long x 40 cm wide) was placed over a release film that is placed over a glass top table. Resin inlet spiral tube and resin outlet port were placed over the preform. No resin distribution (green flow) media was used in order to eliminate the permeability effect in thickness direction. Then, another release film was placed over the preform. All these layers were sealed using double-sided tape under a final layer of infusion plastic bagging. After vacuum application, the system was checked for vacuum leakage by using Amprobe TMULD-300 ultra-sonic leak detector.

After gelation, resin flow stops. Therefore, reinforcement should be completely wetted before the gelation; otherwise, unsaturated (resin starved) areas (dry spots) leave on preform and amount of scrap increases in case of too short gel times. On the other hand, too long gel times increase cycle time that reduces productivity. Therefore, adjustment of gel time is critically important. For a given temperature, gel time of resin can be adjusted by changing the amount of auxiliary curing (initiator, promoter, and accelerator) chemicals.

Typical gel times of Derakane® 8084 at different temperatures and corresponding amount of MEKP-925H (initiator), Cobalt Naphtenate-6% (CoNap6%, promoter) and DMA (accelerator) are given in Table 5.6;

Table 5.6. Typical gel times for Derakane[®] 8084 Resin

Temperature	Auxiliary curing chemicals	Gel time of resin		
		15 ±5 minutes	30 ±10 minutes	60 ±15 minutes
18 ⁰ C	MEKP, wt.%	3.0	3.0	2.5
	CoNap6%, wt.%	0.6	0.4	0.4
	DMA, wt.%	0.3	0.2	0.1
24 ⁰ C	MEKP, wt.%	2.0	2.0	1.5
	CoNap6%, wt.%	0.5	0.4	0.3
	DMA, wt.%	0.3	0.2	0.05
30 ⁰ C	MEKP, wt.%	2.0	1.5	1.5
	CoNap6%, wt.%	0.3	0.3	0.3
	DMA, wt.%	0.2	0.05	0.025

Environment temperature in dyeing lab of NC State University where molding part of this study was performed is about 20 °C. The amounts of initiator, promoter and accelerator mixed with resin were determined according to 60 ±15 minutes gel time at 18°C temperature to obtain the maximum gel time shown as highlighted cells of Table 5.6.

75 and 100 kPa (full vacuum) were used as vacuum level variables. In total, 54 composite panels (27 preforms x 2 pressure levels) were consolidated.

Transparent tooling and bright color glass fiber preform combination provided visual tracking of bulk resin macro-flow between yarn bundles (tows). Tracing of resin flow front as shown in Figure 5.9 was performed for all samples to compare resin flow front and mold filling time of different preform architectures. Arrows in Figure 5.9 show the direction of flow.

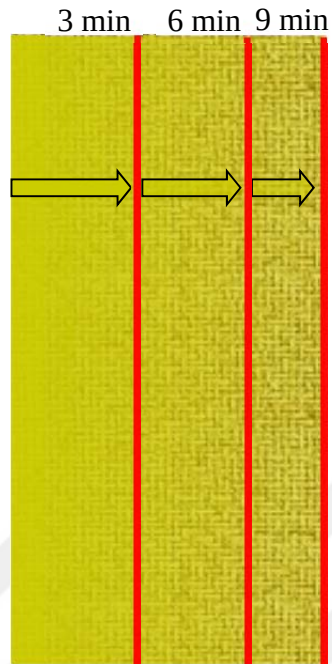


Figure 5.9. Tracing of resin flow fronts at every 3 minutes during infusion

5.7. Sampling

In order to maximize the utilization of the composite panels, sampling was done according to drawing shown in Figure 5.10.

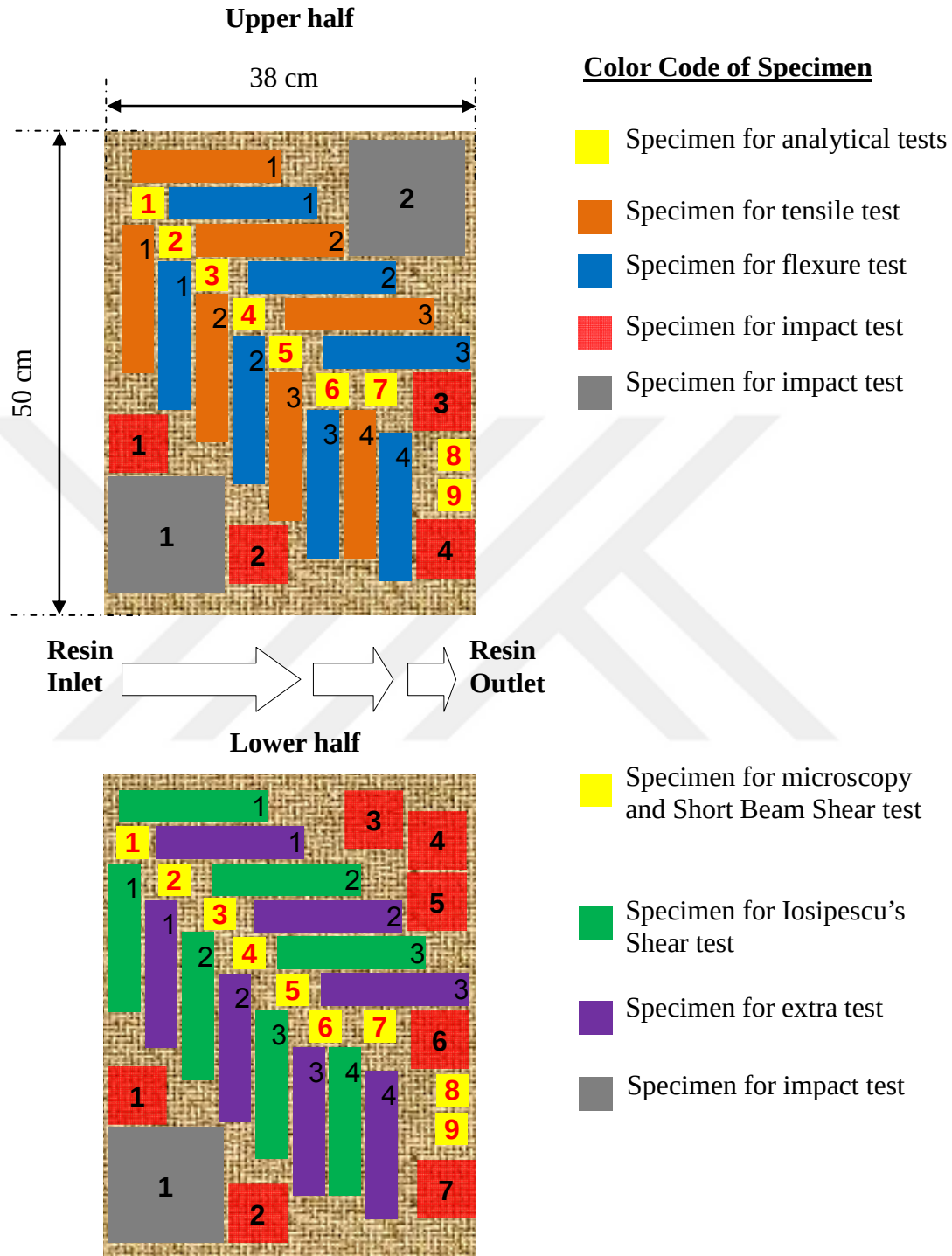


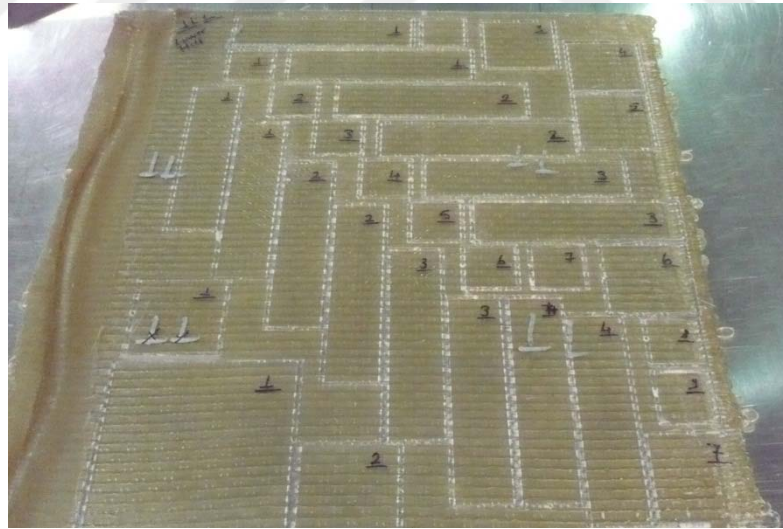
Figure 5.10. Specimen sampling plan

Computerized TurboCam II™ CNC router available at PPG Industries, Shelby, NC was used

for specimen cutting. Low coefficient of variation (less than 0.1%) in specimen width and length measurements shows the reliability of the CNC router in specimen preparation. Figure 5.11 shows the upper- and lower-half composite panels after taken from CNC router.



a



b

Figure 5.11. Upper- (a) and lower-half (b) composite panels after CNC router

According to ASTM standard for textile composites [61] and NASA contractor reports [62] [63]; specimen and strain gage width should be wider than unit cell width of textile preform

to get reliable test data. Maximum unit cell dimension of composite specimens is 16.76 X 16.41 millimeter for the current work. Specimen dimension for physical (analytical) properties was selected as 35.56 x 35.56 millimeters, and minimum specimen width for mechanical property tests was 35.56 millimeters. Therefore, all specimens in this study include minimum two unit cells in their short dimension that is recommended by ASTM D6856 for textile composites.

5.8. Determination of FVF and void content

Specimens used for thickness analysis were taken to PPG Industries, Shelby, NC to measure total FVF and void content. Resin of composites was burned in muffle furnaces at 600 °C. Total FVF and void volume fraction (VVF) of specimens were calculated according to ISO 1172 and ASTM D2734, respectively.

5.9. Mechanical tests

Methods and devices to determine mechanical properties of composites are described in this section.

5.9.1. Tensile test

MTS Landmark, 250 kN load cell capacity, universal testing device available at Composite Core Facility, College of Textile, NC State University was used to test tensile properties of composites.

ASTM D3039 was followed for testing tensile performance of composites in x- and y- directions. Specimens had 152.4 mm length and 35.56 mm width. Preliminary tests were performed to find optimum gripping and gage length to get failure in the gage length area (minimum 5 mm away from the jaws). Optimum failure was obtained at 40 mm gripping length and 72 mm gage length. Cross head speed was selected 1 mm/min. Optimum-gripping pressure was adjusted as 10 MPa to impede both slippages and crushing of specimens in the jaw area. After preliminary tests, neither specimen slippage nor crushing was observed in the gripping area. These parameters allowed testing without the need for tabbing material in the gripping area.

Laser extensometer was used to measure strain. Two parallel retro reflective tapes with at least 20 mm apart, which is much larger than unit cell length of the preform, were placed in the middle of specimen gage length.

5.9.2. Flexure test

Instron test device available at PPG Industries, Shelby, NC was used to test flexural properties of composites. ASTM D790 [64] was adopted. The test method utilizes three-point loading system, and flexural strength of materials those fail before 5.0% strain limit in the outer surface of the specimen can only be measured by this method. Support span-to-depth (specimen thickness) ratio was selected as 32:1. For each layer level, average thickness for this level was used to calculate span length. A strain rate of 0.01 mm/mm/min was picked. Cross head speed was calculated in terms of strain rate, span length, and specimen thickness. Average thickness, calculated spans lengths, and cross head speeds for each layer level are given in Table 5.7. The loading and support noses had cylindrical surfaces, and their radii were 5.0 mm. Test specimens were deflected until failure occurred in the outer surface of the specimen or until a maximum of 5.0 % strain is achieved, which takes place first.

Table 5.7. Flexure test parameters

Number of layers	Average composite thickness, mm	Support span-to-depth ratio	Support span length, mm	Cross head speed, mm/min
2	1.94	32:1	62	3.30
3	2.72	32:1	87	4.64
4	3.35	32:1	107	5.70

5.9.3. Impact test

Dynatup[®] drop-tower impact test device (Figure 5.12) available at PPG Inc., Shelby, NC was used to test impact properties of composites. ISO 6603-2 [65] was followed for testing impact performance of composites. Specimen's dimensions for this test were 60 x 60 mm.

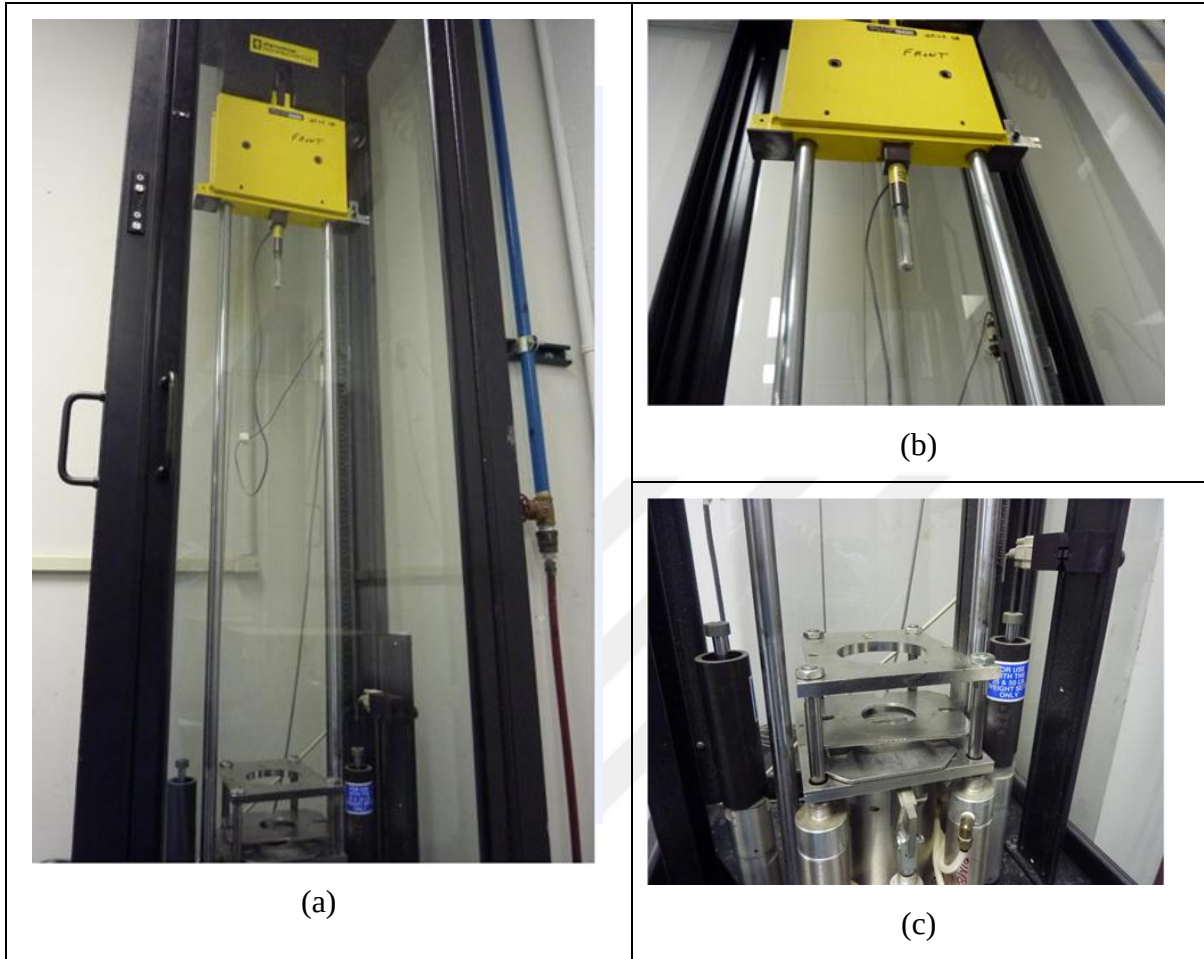


Figure 5.12. Dynatup[®] drop-tower impact test device
a: view of the entire tester, b: hemispherical striker, c: specimen clamping mechanism

The diameter of hemispherical striker used was 12.7 mm. The test device has 11.34 and 22.68 kilograms dead weight options. Preliminary tests were conducted on the strongest sample (four layers composites with the highest x-yarn density of 5.85 x-yarns/layer/cm) to determine required energy level to get full puncture (penetration). According to the standard, impact velocity is 4.4 ± 0.2 m/second and it should be ensured that impact velocity does not change during the puncture process by more than 20% by checking the deflection-time curve. It was observed that velocity change was more than 20% with 11.34 kilograms dead weight; therefore, 22.68 kilograms dead weight was placed over the hemispherical striker, and impact velocity was readjusted to 4.4 ± 0.2 m/second in terms of pneumatic spring system available

at the top of the device. During impact event, specimen was clamped by the pneumatic clamping mechanism.

Piezoelectric sensor connected to the hemispherical striker measures the force exerted by the striker on the test specimen in the direction of impact. Displacement of striker relative to specimen support was also simultaneously measured during impact event as soon as the striker hits the specimen. The software of the device draws force versus displacement curve, and area under this curve gives energy absorbed by the specimen, also called total penetration energy. As the force detected by the striker goes to zero, full penetration is achieved, and impact event is completed.

5.10. Statistical analysis

The effect of structural parameters of 3D orthogonal woven composites on mechanical properties was analyzed by using statistical tools including Analysis of Variance, Multivariate Analysis (correlation matrix), and Tukey HSD (Honestly Significant Difference) Method.

Main independent structural parameters that were considered in statistical analysis were number of y-yarn layers, x-yarn density, z-yarn interlacing pattern and vacuum pressure (Table 5.5). Additionally, response (dependent) analytical parameters given in Table 5.8 were taken into account in statistical analysis. The effect of all these parameters on tensile, flexure and impact properties of composite was investigated.

Table 5.8. Parameters considered in statistical analysis

Parameter type	Variable	Abbreviation used in statistical analysis
Main (independent) parameter	Number of y-yarn layers	layers
	X-yarn density, yarns/layer/cm	xden
	Weave	weave
	Vacuum pressure, kPa	pressure
Response (dependent) parameter	X-yarn weight of dry preform, g/m ²	xweight
	Y-yarn weight of dry preform, g/m ²	yweight
	Areal density of composite specimen, g/m ²	areal
	Thickness of composite specimen, mm	cthick
	Total FVF of composite specimen, %	tfvf
	X-yarn FVF of composite specimen, %	xfvf
	Y-yarn FVF of composite specimen, %	yfvf
	Z-yarn FVF of composite specimen, %	zfvf
	Void content of composite specimen, %	void

Note: Numeric numbers were assigned for weaves. 1, 2, and 3 were assigned for plain, basket, and twill weaves, respectively.

Correlation among response mechanical property, input (independent) parameter, and response (dependent) parameter was investigated by “Multivariate Method” using JUMP[®] software in terms of calculating correlation coefficient (r). Correlation coefficient changes between -1 and +1 in which boundaries represent strong relationship, and negative sign indicates the property reduces with an increase in the independent parameter relationship and vice versa. Correlation matrix gives the effect of each parameter on response mechanical property. Additionally, the strength of relationship between independent and dependent parameters was revealed by the correlation matrix to explain the mechanical test results.

Analysis of Variance and Tukey HSD tests were also performed to analyze the significance of each main (independent) parameter on mechanical properties, and the differences between levels of each main parameter at 95% confidence interval. Details of statistical analysis are given in Appendix P.

6. ANALYTICAL RESULTS AND DISCUSSION

Physical properties of the dry preforms (thickness, constituent yarns weights, and z-yarn crimp) were measured. FVF calculations from dry preform physical properties and volumetric density of yarn material were given and discussed in section 6.3.

For the sake of flow of reading and due to the same trend observed for different layers, only results for 3 layers structures are given in the following sections. The results for 2 and 4 layers preforms, and their composites are given in Appendices.

6.1. Dry preform thickness

Figure 6.1 shows dry preform thickness measurements for 3 layers 3D orthogonal woven dry preforms. For a given weave, as x-yarn density is increased, thickness of dry preform also increases due to increase in thickness of x-yarns. Large spacing between successive x-yarn insertions (low x-yarn density) promotes the flattening of x-yarns, which results in thickness reduction. As x-yarn density is increased, the room for yarn flattening reduces and thickness is increased.

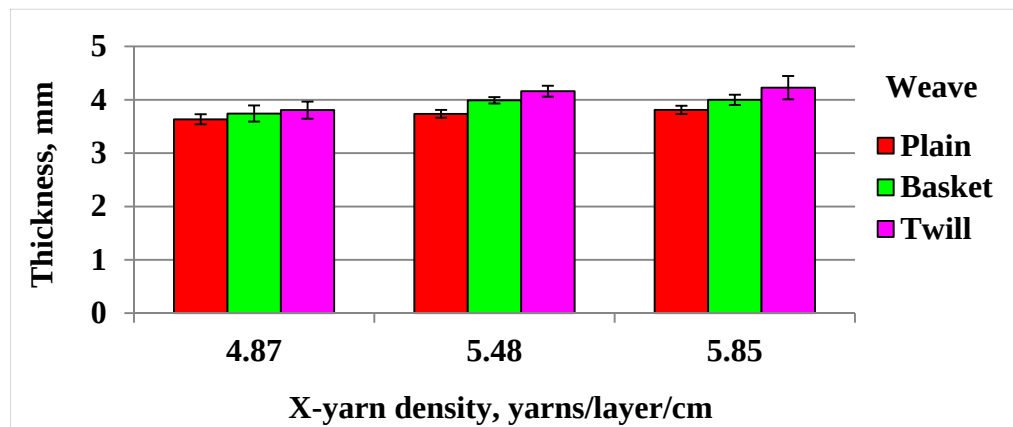


Figure 6.1. Thickness of 3 layers dry preforms

The lowest preform thickness is obtained for plain weaves. The highest interlacing density of plain weave (more through thickness component of z-yarn) creates more tension in z-

direction that decreases thickness due to the pressure imposed by the z-yarns on the x-yarns a matter that causes x-yarns flattening. Additionally, it was observed that plain weave is very compact and easy to handle during dry preform experiments. On the other hand, basket and twill weaves were very loose and easy to distort, difficult to handle, and their x-yarns were easily raveled from preform edges. Dry preform thickness results of 2 and 4 layers composites indicated the same trend as 3 layers (Appendix D).

6.2. Yarn weights

6.2.1. X-yarn weight

Figure 6.2 shows measurements and predictions for x-yarn weight of 3 layers dry preforms. Results indicated that for a given x-yarn density, the weave has no effect on x-yarn weight. The insignificant difference between experimental and predicted x-yarn weights is due to the x-yarn waviness that was noticed for raveled yarns (Figure 5.7). The waviness of the x-yarns resulted from the z-yarns pressure at the crossover points. X-yarn weight of 2 and 4 layers dry preforms exhibited the same trend as 3 layers (Appendix D).

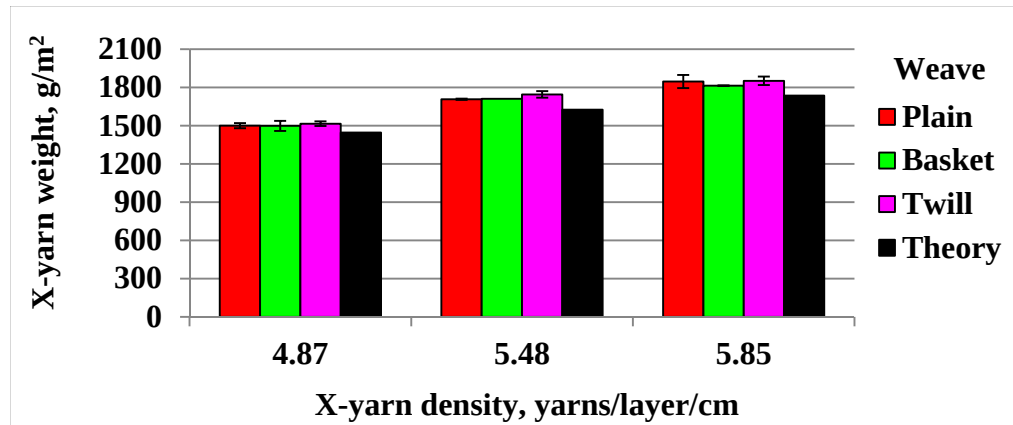


Figure 6.2. X-yarn weight of 3 layers dry preforms

6.2.2. Y-yarn weight

Figure 6.3 shows measured and predicted results of y-yarn weight of 3 layers dry preforms. Y-yarn weight values of all dry preforms are the same regardless of weave or x-yarn density

since constant number of y-yarns (102 yarns/layer) was used to produce all samples. The same can be noticed for y-yarn weight of the preforms with 2 and 4 layers (Appendix D). It can be noticed that the difference between the measured and predicted y-yarn weight is extremely small because the y-yarns are laid perfectly straight and do not interlace with other yarns. Additionally, y-yarns are always under constant tension.

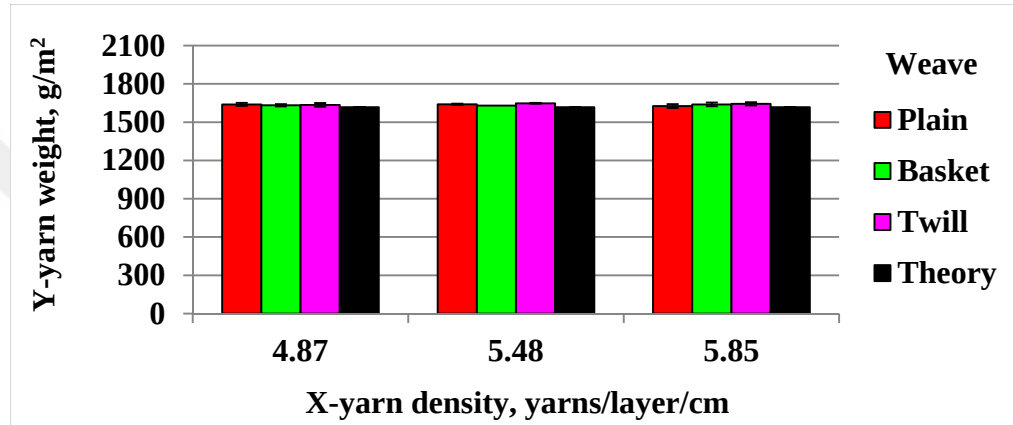


Figure 6.3. Y-yarn weight of 3 layers dry preforms

6.2.3. Z-yarn weight

Figure 6.4 shows measurements for z-yarn weight of 3 layers dry preforms. Plain weave has the highest z-yarn weight due to more through-thickness component of z-yarn than other weaves (or higher yarn crimp as it can be seen from Figure 6.5). The difference between the weight of the z-yarn of twill and basket weaves preforms is insignificant since both weaves have same number of through the thickness components of z-yarns. X-yarn density increased both z-yarn weight and crimp due to increase in thorough the thickness components of z-yarn per unit area. 2 and 4 layers dry preforms indicated the same trend as 3 layers for z-yarn weight and z-yarn crimp results (Appendix D).

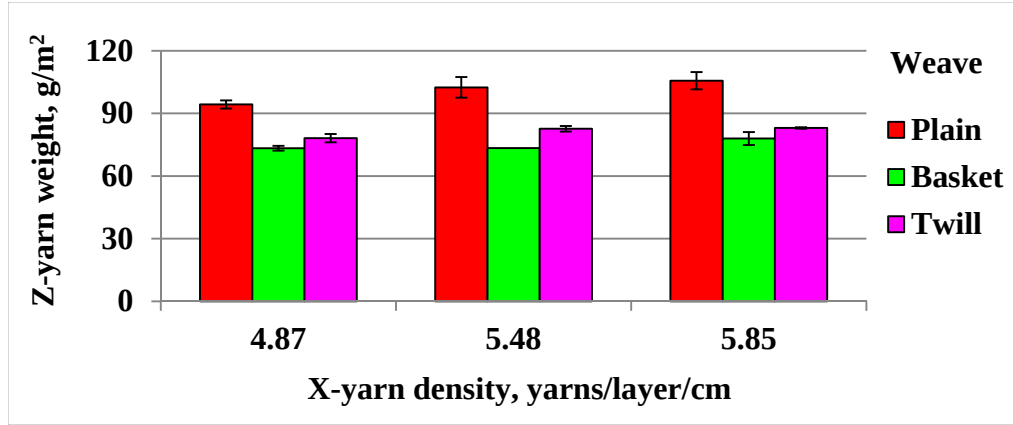


Figure 6.4. Z-yarn weight of 3 layers dry preforms

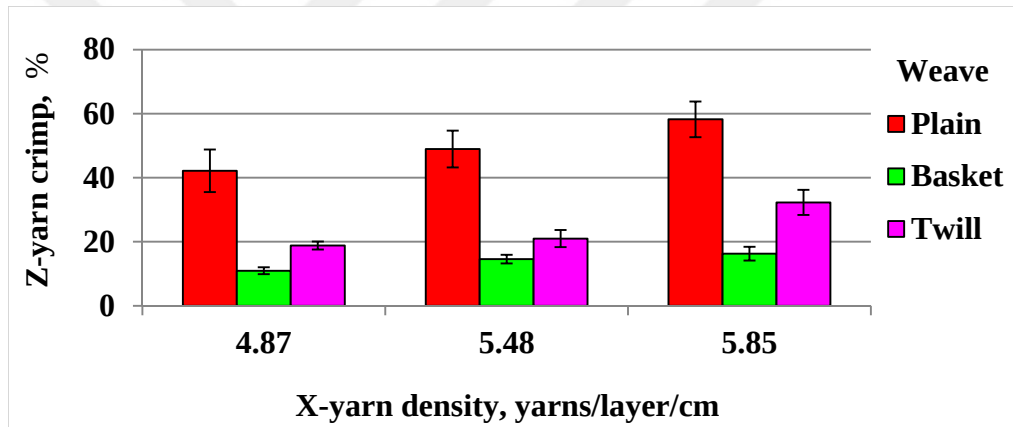


Figure 6.5. Z-yarn crimp of 3 layers dry preforms

6.2.4. Total weight

Figure 6.6 shows measurements for total weight of 3 layers dry preforms. It is obvious total weight increases with x-yarn density for a given weave. Results show that effect of weave on total weight is negligible for a given x-yarn density. This is attributed to the fact that the z-yarn linear density and number of z-yarns are very small compared to the x-yarns and y-yarns and consequently z-yarn contribution to the total weight is very low (2 to 3% wt. for 3 layers preforms). 2 and 4 layers dry preforms exhibited the same total weight trends as 3 layers (Appendix D)

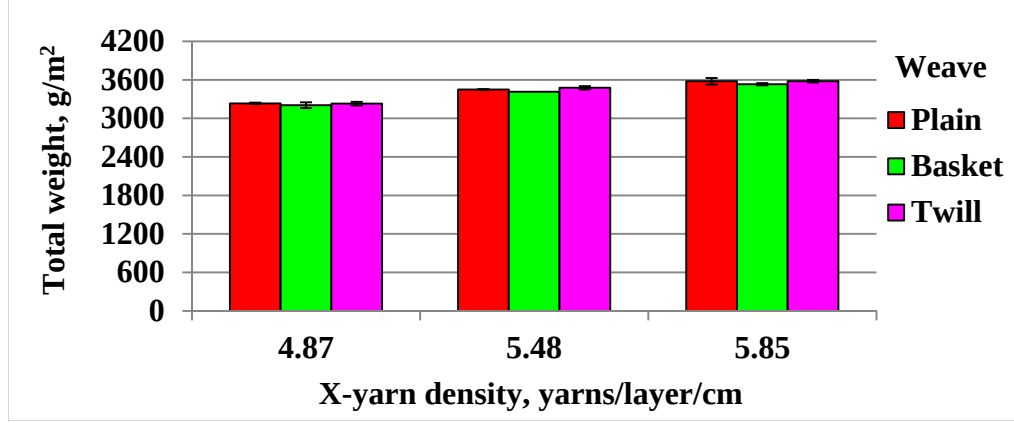


Figure 6.6. Total weight of 3 layers dry preforms

6.3. FVF calculation from physical properties of dry preform

FVF for each constituent yarn (F_{fk}) was calculated in terms of the constituent yarn weight (W_k), preform thickness (L_z), and volumetric density of the yarn material (ρ_{vk}) measurements using equation 6.1.

$$F_{fk}(\%) = \frac{W_k}{L_z \rho_{vk} 100} \quad (6.1.)$$

Figure 6.7 shows calculated x-yarn FVFs for 3 layers dry preforms. As x-yarn density is increased, both weight of x-yarn and thickness of dry preform increase. X-yarn weight increase dominates the preform thickness increase; therefore, x-yarn density causes increase in the x-FVF. For a given x-yarn density, plain weave has the highest x-FVF, and twill weave has the lowest x-FVF which is inversely related with preform thickness (Figure 6.1). X-yarn FVF for 2 and 4 layers dry preforms showed the same trend as 3 layers (Appendix D)

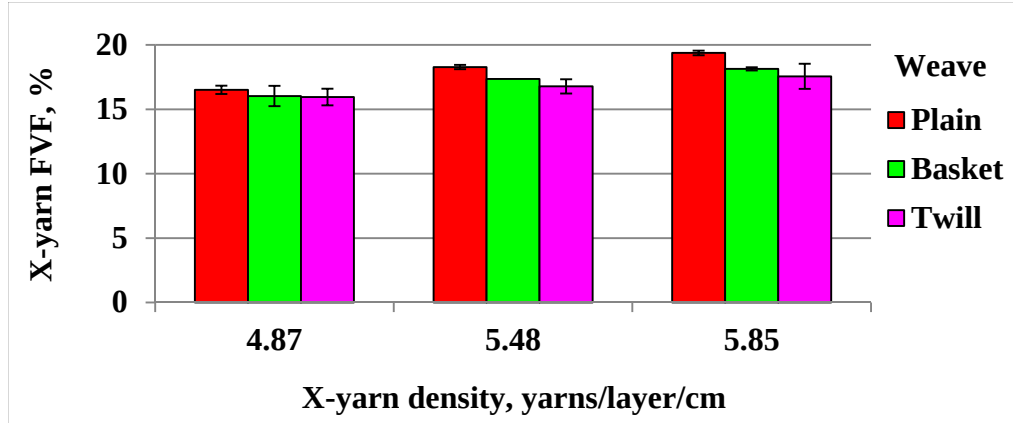


Figure 6.7. X-yarn FVF of 3 layers dry preforms

Figure 6.8 shows calculated FVFs for y-yarn constituent of 3 layers dry preforms. X-yarn density has no effect over y-yarn weight, however, increase in x-yarn density causes increase in dry preform thickness (Figure 6.1); therefore, as x-yarn density is increased, y-FVF is lowered. Through-thickness compact structure of plain weave lowers thickness that increases y-FVF, and loose through-thickness structure of twill and basket weaves increase thickness which lowers y-FVF for a given x-yarn density. The trend is similar to 3 layers for y-yarn FVFs of 2 and 4 layers dry preforms (Appendix D).

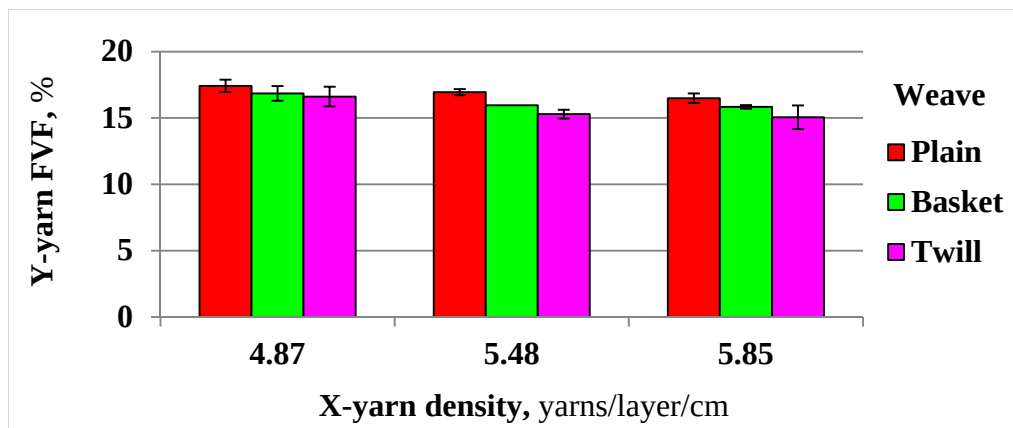


Figure 6.8. Y-yarn FVF 3 layers dry preforms

Figure 6.9 shows calculated FVFs for z-yarn constituent of 3 layers dry preforms. Z-FVF of plain weave is greater than z-FVFs of other weaves. Basket and twill weaves have the same amount of z-yarn FVF. Plain weave has higher z-yarn weight and lower dry preform thickness than other weaves that causes the increase in z-yarn FVF. X-yarn density slightly increases z-FVF of plain weave, however it has non-significant effect on z-FVFs of basket and twill weaves. Z-yarn FVF for 2 and 4 layers dry preforms exhibited same trend as 3 layers (Appendix D).

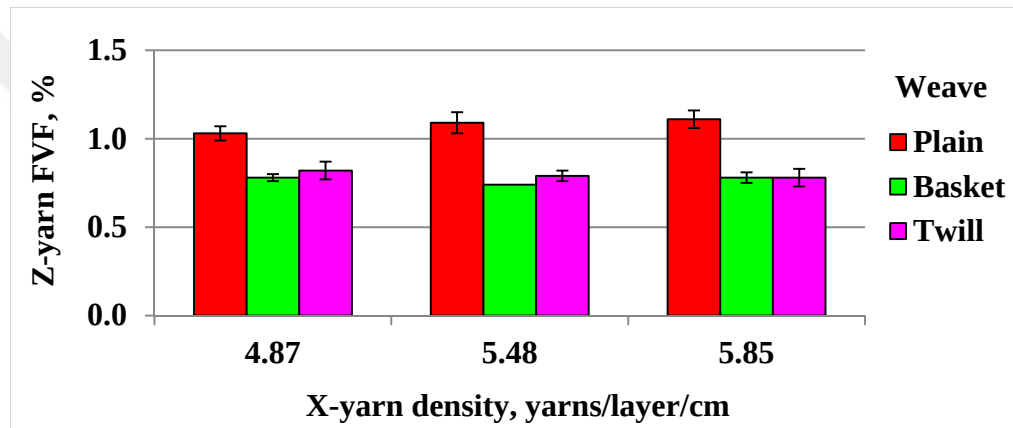


Figure 6.9. Z-yarn FVF of 3 layers dry preforms

Figure 6.10 shows calculated total FVFs (in terms of dry preform total weight and thickness measurements) for 3 layers dry preforms. Plain weave resulted in slightly higher total FVF compared to other weaves due to its lower thickness provided by compact structure through the thickness direction. Total FVF calculations for 2 and 4 layers dry preforms showed the same trend as 3 layers dry preforms (Appendix D).

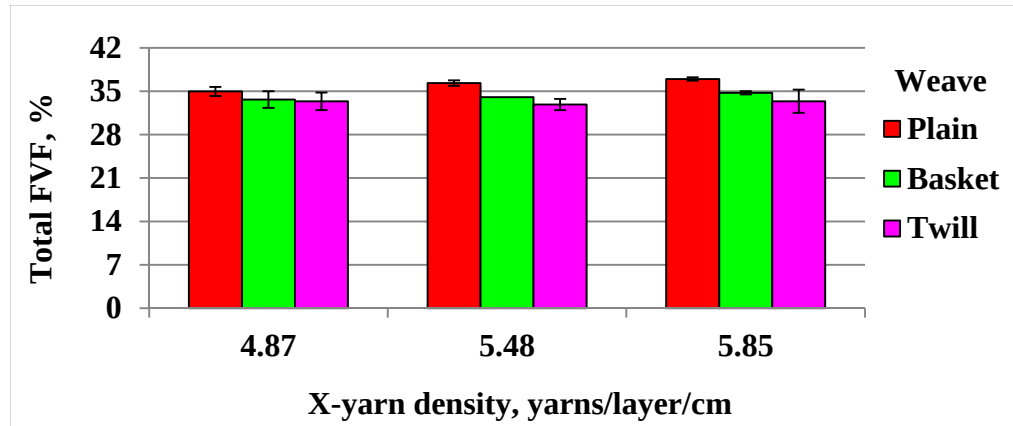


Figure 6.10. Total FVF of 3 layers dry preforms

6.4. Resin infusion performance

In this part, resin infusion performance of 3 layers dry preforms at 75 and 100 kPa vacuums were illustrated and discussed. Infusion performances of 2 and 4 layers preforms are given in Appendix F. Figure 6.11 shows time (minute in horizontal axis) versus resin flow front position (cm in vertical axis) for 3 layer preforms' infusion at 75 kPa vacuums. Mold-filling times of these preforms are given in Table 6.1.

Mold-filling times of plain and basket weaves are less than that of twill waves. For plain weave, narrow but straight channels between successive (adjacent) weft yarns enhance resin flow in x-direction. For basket weaves, straight and wider channels due to merging of two successive insertions in the same shed enhance the resin flow compared to other weaves. Twill weave has narrow and non-straight channels (distorted by z-yarn interlacing with staggered pattern) in x-direction that impede easy resin flow and increase mold-filling time (Figures 5.3 and 5.4).

X-yarn density did not show significant effect on resin flow-front profile for plain and basket weaves, whereas it greatly changed resin flow front profile of twill weaves. For plain and basket weaves the channels, which reduce in size with x-yarn density, are uninterrupted with through the thickness component of z-yarns. While in case of twill weave, the increase in x-

yarn density is associated with increase in through the thickness component of the z-yarns, which are in the way of the resin flow path a matter that caused deceleration of resin flow. For 3 layers dry preforms at 75 kPa vacuum, minimum mold filling time was achieved in basket weave. Twill weaves are the most disadvantageous structures that take long time to fill the mold.

It is worth noting that the x-yarn density effect on resin flow-front length is negligible in case of plain and basket weave because the change in x-yarn density caused increase in the channel height and reduction in channel width. However, the effect of x-yarn density on resin flow front in case of twill weaves is significant due to increase in the number of through the thickness components of the z-yarns.

Figure 6.12 indicates resin flow front tracking for 3 layers dry preforms at 100 kPa vacuum. Table 6.2 shows mold-filling times of these preforms. With the exception of two cases (37 and 58 minutes mold filling time), the behavior of resin front-flow length is similar for 75 and 100 kPa vacuum.

Table 6.1. Mold-filling times of 3 layers dry preforms at 75 kPa vacuums

Weave	X-yarn density, yarns/layer/cm		
	4.87	5.48	5.85
Plain	18	18	23
Basket	18	missing data	15
Twill	24	29	39

Table 6.2. Mold-filling times of 3 layers dry preforms at 100 kPa vacuums

Weave	X-yarn density, yarns/layer/cm		
	4.87	5.48	5.85
Plain	37	15	24
Basket	15	12	missing data
Twill	27	27	58

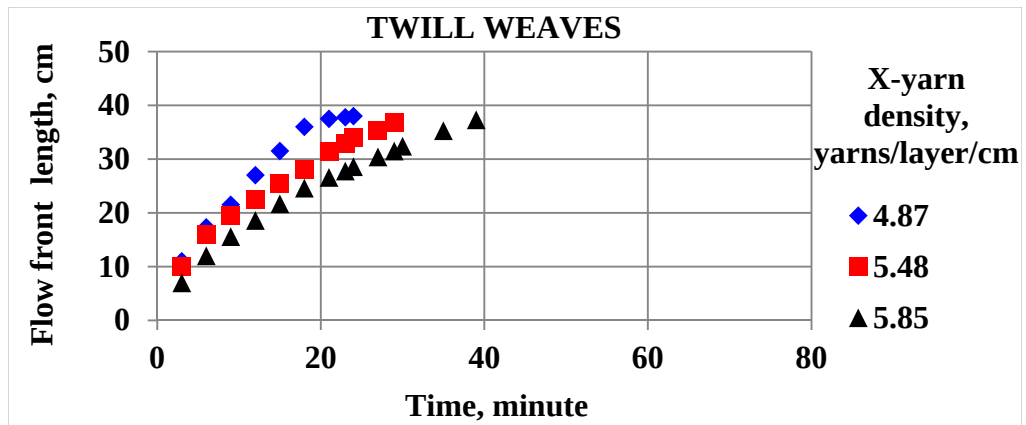
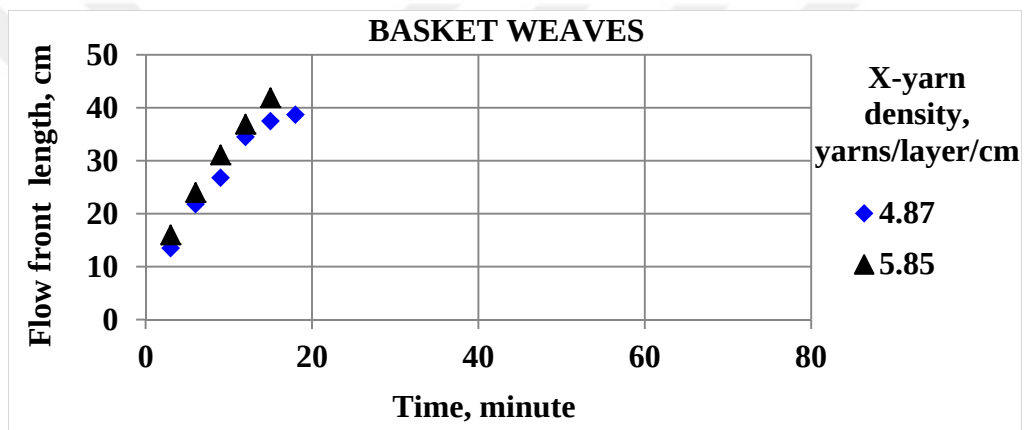
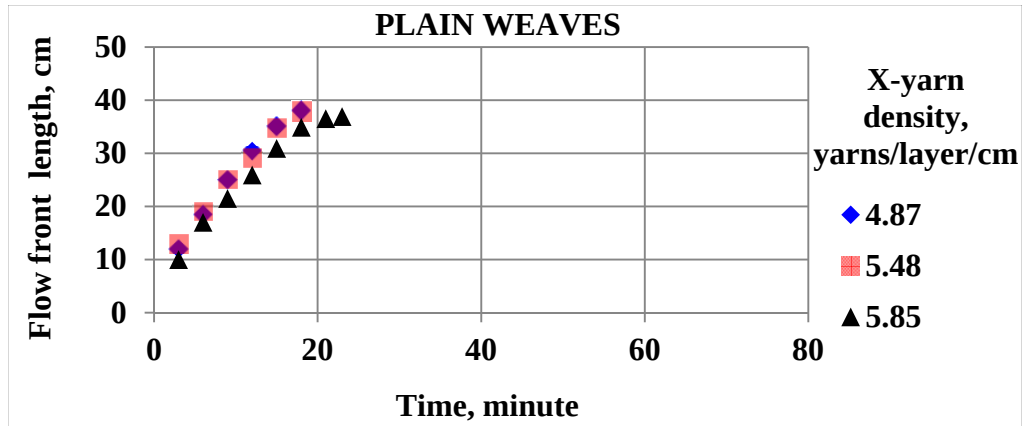


Figure 6.11. Tracing of resin flow fronts of 3 layers preforms at 75 kPa vacuum

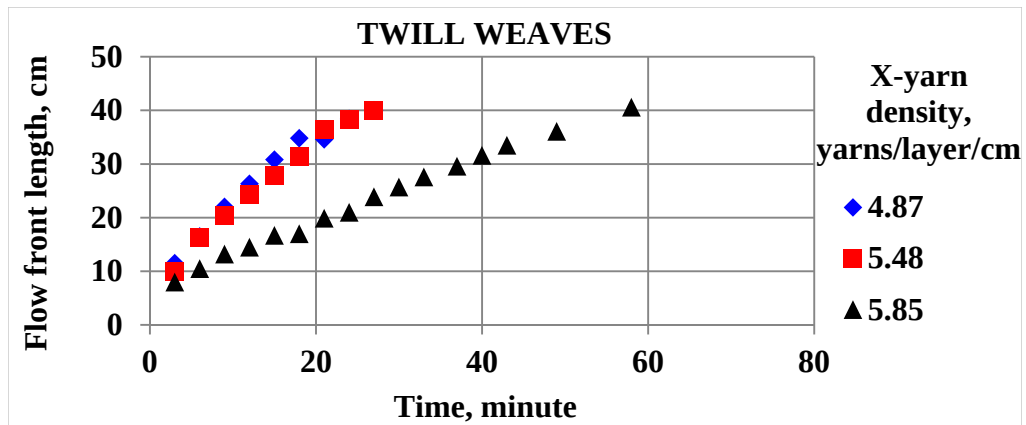
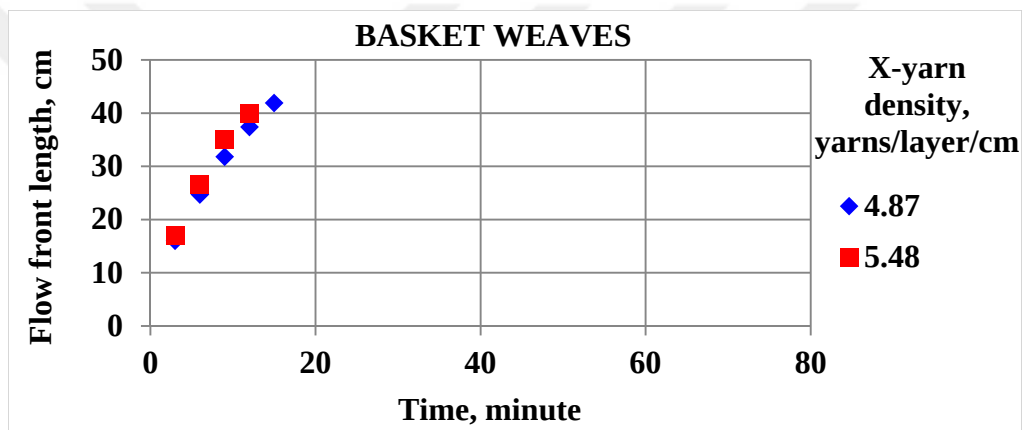
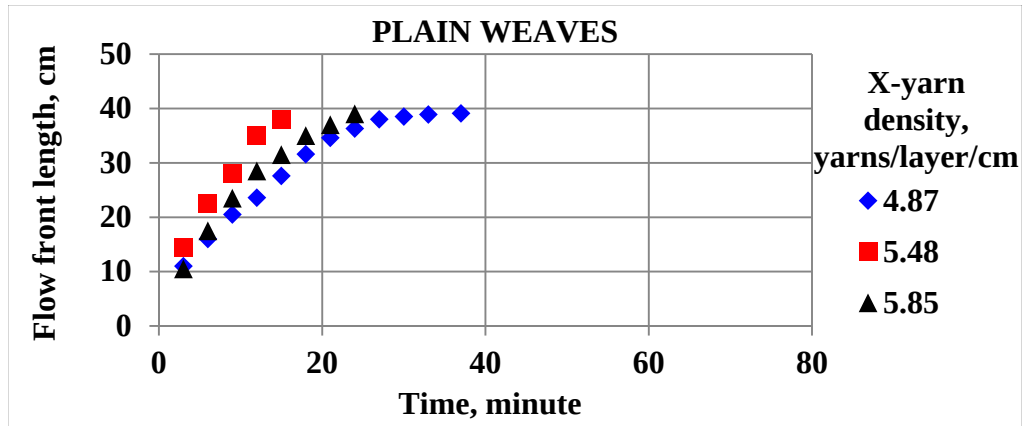


Figure 6.12. Tracing of resin flow fronts of 3 layers preforms at 100 kPa vacuums

6.5. Physical properties of composite

The effect of sample location with respect to resin inlet line and independent structural parameters (number of layers, weave, x-yarn density and vacuum pressure during infusion) on physical (thickness, fiber volume fraction and void content) of composite is given and discussed in this section.

Observations from six analytical specimens each 35.56 mm x 35.56 mm on the upper half of each composite panel (Figure 5.10 and Figure 5.11.a), in total 324 data points (54 panels x 6 specimens), were used for statistical analyses that include correlation matrix, ANOVA, and Tukey multiple means comparison to assess the results.

6.5.1. Thickness

ANOVA indicated that sample location and all independent structural parameters (number of layers, weave, x-yarn density, and vacuum pressure during resin infusion) have statistically significant effect on volume-based thickness of composite (Figure P.2 of Appendix P).

Figures 6.13 and 6.14 indicate volume-based thickness profile of 3 layers composites manufactured at 75 and 100 kPa vacuums, respectively. Figures 6.15 and 6.16 show average composite thicknesses for 3 layers composites manufactured at 75 and 100 kPa, respectively. Volume-based thickness profiles and the averages of 2 and 4 layers composites are given in Appendix G.

Figure 6.17, which shows the main effect of the parameter location, exhibits the effect of distance from resin inlet on volume-based thickness of composite. In addition to ANOVA, Tukey multiple means comparison statistical analysis showed that the thicknesses of different specimen locations are statistically significant from each other at 95% confidence interval (Figure P.2), and thickness of composites indicated a decreasing trend towards outlet.

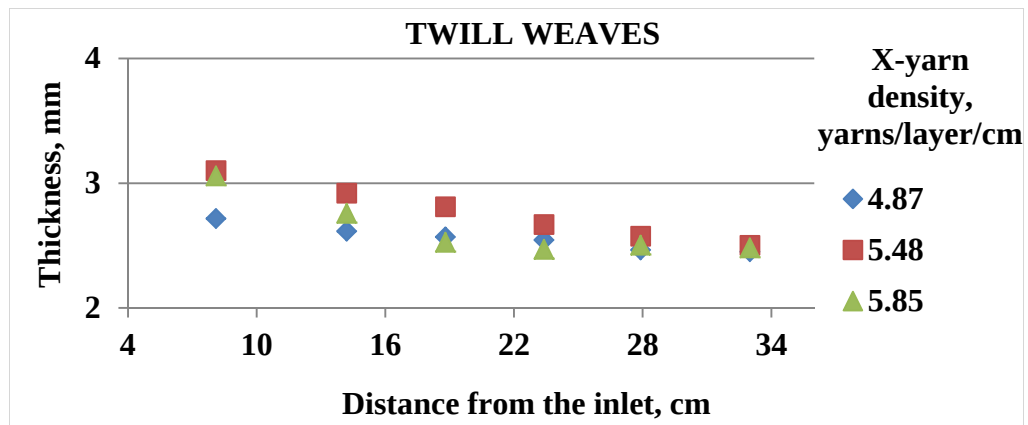
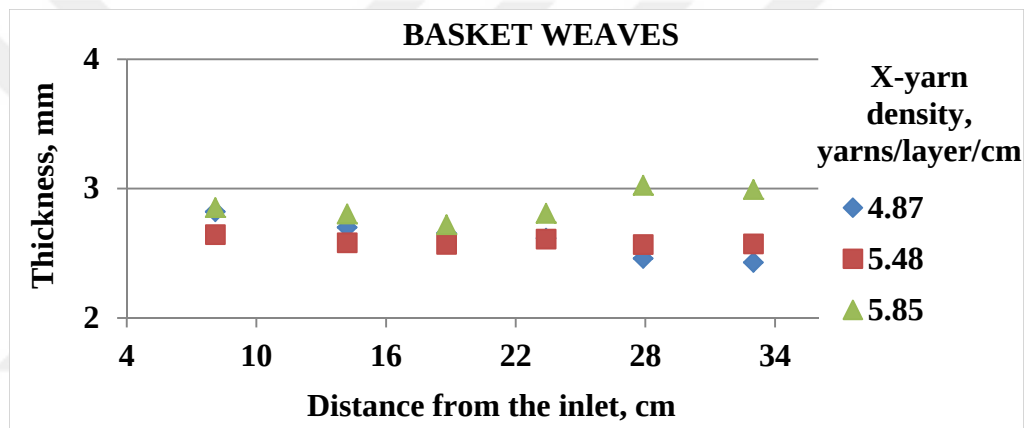
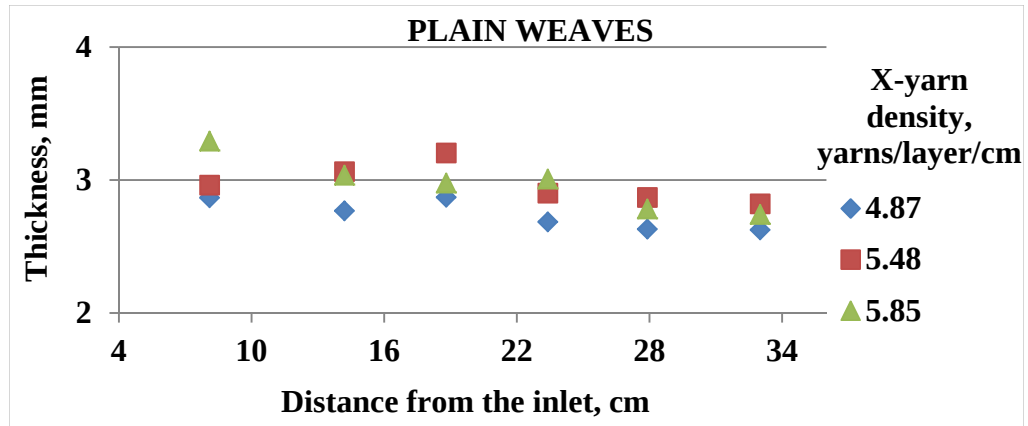


Figure 6.13. Thickness profile of 3 layers composites manufactured at 75 kPa vacuums

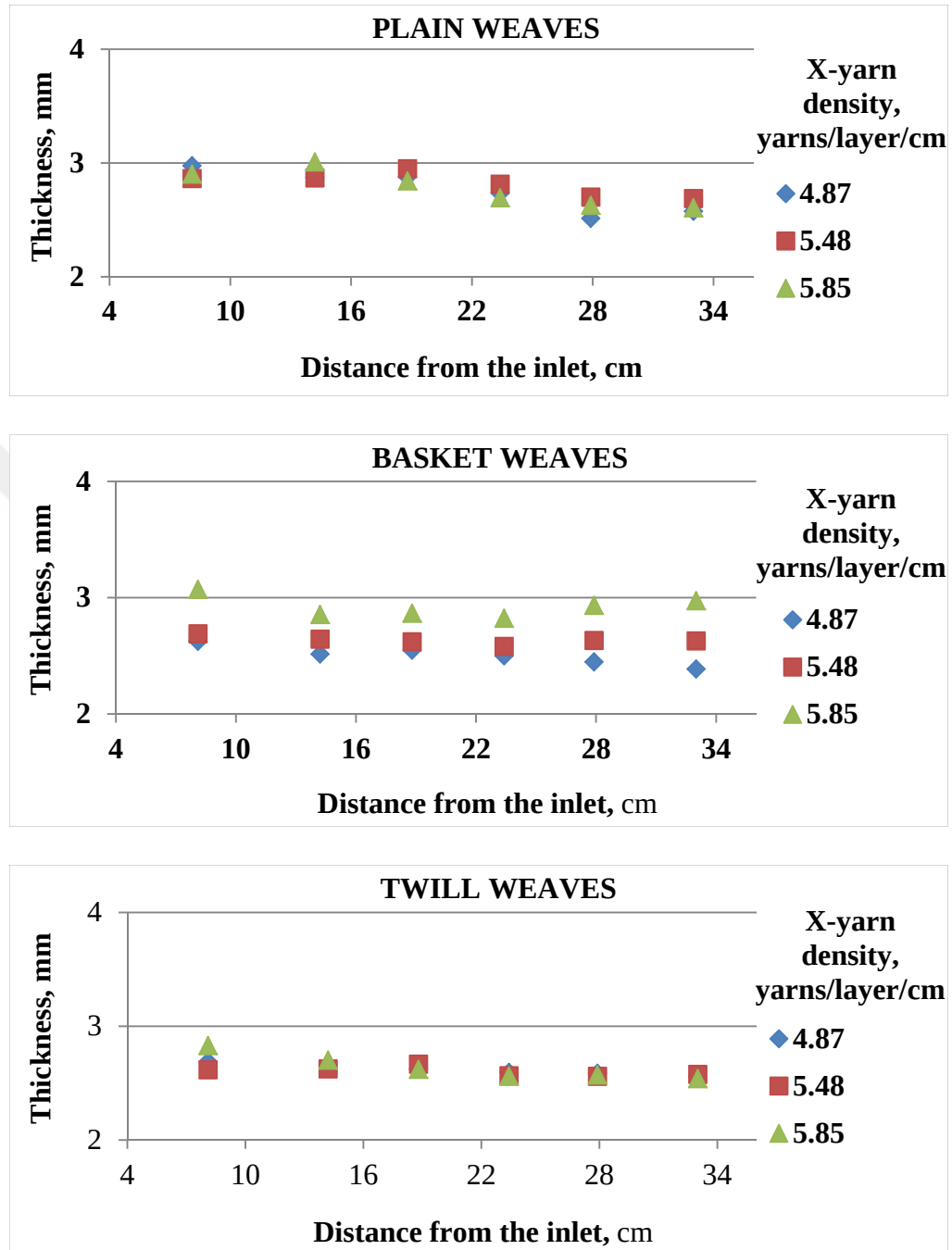


Figure 6.14. Thickness profile of 3 layers composites manufactured at 100 kPa vacuums

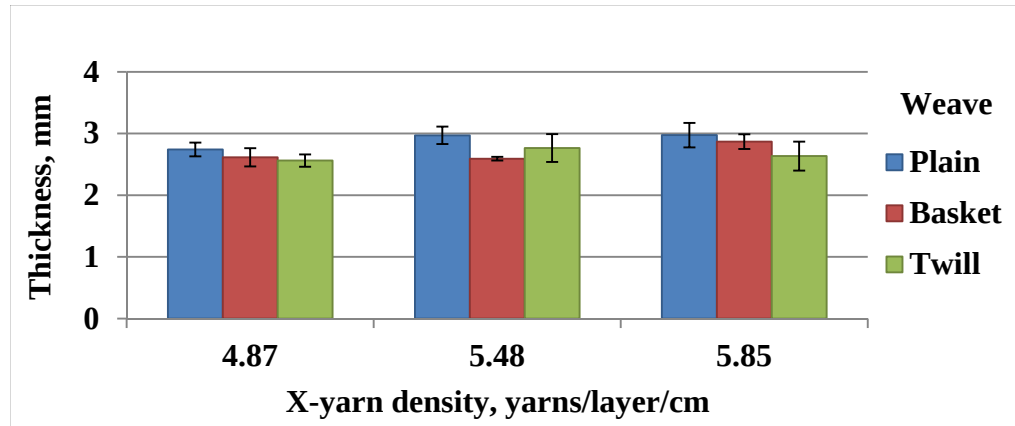


Figure 6.15. Thickness of 3 layers composites manufactured at 75 kPa vacuums (Error bars represent $\pm$ one standard deviation)

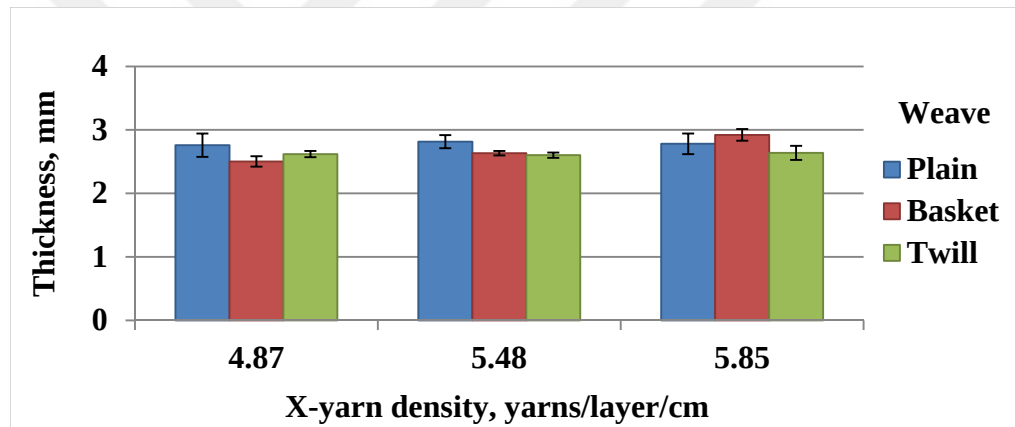


Figure 6.16. Thickness of 3 layers composites manufactured at 100 kPa vacuums

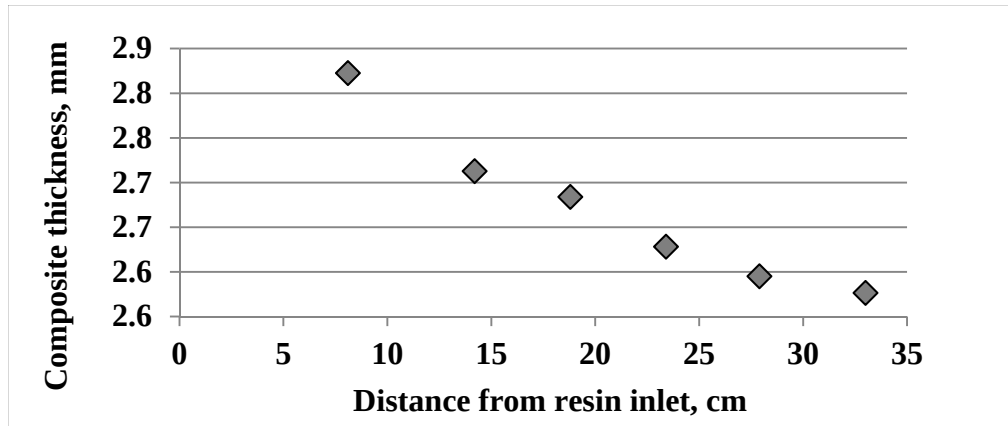


Figure 6.17. Effect of distance from resin inlet on volume-based thickness of composite

Composites with plain weave have the highest average thickness and they are significantly different from composites with other weaves (Figure P.2). In plain weaves, space (channel width) between two successive weft yarns is smaller compared to the same spacing in basket and twill weaves. Therefore, vacuum bag cannot completely collapse over the spacing between successive weft yarns in plain weaves. When vacuum bag collapses over these spacings, average thickness of preform decreases, resin cannot flow with ease and thickness variation as a result of absent of resin in the channels increases. Twill weave does not allow easy resin flow due to the presence of the through the thickness components of z-yarns as discussed earlier; therefore it has the lowest average thickness due to reduction in resin. Average thickness of basket weave is between plain and twill weaves and the difference between composites with basket and twill is not statistically significant per Tukey multiple means comparison (Figure P.2).

Increase in x-yarn density caused increase in volume-based composite thickness due to the reasons discussed in dry preform thickness. Tukey multiple means comparison indicated that composites with different x-yarn density levels are significantly different from each other (Figure P.2).

Increase in vacuum pressure caused a decrease in composite thickness due to increase in compression pressure during infusion. Tukey multiple mean comparisons showed that

thickness difference between composites manufactured at 75 and 100 kPa vacuum is statistically significant at 95% confidence interval (Figure P.2).

6.5.2. Total fiber volume fraction

ANOVA test indicated that the effects of sample location and independent structural parameters (number of layers, weave, x-yarn density, and vacuum pressure during resin infusion) on composite total FVF are statistically significant at 95% confidence interval (Figure P.4).

Total fiber volume fraction profiles of 3 layers composites manufactured at 75 and 100 kPa vacuums are given in Figures 6.18 and 6.19, respectively. The corresponding results of the average total FVF are presented in Figures 6.20 and 6.21. Figures 6.18 and 6.19 indicate areas of composite panel close to resin inlet have more resin and correspondingly have low FVF. Areas close to resin outlet have less resin, therefore; more FVF is observed towards outlet. The results of total FVF of composites are affected by the thickness results (Figures 6.13 - 6.17). The inverse relationship of FVF and thickness is obvious from equation 6.1. Total FVF profile and the averages of 2 and 4 layers composites are given in Appendix H.

Tukey multiple means comparison showed that total FVF difference among different spots on a composite panel is statistically significant at 95% confidence interval (Figure P.4). Figure 6.22 shows the main effect of sample location on composite total FVF. Increase in specimen distance from resin inlet line caused increase in composite total FVF.

4 layers composites showed the highest total FVF, and they were followed by 3 and 2 layers composites respectively. Composites with 4 layers are significantly different than composites with 2 and 3 layers, and the difference between 2 and 3 layers composites in view of total FVF is not statistically significant at 95% confidence interval (Figure P.4)

The effect of weave type on composite FVF is statistically significant per ANOVA and Tukey multiple means comparison (Figure P.4). Composites with plain weaves have the lowest FVF, and they were followed by composites with basket and twill weaves,

respectively. In plain weaves, resin can easily penetrate to the interiors of structure, and decreases fiber volume fraction. For twill weave, resin cannot penetrate as easy as plain weave, which results in increase in FVF of the composite. Therefore, composites with twill weaves have the highest total FVF while FVF of composites with basket weave is higher than composites with plain weave.

An increase in x-yarn density caused an increase in total FVF. Results reported earlier indicated that an increase in x-yarn density caused an increase in thickness (of both dry preform and composite) and in x- and z-yarn weights. Increase in composite total yarn weight surpassed the increase in composite thickness, therefore the total composite FVF, which is ratio between total yarn weight and composite thickness, increases as x-yarn density is increased. Composites with 5.85 x-yarn density level showed the highest total FVF, and they are significantly different from composites with 5.48 and 4.87 x-yarn density levels. The total FVF difference between composites with 5.48 and 4.87 x-yarn density levels is not statistically significant (Figure P.4).

Increase in vacuum resulted in statistically significant increase in composite total FVF per ANOVA and Tukey multiple means comparison (Figure P.4).

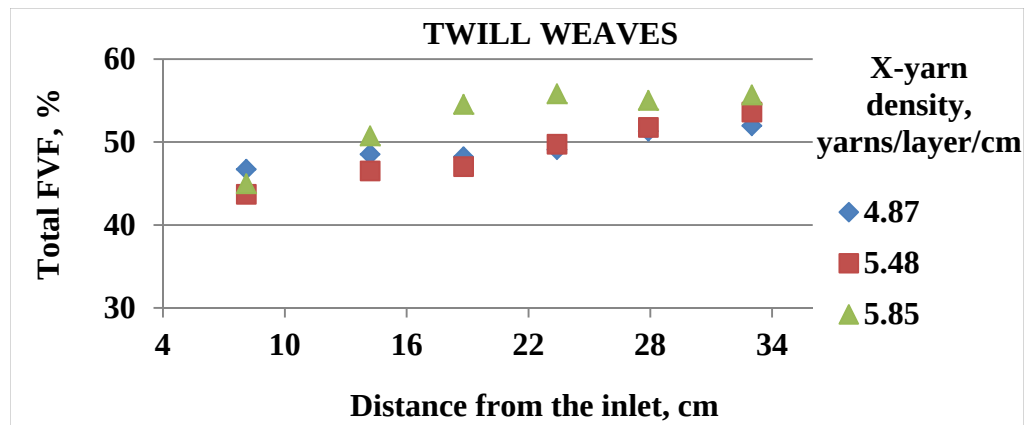
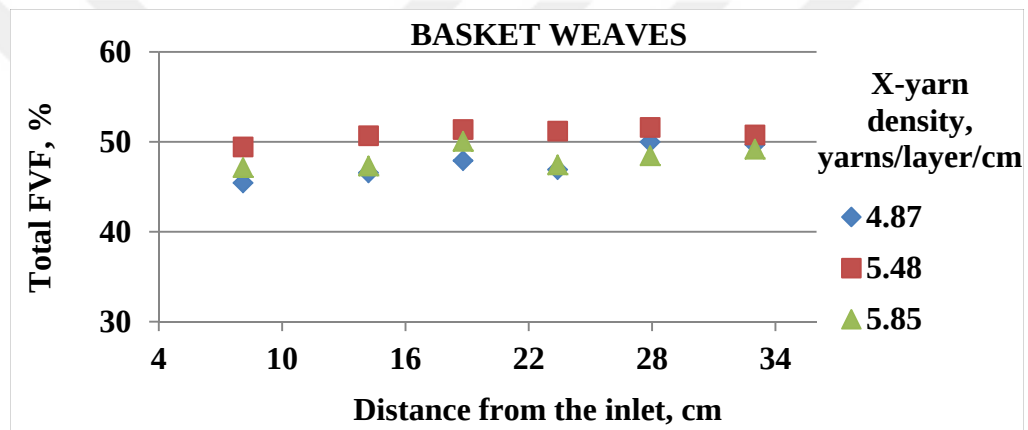
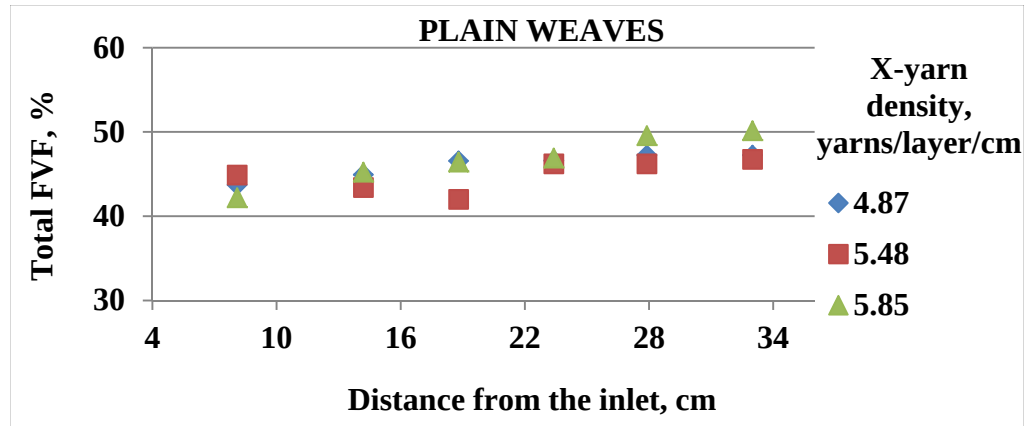


Figure 6.18. Total FVF profile of 3 layers composites manufactured at 75 kPa vacuums

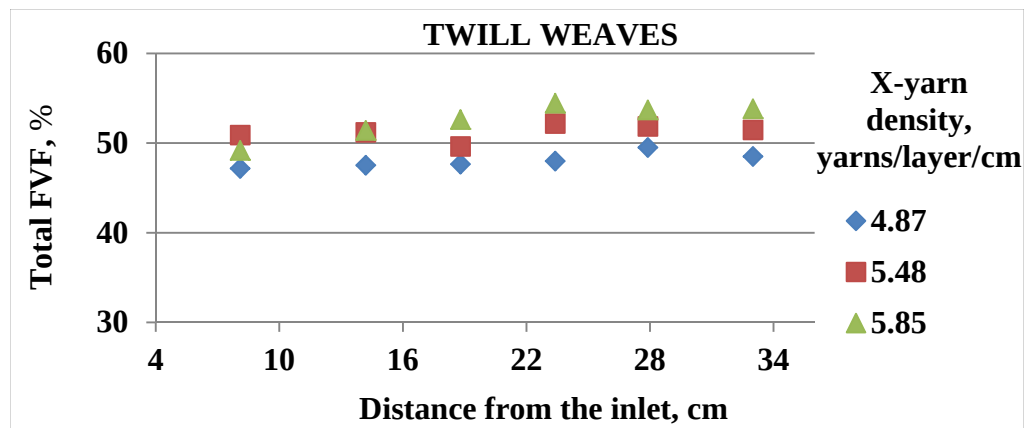
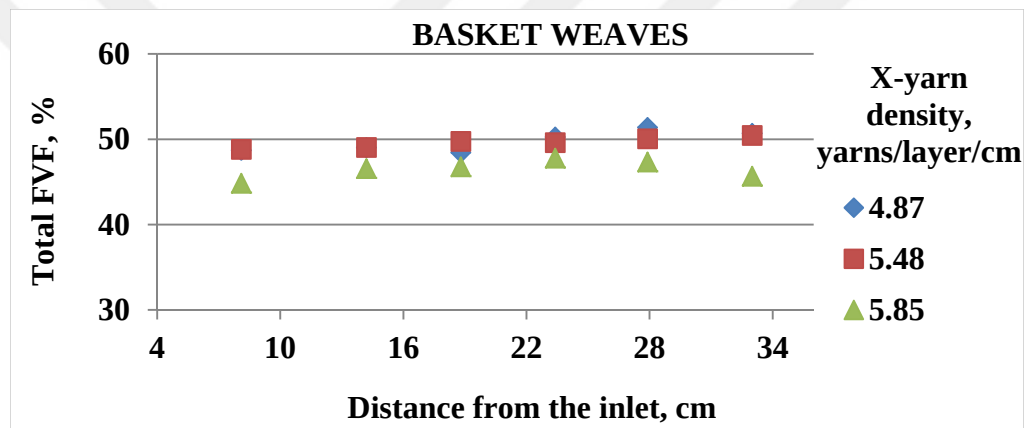
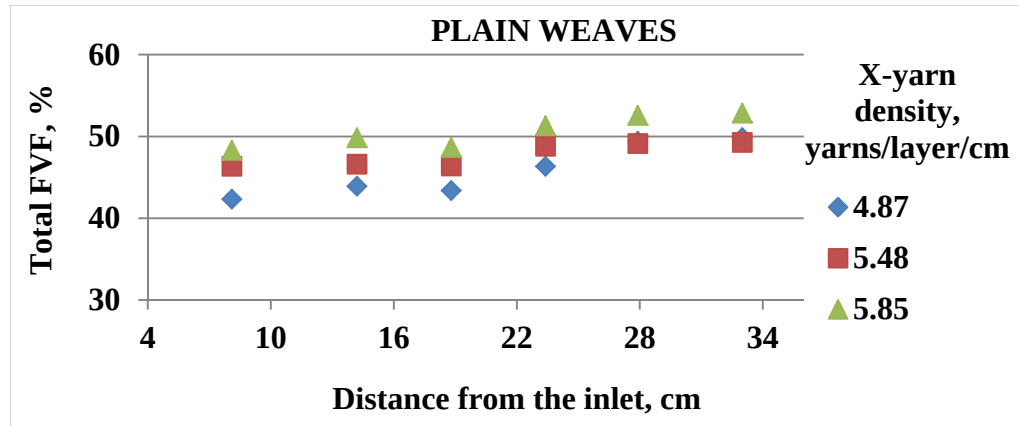


Figure 6.19. Total FVF profile of 3 layers composites manufactured at 100 kPa vacuums

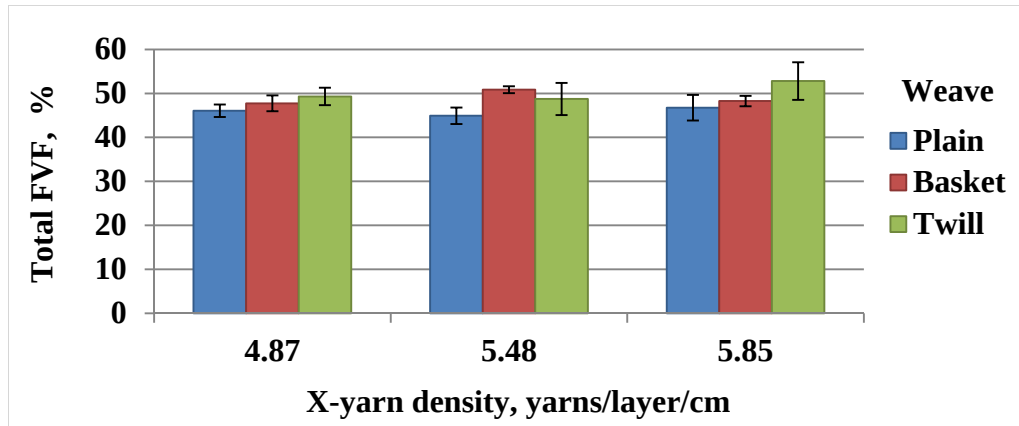


Figure 6.20. Total FVF of 3 layers composites manufactured at 75 kPa vacuums

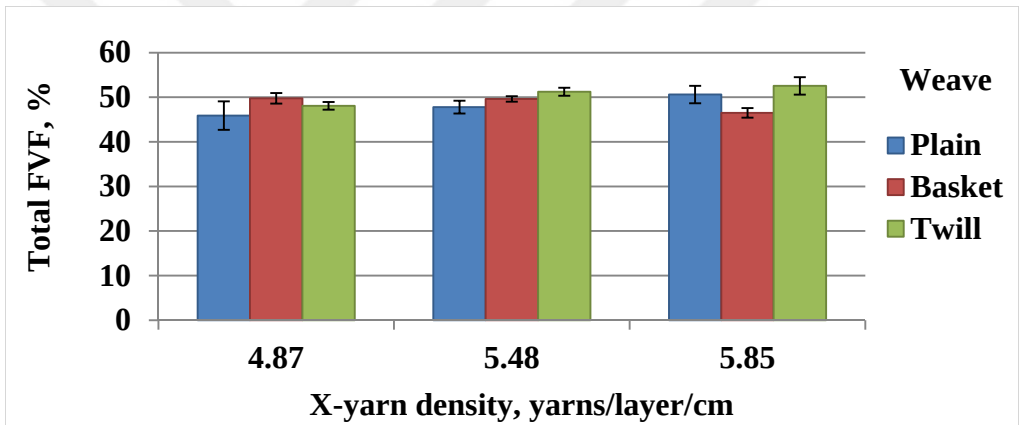


Figure 6.21. Total FVF of 3 layers composites manufactured at 100 kPa vacuums

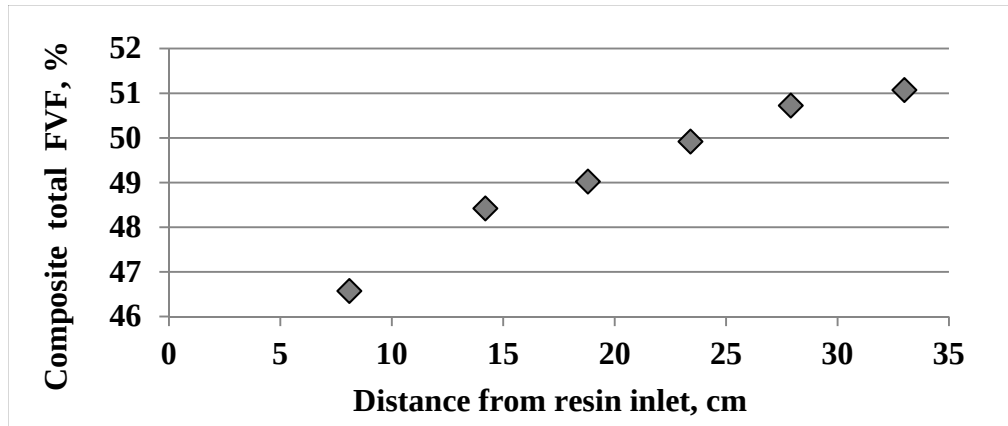


Figure 6.22. Effect of distance from resin inlet on composite total FVF

6.5.3. Void content

ANOVA indicated that the effect of independent structural parameters (number of y-yarn layers, weave, x-yarn density, and vacuum pressure during resin infusion) on void content of composite is statistically significant at 95% confidence interval. However, the effect of sample location on void content of composite is not statistically significant at 95% confidence interval (Figure P.6).

Figures 6.23 and 6.24 show void volume fraction profile of 3 layers composite panels infused at 75 and 100 kPa vacuums, respectively. Figures 6.25 and 6.26 show average VVF of 3 layers composites manufactured at 75 and 100 kPa vacuums, respectively. Void volume fraction profiles and average results for 2 and 4 layers composites are given in Appendix I.

There is no clear trend from inlet to outlet for void volume fraction (VVF, %). The results of void volume fraction agree with the earlier findings by Pearce et al. [31]. Close observation of the composite panels' surface revealed the existence of numerous small spherical voids accumulated around and inside the z-yarns at the crossover points with x-yarns. At these points, the structure is tight, the air is entrapped, and the resin could not fully replace the air in such tight areas.

Correlation matrix and Tukey multiple means comparison analysis indicated that increase in number of layers caused increase in void content of composites (Table P.3 and Figure P.6).

As the thickness of composite is increased, heat exothermic of curing reaction increases. Increase in heat exothermic enhances void formation and growth due to increase in vapor pressure of volatiles in resin [3]. Additionally, the amount of air entrapped in thick preforms is higher than thin preforms and the probability of void formation of thick preforms during VIP is higher than thin preforms.

Tukey multiple means comparison showed that the highest void content was observed in composites with plain weaves, and they are significantly different from composites with other weaves. The void content difference between composites with twill and basket weaves is statistically not significant (Figure P.6). Due to its high interlacing of z-yarns, plain-woven preforms are tight and they tend to keep the voids during resin infusion due to the air entrapment especially at the z-yarn and x-yarn crossover points. Loose structure of basket weaves resulted in lower void content than other two weaves due to easy displacement of air of basket weave by resin during VIP. Large channels between x-yarns in basket weaves enhance resin flow, hence voids can easily move towards resin outlet especially after filling of mold (after resin inlet was clamped), which is known as post-filling stage.

Increase in x-yarn density caused decrease in void content. The lowest void content was observed in composites with 5.48 and 5.85 x-yarn densities and they are significantly different from composites with 4.87 x-yarn densities. The difference between composites with 5.48 and 5.85 x-yarn density levels are statistically not significant (Figure P.6).

Void content of composites manufactured at 75 kPa vacuum is higher than composites manufactured at 100 kPa vacuums, and the difference is statistically significant per Tukey multiple means comparison analysis (Figure P.6). Low vacuum pressure cannot totally remove the air in the mold cavity that results in higher void content.

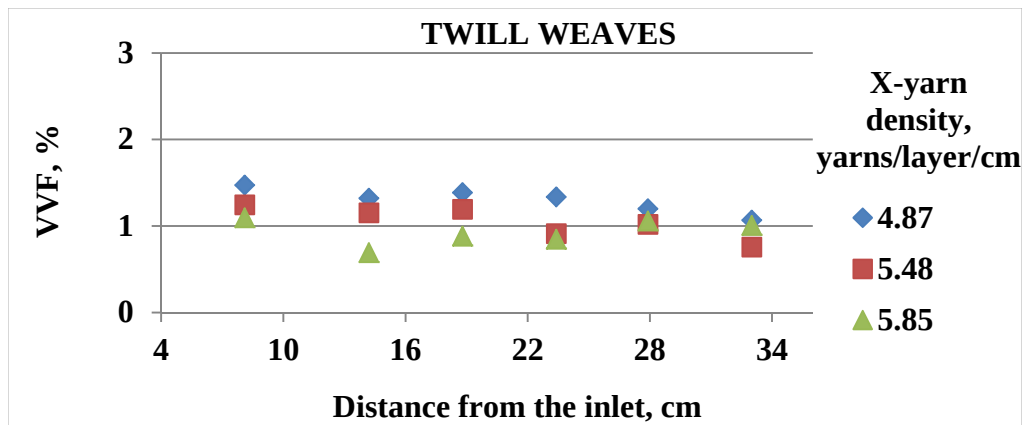
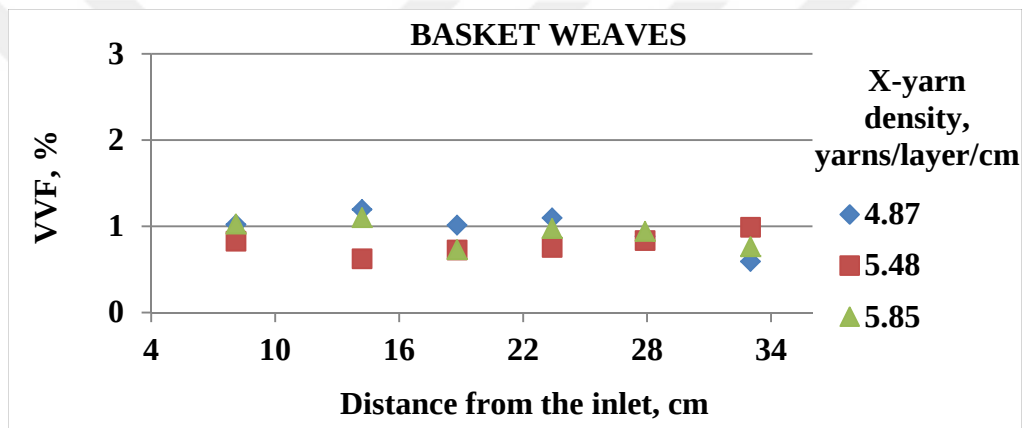
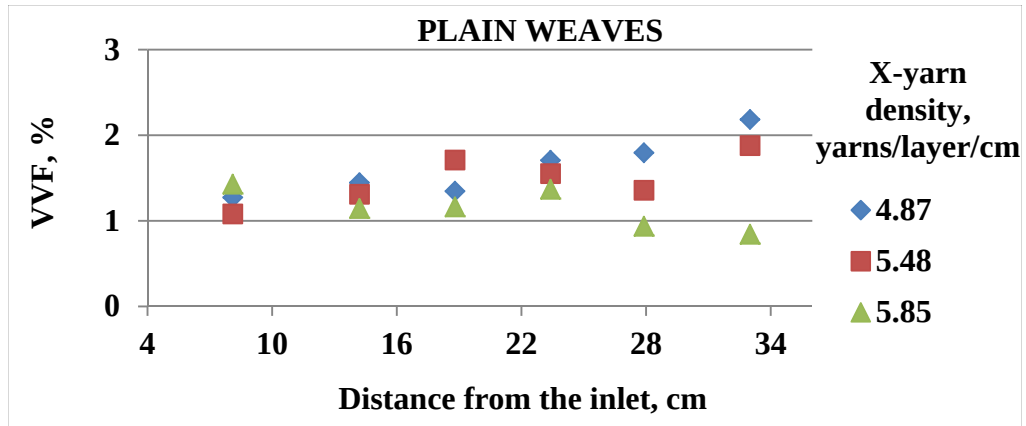


Figure 6.23. VVF profile of 3 layers composites manufactured at 75 kPa vacuums

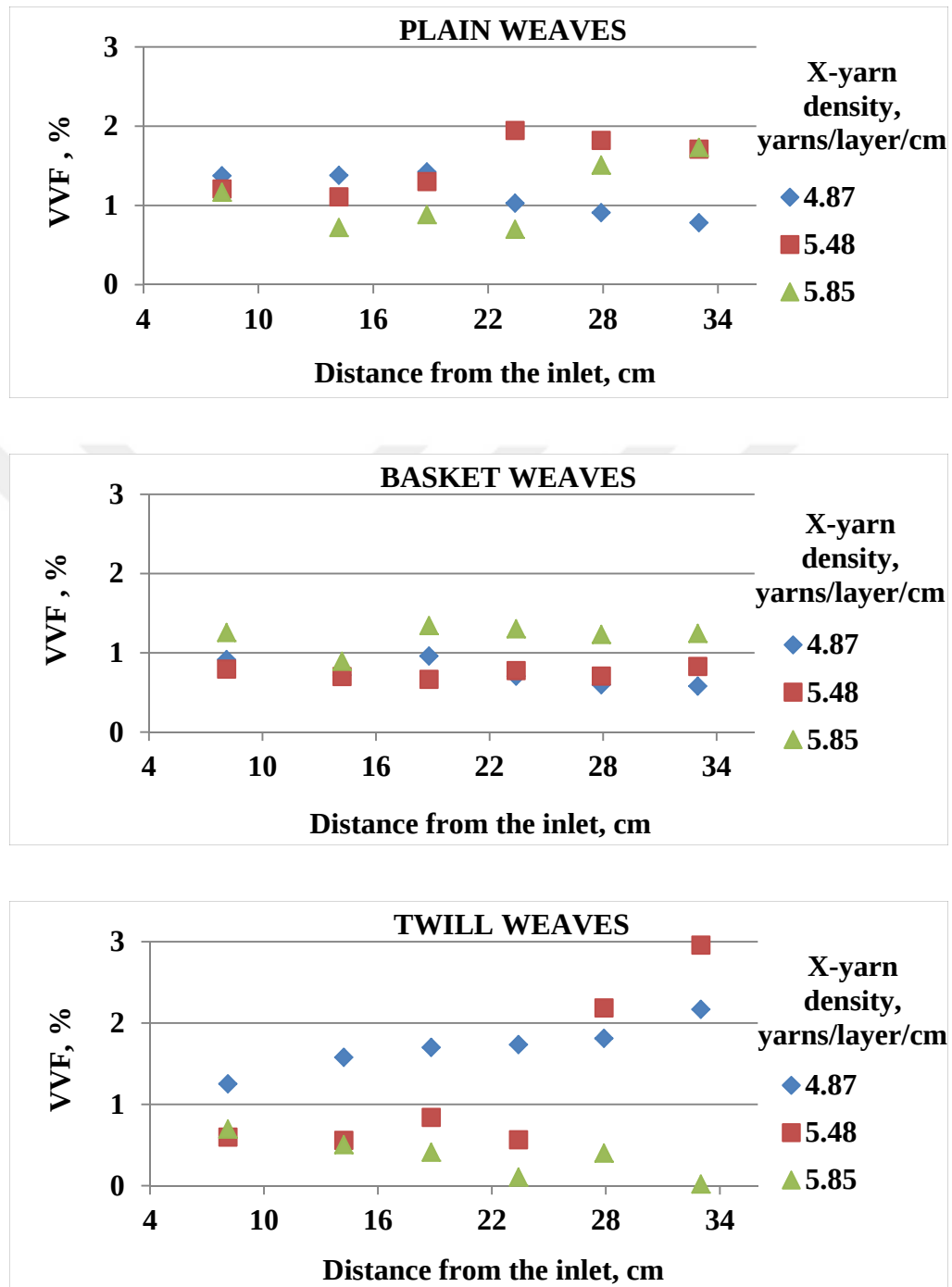


Figure 6.24. VVF profile of 3 layers composites manufactured at 100 kPa vacuums

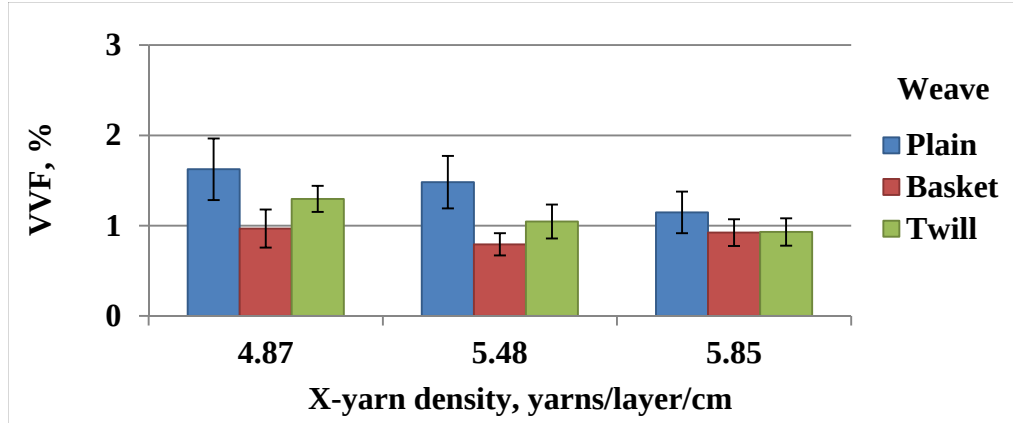


Figure 6.25. VVF of 3 layers composites manufactured at 75 kPa vacuums

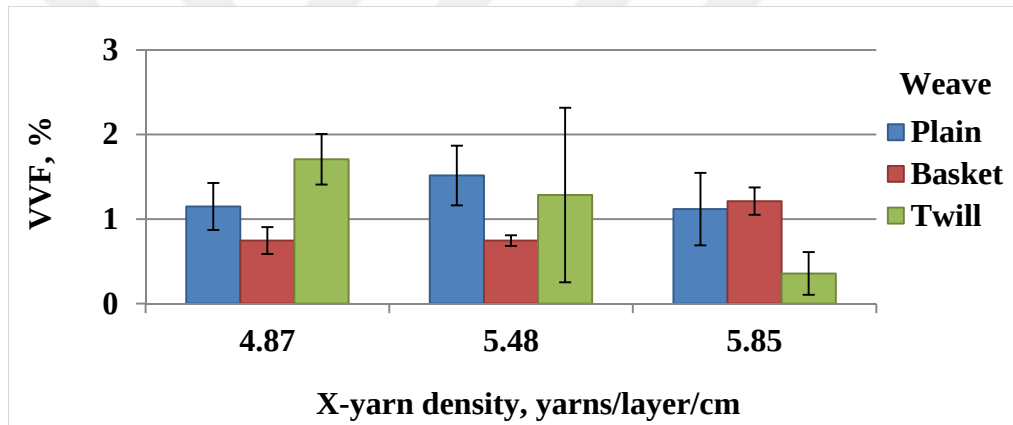


Figure 6.26. VVF of 3 layers composites manufactured at 100 kPa vacuums

6.5.4. Conclusion

Physical properties of composite panels were measured from resin inlet to outlet for a broad range of fabric architectures. Thickness of composite panel decreased from inlet to outlet. The amount of decrease was determined by channel configuration in x-direction of the structure that was dictated by weave (fabric architecture). Plain and basket weaves had less thickness variation than twill weave, due to their straight and open channels, which promoted resin progression in mold cavity.

FVF of composite panels increased from resin inlet to outlet. Local resin pressure, which is the driving force for the flow, decreases from resin source to resin flow front line for any RTM process. Compaction of preform, which is the difference between atmospheric and local resin pressures in VIP due to presence of flexible vacuum bag on top of the molding, increases towards resin outlet line. Therefore, more resin is accumulated in areas close to resin inlet line (less compacted areas) than in areas close to resin outlet line (more compacted areas) that results in FVF variation [48] [49] [50]. In this study, the extent of FVF variation is related to channel geometry of the structures, which is affected by weave. The variation in FVF from inlet to outlet is greater for twill weave compared to the plain and basket weaves due to tortuous channels in x-direction of twill weave.

VVF must be very low because it influences composites' mechanical properties [66]. In contrast to composite thickness and FVF, no trend was observed for void volume fraction. As x-yarn density increased, the VVF got lower. Composites with basket weaves exhibited low VVF compared to those with plain and twill weaves due to loose structure of basket weave. Increase in vacuum of VIP caused statistically significant decrease in VVF of composites.

7. MECHANICAL RESULTS AND DISCUSSION

7.1. Tensile stress

Analytical results of previous chapter indicated that thickness of composite panels decreases from resin inlet to outlet. Areal density (g/m^2) and thickness of each tensile specimen (using hemispherical micrometer) were measured. Decrease in thickness and composite areal density from resin inlet to outlet was observed for tensile specimens. Load versus strain curve of tensile specimens indicated that failure character of composites was brittle. Because, the composite constituents (glass fiber and vinyl ester thermoset resin) are brittle. The composite specimens failed, once they reach peak point, therefore no plastic region was observed on load-strain curve as shown in Figure 7.1, which depicts a typical behavior of load-strain. In many specimens, yield and peak corresponded to the same point, and peak point was very close to break point, and similarly strain at peak point was very close to strain at break point. In some specimens, yield, peak, and break points were the same. Therefore, only peak point as a representative quality parameter for tensile stress was considered. Profile of peak tensile stress for 3 layers composites are given in this chapter. Profile of peak tensile stress for 2 and 4 layers composites are given in Appendix J and K.

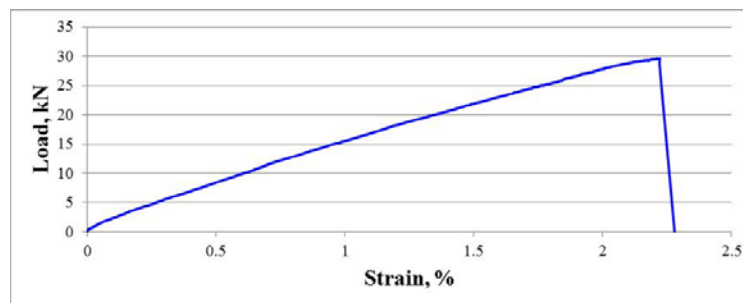


Figure 7.1. Tensile load in x-direction versus strain curve of 2 layers, plain weave, 5.85 x-yarns/layer/cm composite manufactured at 100 kPa vacuums

7.1.1. Tensile stress of composite in x-yarn direction

Three specimens oriented in the x-yarn direction taken from the lower half of each composite panel (labeled 1-3 in Figure 7.2) were utilized for determining tensile properties of composites in x-direction. Perpendicular distance between the resin inlet line and center of each specimen was determined as 14.73, 22.35, and 29.97 cm.

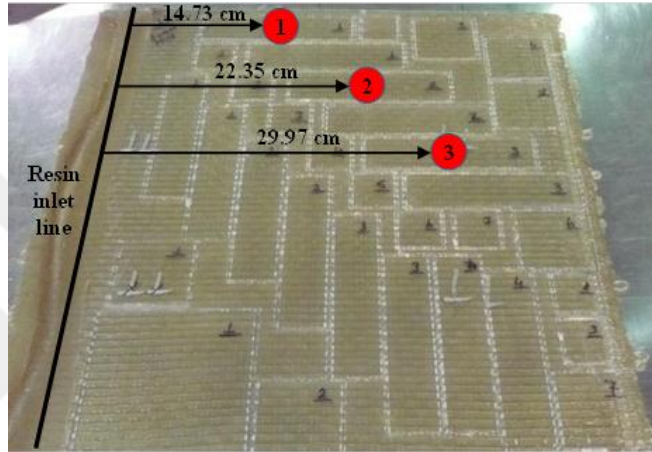


Figure 7.2. Tensile specimens in x-direction on lower-half composite panel

Figures 7.3 and 7.4 show peak tensile stress change in x-direction from resin inlet to outlet for 3 layers composites manufactured at 75 and 100 kPa vacuums, respectively. Tensile failure regions of composites indicated that load is completely transferred from resin to fibers, and dominant failure mechanism is fiber fracture (no fiber pull-out was observed, Figures 7.5 and 7.6).

In the following parts, the results of the average tensile stress in x-direction are presented. For a given composite panel (out of 54), the average was calculated from the three observations of the samples marked 1-3 in Figure 7.2. All observations (54 x 3) were used to infer the results using ANOVA, Tukey multiple means comparison, and correlations statistical analyses.

Table P.4, Figure P.7, and Figure P.8 in Appendix P show the results of the statistical analyses. As it can be seen the effects of distance from resin inlet, number of layers, weave, x-yarn density, and vacuum pressure on the tensile stress in x-direction are statistically significant at confidence level of 95% (Figure P.8).

Slight increase trend, from resin inlet to outlet, was observed for peak tensile stress in x-direction of 3 layers composites (Figure 7.3 and 7.4) due to decrease in thickness (increase in FVF). Tukey multiple means comparison analysis indicated that the sample location has statistically significant effect on tensile stress in x-direction (Figure P.8). Figure 7.7 shows the main effect of sample location on tensile stress in x-direction. Great amount of tensile load, depending on FVF, is carried by the fibers oriented in the load direction, and load share of resin is small compared to fiber due to great difference between tensile properties of dry fiber and neat cast resin. Therefore, increase in FVF resulted in increase in tensile stress of composite.

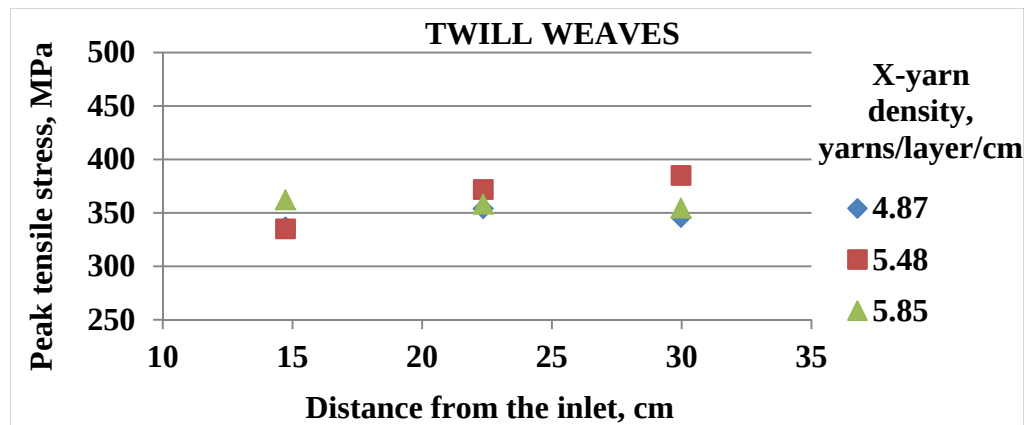
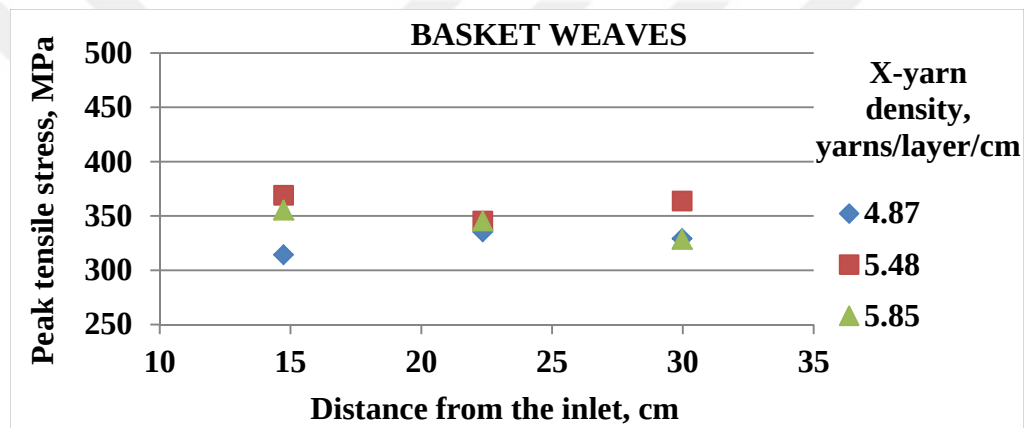
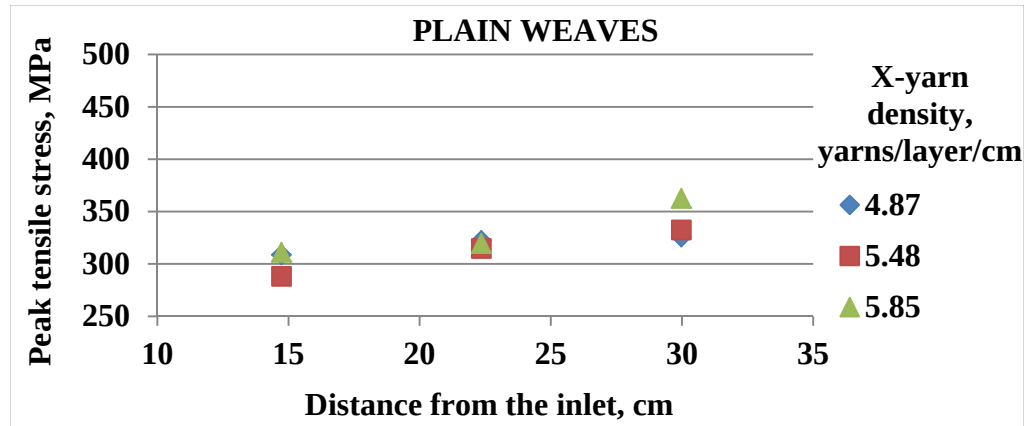


Figure 7.3. Peak tensile stress profile in x-yarn direction of 3 layers composites manufactured at 75 kPa vacuums

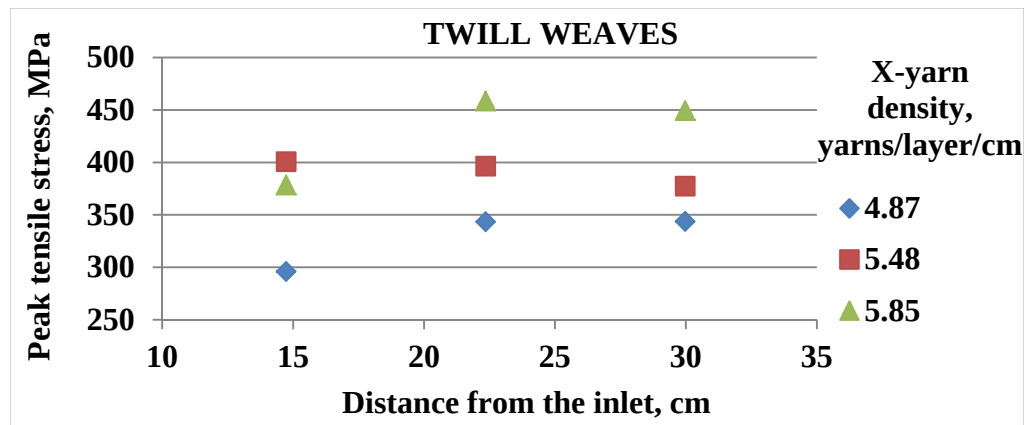
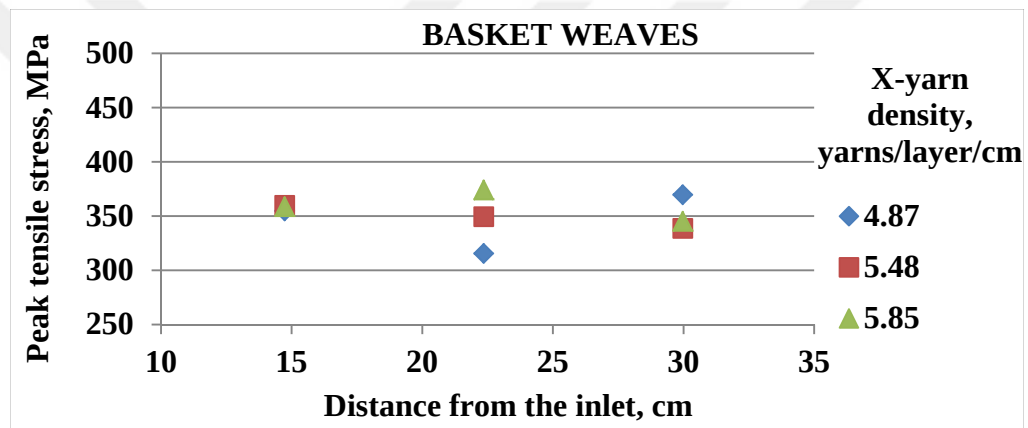
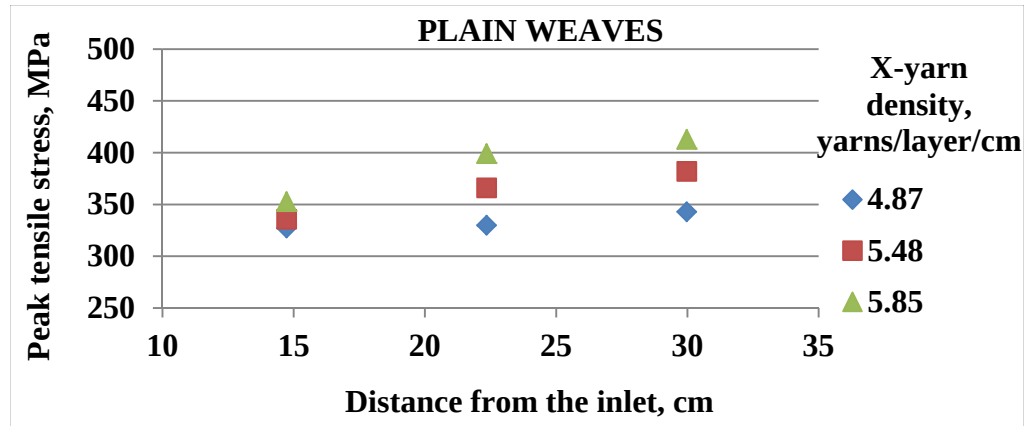


Figure 7.4. Peak tensile stress profile in x-yarn direction of 3 layers composites manufactured at 100 kPa vacuums



Figure 7.5. Tensile failure region in x-yarn direction
(2 layers, plain weave, 5.85 x-yarns/layer/cm composite manufactured at 75 kPa vacuums)

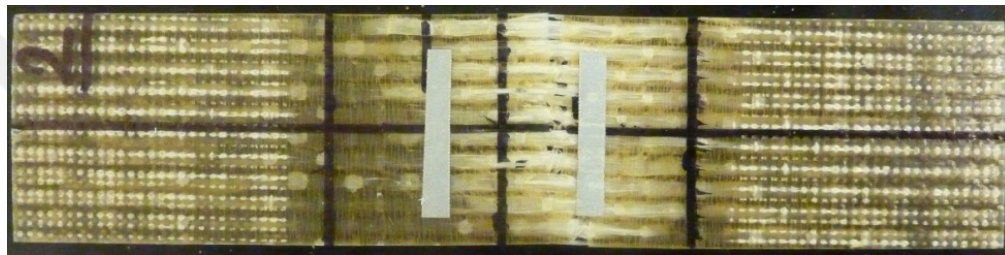


Figure 7.6. Tensile failure in x-yarn direction
(2 layers, plain weave, 5.85 x-yarns/layer/cm composite manufactured at 100 kPa vacuums)

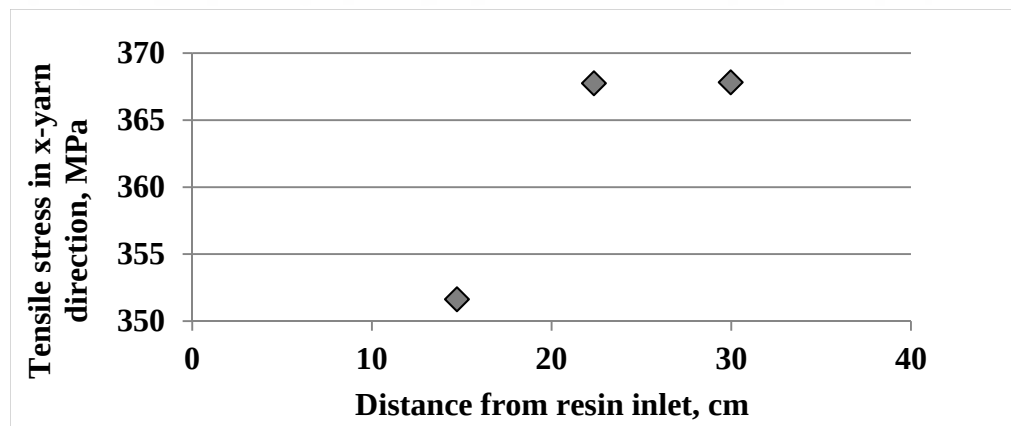


Figure 7.7. Effect of distance from resin inlet on tensile stress in x-direction

Figure 7.8 shows the influence of the main effect of the independent variable the number of y-yarn layers on the tensile stress in x-direction. The figure was created from data of 54 composite panels. Each of the three averages in the figure is calculated from all composites

with 2, 3, and 4 layers (18 panels/layer). The figure shows that the composites with 2 layers are significantly stronger than the other composites, which is supported by Tukey multiple means comparison (Figure P.8). The composites with 3 layers and 4 layers exhibited similar tensile stress (Figure P.8). The correlation analysis (Table P.4 and Figure P.7) supports this finding in that as the number of layers increases the tensile stress in x-direction gets lower (negative correlation of -0.29).

Unlike the isotropic materials, which possess tensile stress that is independent of thickness, the composites from 3D orthogonal preforms exhibited different behavior in x-direction. Table P.4 and Figure P.7 show an inverse correlation between number of y-yarn layers and tensile stress in x-direction. In 3D orthogonal preforms, the number of x-yarn layers is greater than the number of y-yarn layers by one. As the number of y-layers increases, the ratio of number of x-layers to number of y-layers decreases. This is also reflected in the increase of x-FVF as number of y-layers decreases (see Figure 7.9, which shows the data of FVF of basket weave as an example). The ratio of the composite thickness to the number of x-layers gets higher as the number of y-layers increases. While the increase in the number of x-layers caused increase in peak tensile load in x-direction, the tensile stress decreased due to increase in thickness (cross section area) with higher proportional than the increase in the peak tensile load.

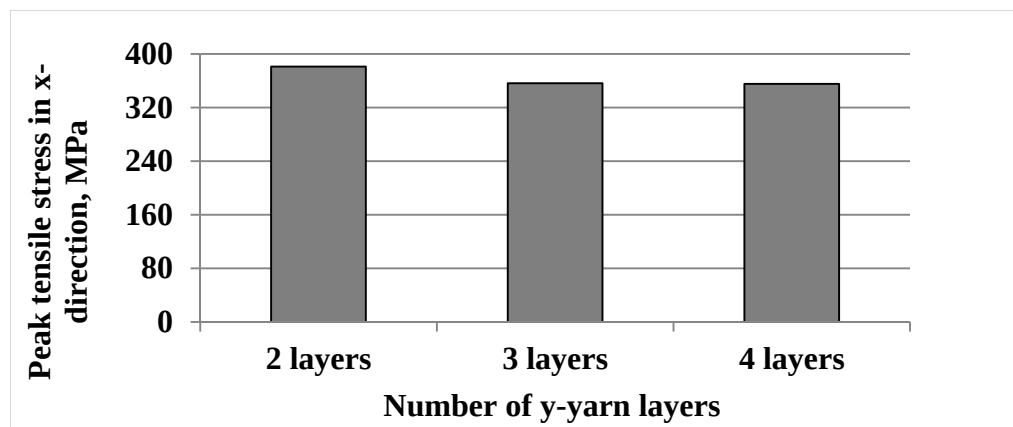


Figure 7.8. Effect of number of y-yarn layers on tensile stress in x-direction

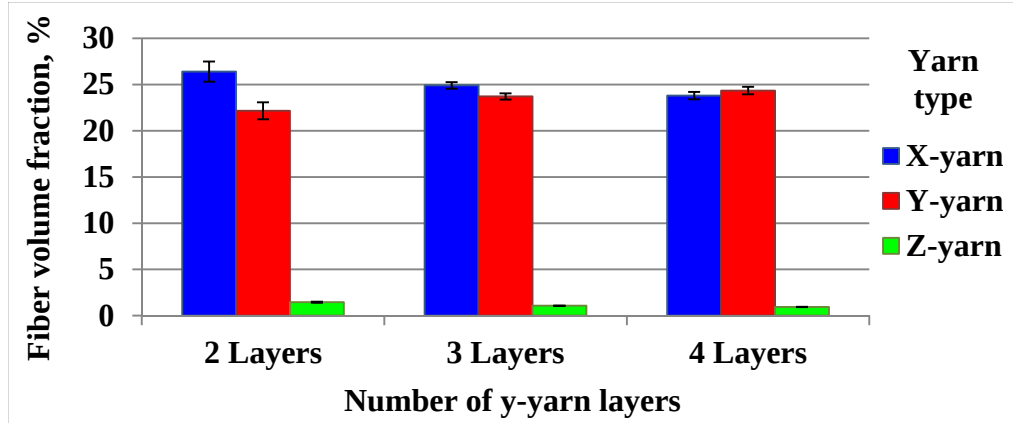


Figure 7.9. Constituent yarn FVFs of basket weaves with 5.85 x-yarn density composites manufactured at 100 kPa vacuums

Figure 7.10 shows the effect of the weave on the tensile stress in x-direction. Positive correlation (Table P.4 and Figure P.7) between weave and tensile stress in x-direction was revealed from the statistical analysis. Composites with twill weave, which were assigned the numerical value 3, performed better than composites with basket (2) and plain weave (1) in terms of tensile stress in x-direction. The composites with plain and basket weaves showed similar tensile stress as it can be noticed from Tukey multiple means comparison (Figure P.8). Infusion (section 6.4) and total FVF (section 6.5.2) experiments indicated that preforms with plain and basket weaves are highly tolerant to resin penetration compared to preforms with twill weaves, and presence of resin in composite decreases FVF. Preforms with twill weave impeded the flow of resin within the structure that resulted in high total and/or constituent yarn FVF (Figure 7.11). Therefore, composites with twill weave have higher x-direction peak tensile stress due to their higher x-FVF than the composites with other two weaves. Additional reason for the effect of weave on peak tensile stress in x-direction is interlacing density difference among weave levels. In plain weaves, z-yarn distorts the alignment of x-yarn due to more frequent interlacing that decreases tensile stress in x-direction compared to basket and twill weaves.

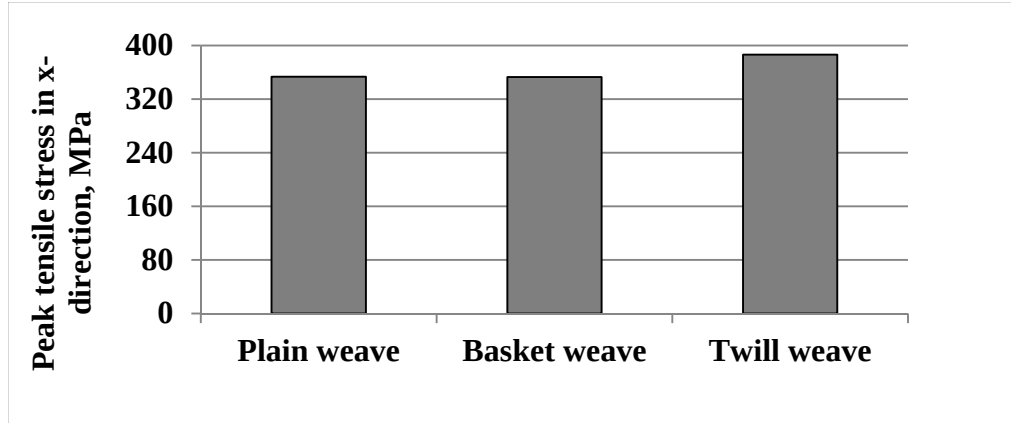


Figure 7.10. Effect of weave on tensile stress in x-direction

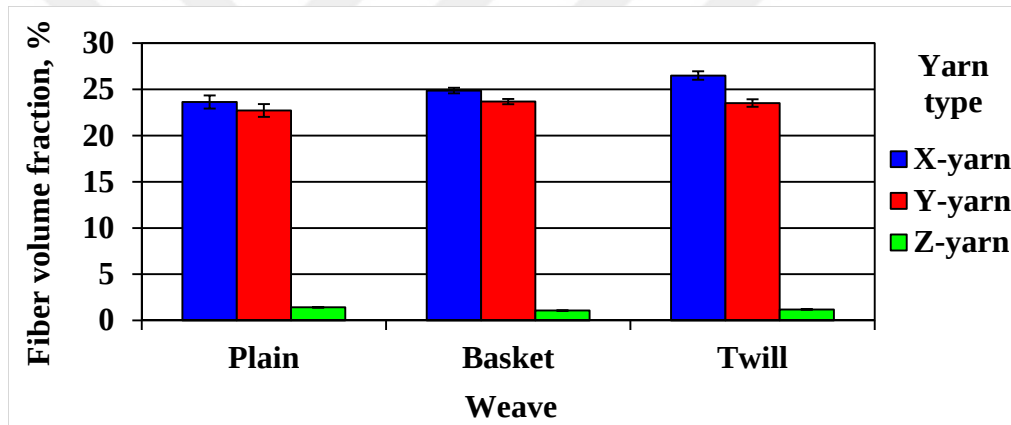


Figure 7.11. Constituent yarn FVFs of 3 layers, 5.48 x-yarn density composites manufactured at 100 kPa vacuums

Figure 7.12 depicts the effect of x-yarn density on tensile stress in x-direction. According to statistical analyses, increase in x-yarn density caused increase in peak tensile stress in x-direction (positive correlation between x-yarn density and tensile stress in x-direction parameters in Table P.4) that attributed to the increase in x-FVF as x-yarn density is increased (Figure 7.13). In other words, increase in x-yarn density caused higher increase in x-yarn weight than in composite thickness, which resulted in improvement in x-FVF.

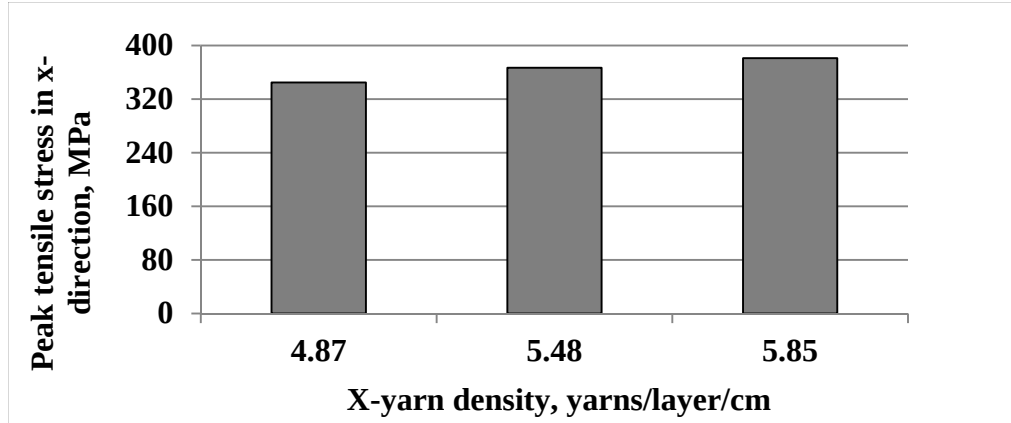


Figure 7.12. Effect of x-yarn density on tensile stress in x-direction

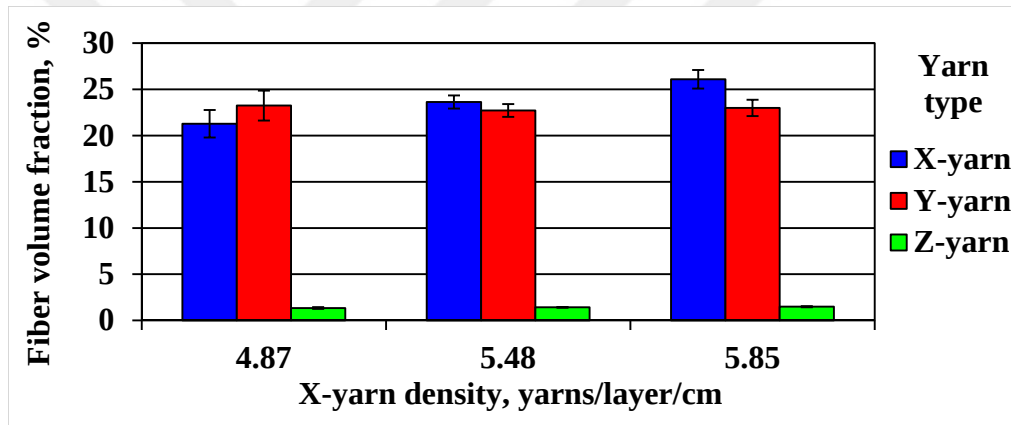


Figure 7.13. Constituent yarn FVFs of 3 layers, plain weave composites manufactured at 100 kPa vacuums

Figure 7.14, which was generated using two averages of 27 panels each, illustrates the influence of vacuum pressure on tensile stress in x-direction. Statistical analysis indicated that increase in vacuum pressure caused statistically significant increase in x-direction tensile stress (Figure P.8). 100 kPa vacuum creates more compression pressure over the preform during infusion process that decreases thickness (Figure P.2) and results in higher total and/or constituent yarn FVFs (Figure P.4).

Generally, the main effects of sample location and independent variable (number of y-yarn layers, weave, x-yarn density, and vacuum pressure) can be seen from Figures J.5 to J.10 in Appendix J, which depict the individual averages of the 54 panels.

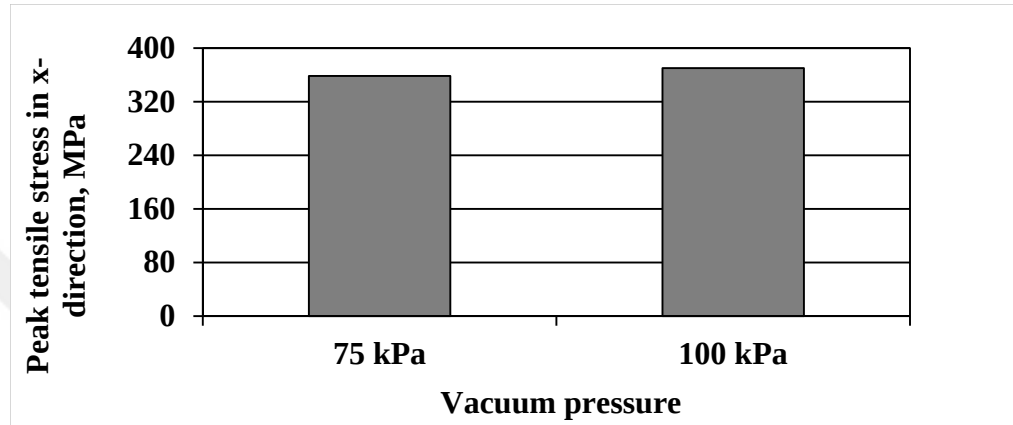


Figure 7.14. Effect of vacuum pressure on tensile stress in x-direction

7.1.2. Tensile stress of composite in y-yarn direction

Y-direction tensile stress of composites manufactured at 75 kPa vacuums were measured using specimens cut from upper half of each composite panel. Figure 7.15 shows the location of four tensile specimens in y-direction on the upper half of a composite panel. Distance from the resin inlet line for each specimen was measured as 5.33, 13.46, 21.59, and 29.72 cm. Y-yarn direction tensile stress of composites infused at 100 kPa vacuums were measured using four specimens cut from lower-half composite panels. Distances of 100 kPa vacuums specimens from the resin inlet line are the same as 75 kPa vacuums specimens.

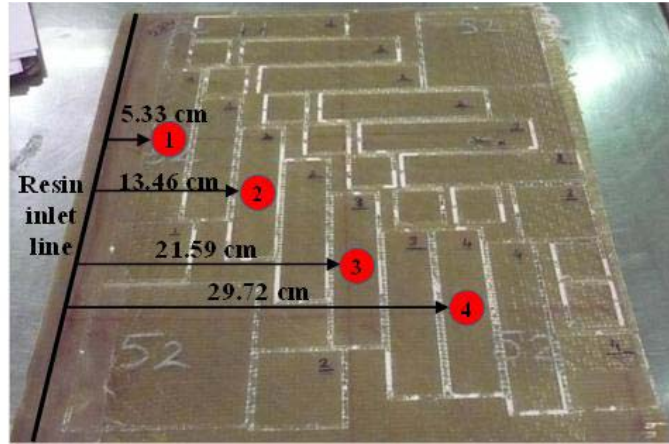


Figure 7.15. Tensile specimens in y-yarn direction on the upper-half composite panel

Similar to x-direction specimens, y-direction specimens' tensile failure was dominated by fiber fracture and no fiber pullout was observed (Figure 7.16). Additionally, the potential of getting failure in the gage length area was greater for y-direction specimens than x-direction. Y-yarns in composite are straighter and have more uniform aspect ratio (uniform distribution of fibers within the tow) than x-yarns that enhance uniform load distribution between fibers and promote load sharing that reflected high tensile stress in y-direction compared to x-direction.

Figures 7.17 and 7.18 show y-direction peak tensile stress profiles of 3 layers composites manufactured at 75 and 100 kPa vacuums, respectively. As it can be seen from the figures, the results show that the location of tensile specimen affected the tensile stress of composite in the y-direction. In general, samples near the resin outlet are stronger than the samples near the resin inlet due to decrease in thickness profile from inlet to outlet (Figures 6.13 and 6.14).

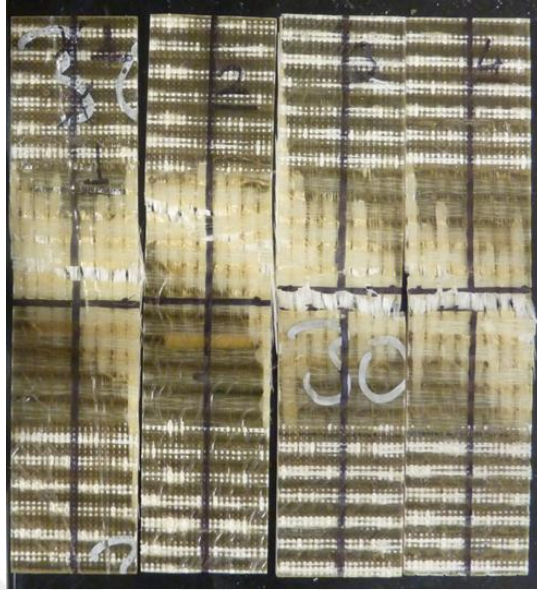


Figure 7.16. Examples of typical tensile failure in y-direction
3 layers, basket weave, 5.85 x-yarns/layer/cm composites manufactured at 100 kPa vacuums

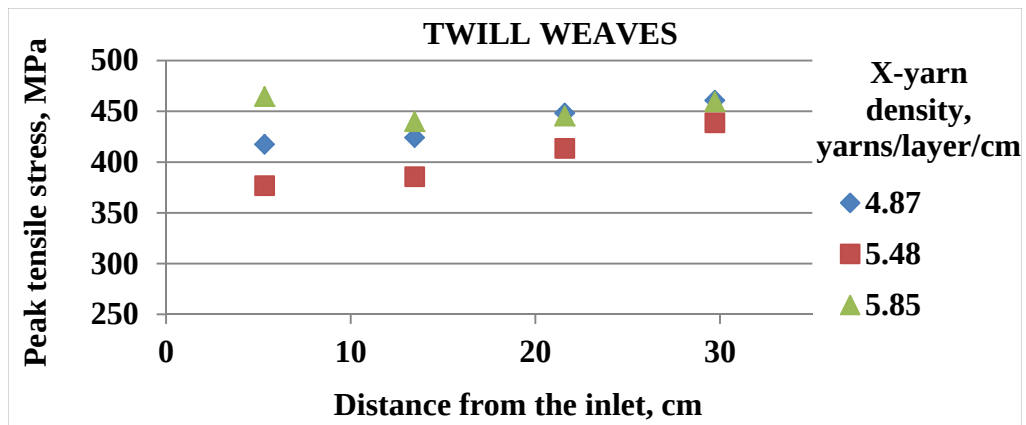
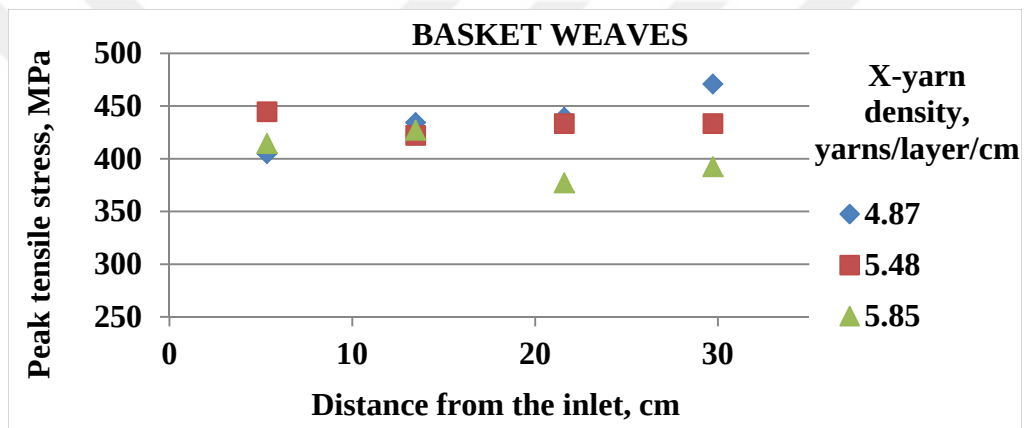
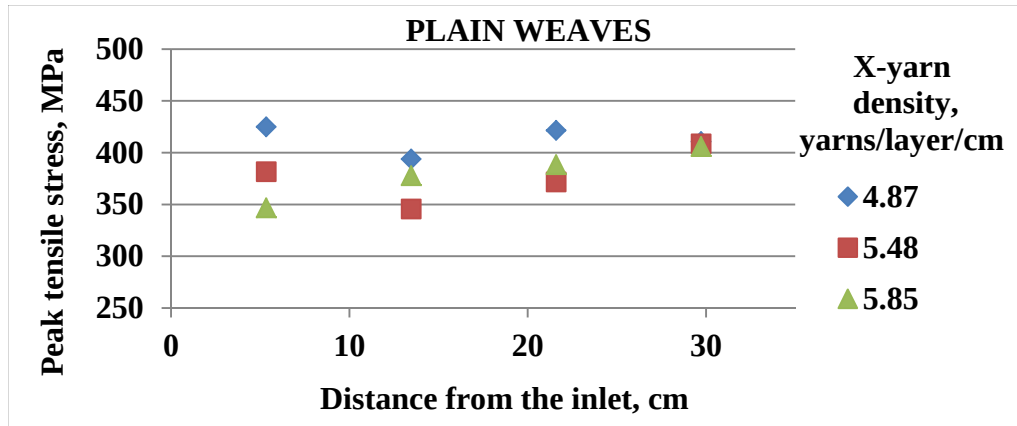


Figure 7.17. Peak tensile stress profile in y-direction of 3 layers composites manufactured at 75 kPa vacuums

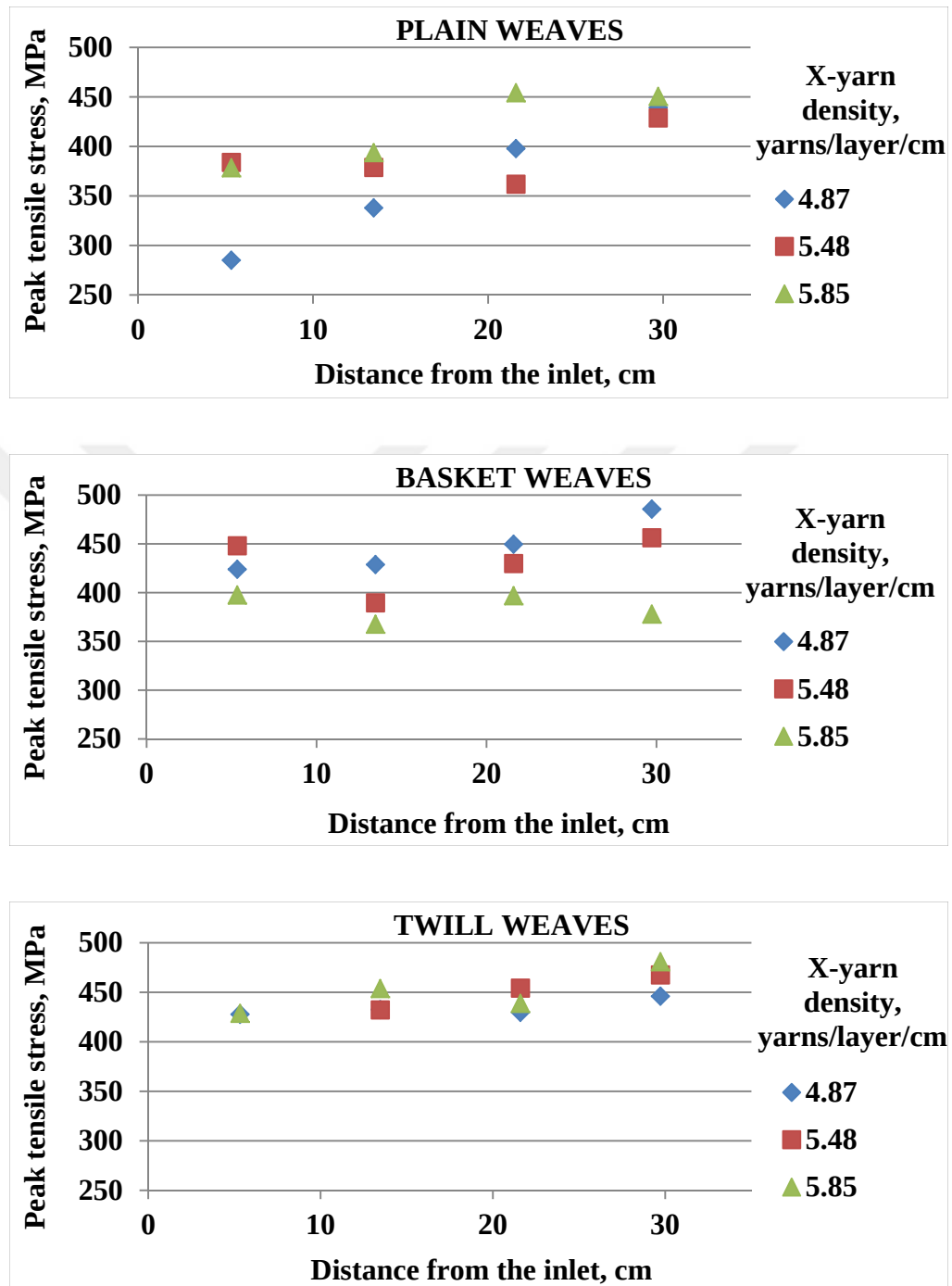


Figure 7.18. Peak tensile stress profile in y-direction of 3 layers composites manufactured at 100 kPa vacuums

The results of average tensile stress in y-direction are given in the following paragraphs. The average of each panel was calculated from four specimens shown in Figure 7.15. Total number of panel is 54. In total, 216 (54x4) tensile stress measurements in y-direction were utilized for deduction of the results in terms of ANOVA, Tukey multiple means comparison, and correlations statistical analyses. The analyses are indicated in Table P.5, Figure P.9, and Figure P.10 of Appendix P. ANOVA analysis at 95% confidence interval exhibited that distance from resin inlet, number of layers, weave, and x-yarn density have significant effect on tensile stress in y-direction (Figure P.10).

Figure 7.19 shows the effect of specimen location on tensile stress in y-direction. ANOVA and Tukey multiple means comparison analyses indicated that the effect of specimen location on tensile stress in y-direction is statistically significant at 95% confidence interval.

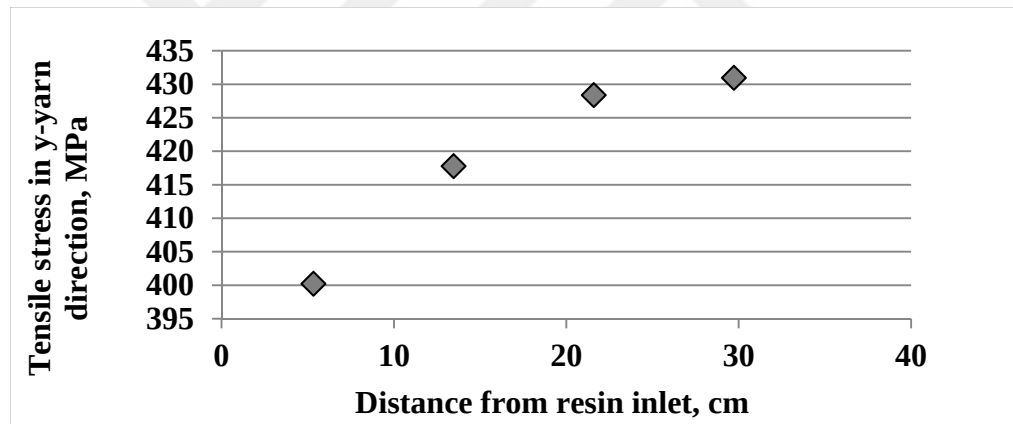


Figure 7.19. Effect of distance (cm) from resin inlet on tensile stress in y-direction

Figure 7.20 indicates the effect of number of y-yarn layers on tensile stress in y-direction. Correlation between number of y-yarn layers (layers) and peak tensile stress in y-direction (tensile-y) is 0.43 (Table P.5 and Figure P.9) that points to increase in number of layers gets higher tensile stress in y-direction. Unlike the tensile stress in x-direction, which decreases as number of y-yarn layers is increased, increase in tensile stress in y-direction was observed as number of y-yarn layers is increased. The increase in the number of y-yarn layers resulted in disproportional increase between tensile load in y-direction (proportional with the amount of

fiber in y-direction) and composite thickness (cross section area). The increase in tensile load had higher proportion than increase in thickness that resulted in overall increase in tensile stress in y-direction.

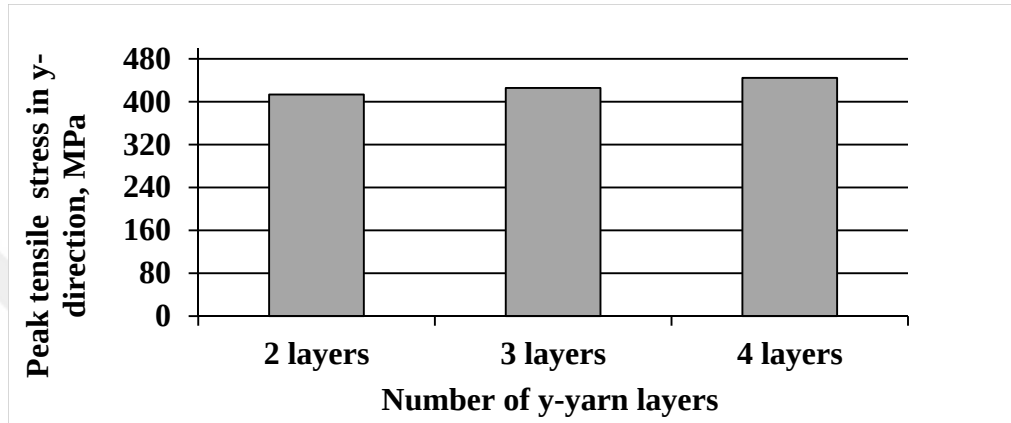


Figure 7.20. Effect of number of y-yarn layer on tensile stress in y-direction

Figure 7.21 exhibits the effect of weave on tensile stress in y-direction. Twill weave composites (represented by # 3 in statistical analysis) showed the highest peak tensile stress in y-direction, and they were followed by composites with basket (# 2) and plain (# 1) weaves, respectively. Tukey analysis indicated that twill and basket weave composites are the same, but plain weave composites are significantly inferior to twill and basket weave composites in view of tensile stress in y-direction (Figure P.10). Twill weave composites have greater FVF than the other two weaves due to their less tolerant (open) interior structure to resin flow than composites with basket and plain weaves. Therefore, composites with twill weaves have higher y-direction peak tensile stress due to their higher y-yarn FVF (Figure 7.11) compared to composites with plain and basket weaves.

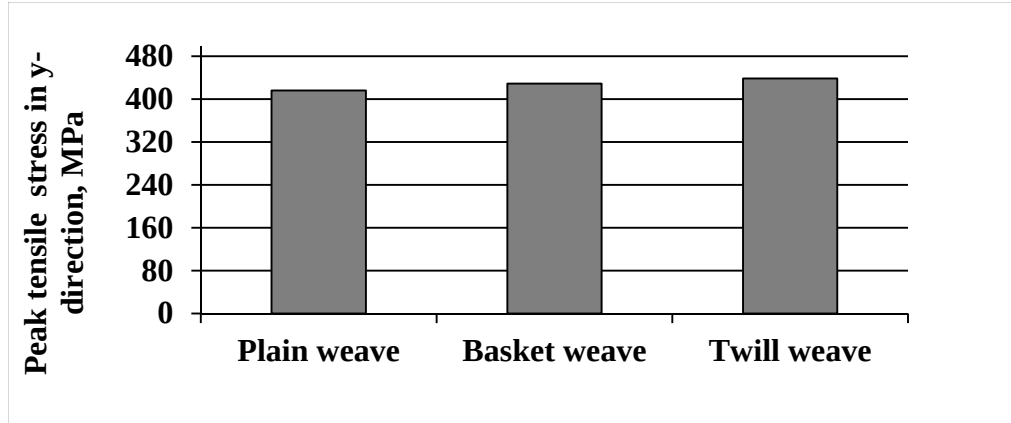


Figure 7.21. Effect of weave on tensile stress in y-direction

Figure 7.22 shows the effect of x-yarn density on tensile stress in y-direction. According to statistical analysis, increase in x-yarn density decreased peak tensile stress in y-direction (-0.26, negative correlation between x-yarn density and tensile stress in y-direction, Table P.5) that indicates thickness increase due to x-yarn density increase (while keeping y-yarn weight constant) lowers y-yarn FVF (shown in experimental results of Figure 7.13). This result also reveals that there is no fabric assistance from x-yarns to y-yarns in 3D orthogonal woven composites contrary to fully interlaced 2D structures. Tukey multiple means comparison indicated that composites with 4.87 x-yarn density are significantly superior to composites with 5.48 and 5.85 x-yarn density, and the difference between composites with 5.48 and 5.85 x-yarn density is not significant at 95% confidence interval (Figure P.10).

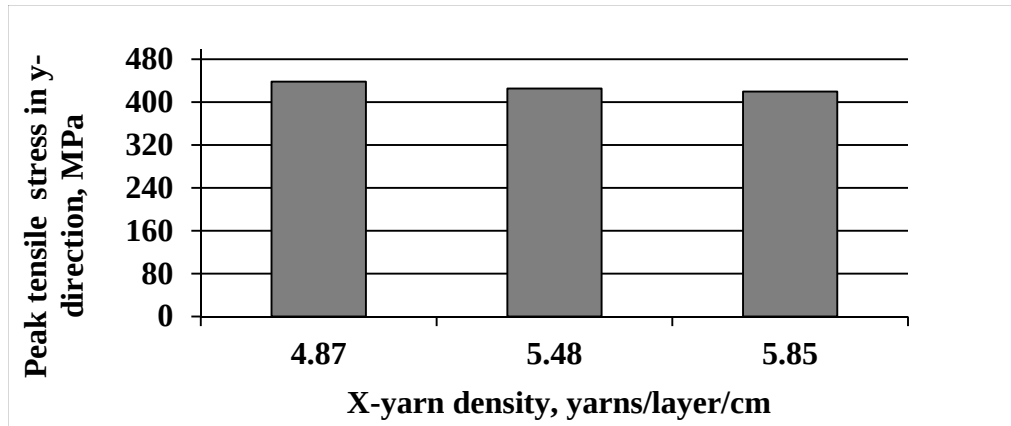


Figure 7.22. Effect of x-yarn density on tensile stress in y-direction

Figure 7.23 exhibits the effect of vacuum pressure on y-direction tensile stress. Composites manufactured at 100 kPa vacuums showed slightly greater peak tensile stress in y-direction than composites manufactured at 75 kPa vacuums (positive but low correlation coefficient, 0.12, between vacuum pressure and peak tensile stress in y-direction and shown in Table P.5). However, according to Tukey multiple means comparison at 95% confidence interval, vacuum pressure had no statistically significant effect on peak tensile stress in y-direction (Figure P.10).

Figures K.5 to K.10 in Appendix K show the individual averages of the 54 panels, in which the main effects of sample location and the independent variables (number of y-yarn layers, weave, x-yarn density, and vacuum pressure) can be observed.

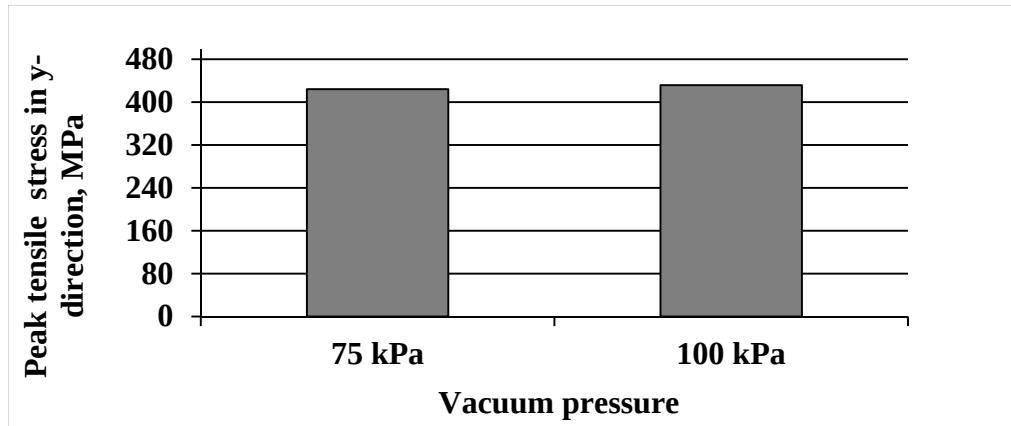


Figure 7.23. Effect of vacuum pressure on tensile stress in y-direction

7.1.3. Tensile stress of balanced composites in x- and y-directions

Experimental design was structured to include balanced (defined as identical total denier in x- and y-directions/unit sample width) composites having same weight of x- and y-yarn fibers per unit area. For 3 layers structures, 5.48 x-yarns/layer/cm composites are balanced. Balanced 3 layers composites manufactured at 75 and 100 kPa vacuums were considered for comparison of tensile properties in x- and y-directions (Figures 7.24 and 7.25).

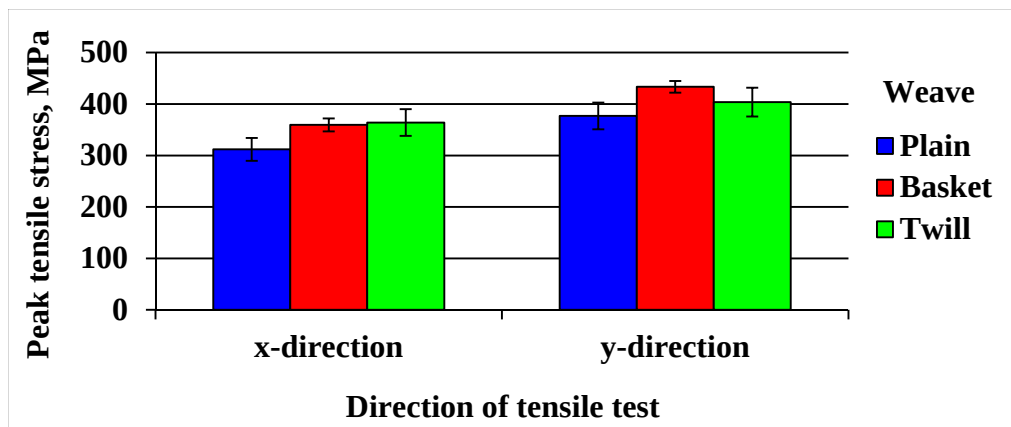


Figure 7.24. Tensile stresses of balanced, 3 layers, 5.48 x-yarns/layer/cm composites manufactured at 75 kPa vacuums

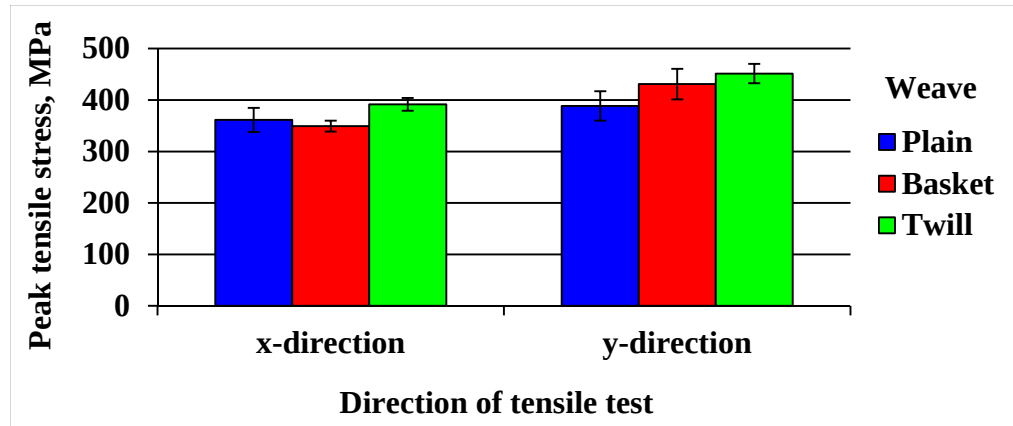


Figure 7.25. Tensile stresses of balanced, 3 layers, 5.48 x-yarns/layer/cm composites manufactured at 100 kPa vacuums

For the balanced composites, peak tensile stress in y-direction is greater than peak tensile stress in x-direction due to more uniform placement of y-yarns than x-yarns regardless of the vacuum level. Peak tensile stress of 2 and 4 layers balanced composites showed the same trend as 3 layers (Appendix L).

7.2. Flexural stress

This section reports flexural stress of 3 layers composites in x- and y-directions. Flexural stress results for 2 and 4 layers composites are given in Appendices M and N.

7.2.1. Flexural stress of composite in x-direction

Figure 7.26 shows a lower-half composite panel and the locations of three x-direction flexure specimens on the panel. The specimens were numbered according to their distance from resin inlet line. The distances from the resin inlet line were measured as 20.32, 25.91, and 33.53 cm.

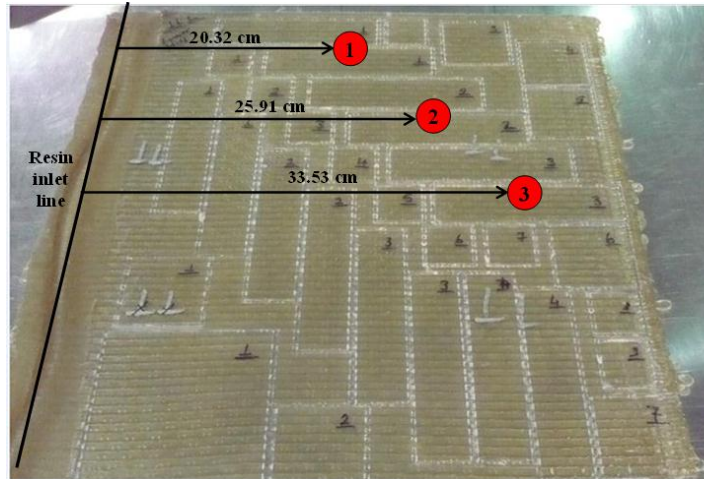


Figure 7.26. Flexure specimens in x-direction on lower-half composite plate

Figures 7.27 and 7.28 show peak flexure stress profile in x-direction of 3 layers composites manufactured at 75 and 100 kPa vacuums, respectively. Peak flexure stress profile in x-direction of 2 and 4 layers composites are given in Appendix M.

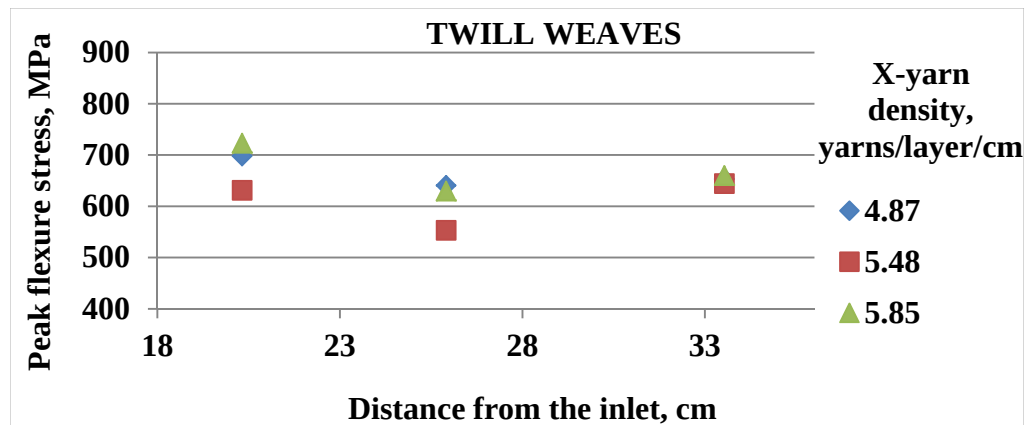
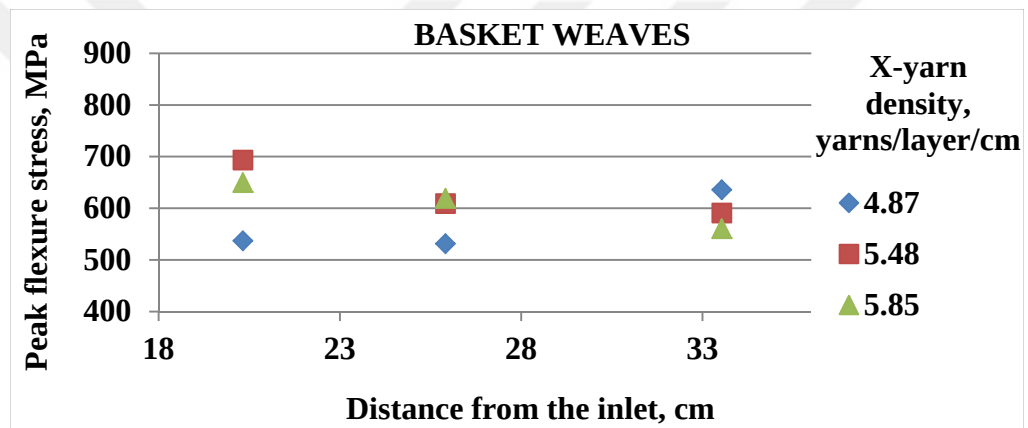
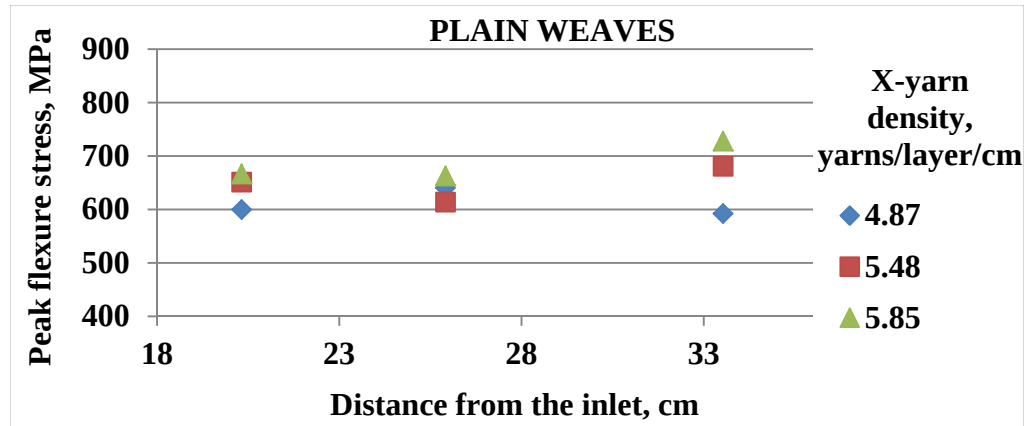


Figure 7.27. Profile of peak flexure stress in x-direction of 3 layers composites manufactured at 75 kPa vacuums

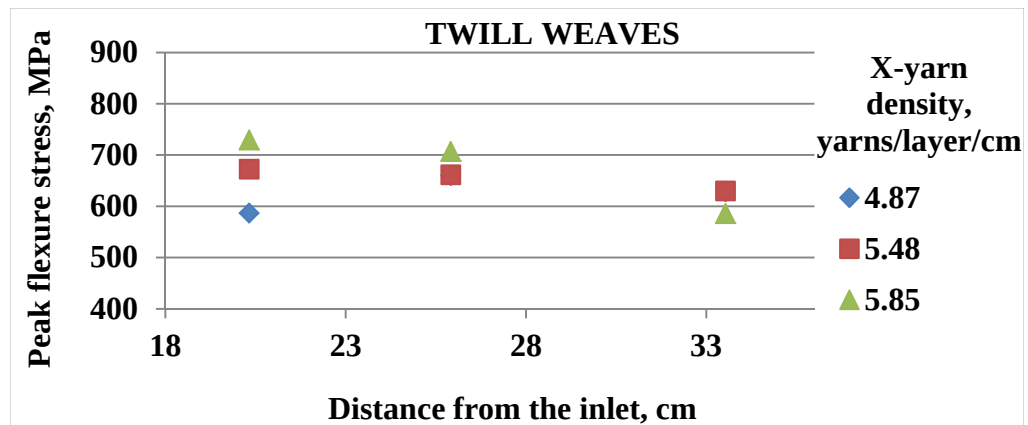
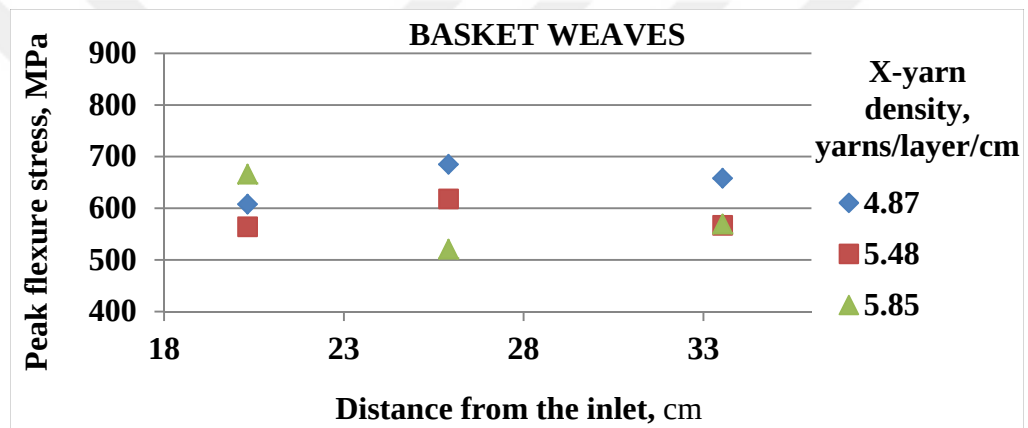
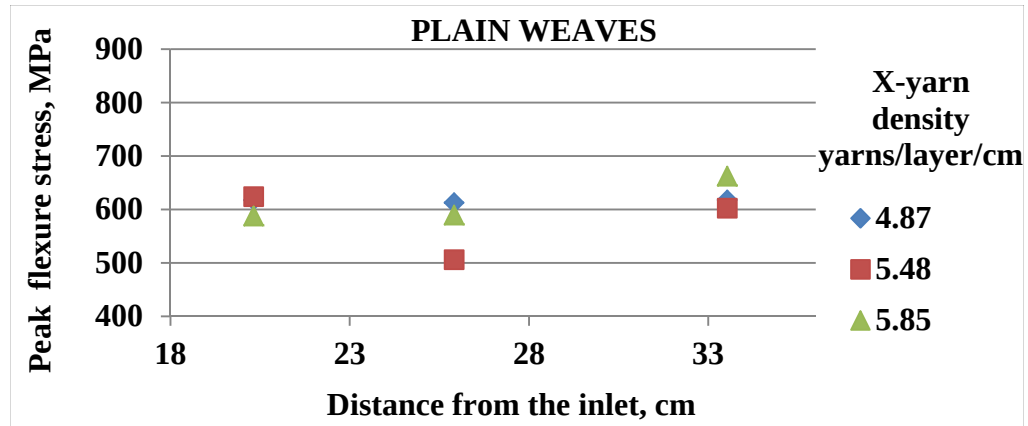


Figure 7.28. Profile of peak flexure stress in x-yarn direction of 3 layers composites manufactured at 100 kPa vacuums

The average of a panel (out of 54) was determined from three specimens numbered 1-3 in Figure 7.26. Flexure stress in x-direction of all 162 (54x3) specimens were utilized in statistical analyses of ANOVA, Tukey, and correlation to deduce the results (Table P.6, Figure P.11, Figure P.12). The ANOVA revealed that number of y-yarn layers, weave, and x-yarn density variables have significant effect on the flexure stress in x-direction at 95% confidence interval. Distance from resin inlet line, and vacuum pressure variables did not show any statistically significant effect on peak flexure stress in x-direction per ANOVA (Figure P.12).

Figure 7.29 shows the effect of number of y-yarn layers on peak flexure stress in x-direction. 2 layers composites showed the highest peak flexure stress in x-direction, and they were followed by 3 and 4 layers, respectively (negative correlation between number of layers and peak flexure stress in x-direction, Table P.6). As previously mentioned, as the number of layers is increased while keeping all other variables constant, x-yarn FVF shows a decreasing trend (Figure 7.9) that caused decrease in peak flexure stress in x-direction.

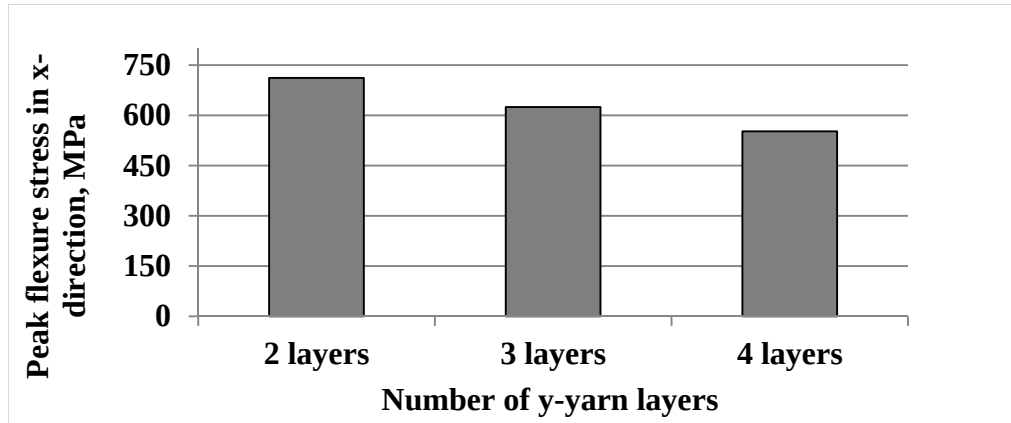


Figure 7.29. Effect of number of y-yarn layers on flexure stress in x-direction

Figure 7.30 shows the effect of weave on flexure stress in x-direction. Twill weave composites showed the highest peak flexure stress in x-direction among different weaves, and they were followed by plain and basket weaves, respectively. Tukey multiple means

comparison indicated that twill weave composites are significantly different from basket weaves in terms of peak flexure stress in x-direction. No significant difference was observed between plain and the other two weave structures. Section 6.5 revealed that plain and basket weaves are highly convenient for resin penetration compared to twill weaves. Twill weaves resisted against the flow of resin within the structure that resulted in high total and/or constituent yarn FVF (Figure 7.11). Therefore, twill weave composites exhibited higher peak flexure stress in x-direction due to their high x-FVF than plain and basket weave composites (Figure P.12).

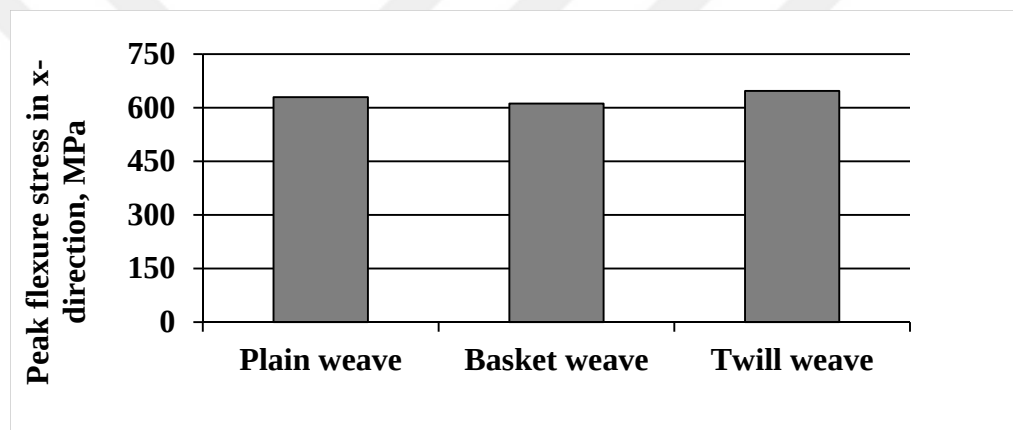


Figure 7.30. Effect of weave on flexure stress in x-direction

Figure 7.31 shows the effect of x-yarn density on peak flexure stress in x-direction. Increasing the x-yarn density caused a statistically significant increase in the peak flexure stress in x-direction at 95% confidence interval as indicated by ANOVA and Tukey (Figure P.12) results. This result is again attributed to increase in x-yarn FVF as x-yarn density increase is increased. Figure 7.13 and Table P.6, which shows positive correlation between x-yarn density and x-FVF, support the findings by ANOVA and Tukey.

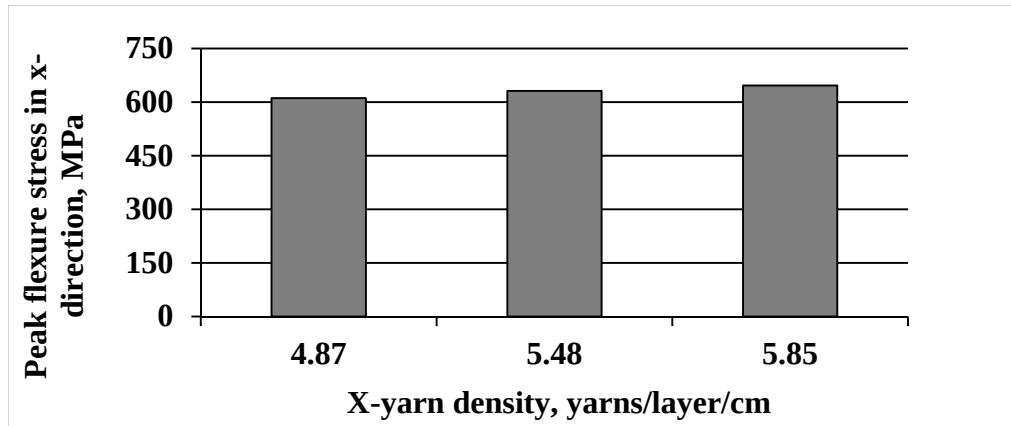


Figure 7.31. Effect of x-yarn density on peak flexure stress in x-direction

Figure 7.32 shows the effect of vacuum pressure on peak flexure stress in x-direction. Composites manufactured at 100 kPa vacuums showed better peak flexure stress in x-direction than composites manufactured at 75 kPa vacuums. However, ANOVA and Tukey multiple means comparison revealed that this difference was not significant at 95% confidence interval (Figure P.12).

Individual averages of 54 panels are given in Figures M.5 to M.10 of Appendix M to show the effects of the independent variables considered.

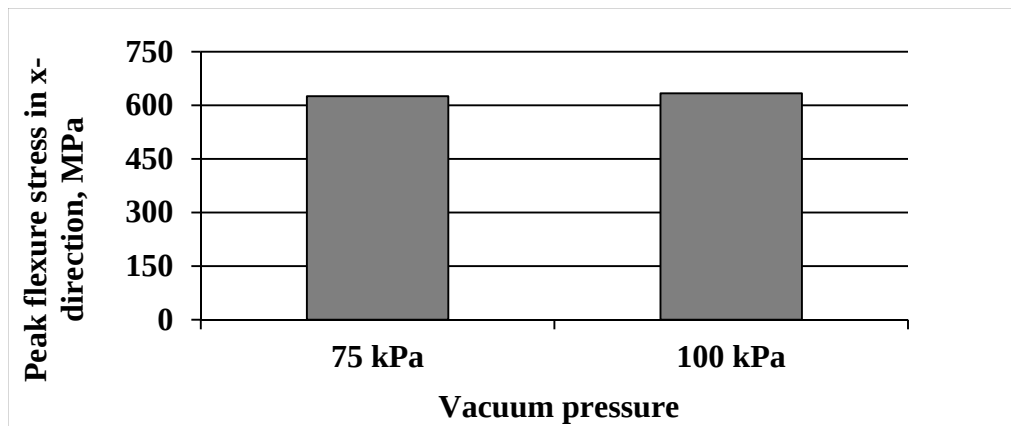


Figure 7.32. Effect of vacuum pressure on peak flexure stress in x-direction

7.2.2. Flexural stress of composite in y-direction

Figure 7.33 shows a lower-half composite panel and the locations of four y-direction flexure specimens on the panel. The specimens were numbered according to their distance from resin inlet. The distances from the resin inlet were measured as 9.41, 17.54, 25.66, and 33.79 cm.

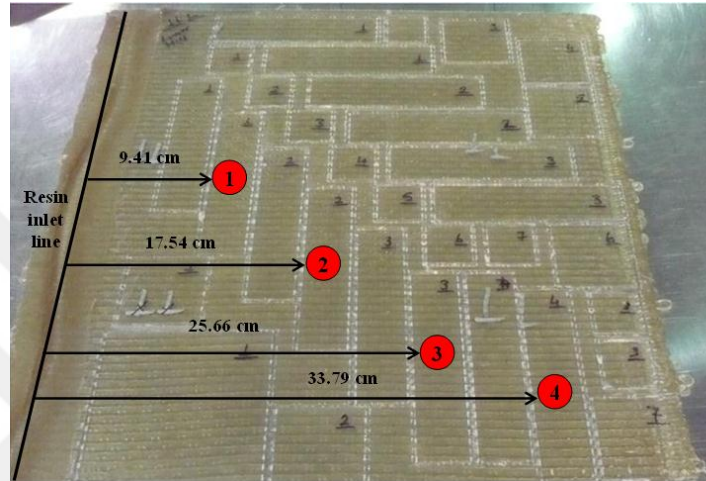


Figure 7.33. Flexure specimens in y-direction on lower-half composite plate

Figures 7.34 and 7.35 show peak flexure stress profile in y-direction of 3 layers composites manufactured at 75 and 100 kPa vacuums, respectively. Slight increase in peak flexure stress of composite in y-direction was observed from resin inlet to outlet. Thickness of individual flexure specimens are decreased from resin inlet to outlet, however flexure load carrying capacity dictated by the amount of fiber is not changing, therefore increase in flexure stress with location was observed. Variation in flexural properties is greater than the variation in tensile properties within a panel, because flexural stress equation has square of thickness multiplier in the denominator that makes flexural properties more sensitive to thickness change.

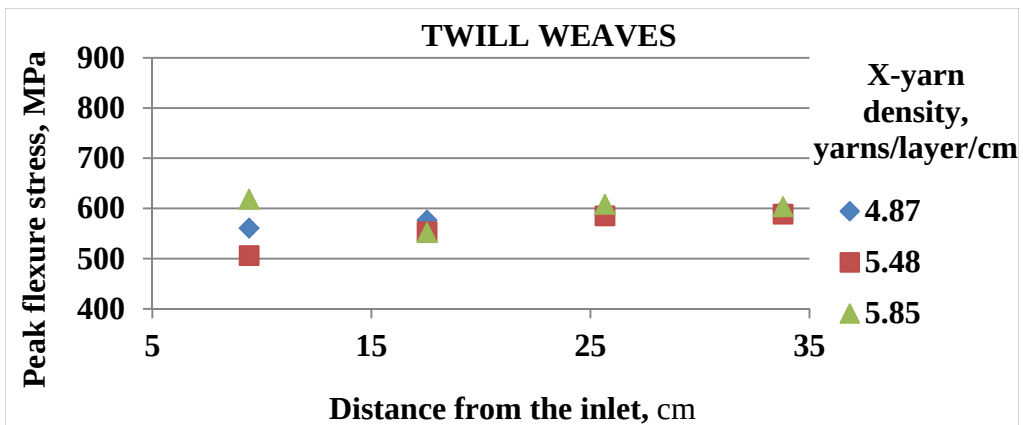
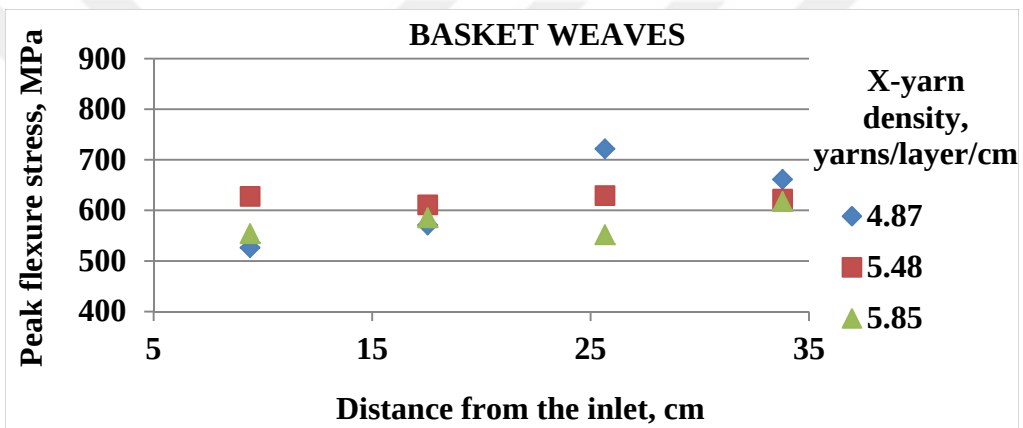
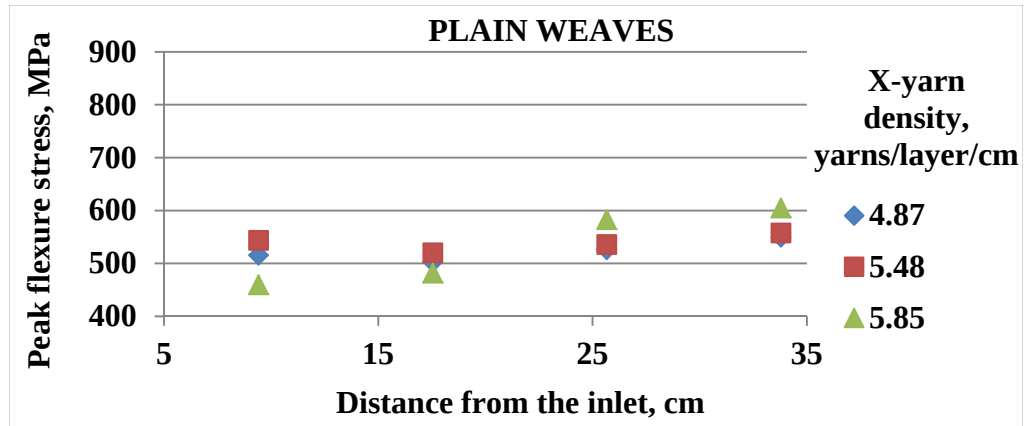


Figure 7.34. Profile of peak flexure stress in y-yarn direction of 3 layers composites manufactured at 75 kPa

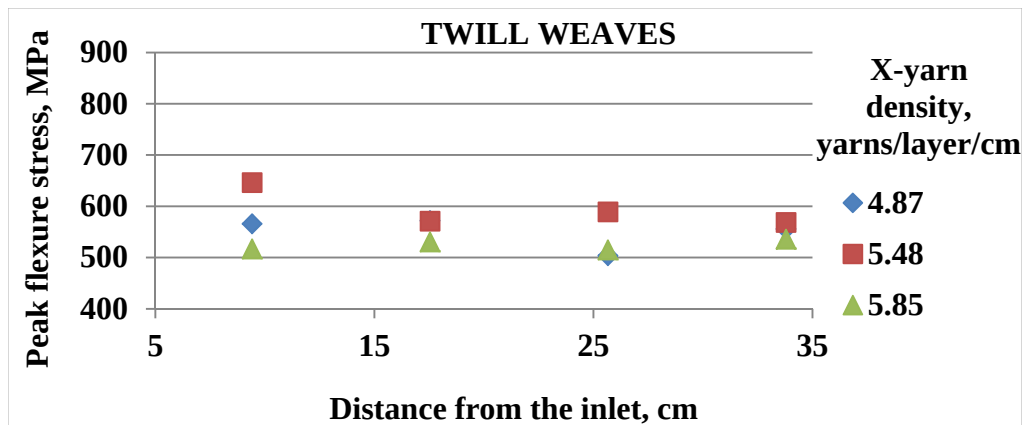
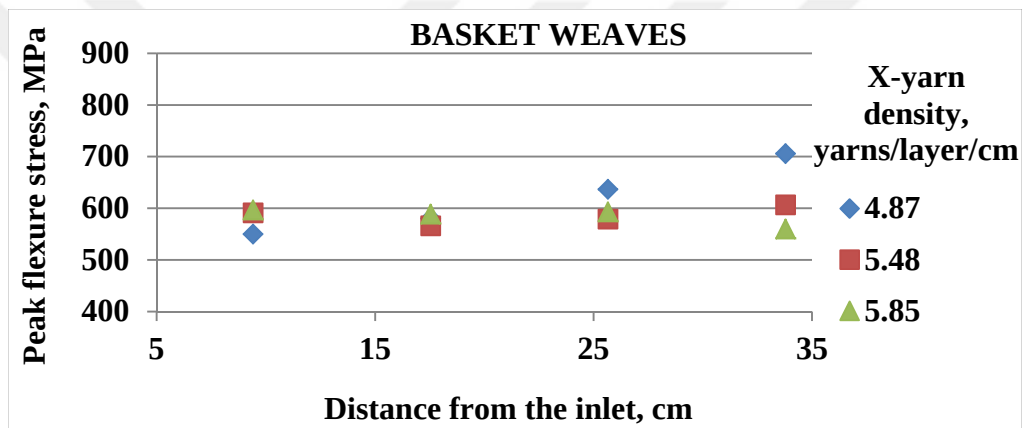
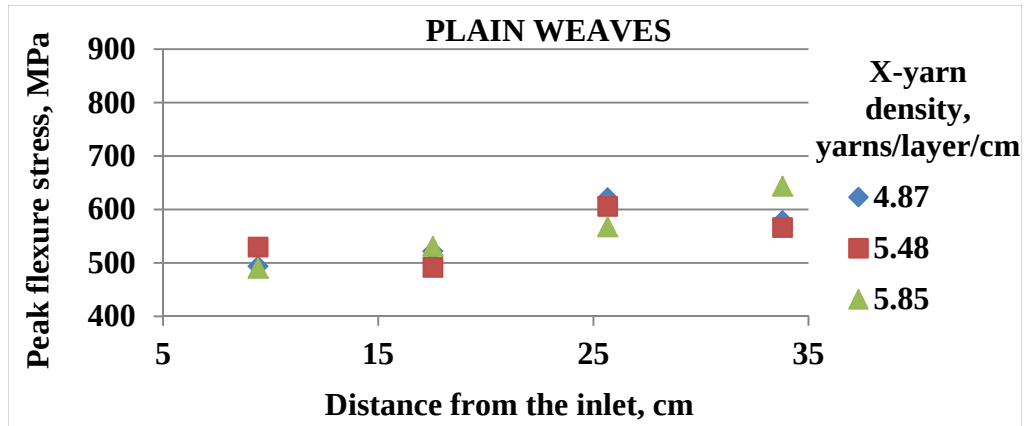


Figure 7.35. Profile of peak flexure stress in y-yarn direction of 3 layers composites manufactured at 100 kPa vacuums

The averages of flexure stress results in y-direction are discussed in the following paragraphs. 4 specimen shown in Figure 7.33 were used to calculate the average flexure stress in y-direction of a composite panel. Total number of observation for flexure stress in y-direction was (54 panels x 4 specimens/panel) 216, which was used in statistical analyses of ANOVA, Tukey and correlation to evaluate the main effect of specimen location and independent variables on flexure stress in y-direction (Table P.7, Figure P.13, and Figure P.14).

ANOVA analysis showed that distance from resin inlet, number of y-yarn layers, weave, and x-yarn density independent variables have significant effect on the peak flexure stress in y-direction. Vacuum pressure during infusion did not show any statistically significant effect on peak flexure stress at 95% confidence interval (Figure P.14).

Figure 7.36 shows the main effect of distance from resin inlet on peak flexure stress in y-direction. Increase in distance from resin inlet caused statistically significant increase in peak flexure stress in y-direction at 95% confidence interval due to increase in FVF towards resin outlet.

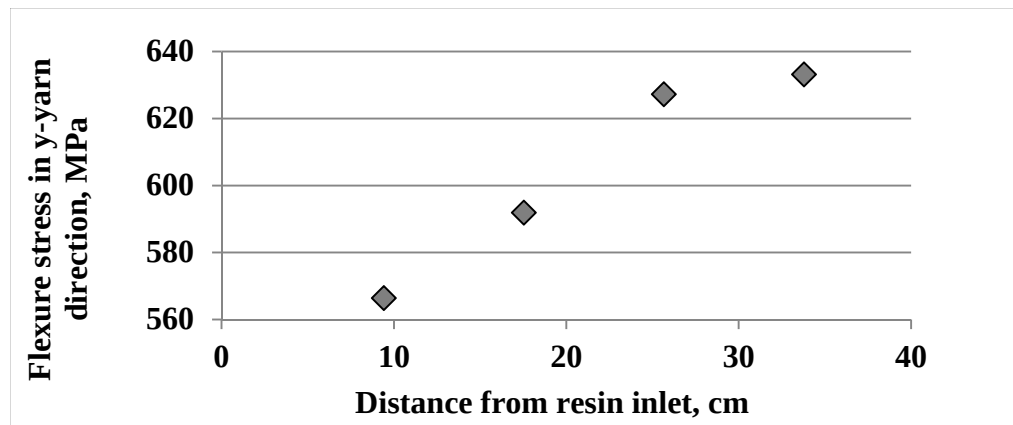


Figure 7.36. Effect of distance (cm) from resin inlet on flexure stress in y-direction

Figure 7.37 shows the effect of number of y-yarn layers on flexure stress in y-direction. Contrary to the effect of number of y-yarn layers on peak tensile stress in y-direction where

increase in number y-yarn layers caused increase in tensile stress in y-direction, 2 layers composites showed the highest peak flexure stress in y-direction, and they were followed by 4 and 3 layers, respectively (Table P.7 and Figure P.14). Tukey multiple means comparison test indicated that all means are significantly different from each other (Figure P.14). Flexure test standard (ASTM D790) adopted in this study states that the standard is applicable for materials failing before 5% strain limit. However, 2 layers composites initially failed after 5% failure strain, therefore their span length was decreased, and cross head speed of the flexure test was increased to get failure before the strain limit. Thus, the span length and the cross head speed was different from what was used for the 3 and 4 layers composites. It is anticipated that the reason for the highest flexure stress in y-direction of 2 layers composites is as a result of the change in test parameters. 3 and 4 layers composites failed before 5% strain limit with the same test parameters; therefore, their expected flexure stress sequence in the statistical analysis is correct. ASTM D790 recommends tensile test instead of flexure in case of flexure failure after %5 strain limit.

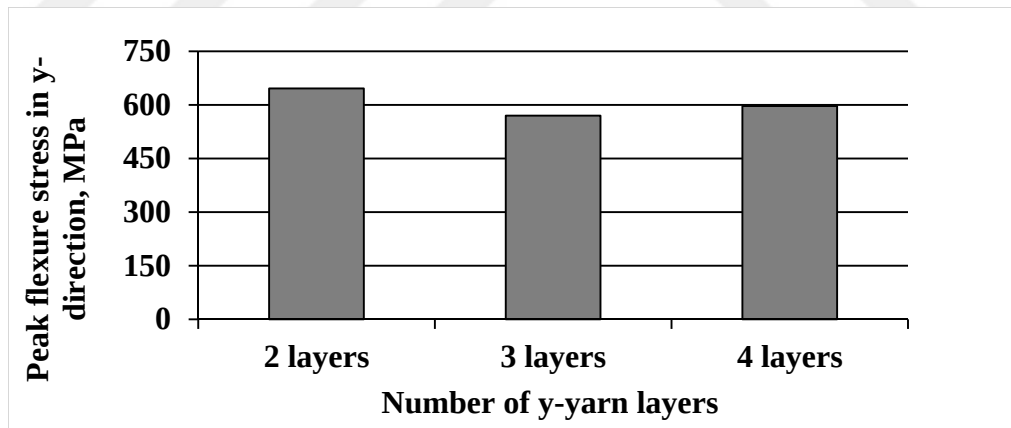


Figure 7.37. Effect of number of y-yarn layers on peak flexure stress in y-direction

Figure 7.38 indicates the effect of weave on peak flexure stress in y-direction. Basket weave composites showed the highest peak flexure stress in y-direction, and they were followed by twill and plain weave composites, respectively. Tukey multiple means comparison test indicated that twill and basket weave composites are the same and they are significantly

different from plain weave composites in terms of peak flexure stress in y-direction (Figure P.14). As shown previously in Figure 7.11, twill weave composites had greater total and/or constituent FVFs than the plain weave that resulted in better flexure stress of twill weave composites than those of plain weaves.

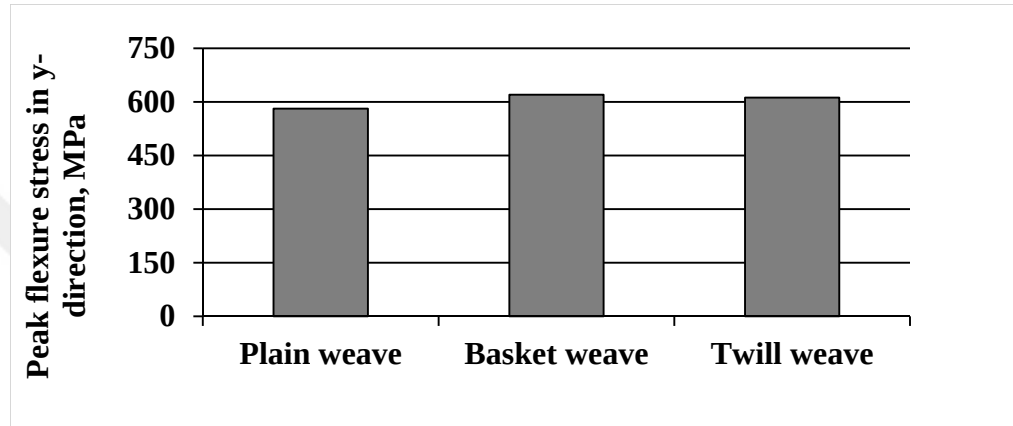


Figure 7.38. Effect of weave on peak flexure stress in y-direction

Figure 7.39 shows the effect of x-yarn density on peak flexure stress in y-direction, which is the same as the effect of x-yarn density on peak tensile stress in y-direction (Figure 7.22). According to Tukey multiple mean comparison, the highest flexure stress in y-direction was achieved at the lowest x-yarn density level (4.87 x-yarns/layer/cm). However, 5.48 x-yarn density composites did not show any significant difference from composites with the other two levels of x-yarn density (Figure P.14). The highest and lowest x-yarn density levels had statistically significant difference on the flexure stress in y-direction. Increase in x-yarn density decreased peak flexure stress in y-direction (-0.15, negative correlation between x-yarn density and peak flexure stress in y-direction, Table P.7) due to increase in composite thickness as x-yarn density increased that caused decrease in y-FVF (Figure 7.13). This result reveals that there is no fabric assistance from x-yarns to y-yarns in terms of flexure stress for 3D orthogonal woven composites, which is also the same case in tensile stress shown previously.

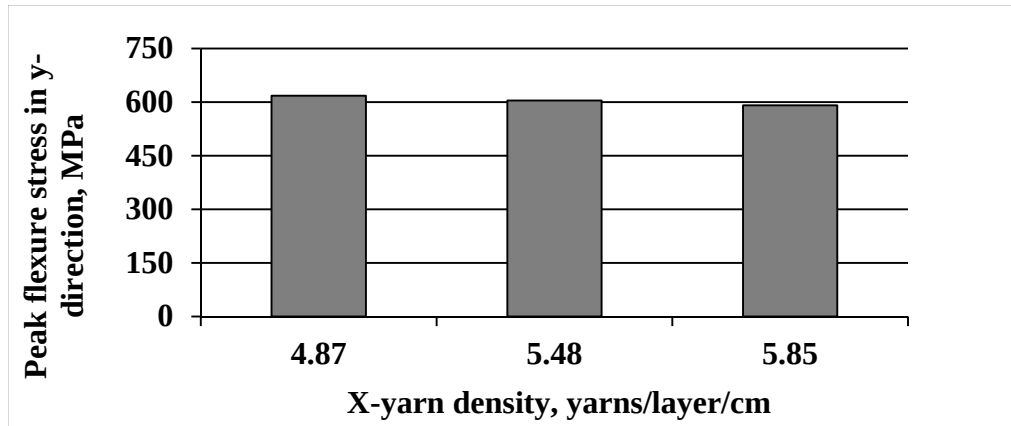


Figure 7.39. Effect of x-yarn density on peak flexure stress in y-direction

Figure 7.40 shows the effect of vacuum pressure on peak flexure stress in y-direction. Similar to the effect of vacuum pressure on tensile stress in y-direction, composites manufactured at 100 kPa vacuums showed slightly greater peak flexure stress in y-direction than composites manufactured at 75 kPa vacuums (0.08, positive but very small correlation in Table P.7). However, according to statistical analysis at 95% confidence interval, vacuum pressure has no significant effect on peak flexure stress in y-direction per ANOVA and Tukey (Figure P.14).

The individual averages of peak flexure stress in y-direction of the 54 panels are shown in Figures N.5 to N.10 in Appendix N, in which the main effects of the independent variables (sample location, number of y-yarn layers, weave, x-yarn density, and vacuum pressure) can be visualized.

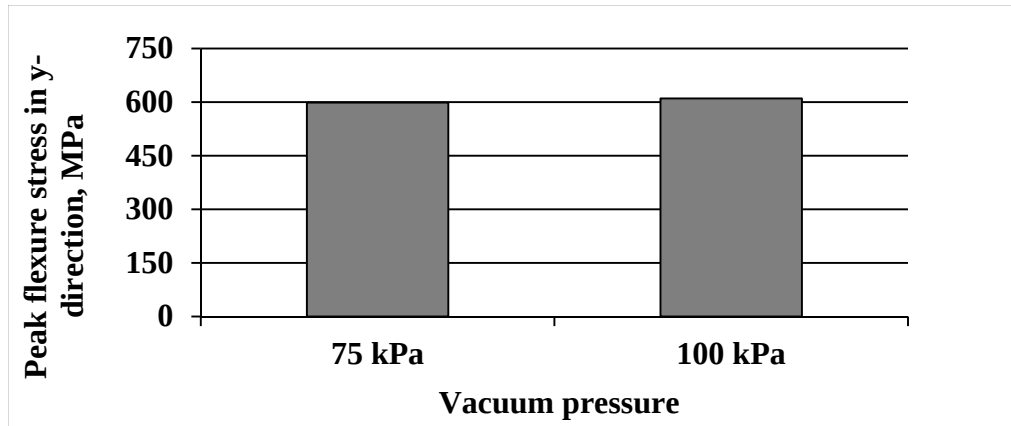


Figure 7.40. Effect of vacuum pressure on peak flexure stress in y-direction

7.3. Impact properties

This section covers impact performance of 3 layers composites. Figure 7.41 shows a lower-half composite panel and the locations of seven impact specimens on the panel. The specimens were numbered according to their distance from resin inlet. The distances from the resin inlet are 6.57, 19.32, 29.50, 36.20, 36.20, 38.30, and 39.00 cm.

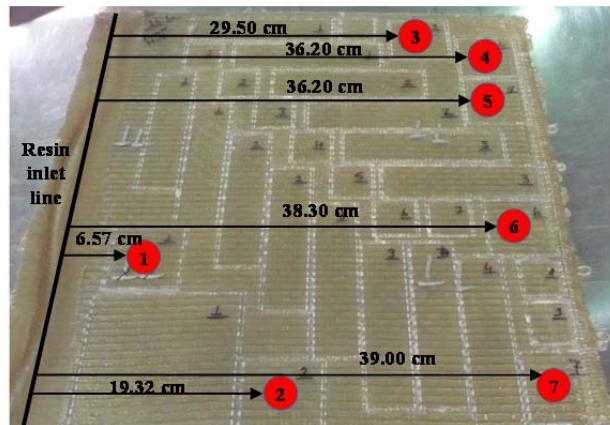


Figure 7.41. Locations of impact specimens on lower-half composite plate

ISO 6603-2 standard was followed to determine the impact resistance of the samples. It classifies impact behavior of the material into four types of failure. These types are,

- a) yielding (zero slope at maximum force) followed by deep drawing
- b) yielding (zero slope at maximum force) followed by (at least partially) stable cracking
- c) yielding (zero slope at maximum force) followed by unstable cracking
- d) no yielding

Figure 7.42 shows examples of force-deflection diagrams, and typical appearance of specimens after testing for this different impact failure types. Impact results indicated that the specimens in this study generally fallen into “yielding (zero slope at maximum force) followed by stable crack growth” type as shown in Figure 7.42 (b). It was noticed that some specimens (labeled 4-7 in Figure 7.41) that are close to the outlet had variable thickness and were not clamped uniformly. This caused the sample to fail at significantly different impact load and energy compared to the other specimens. The data of these specimens was discarded.

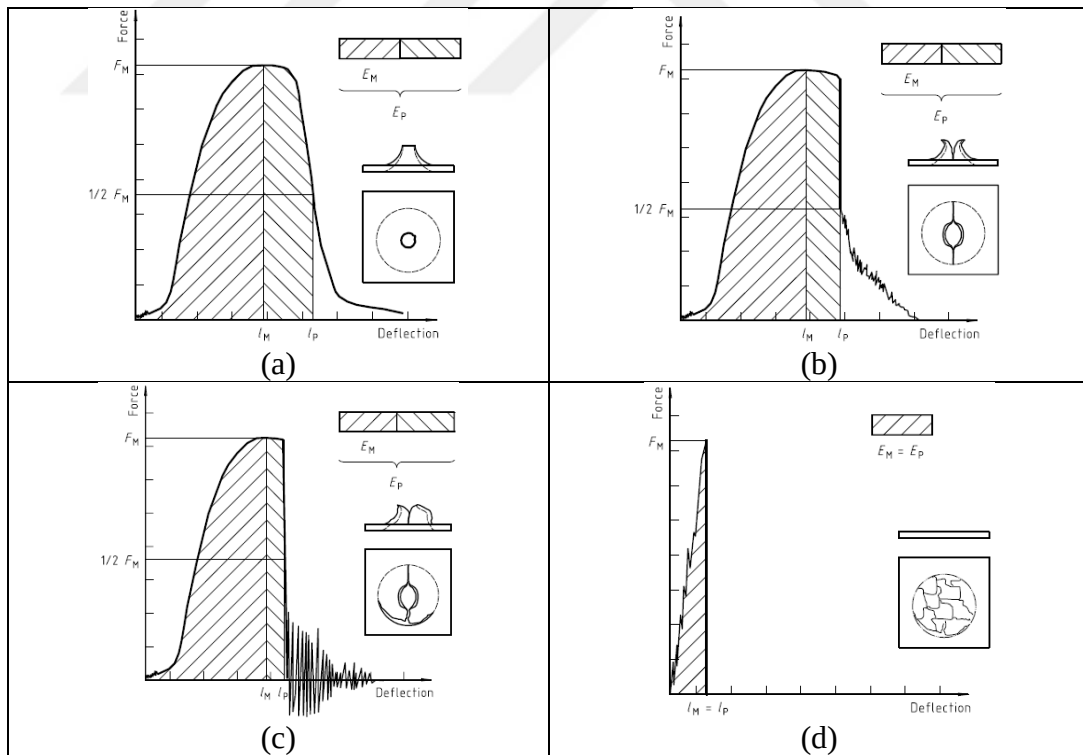


Figure 7.42. Impact behavior types according to ISO 6603-2 [65]

Figure 7.43 shows load versus deflection diagrams of seven specimens from 3 layers, twill weave, 4.87 x-yarns/layer/cm composite panel infused at 75 kPa vacuum and Figure 7.44 shows the images of the seven specimens after the impact test was conducted. The diagrams fall under the category “yielding (zero slope at maximum force) followed by stable crack growth”. Numeric results of the seven impact specimens in Figure 7.44 indicated that peak impact load, composite thickness and composite areal density of specimens are decreasing from resin inlet to outlet. Specimens close to resin inlet area have more resin (material) than specimens close to resin outlet area have, which resulted in higher thickness and areal density in specimens close to resin inlet. Increase in resin amount caused increase in peak impact load. Therefore, peak impact load indicated a decreasing trend toward resin outlet. In other words, properties of fiber reinforced polymer matrix composites are dominated by fiber and/or resin. Impact resistance is an interlaminar property and both fiber and resin play role in it. Proximity of impact specimen to resin inlet increased the amount of resin in the specimen, and more resin resulted in better impact load than the specimens away from the resin inlet.

Peak impact load was normalized by thickness to eliminate the thickness variation on the panel. Figures 7.45 and 7.46 show normalized peak impact load profile of 3 layers composites produced at 75 and 100 kPa vacuums, respectively. Normalized peak impact load profiles of composites with 2 and 4 layers are given in Appendix O.

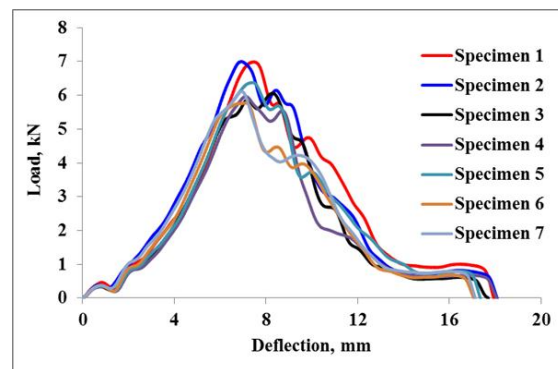


Figure 7.43. Load versus deflection diagrams of specimens from 3 layers, twill weave, 4.87 x-yarns/layer/cm composite panel infused at 75 kPa vacuum

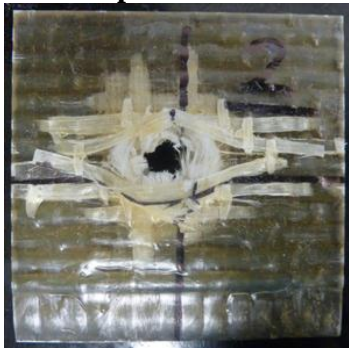
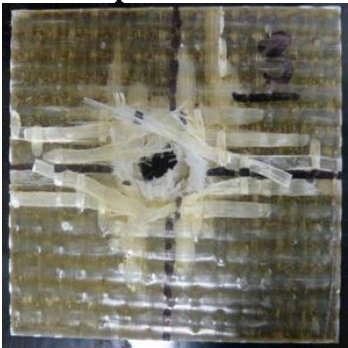
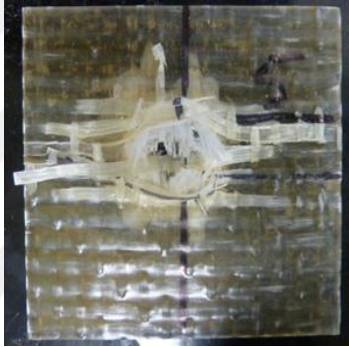
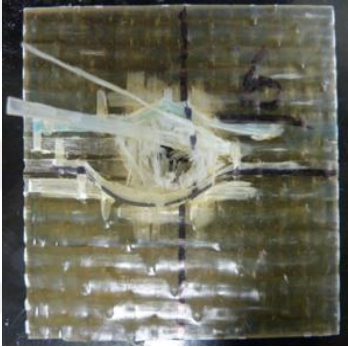
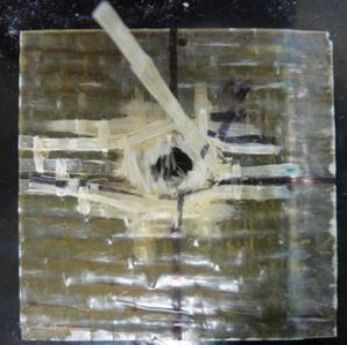
Specimen 1  Peak impact load: 6.99 kN Thickness: 2.78 mm Areal density: 5013.27 g/m²	Specimen 2  Peak impact load: 7.00 kN Thickness: 2.59 mm Areal density: 4592.35 g/m²	Specimen 3  Peak impact load: 6.06 kN Thickness: 2.46 mm Areal density: 4534.73 g/m²
Specimen 4  Peak impact load: 5.97 kN Thickness: 2.44 mm Areal density: 4496.89 g/m²	Specimen 5  Peak impact load: 6.38 kN Thickness: 2.44 mm Areal density: 4659.18 g/m²	Specimen 6  Peak impact load: 5.79 kN Thickness: 2.44 mm Areal density: 4734.01 g/m²
Specimen 7  Peak impact load: 6.12 kN Thickness: 2.42 mm Areal density: 4412.03 g/m²		

Figure 7.44. Appearances of specimens after impact test from 3 layers, twill weave, 4.87 x-yarns/layer/cm composite panel infused at 75 kPa vacuum

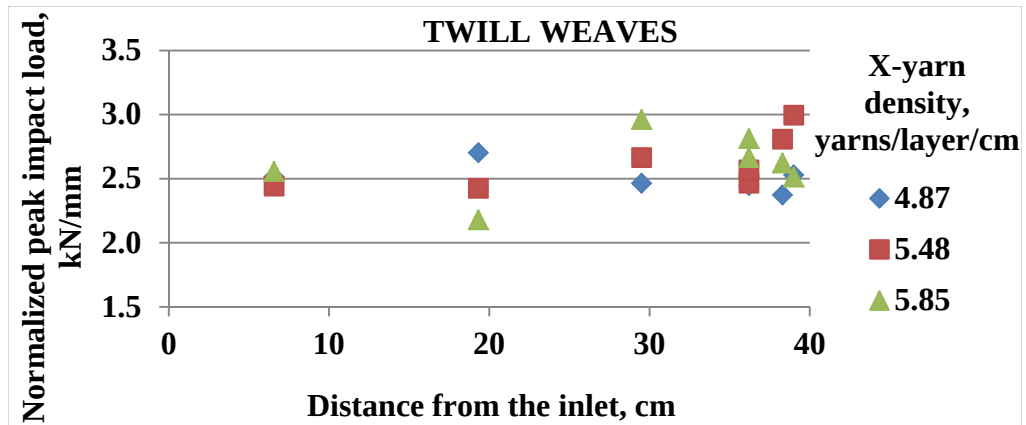
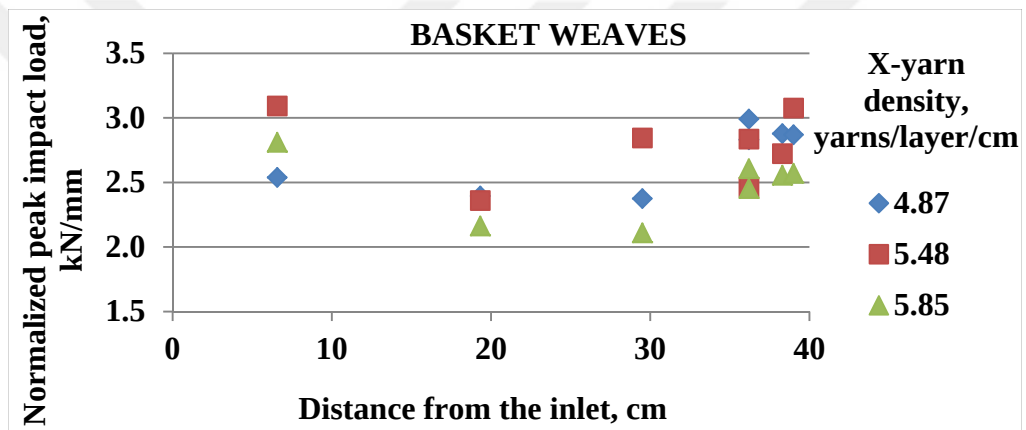
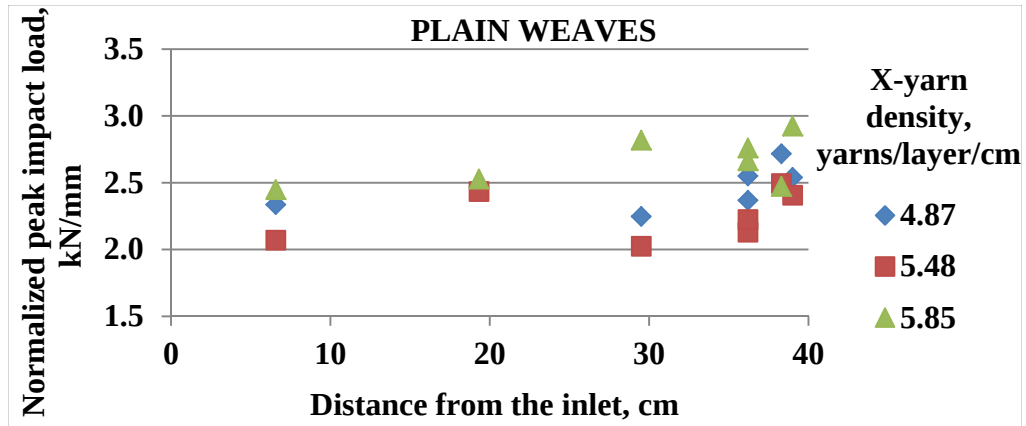


Figure 7.45. Normalized peak impact load profile of 3 layers composites manufactured at 75 kPa vacuums

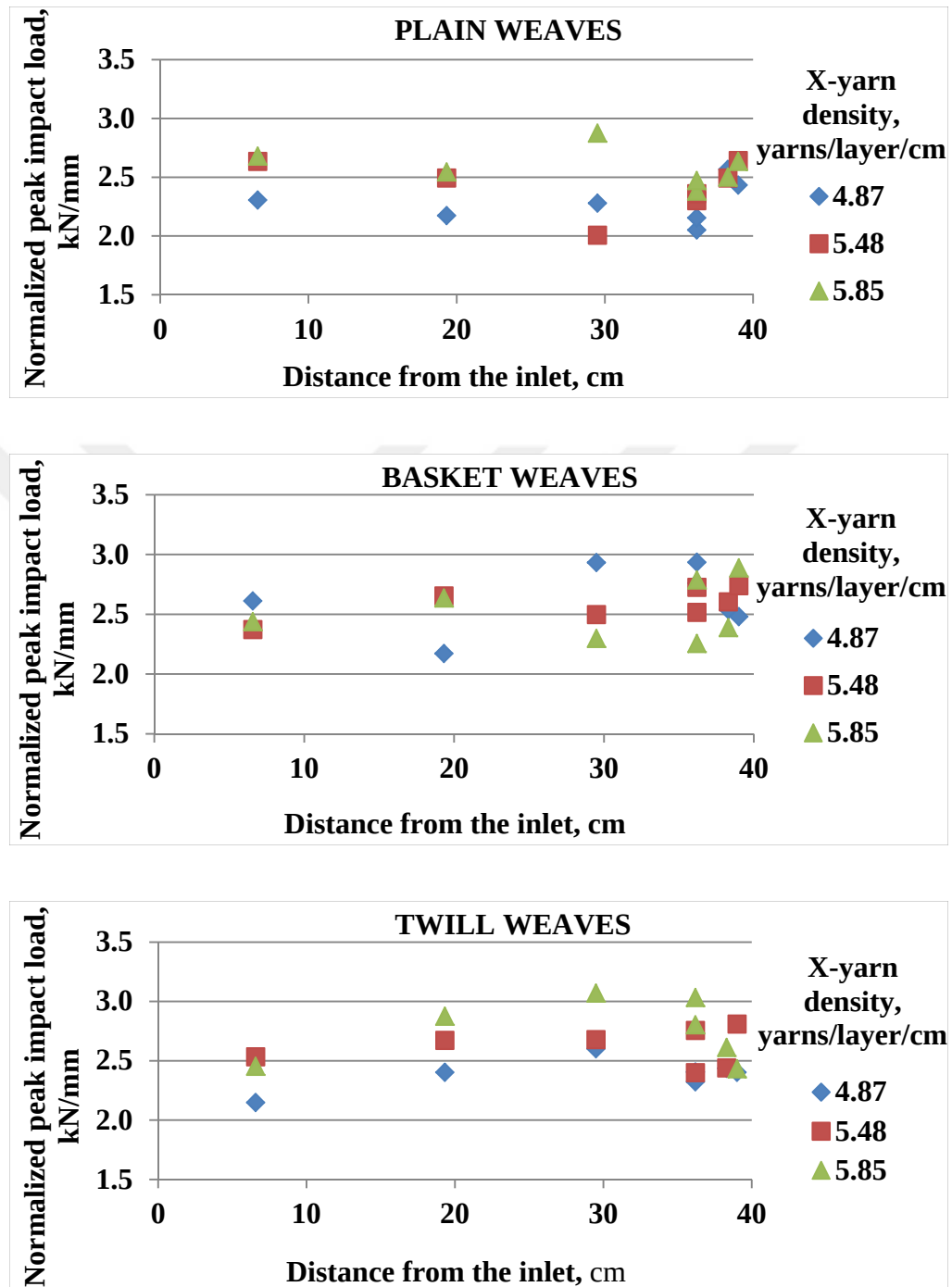


Figure 7.46. Normalized peak impact load profile of 3 layers composites manufactured at 100 kPa vacuums

7.3.1. Impact load

Peak impact load of each specimen was normalized by the thickness to reveal the effect of number of y-yarn layers on peak impact load. Thickness normalization also eliminated thickness variation in each panel as mentioned in previous section. The average of each panel (out of 54) was calculated from seven locations shown in Figure 7.41. All observations (54x7) were used to conclude the results using ANOVA, Tukey multiple means comparison, and correlation statistical analyses. Table P.8, Figure P.15, and Figure P.16 in Appendix P show the results of the statistical analyses. As it can be seen the effects of distance from resin inlet, number of layers, weave, and vacuum pressure on normalized peak impact load are statistically significant at confidence level of 95% (Figure P.16).

Figure 7.47 shows the effect of distance from resin inlet on peak impact load normalized by thickness. Specimens close to resin outlet area showed higher normalized peak impact load than specimen close to resin inlet area.

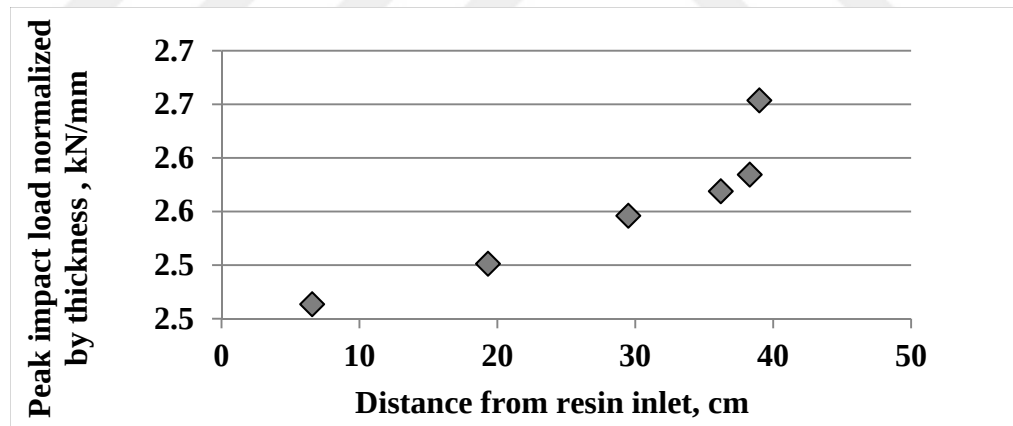


Figure 7.47. Effect of distance (cm) from resin inlet on peak impact load normalized by thickness

Figure 7.48 shows the effect of number of y-yarn layers on normalized peak impact load. Positive correlation (0.13) between number of layers and normalized peak impact load indicated that increase in number of y-yarn layers caused increase in normalized peak impact load (Table P.8 and Figure P.15). 4 layers composites showed the highest normalized peak

impact load among different layers, and they were followed by 3 and 2 layers composites, respectively. Tukey multiple means comparison test indicated that 4 layers composites are significantly different from 2 layers composites, and there is no statistically significant difference between 3 layers composites and the other composites in view of normalized peak impact load (Figure P.16).

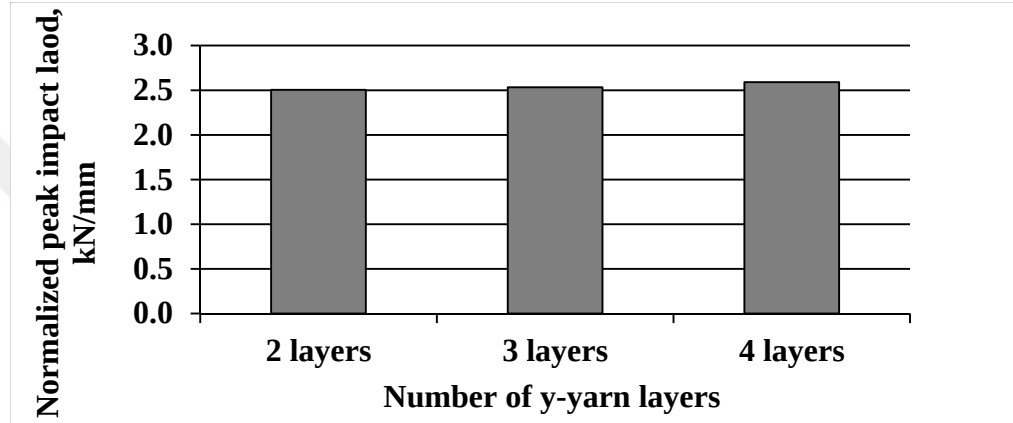


Figure 7.48. Effect of number of y-yarn layers on normalized peak impact load

In order to explain the effect of number of y-yarn layers on normalized peak impact load, Tukey multiple means comparison analysis for the effect of number of yarn layers on total fiber volume fraction was performed (Figure P.16). The analysis indicated 4 layers composites had significantly higher total FVF than 3 and 2 layers composites, and there is no significant difference between 2 and 3 layers composites in terms of total FVF that proves the effect of number of layers on normalized peak impact load. Additional Tukey multiple means comparison analysis for the effect of number of y-yarn layers on z-FVF was performed and the result indicated that increase in number of y-yarn layers caused significant decrease in z-FVF (Figure P.16). Therefore, it is concluded that increase in total FVF is the main reason for the increase in normalized peak impact load as number of y-yarn layers is increased. For the adopted design of experiment in this study, increase in number of layers decreased x- and z-yarn FVF, and increased y- and total FVFs that was proved by the experiment as shown in Figure 7.9, and was revealed in statistical analysis in Table P.8.

Figure 7.49 shows the effect of weave on normalized peak impact load. Twill weave composites showed the highest normalized peak impact load among different weaves, and they were followed by composites with basket and plain weaves, respectively. Tukey multiple means comparison test indicated that there is no significant difference between twill and basket weave composites; however, twill and basket weave composites are significantly different from plain weave composites in terms of normalized peak impact load (Figure P.16). Tukey multiple means comparison analysis for the effect of weave on total FVF of impact specimens revealed that composites with twill weaves had the highest total FVF, and they were followed by composites with basket and plain weaves, and the difference between all composites are significantly different. Again, the effect of weave on normalized peak impact load is related to total FVF (Figure P.16).

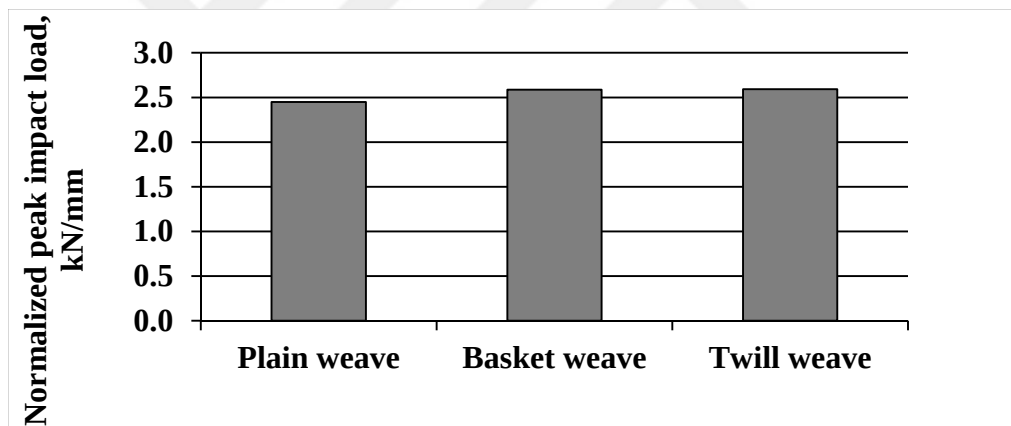


Figure 7.49. Effect of weave on normalized peak impact load

Figure 7.50 shows the effect of vacuum pressure on normalized peak impact load. Tukey multiple means comparison indicated that normalized peak impact load of composites manufactured at 75 kPa vacuums are significantly higher than composites manufactured at 100 kPa vacuums (Figure P.16). The effect of vacuum pressure on total FVF based on Tukey multiple means comparison indicated that composites manufactured at 100 kPa vacuums have greater total FVF than composites with 75 kPa vacuum; however, the difference is not statistically significant (Figure P.16). Therefore, the reason behind the difference between

normalized peak impact load of composites infused at 75 and 100 kPa vacuum levels must be related to other parameters than total FVF. The most probable reason could be void content difference between composites manufactured at 75 and 100 kPa vacuums. Therefore, the effect of vacuum pressure on void content was statistically analyzed using Tukey multiple means comparison, which indicated that composites manufactured at 75 kPa vacuums have significantly greater void content than composites manufactured at 100 kPa vacuums. The results show that higher void content composites (manufactured at 75 kPa vacuums) showed better peak load impact performance than lower void content composites (manufactured at 100 kPa vacuums (Figure P.16). This agrees with the finding by Baucom and Zikry [37] who investigated the effect of void content on three-point bending and ballistic impact performance of 3D orthogonal woven composites. They stated that porous 3D orthogonal composites resulted in weight reduction, while ballistic impact and bending resistance are maintained. They showed that void sites might behave as points where failure surface are deflected and mitigated in bending test. The advantage of porous composites in bending and ballistic impact is explained that transverse cracks are deflected by pores, therefore impeding and spreading failure over larger radial areas.

The individual averages of normalized peak impact load of the 54 panels are shown in Figures O.5 to O.10 in Appendix O, in which the main effects of the independent variables (number of y-yarn layers, weave, x-yarn density, and vacuum pressure) can be seen.

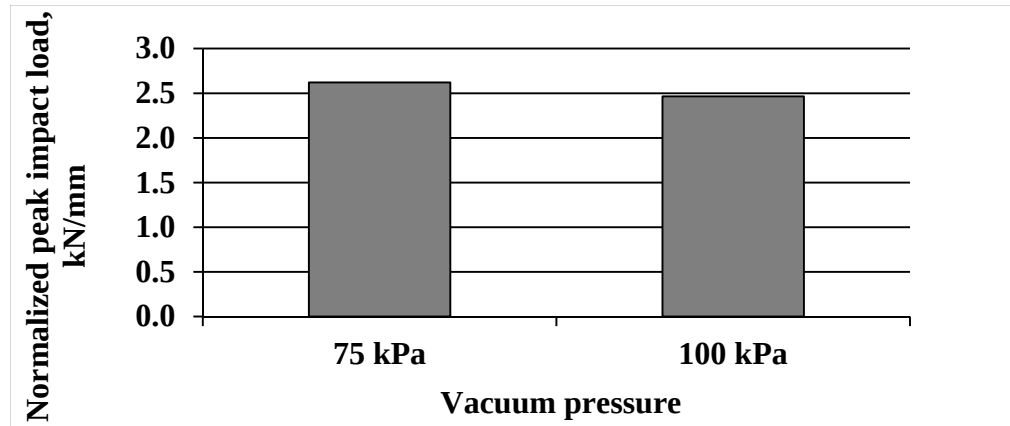


Figure 7.50. Effect of vacuum pressure on normalized peak impact load

7.3.2. Total penetration energy

Total penetration energy of each specimen was normalized by thickness in order to reveal the effect of number of y-yarn layers on total penetration energy. The averages of normalized total penetration energy are given in the following section. Specimens shown in Figure 7.41 were used to calculate the average normalized total penetration energy of each panel. All observations including 54 panels were used to evaluate the results using ANOVA, Tukey multiple means comparison, and correlation statistical analyses (Table P.9, Figure P.17, and Figure P.18). According to ANOVA, the influence of each of the main effect (number of y-yarn layers, weave, x-yarn density, and vacuum pressure) on the normalized total penetration energy is significant at 95% confidence interval (Figure P.18).

Figure 7.51 shows the effect of number of y-yarn layers on normalized total penetration energy. 4 layers composites showed the highest normalized total penetration energy performance among composites with different layers, and they were followed by composites with 3 and 2 layers, respectively. Tukey multiple means comparison test indicated that normalized total penetration energy of composites with different layers are significantly different from each other (Figure P.18). Positive (0.56) correlation between number of y-yarn layers and total penetration energy supported the findings (Table P.9). As number of y-yarn layers is increased; x- and z-yarn FVFs decrease, and y- and total FVFs increase (Figure 7.9,

Table P.9). Normalized total penetration energy performance of composites is decided by total FVF as normalized peak load performance of composites is.

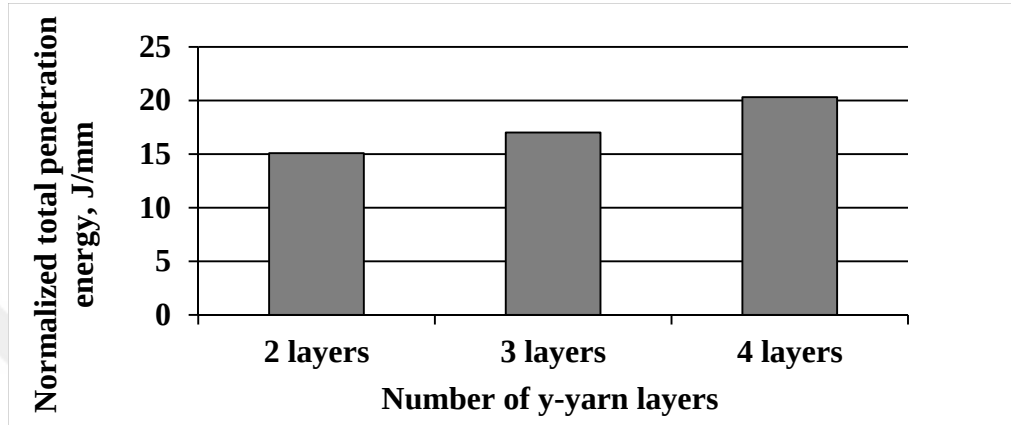


Figure 7.51. Effect of number of y-yarn layers on normalized total penetration energy

Figure 7.52 shows the effect of weave on normalized total penetration energy. The effect of weave on normalized total penetration energy is the same as effect of weave on normalized peak impact load. Composites with twill weave showed the highest total penetration energy, and they were followed by composites with basket and plain weaves, respectively. Tukey multiple means comparison test indicated that there is no significant difference between composites with twill and basket weaves; however, twill weave composites are significantly different from plain weave composites in terms of total penetration energy (Figure P.18). Additional Tukey multiple means comparison analysis for the effect of weave on total FVF revealed that twill weaves had the highest total FVF, and they were followed by basket and plain weave composites. No significant difference between composites with twill and basket weaves was observed, however, total FVF of composites with plain weaves is significantly different from those with basket and twill weaves (Figure P.18). Again, the effect of weave on normalized total penetration energy performance is related to total FVF parameter.

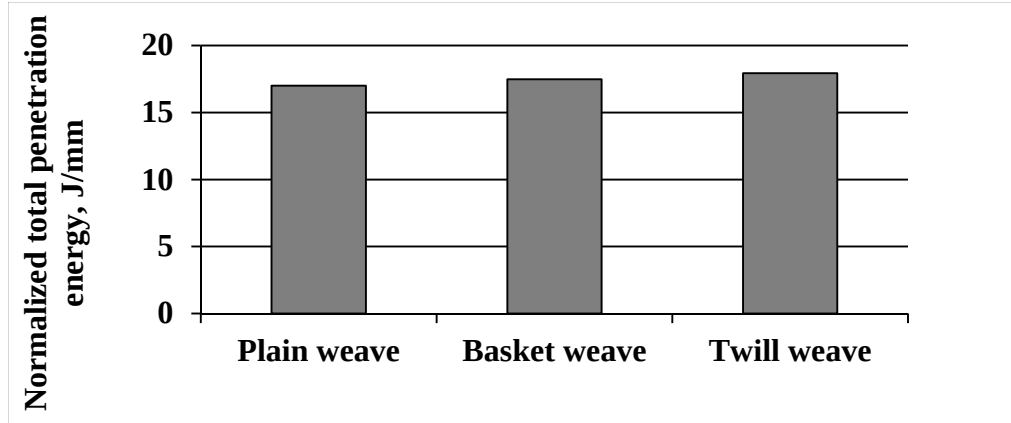


Figure 7.52. Effect of weave on normalized total penetration energy

Figure 7.53 shows the effect of x-yarn density on normalized total penetration energy. According to Tukey multiple means comparison statistical analysis, 5.85 x-yarn density composites had the highest normalized total penetration energy, and they were followed by composites with 4.87 and 5.48 x-yarn density levels. No significant difference between 4.87 and those with x-yarn density of 5.48 and 5.85 was observed (Figure P.18).

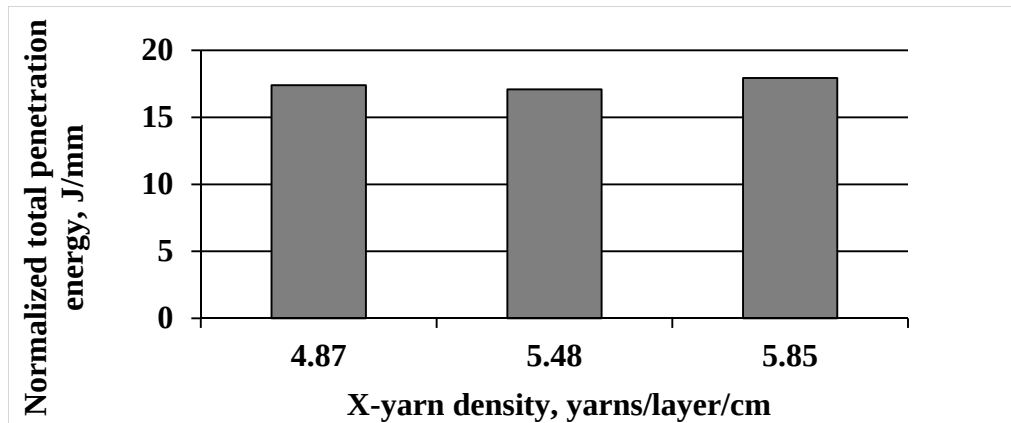


Figure 7.53. Effect of x-yarn density on normalized total penetration energy

Similar to the effect of vacuum on normalized peak impact load, normalized total penetration energy of composites manufactured at 75 kPa vacuums were significantly higher than composites manufactured at 100 kPa vacuums (Figure 7.54 and Figure P.18), which was

supported by correlation analysis (-0.51, negative correlation between vacuum pressure and normalized total penetration energy, Table P.9). The effect of vacuum pressure on total FVF indicated that composites manufactured at 100 kPa vacuums had significantly greater total FVF than composites manufactured at 75 kPa vacuum. As it was previously mentioned, composites infused at 100 kPa showed significantly less void content than composites infused at 75 kPa vacuum. The results again pointed that low total FVF and high void content composites manufactured at 75 kPa vacuums showed higher normalized total penetration energy than high total FVF and low void content composites manufactured at 100 kPa vacuums.

The individual averages of normalized total penetration energy of the 54 panels are shown in Figures O.11 to O.16 in Appendix O, in which the main effects of the independent variables (number of y-yarn layers, weave, x-yarn density, and vacuum pressure) can be seen.

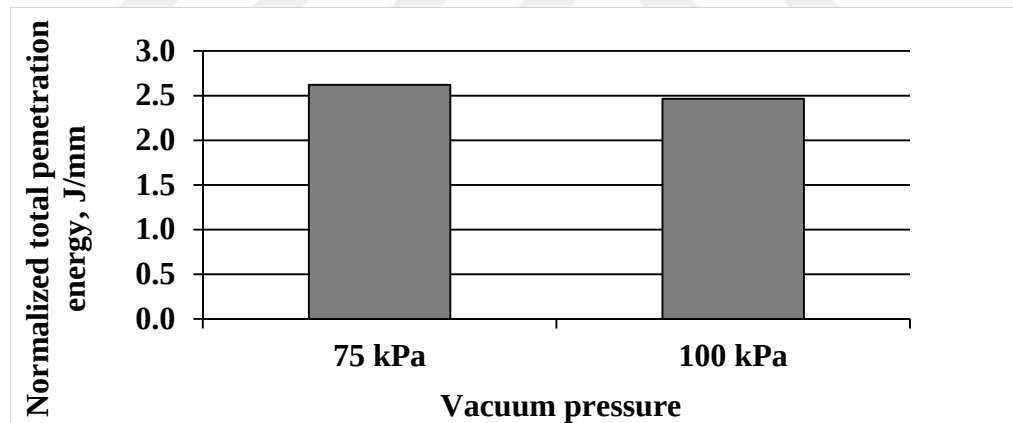


Figure 7.54. Effect of vacuum pressure on normalized total penetration energy

7.4. Conclusion on mechanical properties

The effects of main independent structural parameters (number of y-yarn layers, weave, x-yarn density and vacuum level during VIP), and sample location on mechanical properties were examined. Additionally, assessment of the mechanical properties in terms of physical properties (dependent structural parameters) especially constituent yarn and total FVFs of

composite were provided. Increase in number of y-yarn layers caused decrease in tensile and flexure stress in x-direction, while it resulted in increase in tensile and flexure stress in y-direction, which was explained in terms of effect of number of y-yarn layers on x- and y-yarn FVFs, respectively. Composites with twill weaves provided better tensile, flexure, and impact performance than composites with plain and basket weaves, due to their higher FVFs than those of other weaves. Increase in x-yarn density increased tensile and flexure stress in x-direction, while it caused decrease in tensile and flexure stress in y-direction, which are related to the effect of x-yarn density on constituent yarn FVFs. Increase in vacuum pressure during VIP caused increase in tensile and flexural stresses. However, normalized peak impact load and normalized total penetration energy were decreased by increase in vacuum pressure. Low total FVF and high void content composites manufactured at 75 kPa vacuum demonstrated better impact properties (normalized peak impact load and normalized total penetration energy) than high FVF and low void content composites manufactured at 100 kPa vacuums.

8. OVERALL CONCLUSION AND SUGGESTION FOR FUTURE STUDIES

Generalized geometric models considering jammed and non-jammed cases for both natural spun (circular) and filament (rectangular) yarn were developed. The input parameters of the models are yarn material density, yarn packing factor, yarn cross-sectional shape, yarn linear density, yarn spacing, number of y-yarn layers, and z-yarn interlacing pattern. The outputs of the model are thickness, areal density, constituent yarn FVFs, maximum z-yarn angle with preform plane, and maximum yarn spacing for jammed cases. The z-yarn interlacing pattern, which was represented by a numeric value termed weave factor in this study (not considered in previous studies), enabled to generalize the model that considers all weave design options.

The significance of the generalized models was demonstrated as a design tool to predict parameters of interest (output parameters) in terms of independent parameters (input variables) without the need to form the preforms and composites first. Researchers can utilize the models to predict resin infusion performance (resin flow front progress and mold filling time) of different dry preform structures in generalized case. The models can also be used to predict mechanical properties, which are tightly related to constituent yarn FVFs of composite.

The model for rectangular filament yarn was verified. Thickness, and the structural parameters related to x- and y-yarns were predicted well by the model. Due to tension on z-yarn that caused flattening of x-yarn at cross overs, through thickness component of z-yarn was shortened that caused overestimation of z-FVF by the model. Therefore, the model should be improved to include yarn flattening due to z-yarn tension, and compression pressure during infusion. Additionally, the accuracy of FVF prediction of the geometric models could be improved by considering the compressibility of the dry and saturated preform. The experimental measurements of the aspect ratio conducted in this work could be used to verify the model.

Geometric model developed for circular cross section is suitable for single ply spun yarns and its verification can be performed by manufacturing 3D orthogonal woven preforms from single ply spun yarns.

Broad range of 3D orthogonal woven preforms from glass fiber was woven. The main independent parameters were number of y-yarn layers, weave (z-yarn interlacing pattern), and x-yarn density for dry preform weaving. Physical properties of dry preform (thickness, constituent yarn weights and FVFs) were measured to unveil the effect of main independent parameters on physical properties of dry preform. The data gathered from these experiments were also used to calculate constituent yarn FVFs of composite, which are directly related to mechanical properties of composite in different directions.

The 3D orthogonal woven preforms were converted into composite by vacuum infusion process (VIP). In addition to main independent parameters in dry preform formation, vacuum pressure was considered as VIP main independent parameter. Infusion performance (mold filling time and flow front progress) of dry preforms were explained by channel configurations in x-direction of preforms with different weaves.

Previous researches on VIP dealt with the effect of variable compaction pressure and flexible (vacuum bag) side of the molding on resin pressure, thickness, and FVF change. They did not consider the effect of these changes on mechanical properties of cured composite. In this study, physical and mechanical properties of 3D orthogonal woven glass fiber reinforced composites were tracked according to position of specimen relative to resin inlet. It was observed that while thickness was decreasing with distance from the inlet, FVF increased towards resin outlet, which is in agreement with previous research. Void volume fraction did not indicate any trend in this study, which is again in agreement with previous studies. Similarly, the effect of specimen location on mechanical properties (tensile, flexure, and impact) was analyzed. Tensile and flexure properties improved towards resin outlet due to thickness decrease (FVF increase) while keeping load carrying capacity of specimen constant that is dictated by amount of fiber. On the other hand, peak impact load as an interlaminar

property determined by both fiber and resin amount decreased towards resin outlet. The profile of peak impact load normalized by thickness showed an increasing trend from inlet to outlet.

Edge-to-edge resin infusion strategy in the x-yarn direction was followed in this study. For future studies, infusion strategies other than edge-to-edge, for example radial flow, in which resin inlet is placed into the mid-point of preform, and suction is applied around the overall peripheral of the preforms or vice versa can be conducted to alleviate the variation in physical properties (thickness and FVF) of composites.

For future studies, a composite manufacturing technique other than vacuum infusion, such as compression molding with dry preform can be used. In compression molding, thickness of final composite is accurately controlled; therefore, effect of thickness variation on physical and mechanical results will be eliminated. If vacuum infusion will be used, then a distribution (green flow) media should be used to get full wetting and to minimize thickness variation.

In this study, two, three and four layers composites were produced due to limitation in creel capacity and number of weft insertion at the time of formation of the preforms. For future studies, preforms with six or more layers (up to fourteen) in jammed case those are more predictable for design perspective, and where flattening of x-yarn at z-yarn cross over disappears, can be produced to investigate the effect of number of layers on physical and mechanical properties of thick and jammed composites.

The reed number in this study was 6 dents/inch. It is expected that higher reed number would cause change in the y-yarn aspect ratio and may result in aspect ratios lower than one (rectangle cross-section with horizontal dimension lower than vertical dimension). Such high reed number would affect the FVFs as a result of change in thread density and preform/composite thickness.

Generalized geometric models developed in this study indicated how to control constituent yarn FVFs by changing weave and z-yarn linear density. The balance between in-plane (x- and y-yarn) and out-of-plane (z-yarn) FVFs determines overall composite performance. Increase in z-yarn content causes improvement in interlaminar properties at the expense of in-plane properties. Jammed (high yarn density) structures with z-yarn that is thicker than z-yarn used in in this study should be manufactured with different weaves to reveal the effect of weave on constituent (x-, y-, and z-) yarn FVFs. In order to reveal the effect of weave and z-yarn linear density on mechanical properties, focus should be on impact resistance and shear, especially interlaminar shear properties of composite for future studies.

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APPENDICES



APPENDIX A: Nomenclature for the models

A consistent system of nomenclature capable of representing the preform structural parameters is given here. Subscripts x, y, and z are used to denote filling, warp, and z-yarn (known as binding yarn), respectively.

k	yarn index ($k = x, y, z$)
ρ_{vk}	volumetric density of yarn material (g/cm^3)
$\rho_{\ell k}$	linear density of yarn (g/km or tex)
d_k	yarn diameter for circular cross section (cm)
w_k	yarn width for rectangular cross section (cm)
t_k	yarn thickness for rectangular cross section (cm)
AR_k	yarn aspect ratio (ratio between yarn width and thickness, dimensionless)
Φ_k	yarn packing factor (dimensionless)
p_x	x-yarn spacing for non-jammed structure (cm)
p_{xi}	x-yarn spacing at weave intersection for jammed structure (cm)
p_{xf}	x-yarn spacing under the z-yarn float for jammed structure (cm)
$\bar{p}_x$	average x-yarn spacing for jammed structure (cm)
p_y	y-yarn spacing for non-jammed structure (cm)
p_{y1}	spacing of y-yarn followed by z-yarn for jammed structure (cm)
p_{y2}	spacing of two successive y-yarns for jammed structure (cm)
$\bar{p}_y$	average y-yarn spacing for jammed structure (cm)
N_k	number of yarns per layer per weave repeat
i_z	number of z-yarn intersections per weave repeat
M_z	z-yarn weave factor (ratio between N_x and i_z)
θ	maximum angle of z-yarn axis to plane of preform (radian)
n_x	number of x-yarn layers
n_y	number of y-yarn layers
a	arc part length of z-yarn (cm)

b	through the thickness part length of z-yarn (cm)
L_x	weave repeat width (cm)
L_y	weave repeat length (cm)
L_z	preform thickness (cm)
V_{repeat}	preform volume per weave repeat (cm ³)
ℓ_k	total length of a yarn per weave repeat (cm)
V_{fk}	fiber volume of a yarn per weave repeat (cm ³)
F_{fk}	fiber volume fraction of a yarn (%)
F_{fxyz}	total fiber volume fraction of yarns (%)
W_k	weight of a yarn in dry preform (g/m ²)
W_{xyz}	total weight of dry preform (g/m ²)

APPENDIX B: Calculation of “ θ ” for non-jammed case with circular yarns

Derivation will be performed for maximum angle of the z-yarn axis to the plane of dry preform (θ in radian). For this purpose, two equations are derived to calculate the angle. First equation is derived through-thickness direction using Figure B.1.



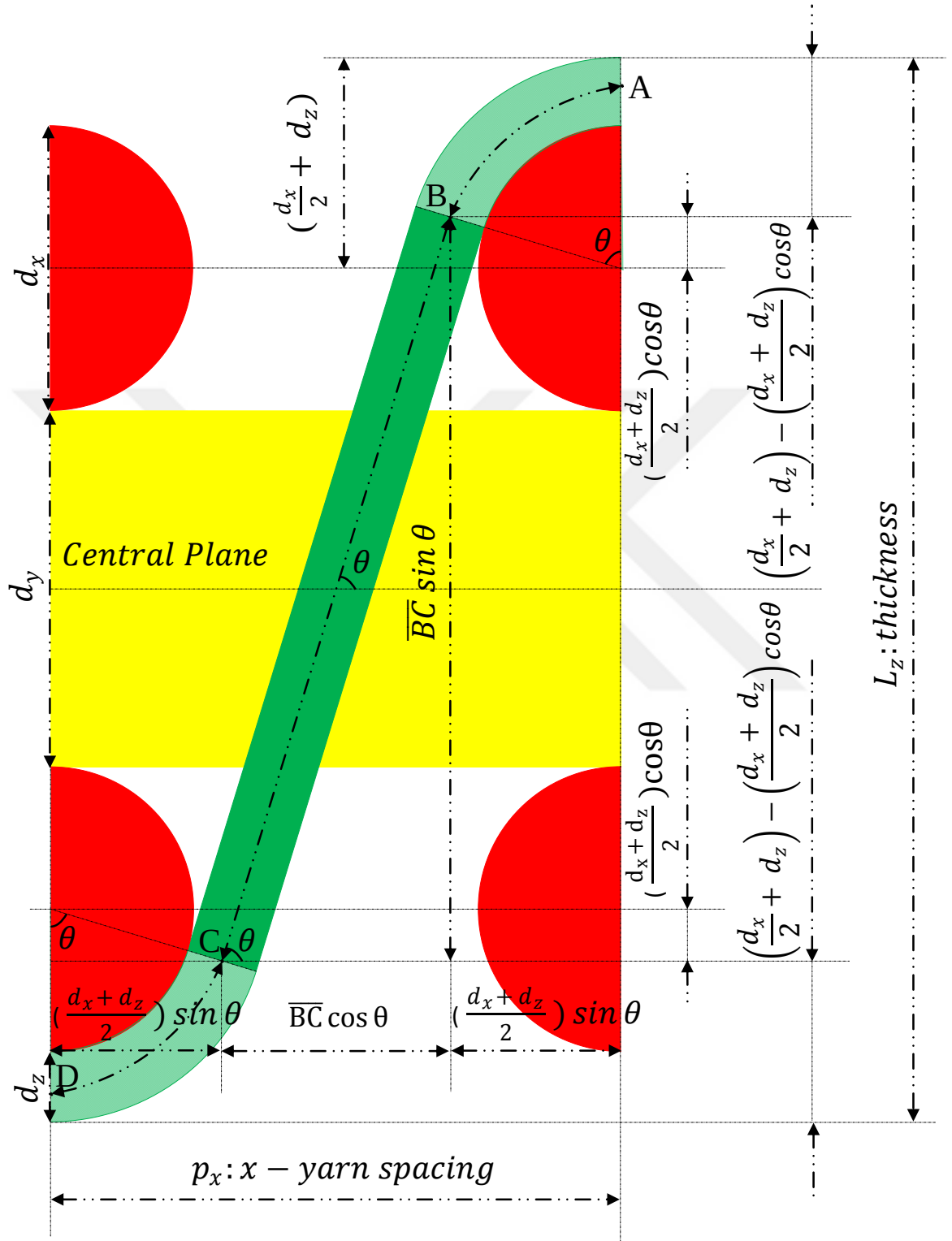


Figure B.1. Geometry at z-yarn interlacing (x-yarn cross section)

$$\begin{aligned}\overline{BC} \sin\theta &= L_z - 2 \left(\left(\frac{d_x}{2} + d_z \right) - \left(\frac{d_x + d_z}{2} \right) \cos\theta \right) \\ \overline{BC} = b &= \frac{L_z - 2 \left(\left(\frac{d_x}{2} + d_z \right) - \left(\frac{d_x + d_z}{2} \right) \cos\theta \right)}{\sin\theta}\end{aligned}\tag{B.1}$$

Second equation is derived along x-yarn spacing direction as shown in Figure B.1.

$$\begin{aligned}\overline{BC} \cos\theta &= p_x - 2 \left(\left(\frac{d_x + d_z}{2} \right) \sin\theta \right) \\ \overline{BC} = b &= \frac{p_x - 2 \left(\left(\frac{d_x + d_z}{2} \right) \sin\theta \right)}{\cos\theta}\end{aligned}\tag{B.2}$$

Equations B.1 and B.2 are equal to each other.

$$\begin{aligned}\frac{L_z - 2 \left(\left(\frac{d_x}{2} + d_z \right) - \left(\frac{d_x + d_z}{2} \right) \cos\theta \right)}{\sin\theta} &= \frac{p_x - 2 \left(\left(\frac{d_x + d_z}{2} \right) \sin\theta \right)}{\cos\theta} \\ p_x \sin\theta - 2 \left(\frac{d_x + d_z}{2} \right) \sin^2\theta &= L_z \cos\theta - 2 \left(\frac{d_x}{2} + d_z \right) \cos\theta + 2 \left(\frac{d_x + d_z}{2} \right) \cos^2\theta \\ p_x \sin\theta - 2 \left(\frac{d_x + d_z}{2} \right) (\sin^2\theta + \cos^2\theta) &= L_z \cos\theta - 2 \left(\frac{d_x}{2} + d_z \right) \cos\theta \\ p_x \sin\theta - 2 \left(\frac{d_x + d_z}{2} \right) (1) &= L_z \cos\theta - 2 \left(\frac{d_x}{2} + d_z \right) \cos\theta \\ p_x \sin\theta - 2 \left(\frac{d_x + d_z}{2} \right) (1) &= \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) \cos\theta\end{aligned}$$

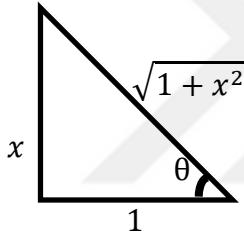
$$p_x \sin\theta - \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) \cos\theta - 2 \left(\frac{d_x + d_z}{2} \right) = 0$$

If both sides of the equation are divided by $\cos\theta$;

$$\frac{p_x \sin\theta}{\cos\theta} - \frac{\left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) \cos\theta}{\cos\theta} - \frac{2 \left(\frac{d_x + d_z}{2} \right)}{\cos\theta} = 0$$

$$p_x \tan\theta - \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) = \frac{2 \left(\frac{d_x + d_z}{2} \right)}{\cos\theta}$$

If it is assumed that $\tan\theta = x$, which is different than subscript x , then



$$\cos\theta = \frac{1}{\sqrt{1 + x^2}}$$

If $\tan\theta$ and $\cos\theta$ values, in terms of x , are plugged into the equation above

$$p_x x - \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) = \frac{(d_x + d_z)}{\frac{1}{\sqrt{1 + x^2}}}$$

$$p_x x - \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) = (d_x + d_z) \sqrt{1 + x^2}$$

If the both sides of the equation are squared;

$$\left(p_x x - \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) \right)^2 = \left((d_x + d_z) \sqrt{1 + x^2} \right)^2$$

$$p_x^2 x^2 - 2p_x x \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) + \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right)^2 = (d_x + d_z)^2 (1 + x^2)$$

Finally second order “ $ax^2 + bx + c = 0$ ” equation is obtained as below.

$$(p_x^2 - (d_x + d_z)^2)x^2 - 2p_x \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right)x + \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right)^2 - (d_x + d_z)^2 = 0$$

Where;

$$a = (p_x^2 - (d_x + d_z)^2)$$

$$b = -2p_x \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right)$$

$$c = \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right)^2 - (d_x + d_z)^2$$

The roots of the equation are;

$$x_{1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

The real root is;

$$x = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

$$x = \frac{2p_x \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) + \sqrt{\left(-2p_x \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) \right)^2 - 4(p_x^2 - (d_x + d_z)^2) \left(\left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right)^2 - (d_x + d_z)^2 \right)}}{2(p_x^2 - (d_x + d_z)^2)}$$

x is equal to $\tan\theta$, then θ is;

$$\theta = \tan^{-1} \left(\frac{2p_x \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) + \sqrt{\left(-2p_x \left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right) \right)^2 - 4(p_x^2 - (d_x + d_z)^2) \left(\left(L_z - 2 \left(\frac{d_x}{2} + d_z \right) \right)^2 - (d_x + d_z)^2 \right)}}{2(p_x^2 - (d_x + d_z)^2)} \right) \quad (B.3)$$



APPENDIX C: Calculation of “ θ ” for non-jammed case with rectangular yarns

Derivation will be performed for maximum angle of the z-yarn axis to the plane of the dry preform (θ in radian). For this purpose, two equations are derived to calculate the angle. First equation is derived through-thickness direction using Figure C.1.



$$\overline{CD} \sin \theta = n_x t_x + n_y t_y + t_z \cos \theta$$

$$\overline{CD} = b = \frac{n_x t_x + n_y t_y + t_z \cos \theta}{\sin \theta} \quad (C.1.)$$

Second equation is derived along x-yarn spacing direction as shown in Figure C.1.

$$\overline{CD} \cos \theta = p_x - w_x - t_z \sin \theta$$

$$\overline{CD} = b = \frac{p_x - w_x - t_z \sin \theta}{\cos \theta} \quad (C.2.)$$

Equations C.1 and C.2 are equal to each other.

$$\frac{n_x t_x + n_y t_y + t_z \cos \theta}{\sin \theta} = \frac{p_x - w_x - t_z \sin \theta}{\cos \theta}$$

Solution of this equation is;

$$\theta = \tan^{-1} \left(\frac{-2(p_x - w_x)(n_x t_x + n_y t_y) - \sqrt{(2(p_x - w_x)(n_x t_x + n_y t_y))^2 - 4(t_z^2 - (p_x - w_x)^2)(t_z^2 - (n_x t_x + n_y t_y)^2)}}{2(t_z^2 - (p_x - w_x)^2)} \right) \quad (C.3.)$$

APPENDIX D: Characterization of dry preforms

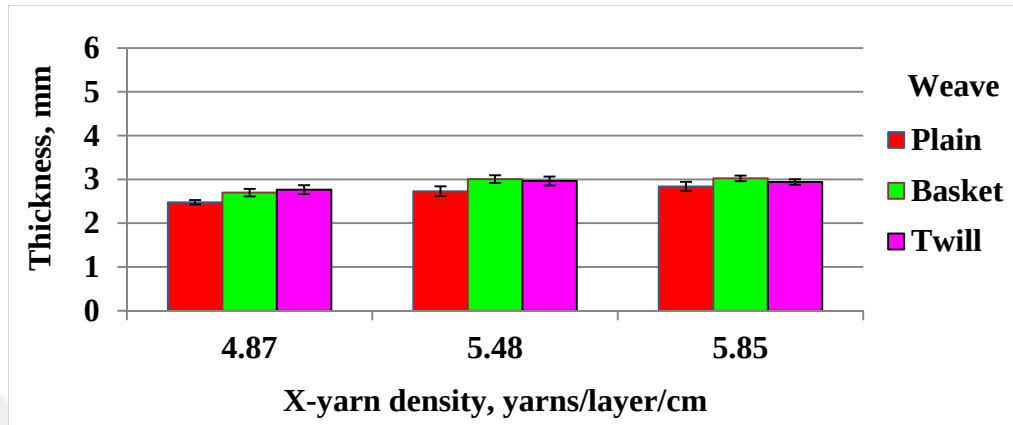


Figure D.1. Thickness of 2 layers dry preforms

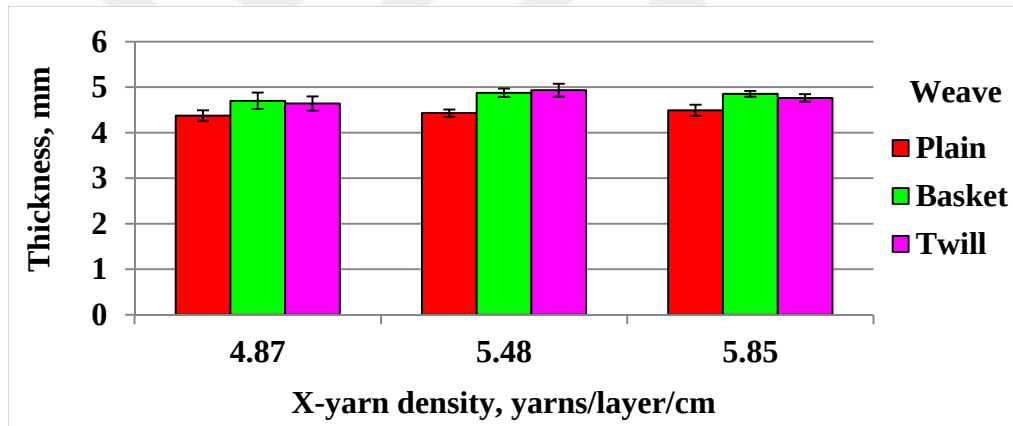


Figure D.2. Thickness of 4 layers dry preforms

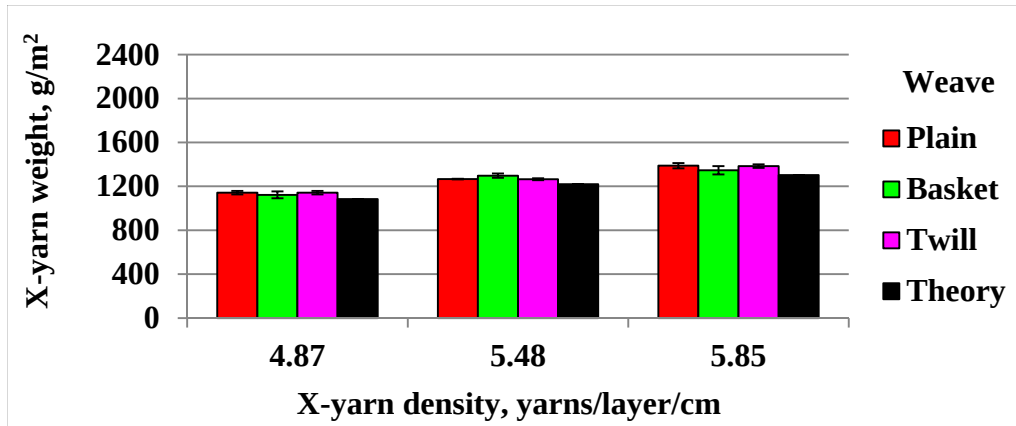


Figure D.3. X-yarn weight of 2 layers dry preforms

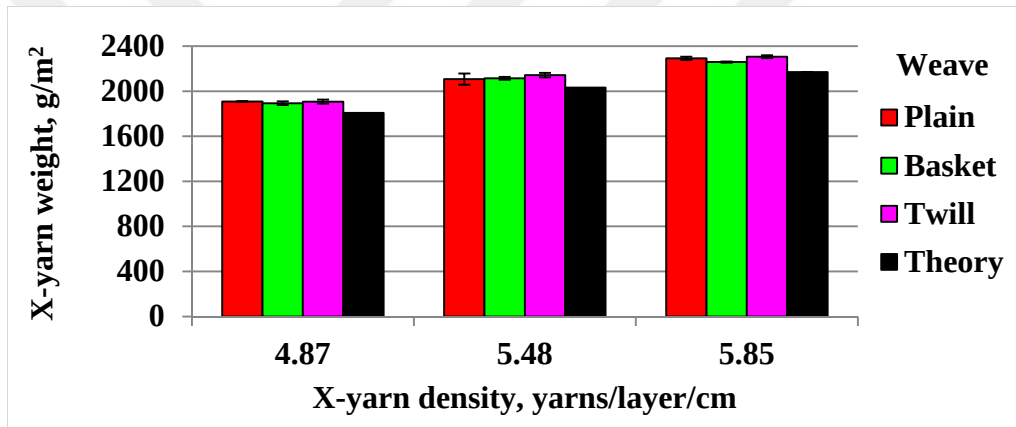


Figure D.4. X-yarn weight of 4 layers dry preforms

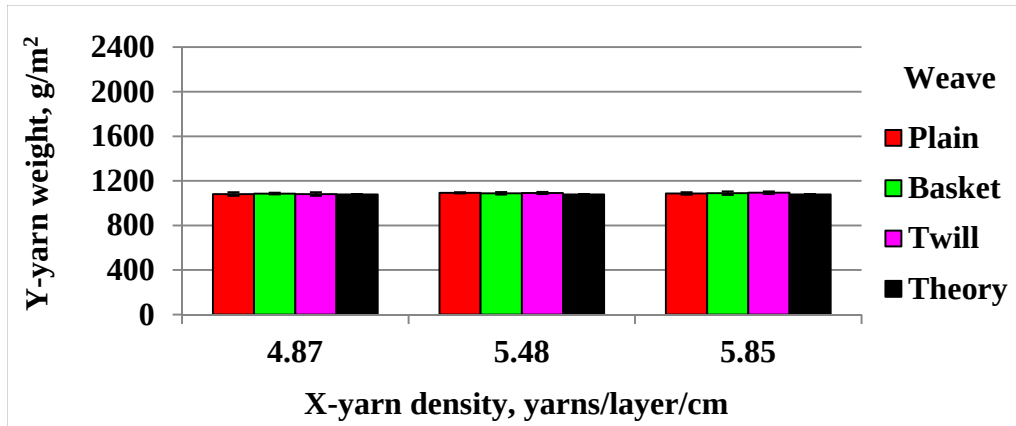


Figure D.5. Y-yarn weight of 2 layers dry preforms

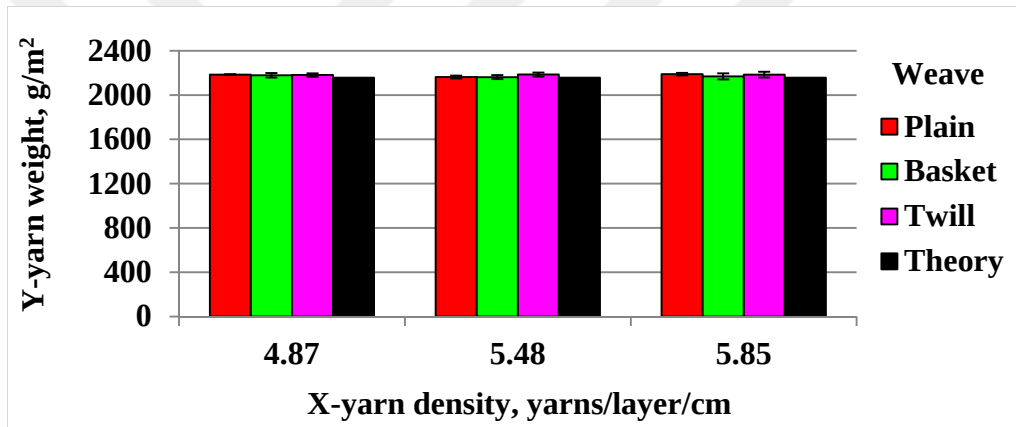


Figure D.6. Y-yarn weight of 4 layers dry preforms

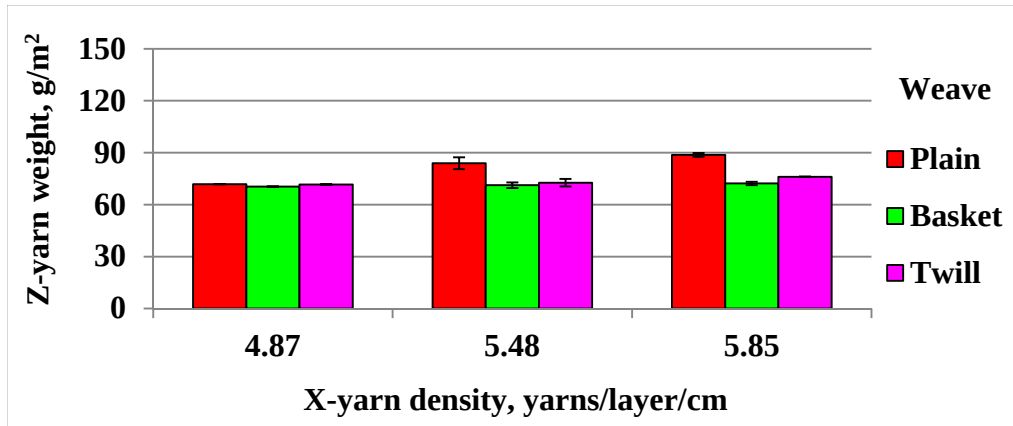


Figure D.7. Z-yarn weight of 2 layers dry preforms

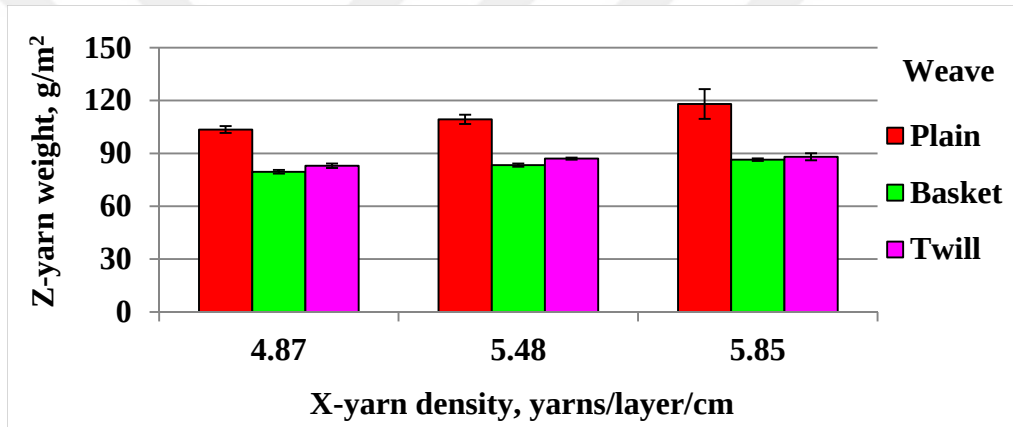


Figure D.8. Z-yarn weight of 4 layers dry preforms

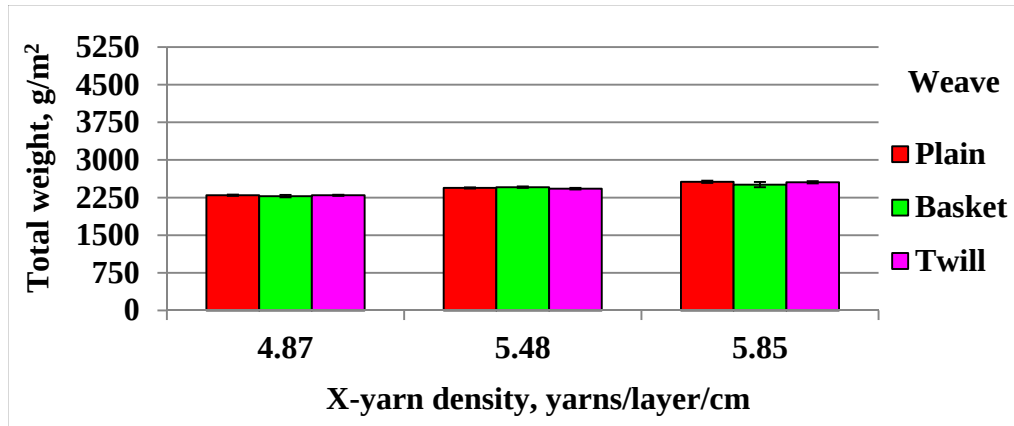


Figure D.9. Total weight of 2 layers dry preforms

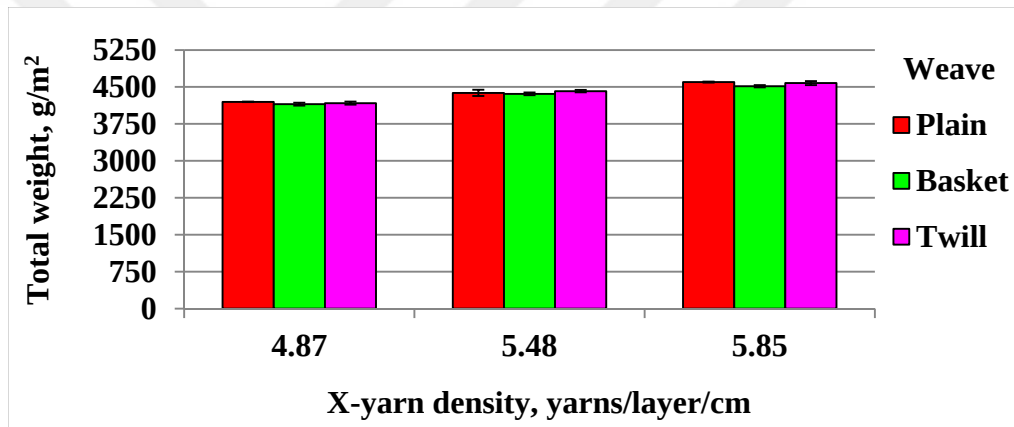


Figure D.10. Total weight of 4 layers dry preforms

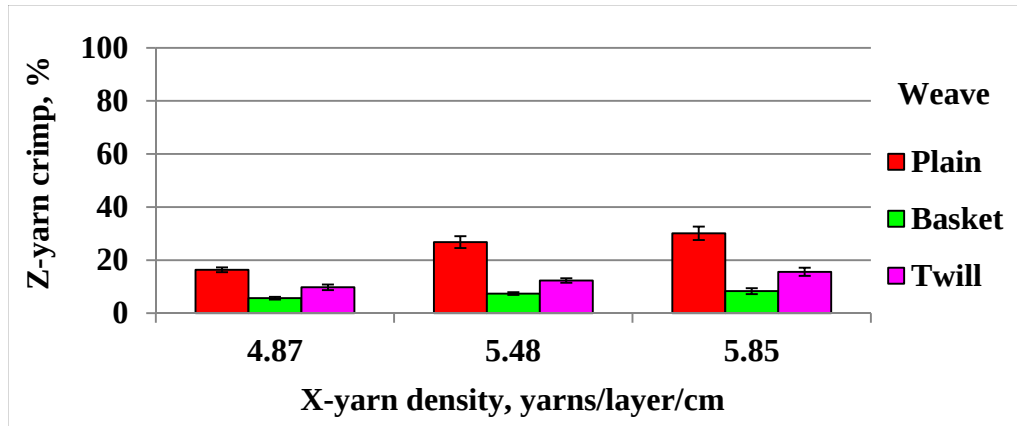


Figure D.11. Z-yarn crimp of 2 layers dry preforms

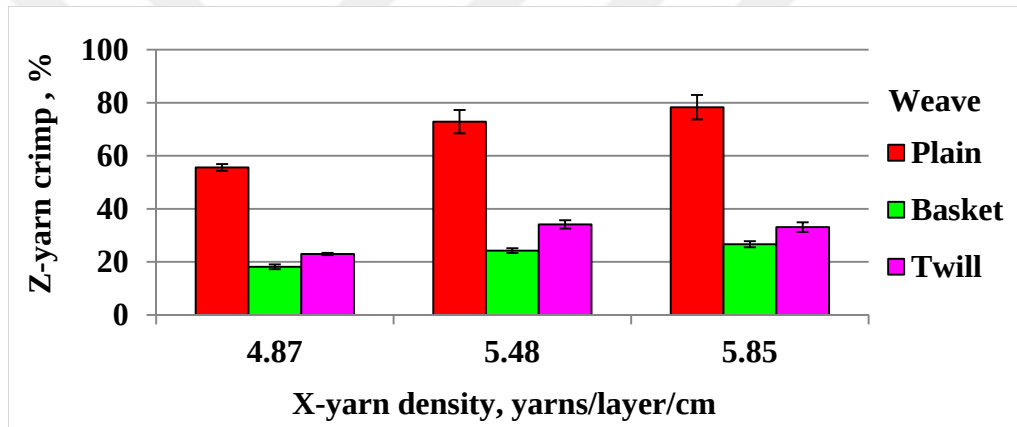


Figure D.12. Z-yarn crimp of 4 layers dry preforms

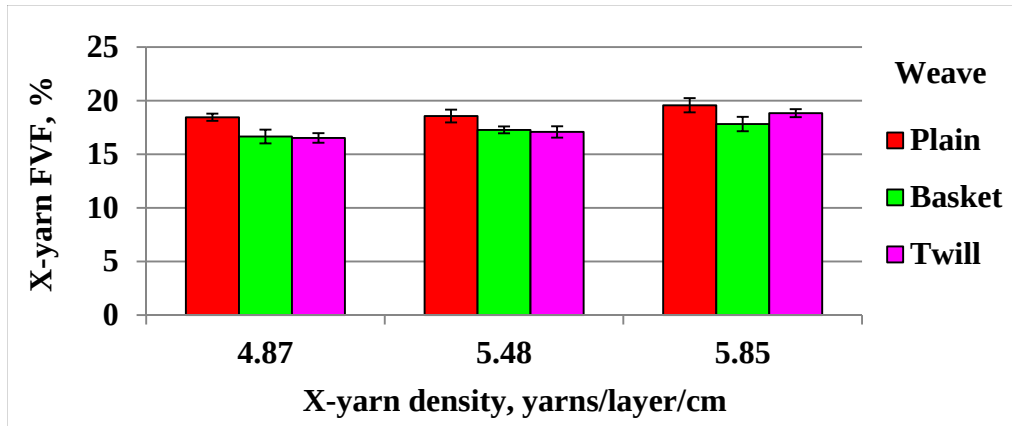


Figure D.13. X-yarn FVF of 2 layers dry preforms

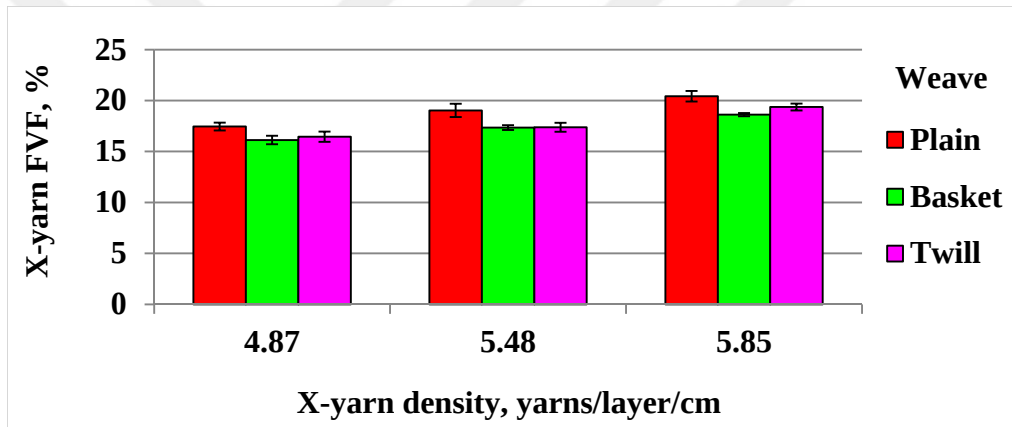


Figure D.14. X-yarn FVF of 4 layers dry preforms

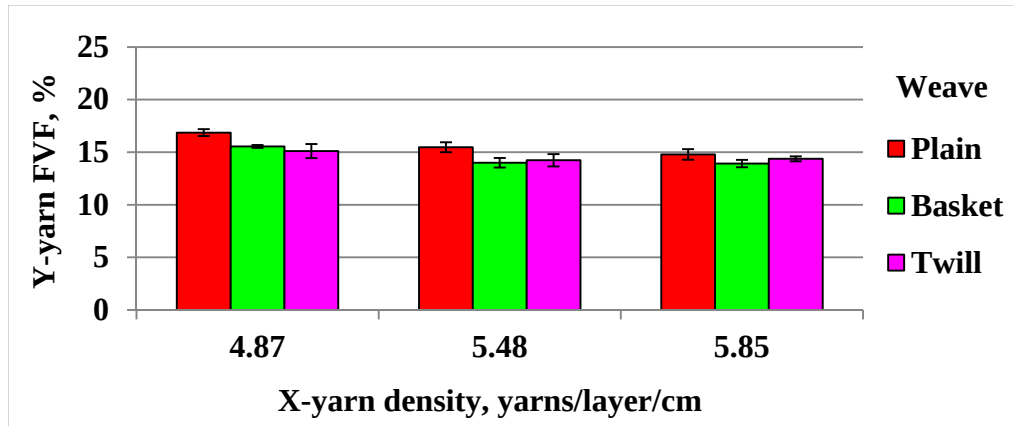


Figure D.15. Y-yarn FVF of 2 layers dry preforms

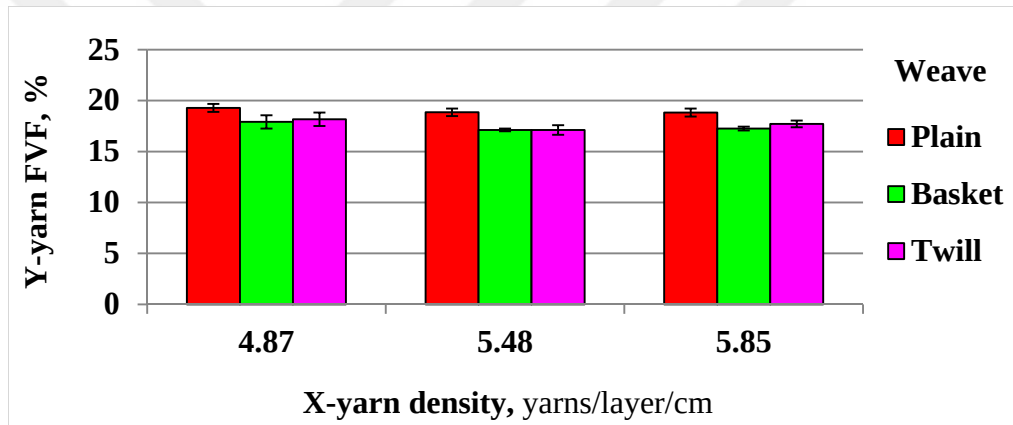


Figure D.16. Y-yarn FVF of 4 layers dry preforms

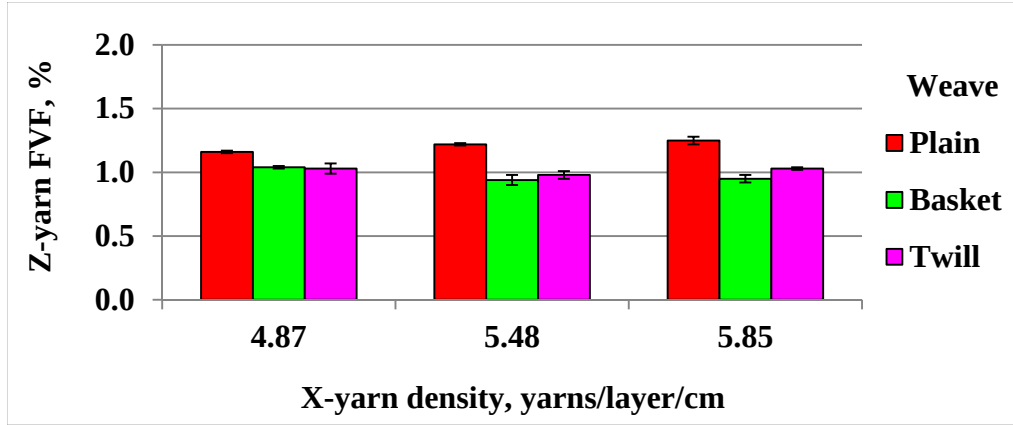


Figure D.17. Z-yarn FVF of 2 layers dry preforms

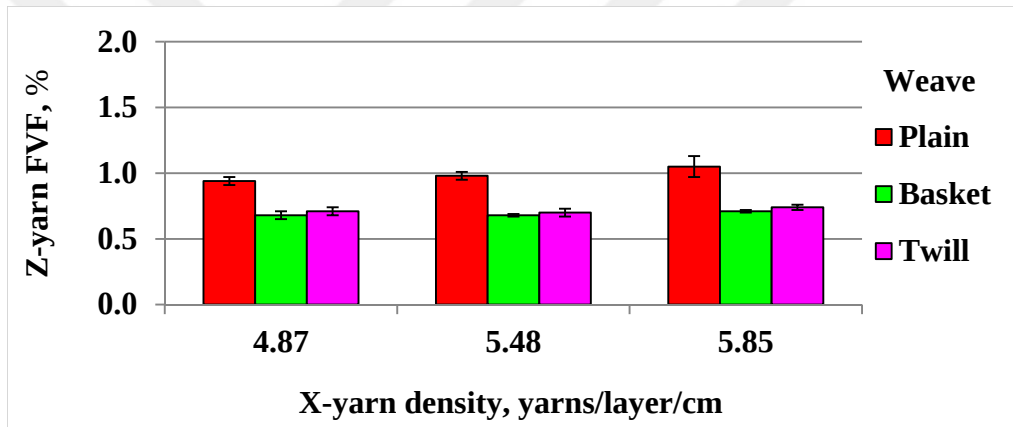


Figure D.18. Z-yarn FVF of 4 layers dry preforms

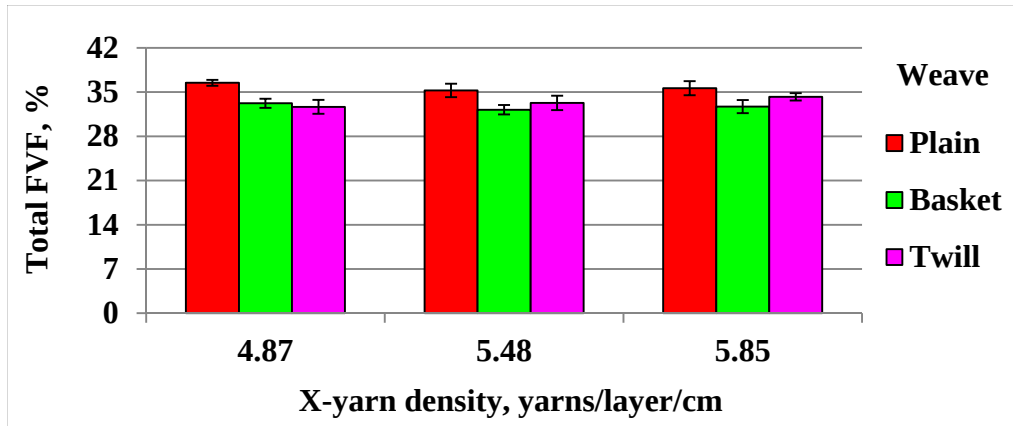


Figure D.19. Total FVF of 2 layers dry preforms

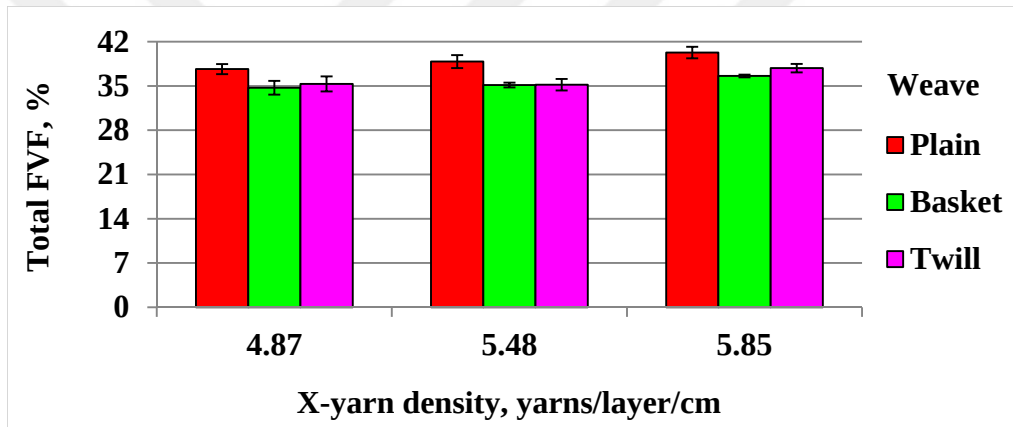


Figure D.20. Total FVF of 4 layers dry preforms

APPENDIX E: Properties of neat cured resin

Casting (neat cured) properties of the resin is given as a table below;

Table E.1. Typical properties of post cured Derakane[®] 8084 resin clear casting

Property	Value	Test Method
Tensile strength	76 MPa	ASTM D-638 / ISO 527
Tensile modulus	2.9 GPa	ASTM D-638 / ISO 527
Tensile elongation, yield	8-10%	ASTM D-638 / ISO 527
Flexural strength	130 MPa	ASTM D-790 / ISO 178
Flexural modulus	3.3 GPa	ASTM D-790 / ISO 178
Density	1.14 g/cm ³	ASTM D-792 / ISO 1183
Volume shrinkage	8.2%	
Heat distortion temperature	82 ⁰ C	ASTM D-648 Method A / ISO 75
Glass transition temperature, Tg2	115 ⁰ C	ASTM D-3419 / ISO 11359-2
IZOD impact (unnotched)	480 J/m	ASTM D-256
Barcol hardness	30	ASTM D-2583 / EN59

Note: Cure schedule: 24 hours at room temperature; 2 hours at 99⁰C. Maximum stress is 182 MPa for Heat Distortion Temperature test.

APPENDIX F: Effect of fabric architecture on infusion performance of preforms

Table F.1. Mold filling time of 2 layers dry preforms at 75 kPa vacuum

Weave	X-yarn density, yarns/layer/cm		
	4.87	5.48	5.85
Plain	12	18	15
Basket	22	20	22
Twill	24	36	50

Table F.2. Mold filling time of 2 layers dry preforms at 100 kPa vacuum

Weave	X-yarn density, yarns/layer/cm		
	4.87	5.48	5.85
Plain	12	15	12
Basket	19	15	12
Twill	missing data	30	45

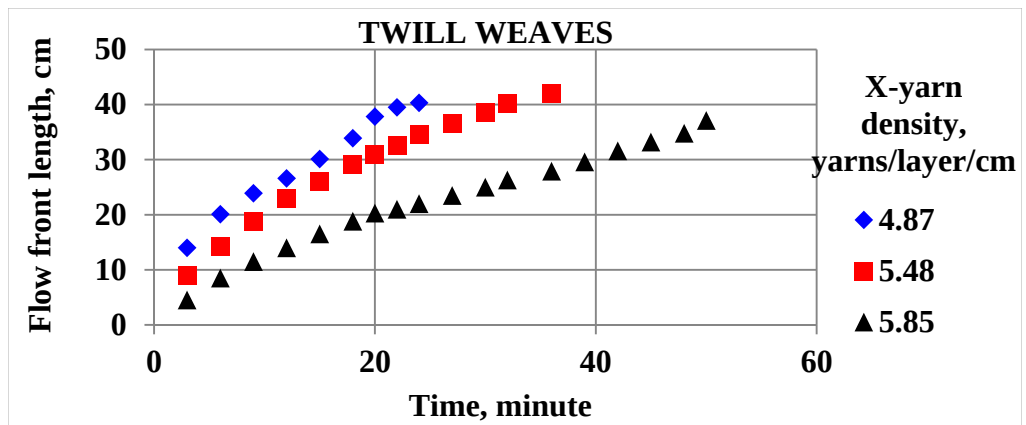
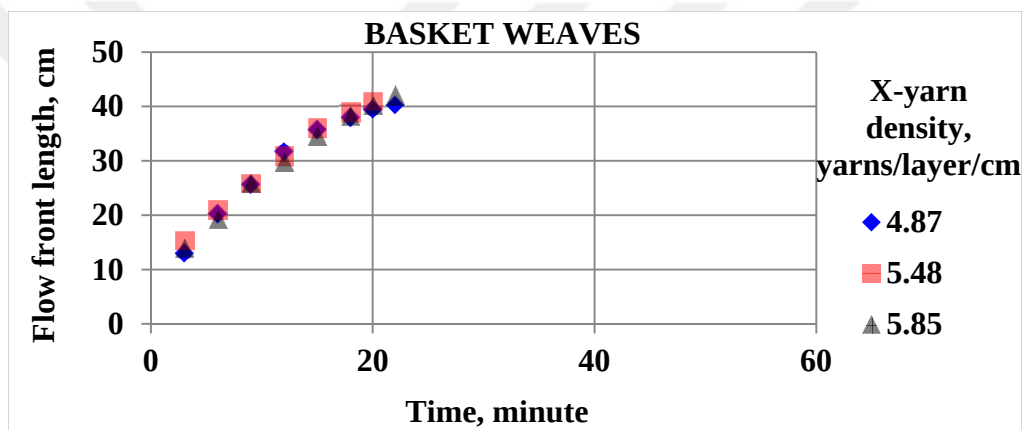
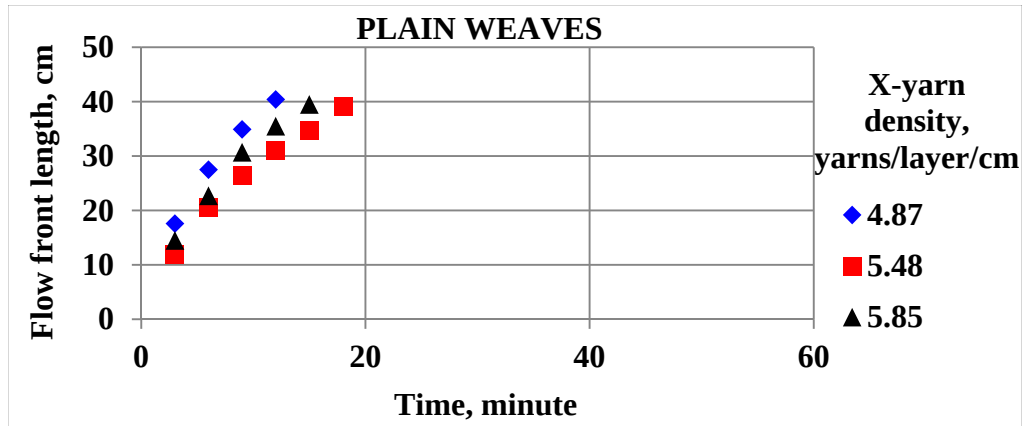


Figure F.1. Tracing of resin flow fronts during infusion of 2 layers preforms at 75 kPa vacuum

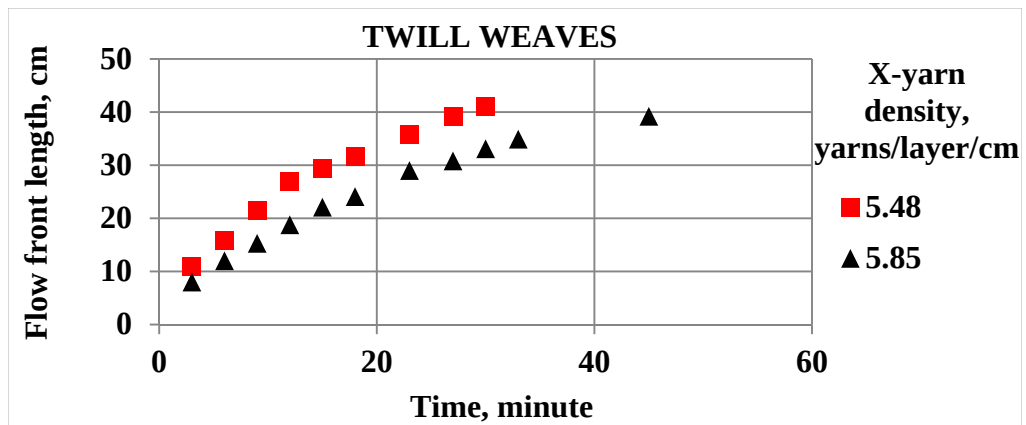
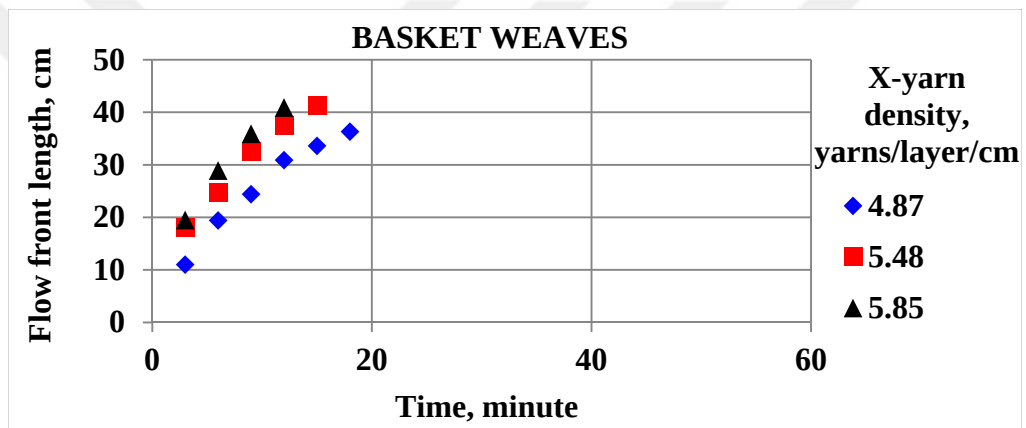
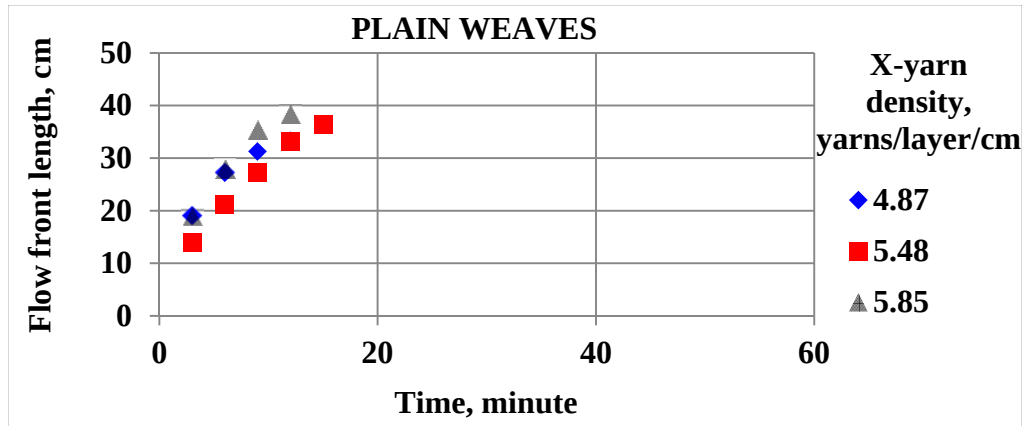


Figure F.2. Tracing of resin flow fronts during infusion of 2 layers preforms at 100 kPa vacuum

Table F.3. Mold filling time of 4 layers dry preforms at 75 kPa vacuum

Weave	X-yarn density, yarns/layer/cm		
	4.87	5.48	5.85
Plain	18	24	27
Basket	Data missing	15	21
Twill	42	74	70

Table F.4. Mold filling time of 4 layers dry preforms at 100 kPa vacuum

Weave	X-yarn density, yarns/layer/cm		
	4.87	5.48	5.85
Plain	14	20	36
Basket	Data missing	12	15
Twill	27	36	Data missing

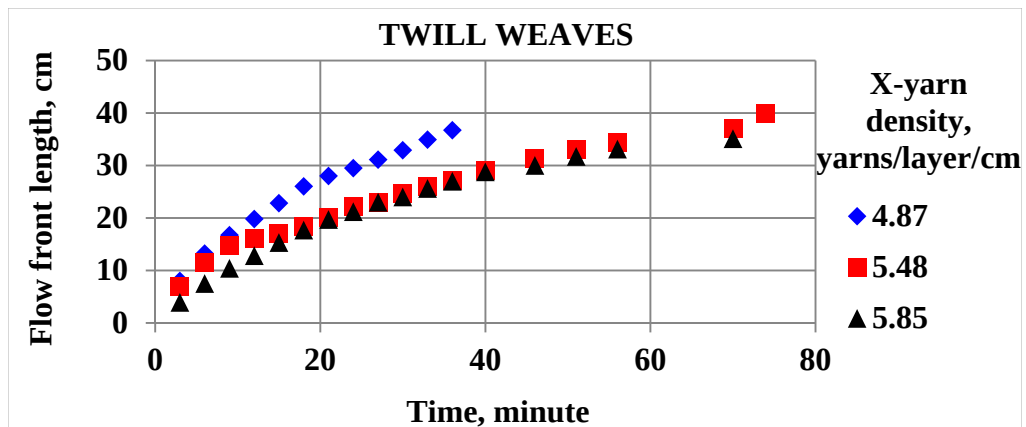
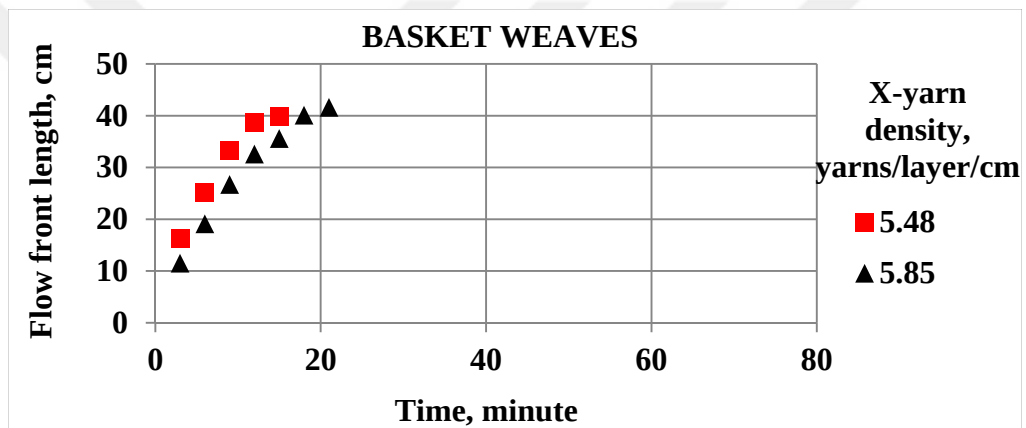
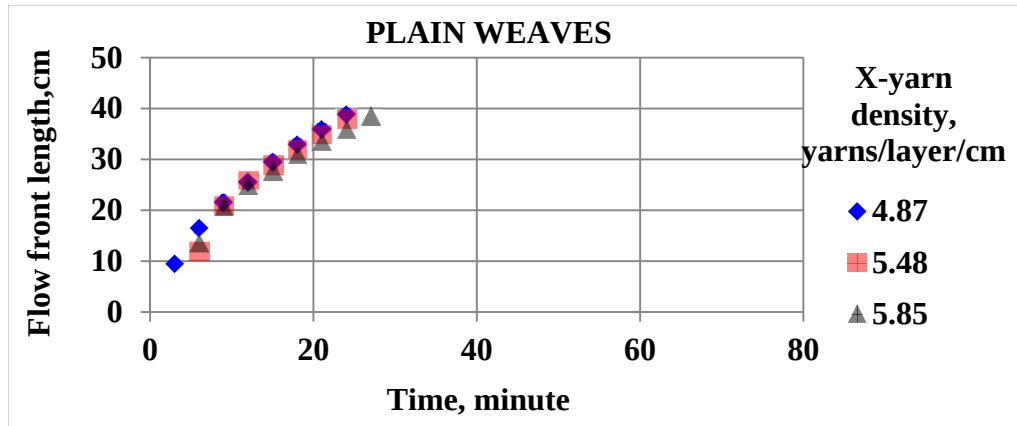


Figure F.3. Tracing of resin flow fronts during infusion of 4 layers preforms at 75 kPa vacuum

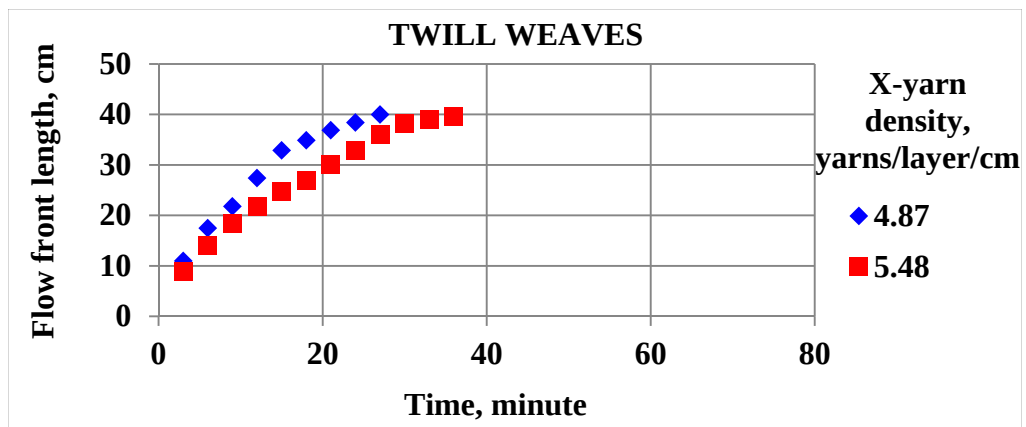
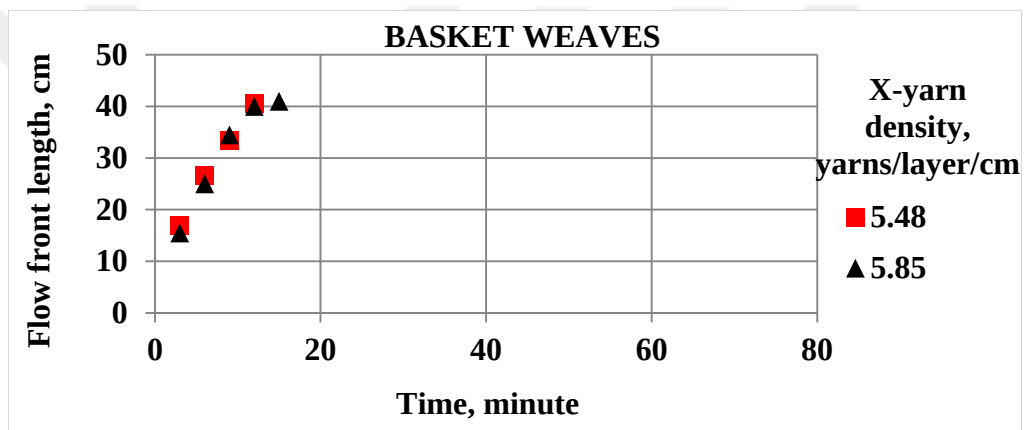
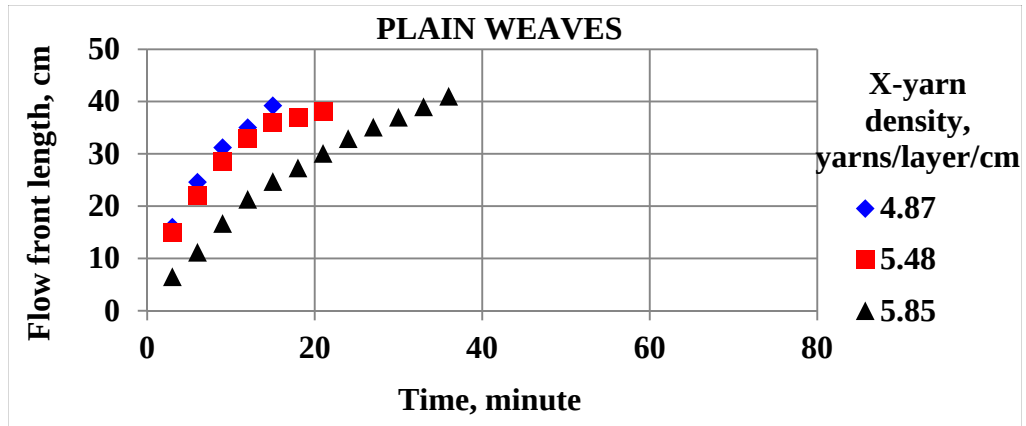


Figure F.4. Tracing of resin flow fronts during infusion of 4 layers preforms at 100 kPa vacuums

APPENDIX G: Thickness of composites

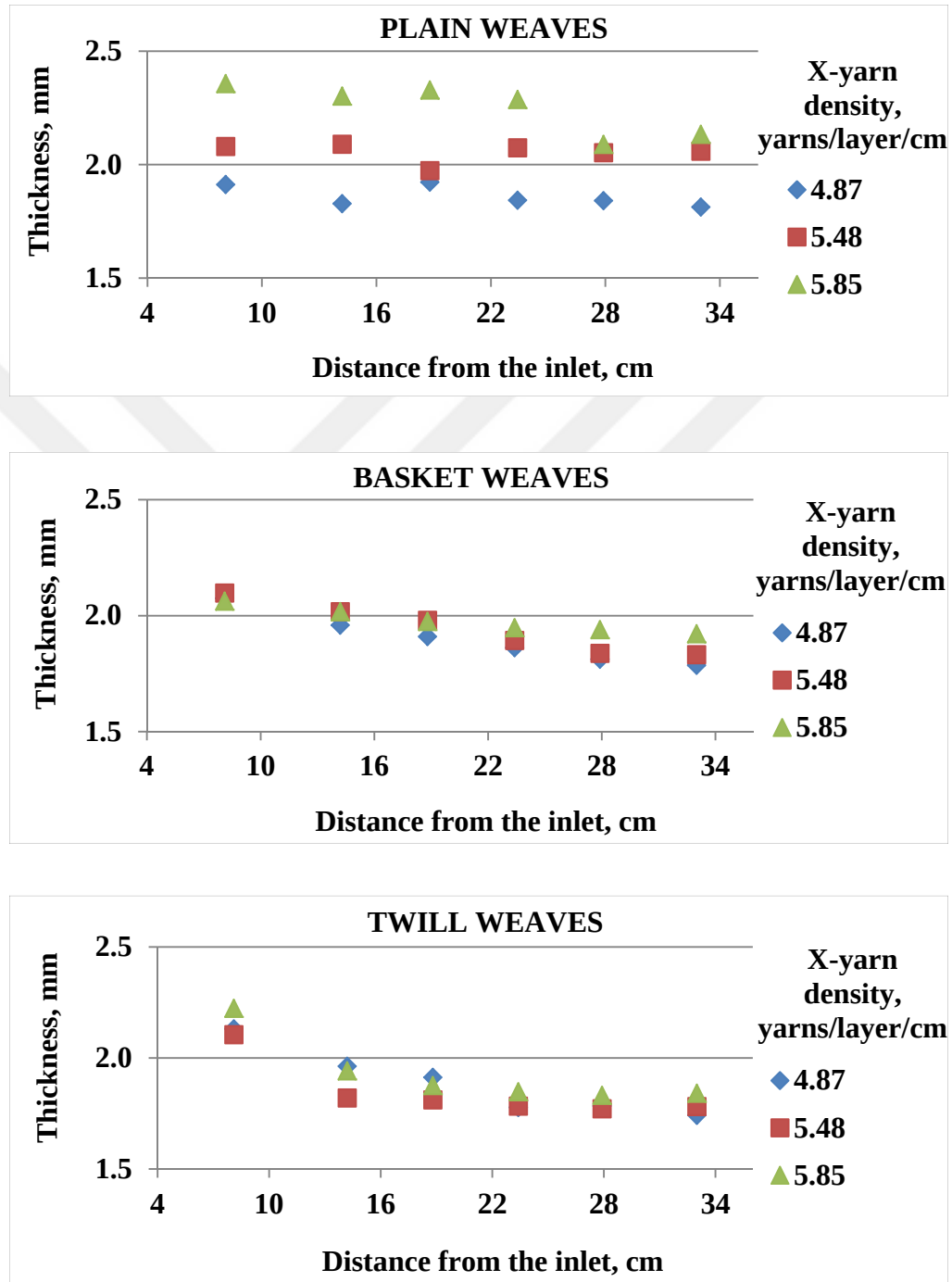


Figure G.1. Thickness profile of 2 layers composites manufactured at 75 kPa vacuums

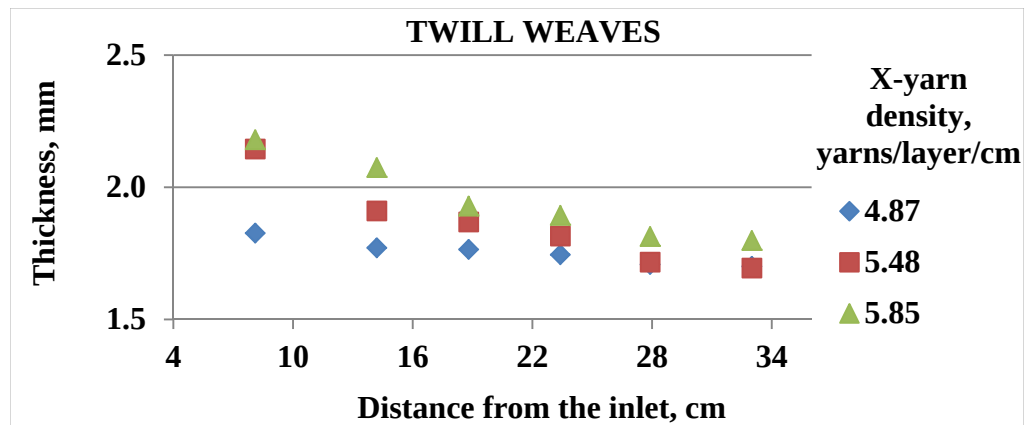
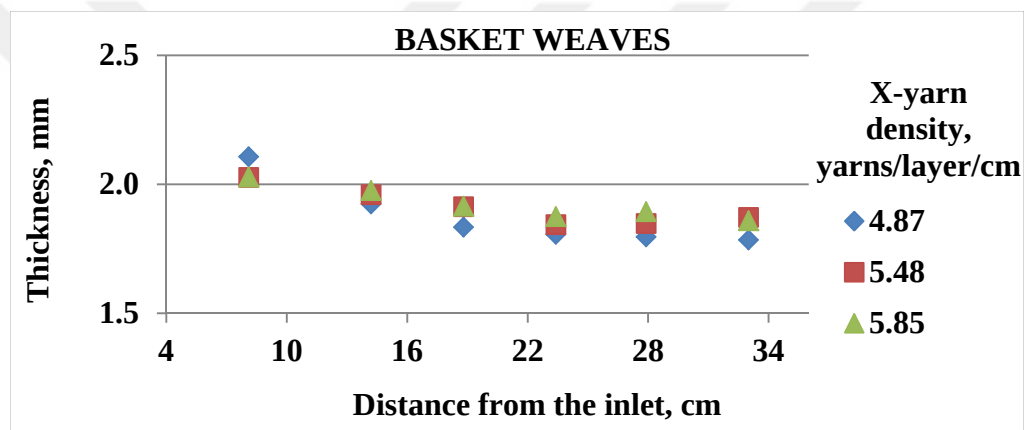
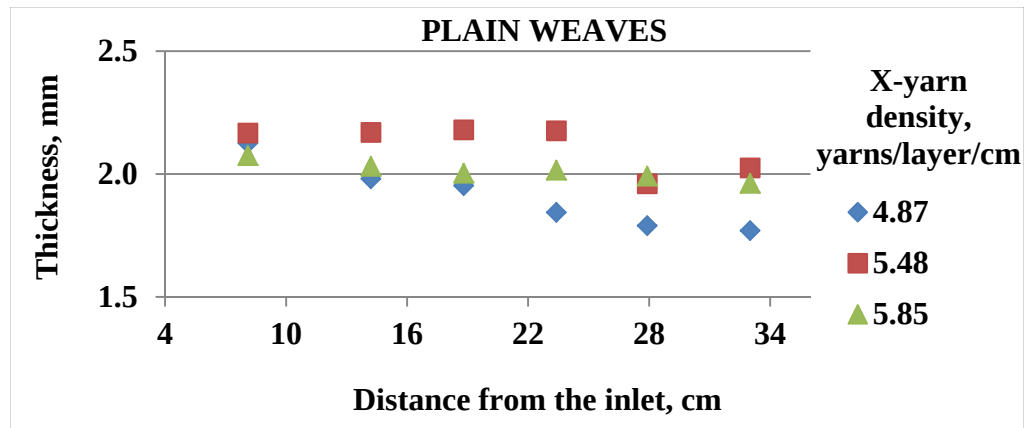


Figure G.2. Thickness profile of 2 layers composites manufactured at 100 kPa vacuum

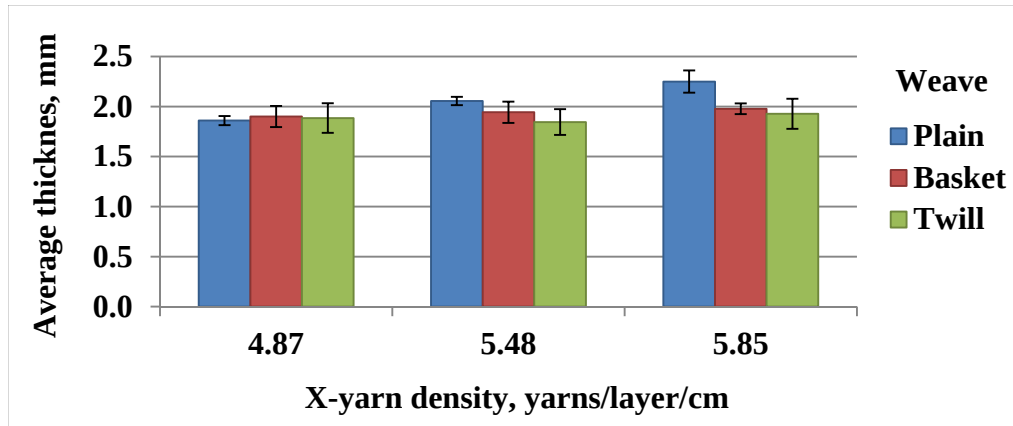


Figure G.3. Thickness of 2 layers composites manufactured at 75 kPa vacuum (Error bars represent $\pm$ one standard deviation)

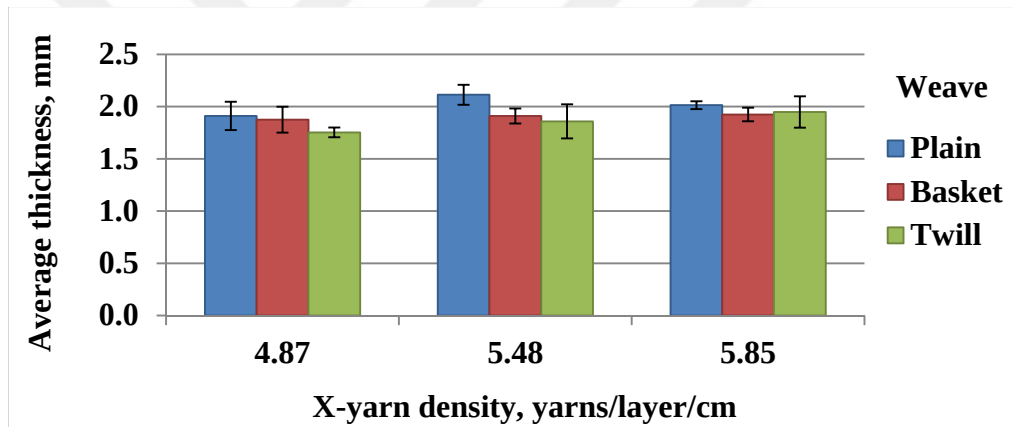


Figure G.4. Thickness of 2 layers composites manufactured at 100 kPa vacuum

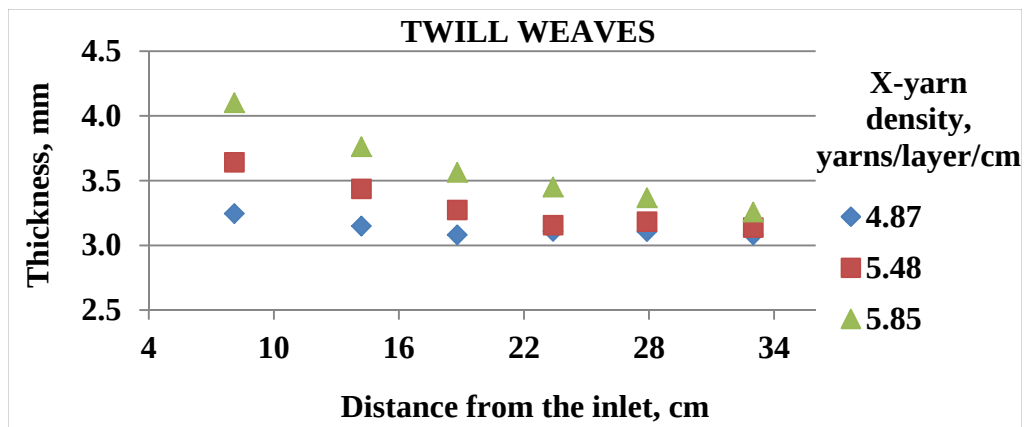
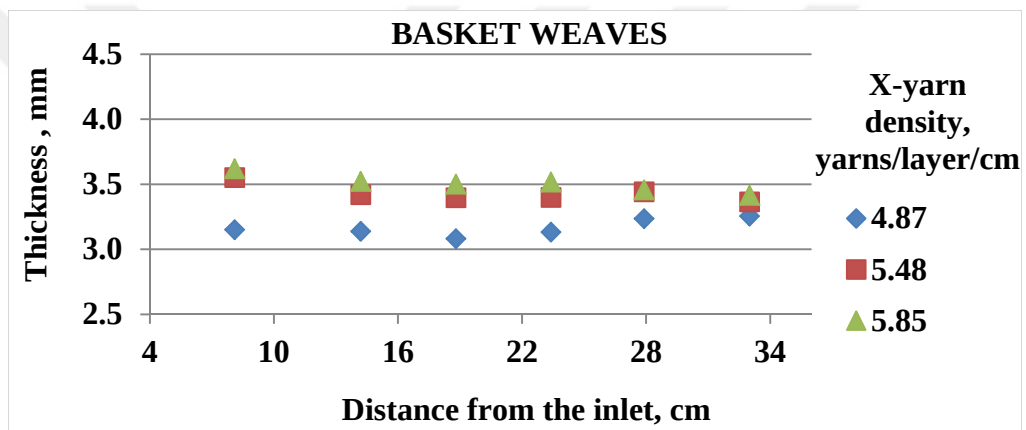
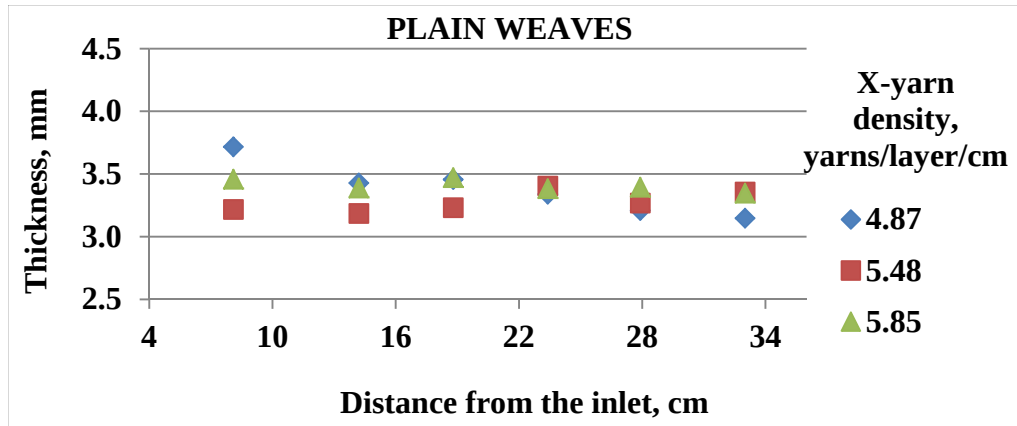


Figure G.5. Thickness profile of 4 layers composites manufactured at 75 kPa vacuums

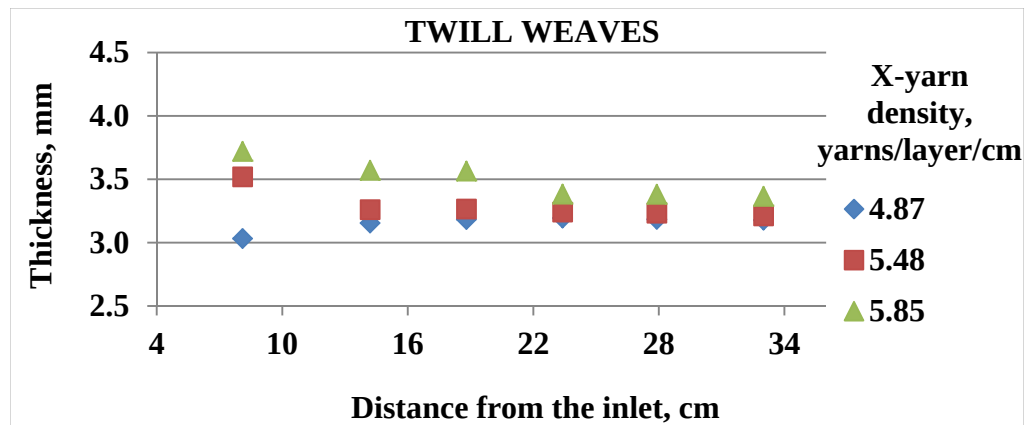
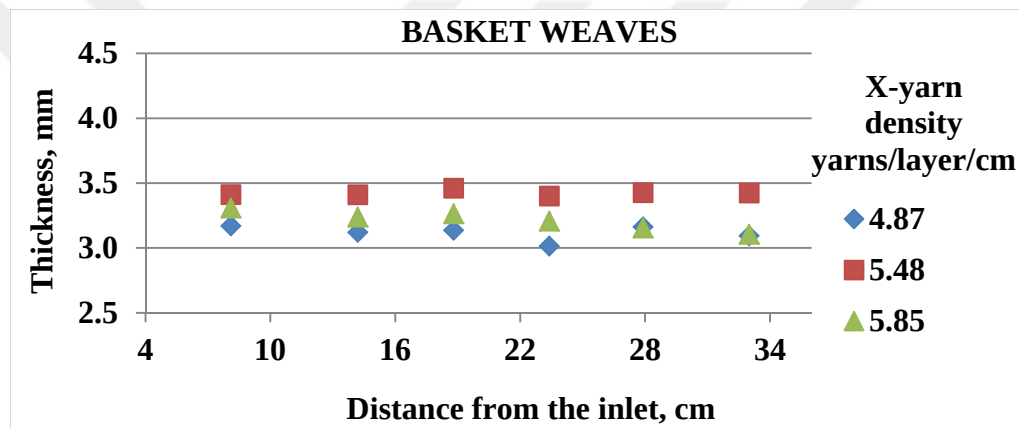
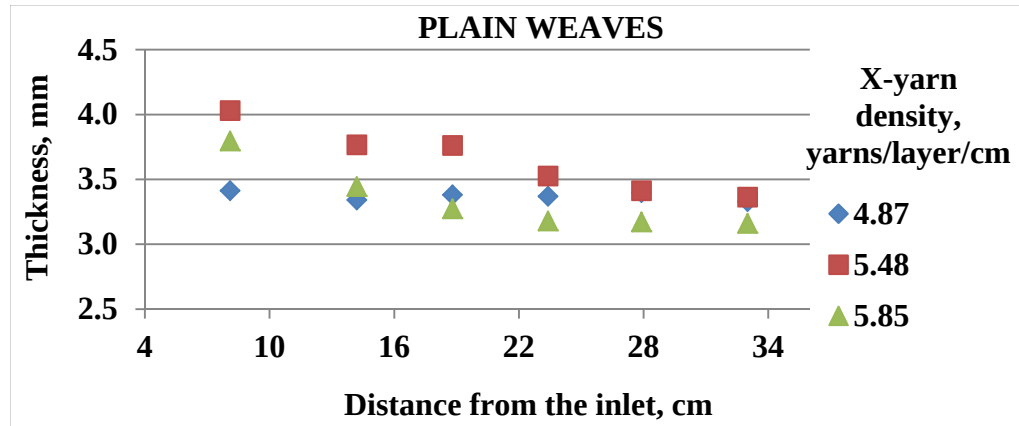


Figure G.6. Thickness profile of 4 layers composites manufactured at 100 kPa vacuums

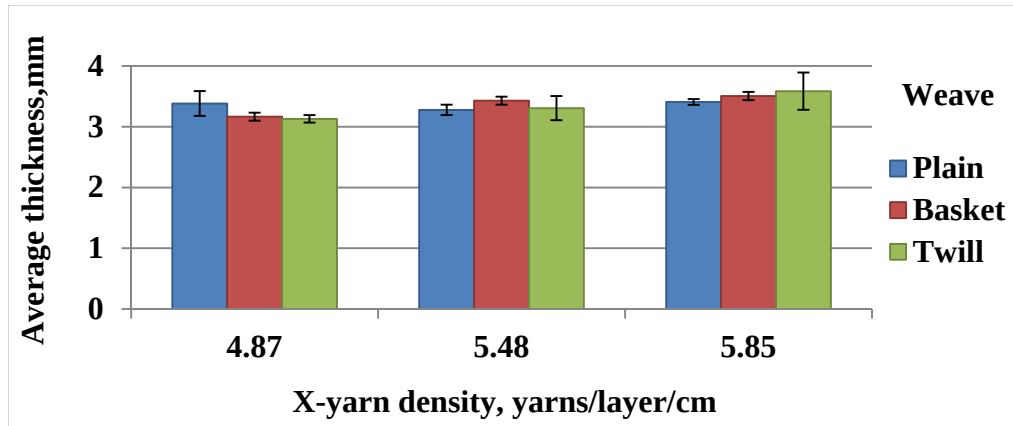


Figure G.7. Thickness of 4 layers composites manufactured at 75 kPa vacuum

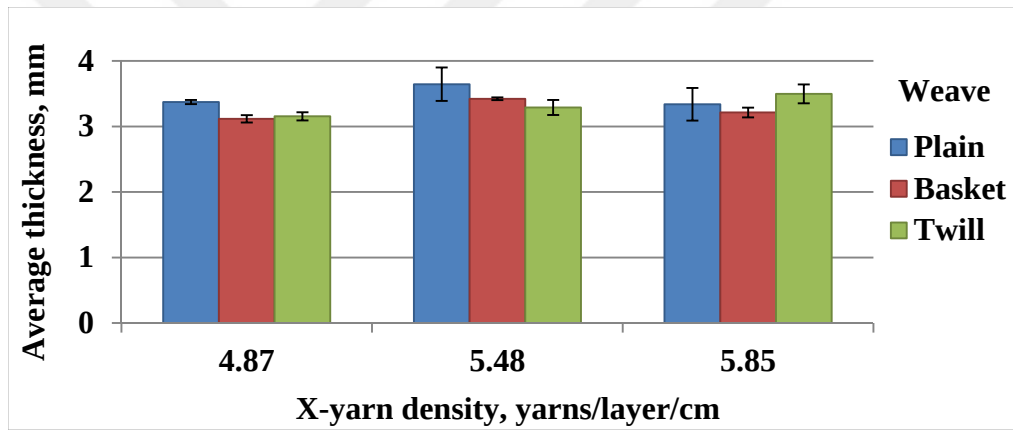


Figure G.8. Thickness of 4 layers composites manufactured at 100 kPa vacuum

APPENDIX H: Total FVF of composites

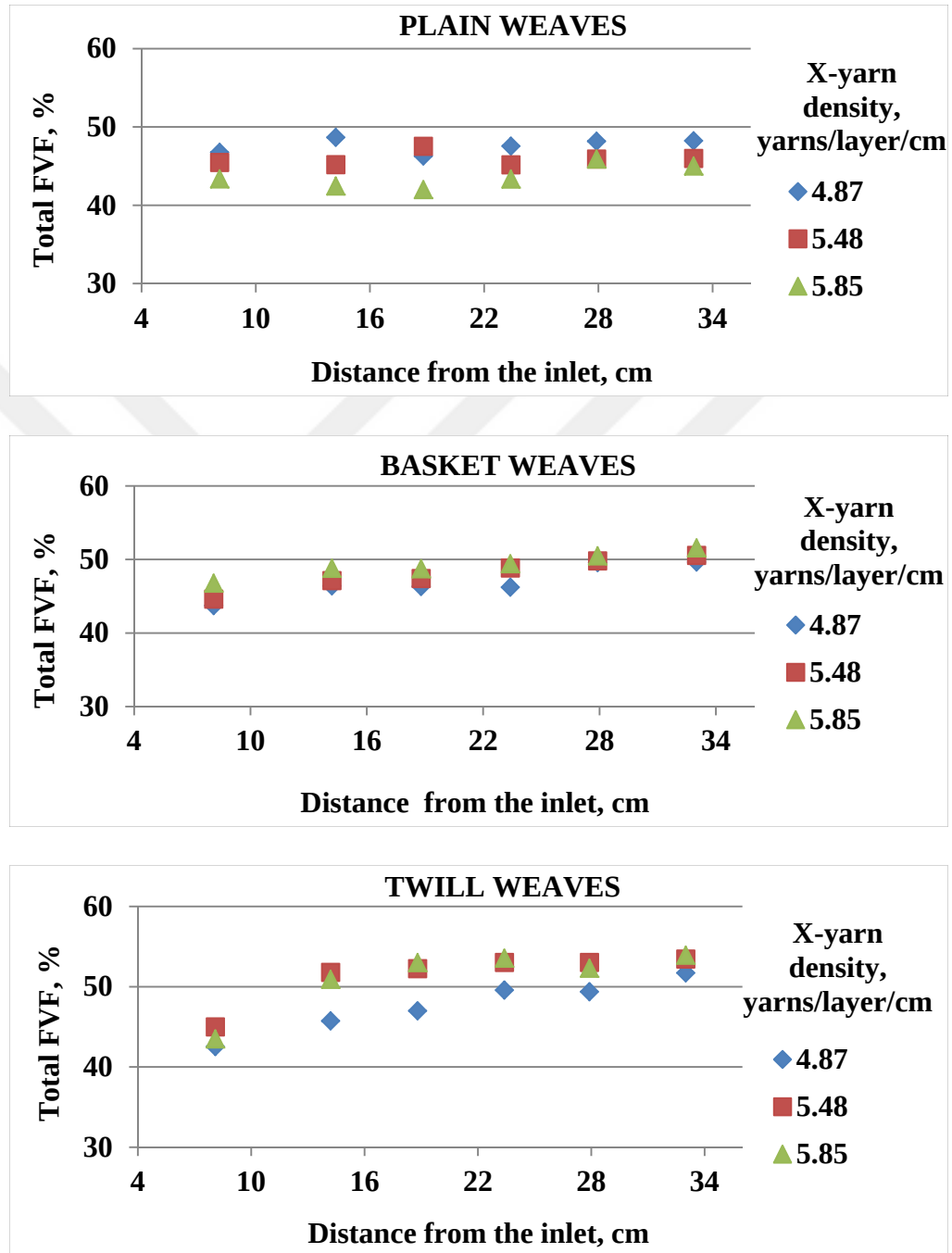


Figure H.1. Total FVF profile of 2 layers composites manufactured at 75 kPa vacuums

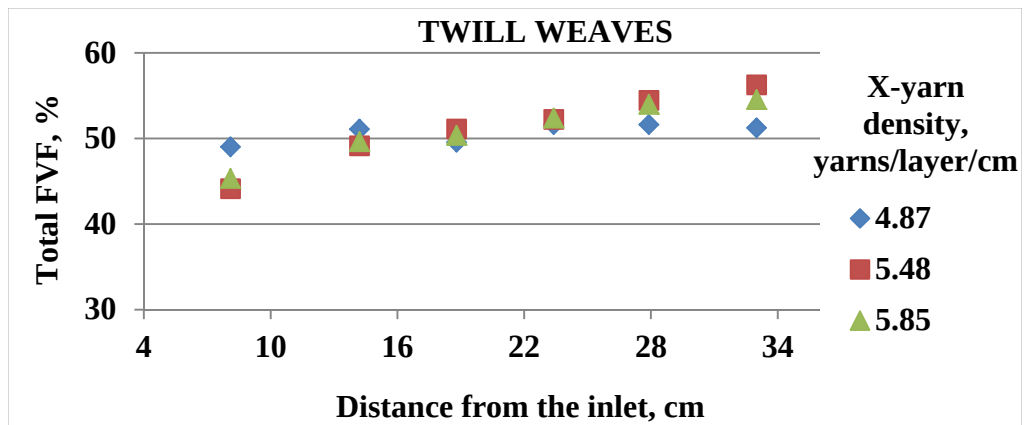
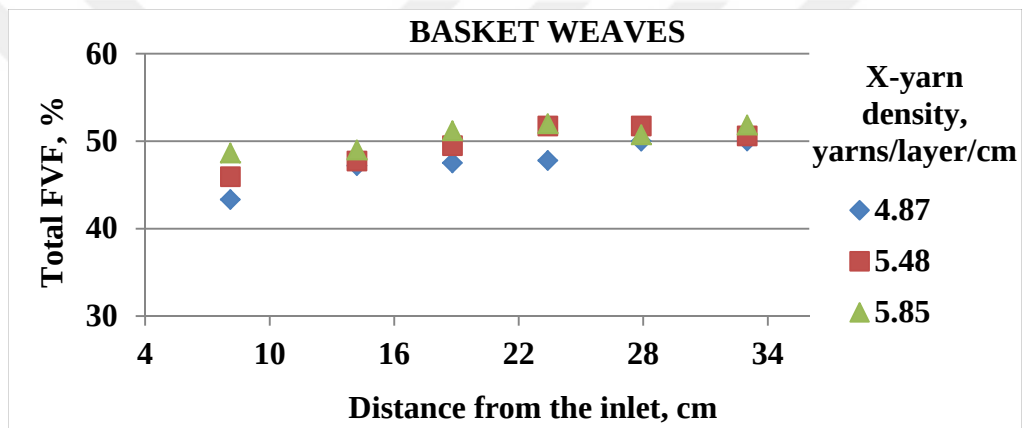
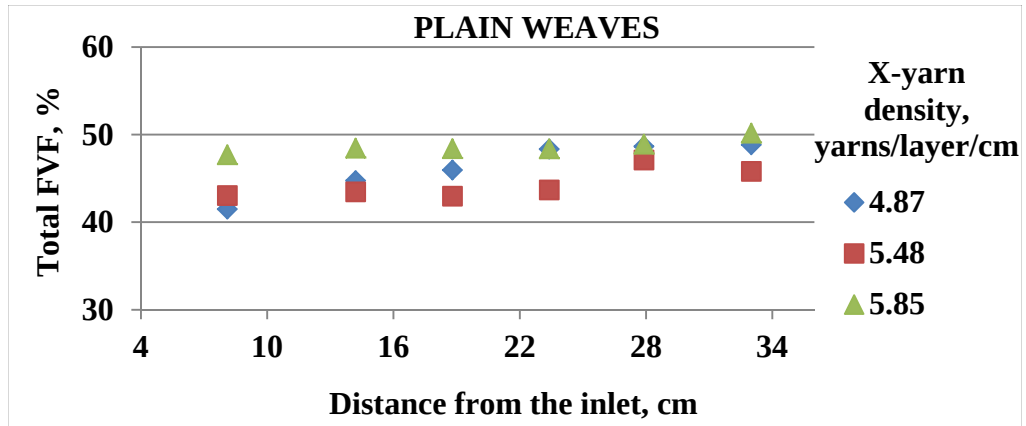


Figure H.2. Total FVF profile of 2 layers composites manufactured at 100 kPa vacuums

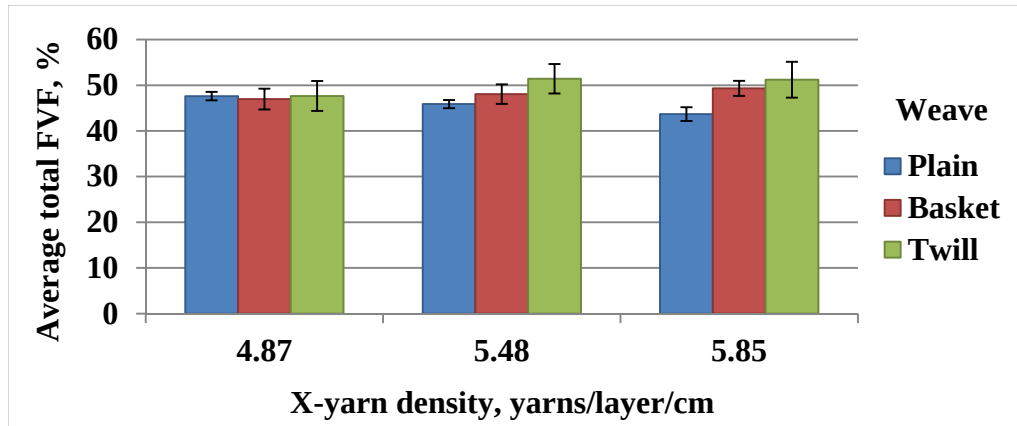


Figure H.3. Average total FVF of 2 layers composites manufactured at 75 kPa vacuums

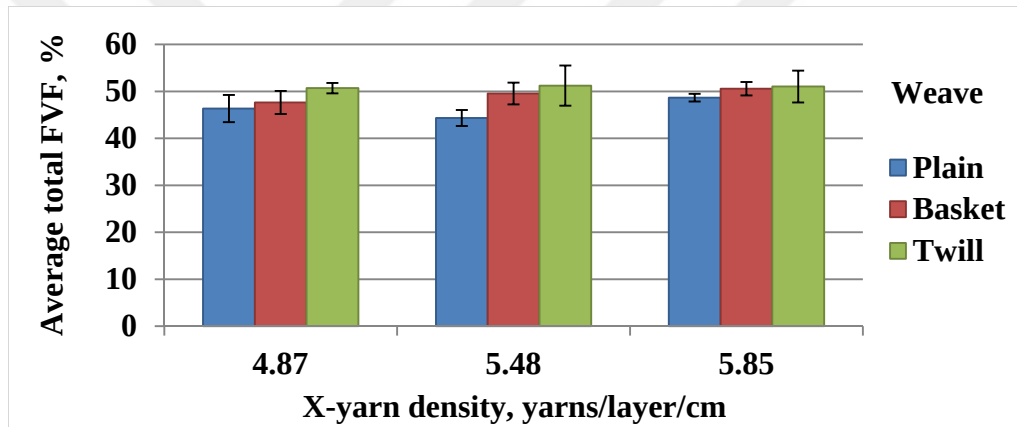


Figure H.4. Average total FVF of 2 layers composites manufactured at 100 kPa vacuums (Error bars represent $\pm$ one standard deviation)

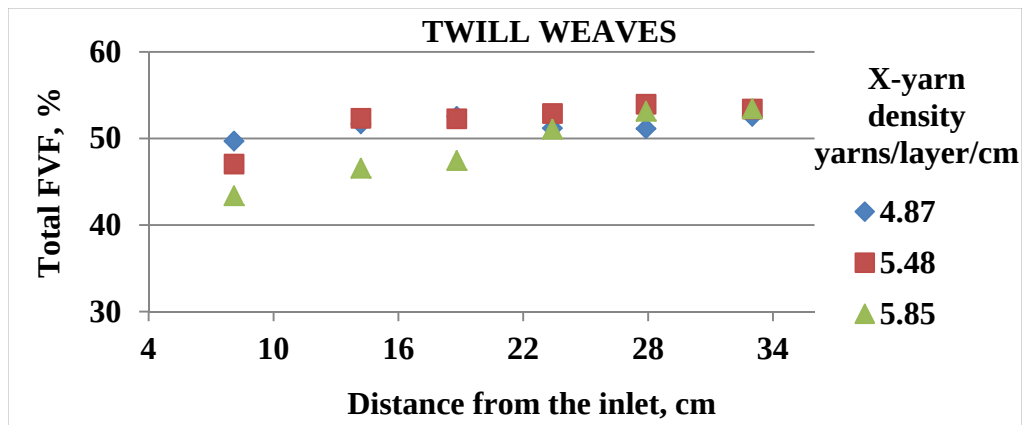
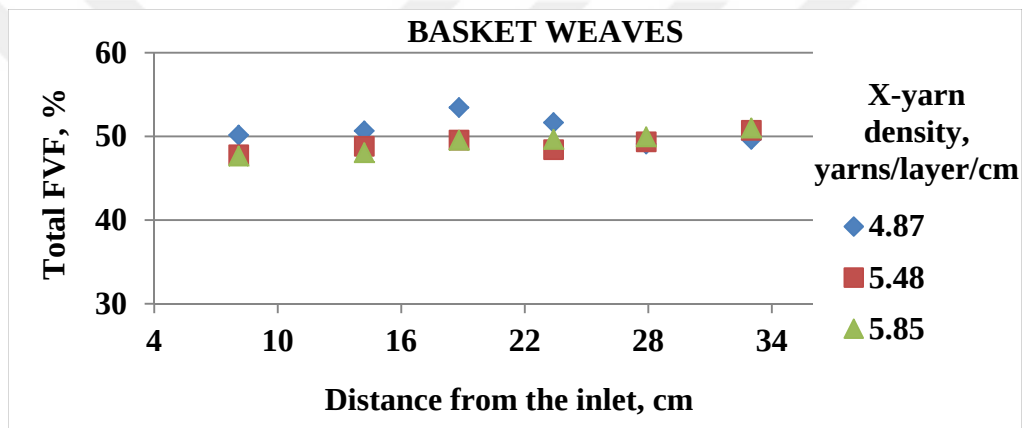
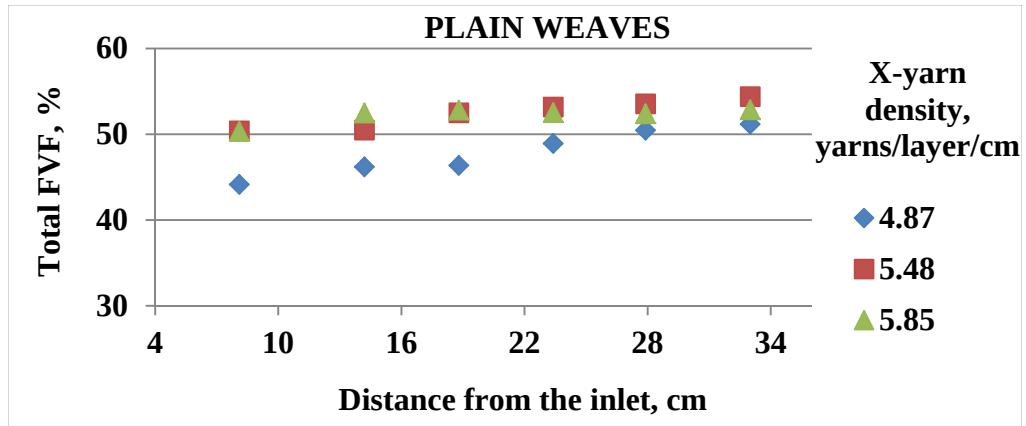


Figure H.5. Total FVF profile of 4 layers composites manufactured at 75 kPa vacuum

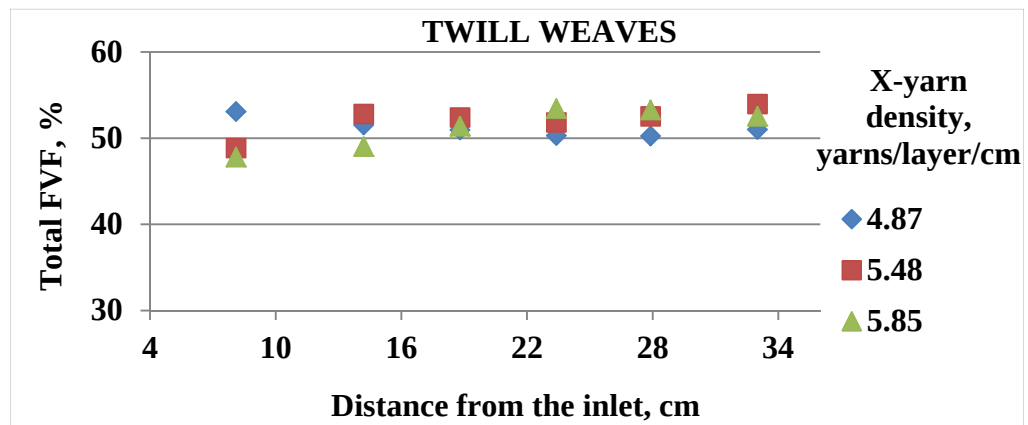
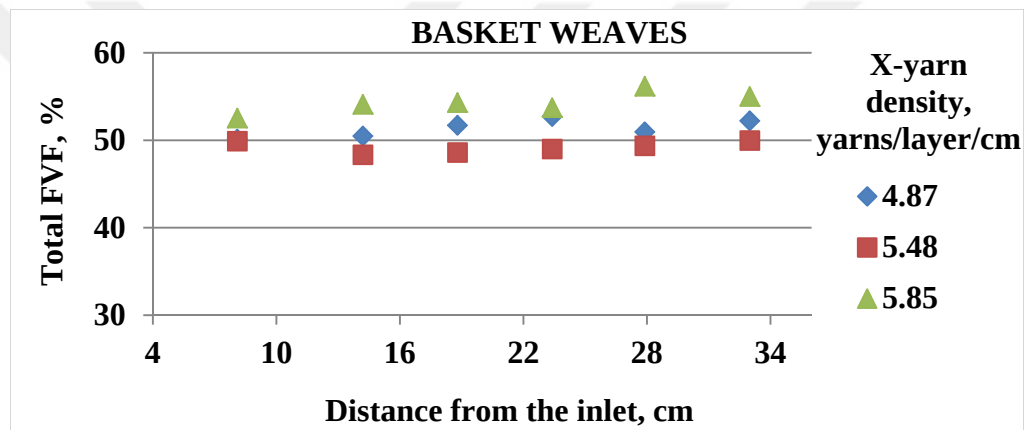
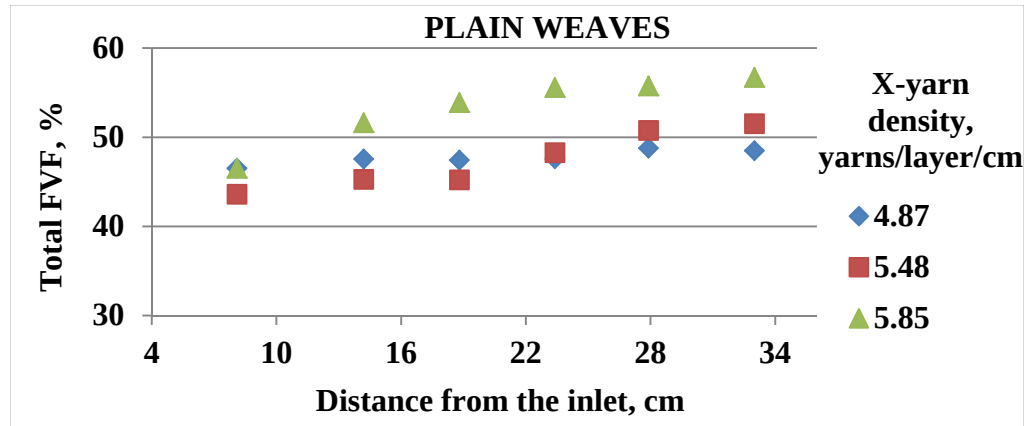


Figure H.6. Total FVF profile of 4 layers composites manufactured at 100 kPa vacuums

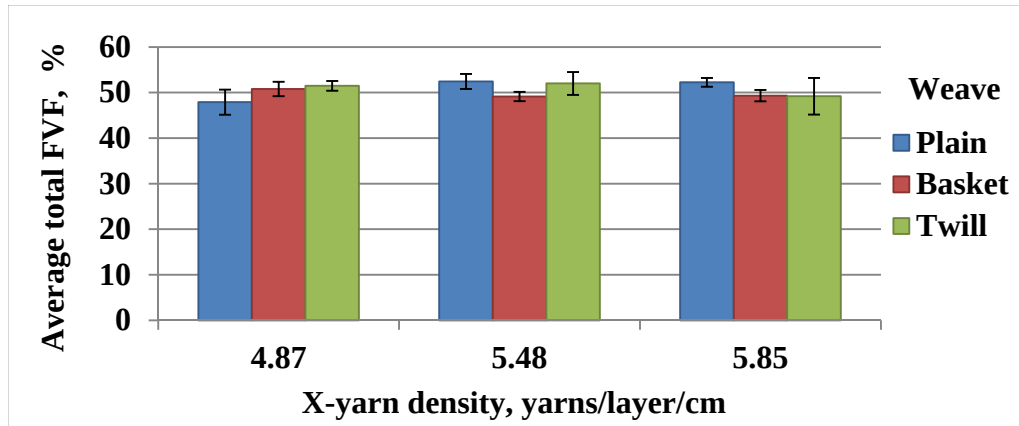


Figure H.7. Average total FVF of 4 layers composites manufactured at 75 kPa vacuum

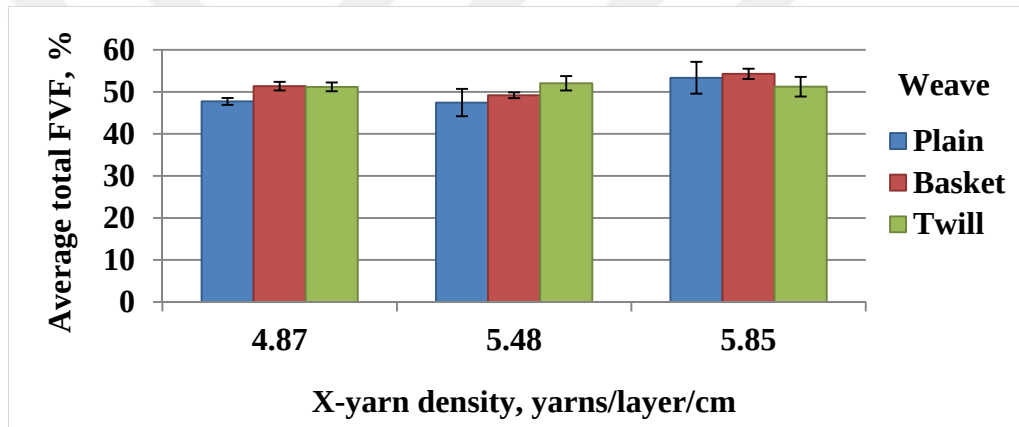


Figure H.8. Average total FVF of 4 layers composites manufactured at 100 kPa vacuum

APPENDIX I: Void volume fraction of composites

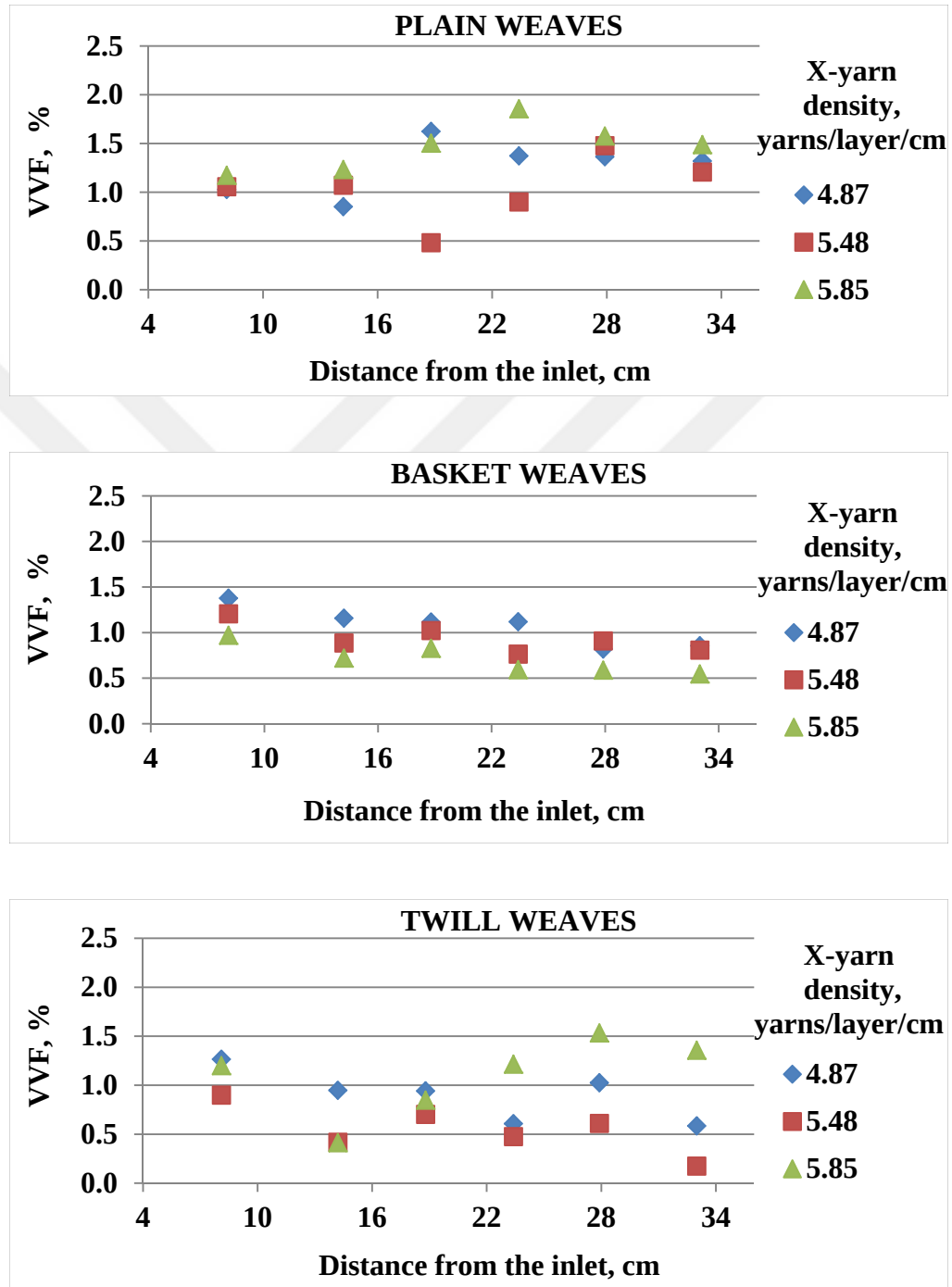


Figure I.1. Void volume fraction (VVF) profile of 2 layers composites manufactured at 75 kPa vacuums

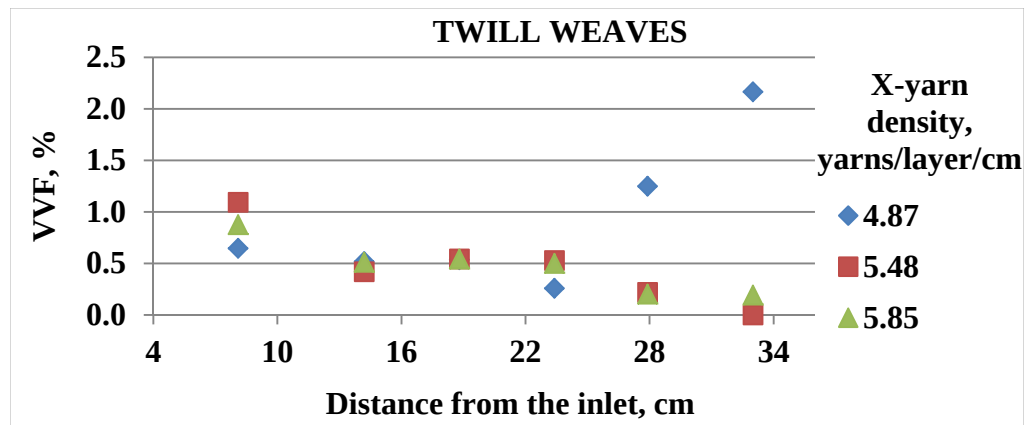
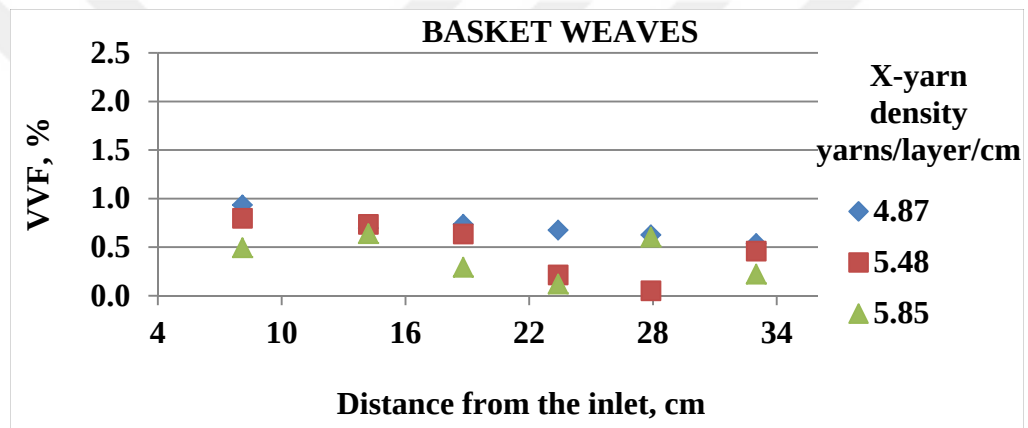
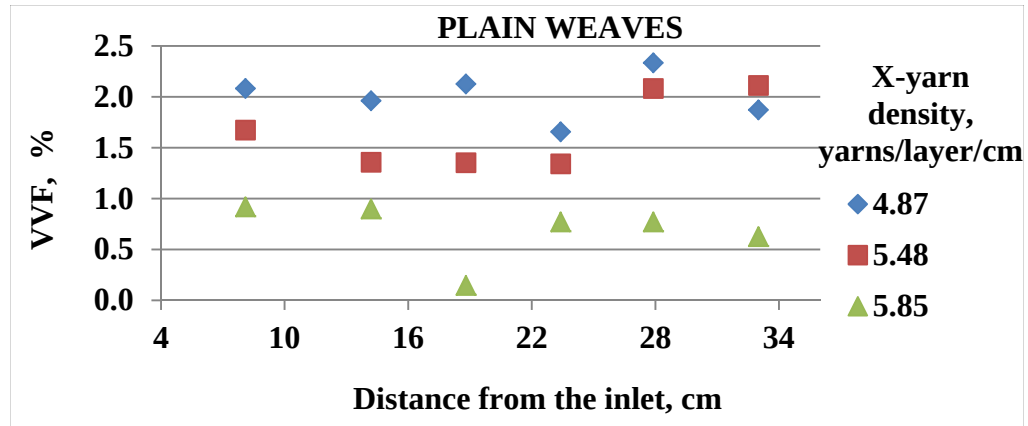


Figure I.2. Void volume fraction profile of 2 layers composites manufactured at 100 kPa vacuums

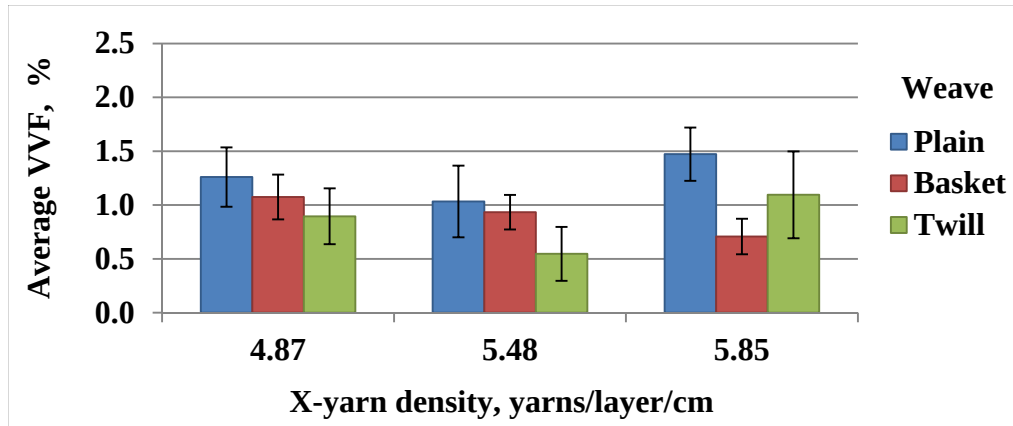


Figure I.3. Void volume fraction of 2 layers composites manufactured at 75 kPa vacuums

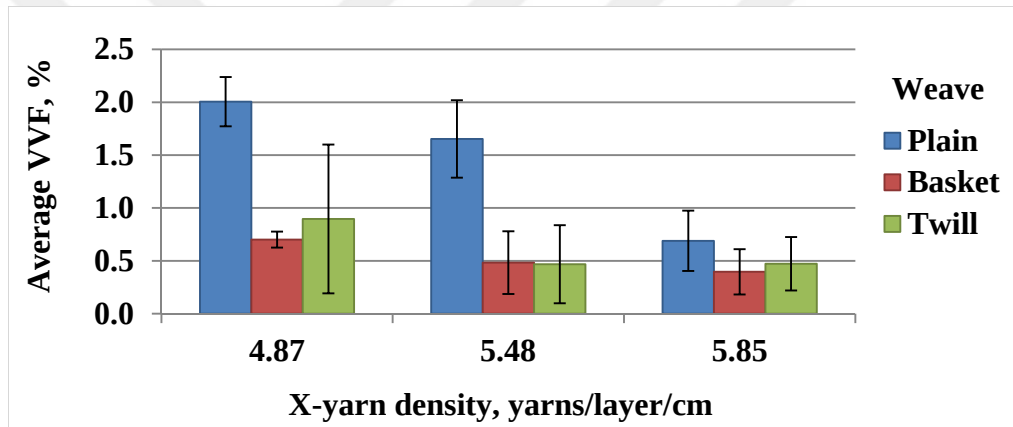


Figure I.4. Void volume fraction of 2 layers composites manufactured at 100 kPa vacuums

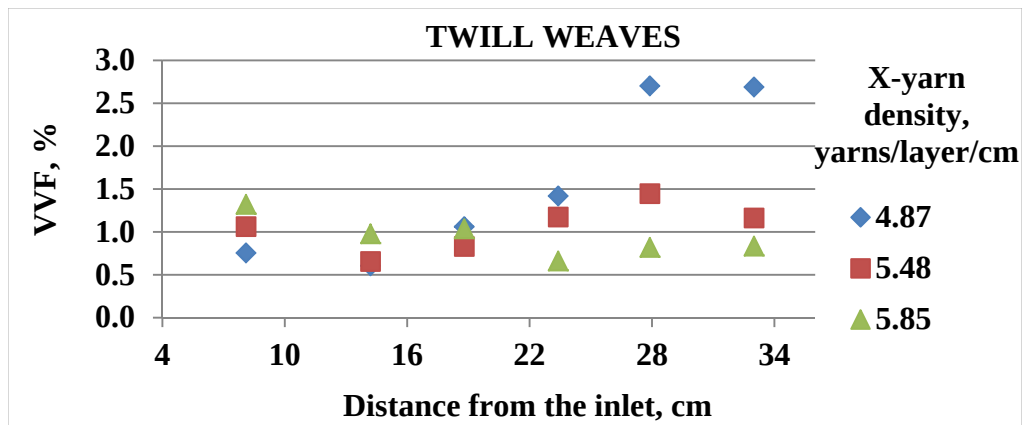
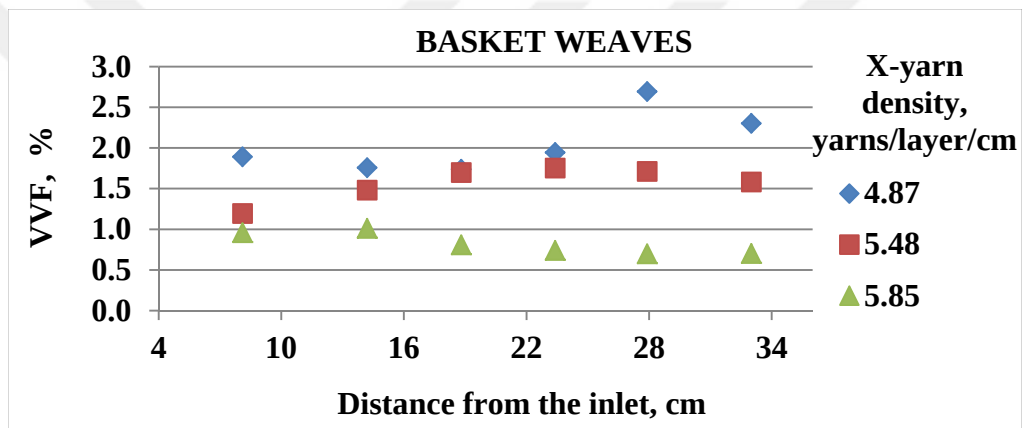
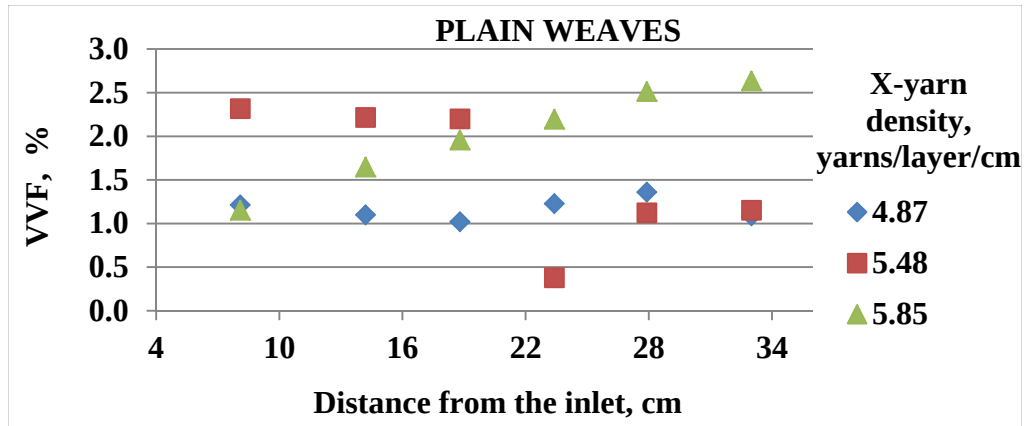


Figure I.5. Void volume fraction profile of 4 layers composites manufactured at 75 kPa vacuums

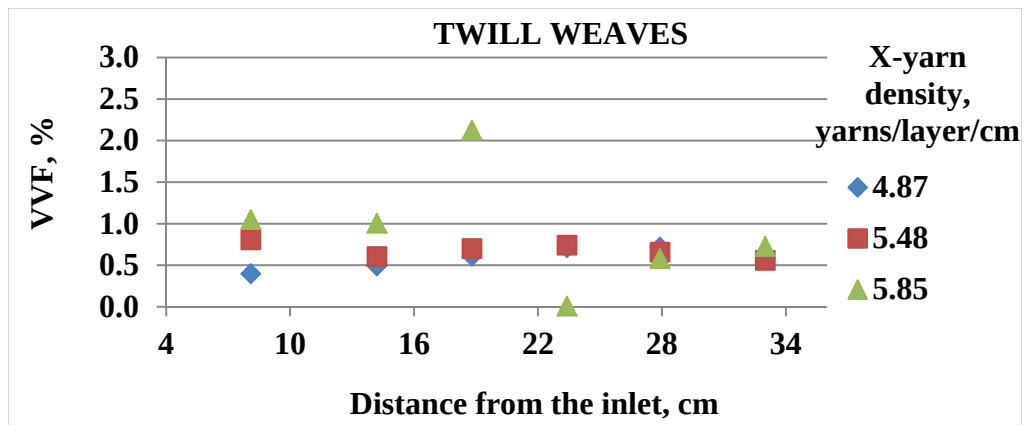
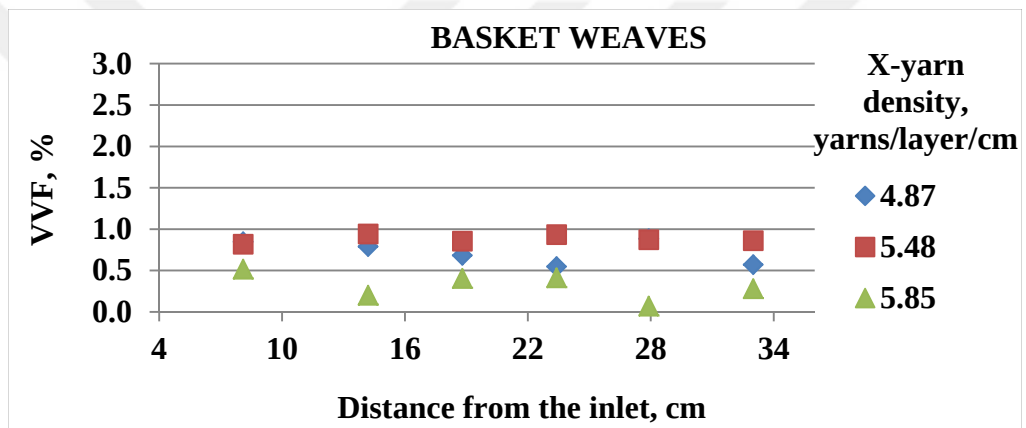
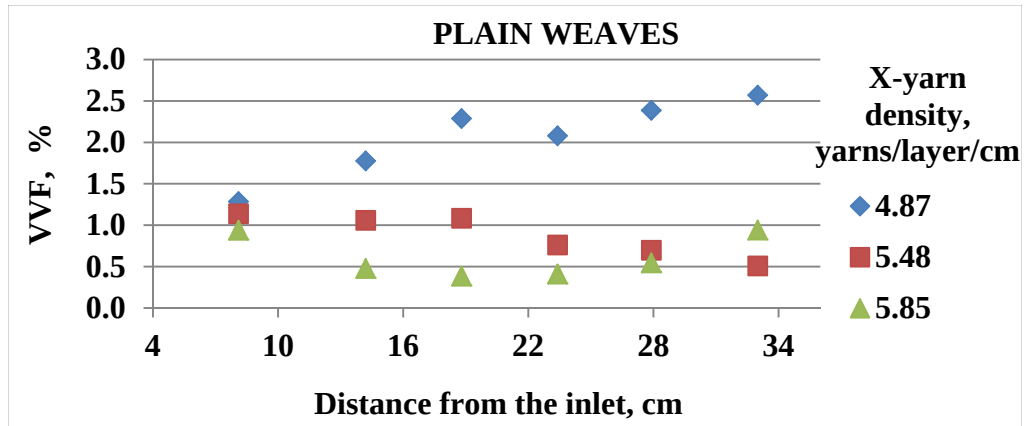


Figure I.6. Void volume fraction profile of 4 layers composites manufactured at 100 kPa vacuums

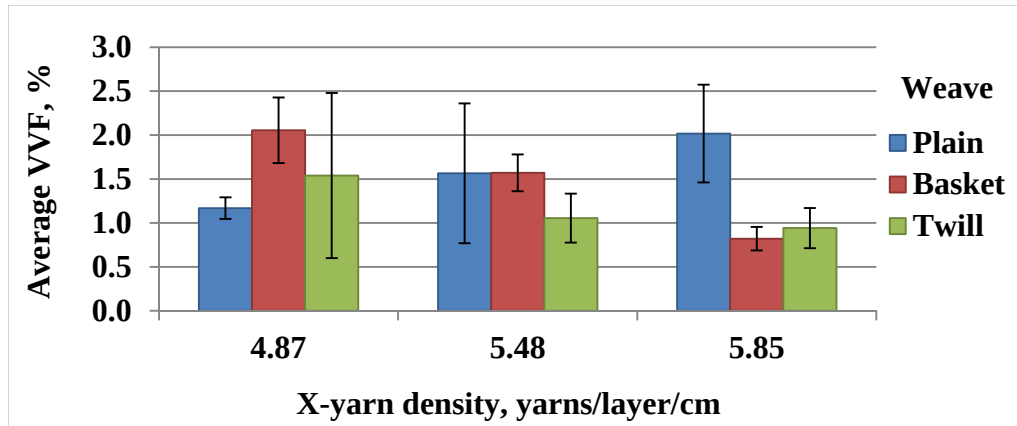


Figure I.7. Void volume fraction of 4 layers composites manufactured at 75 kPa vacuums

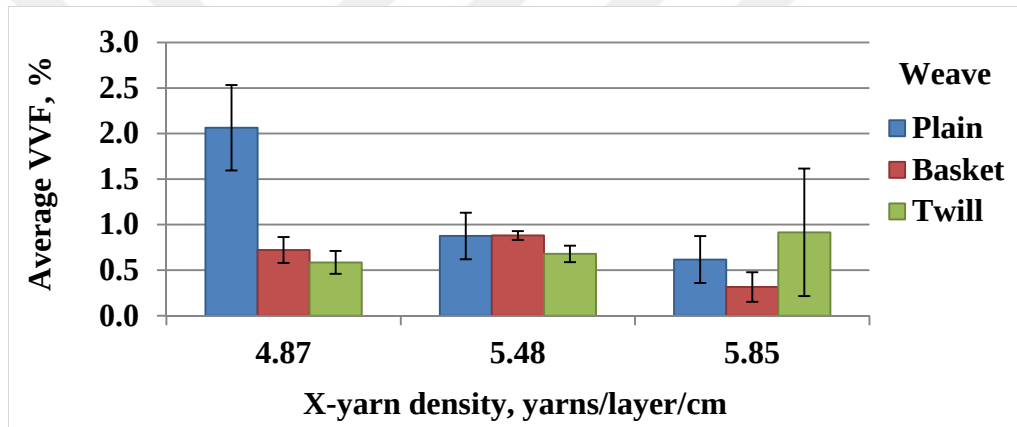


Figure I.8. Void volume fraction of 4 layers composites manufactured at 100 kPa vacuums

APPENDIX J: Peak tensile stress in x-yarn direction

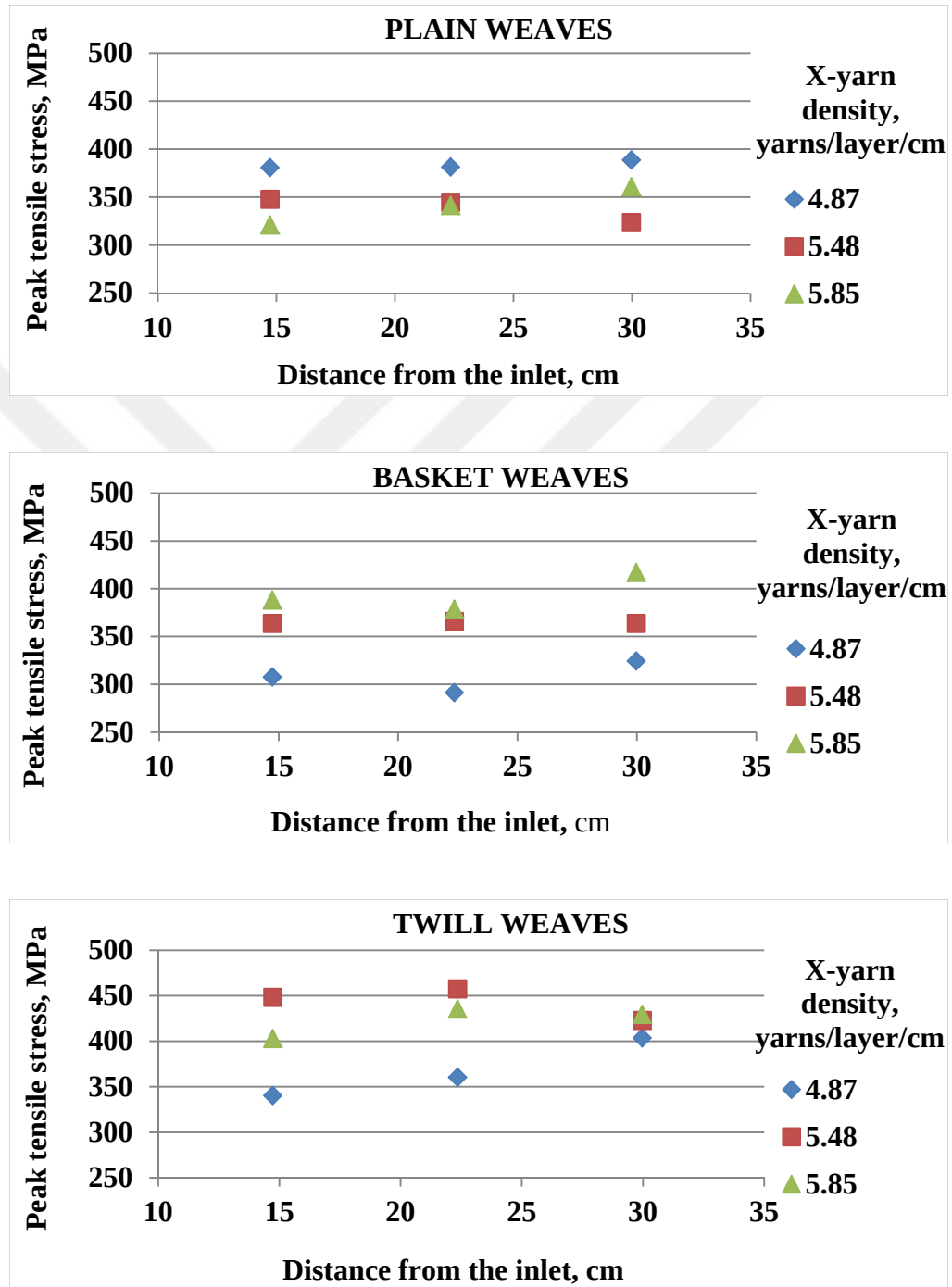


Figure J.1. Peak tensile stress profile in x-yarn direction of 2 layers composites manufactured at 75 kPa vacuums

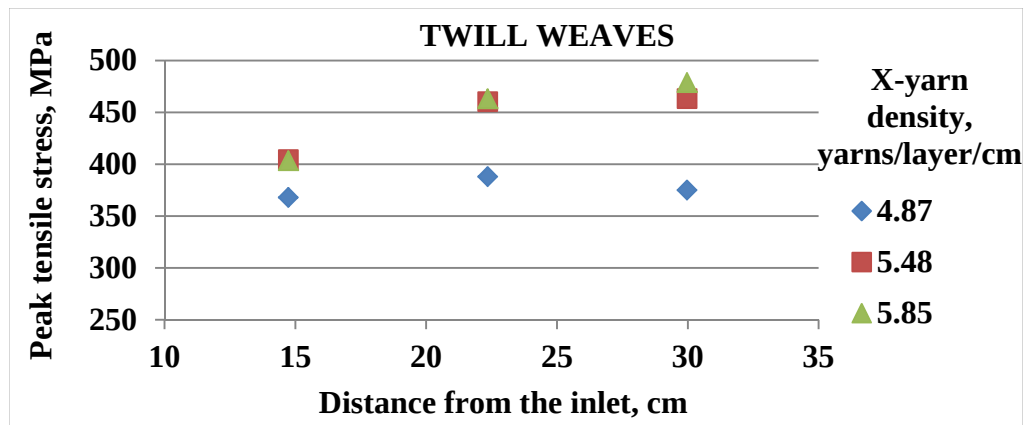
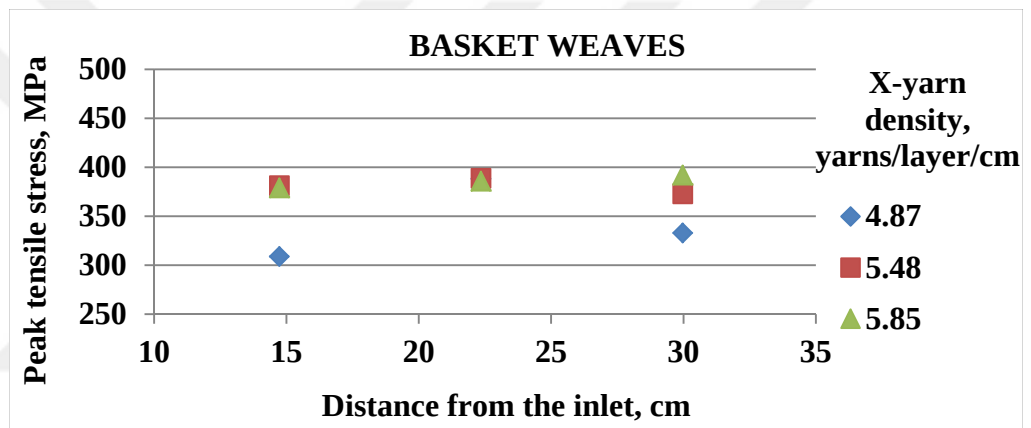
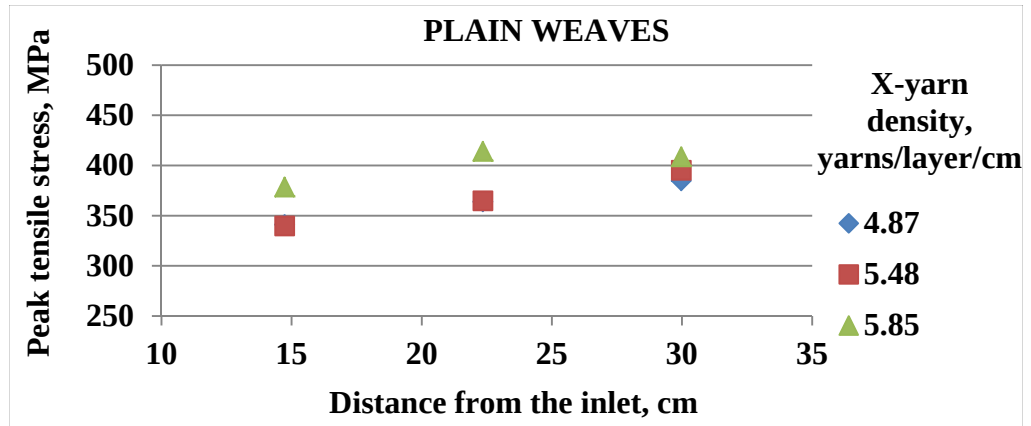


Figure J.2. Peak tensile stress profile in x-yarn direction of 2 layers composites manufactured at 100 kPa vacuums

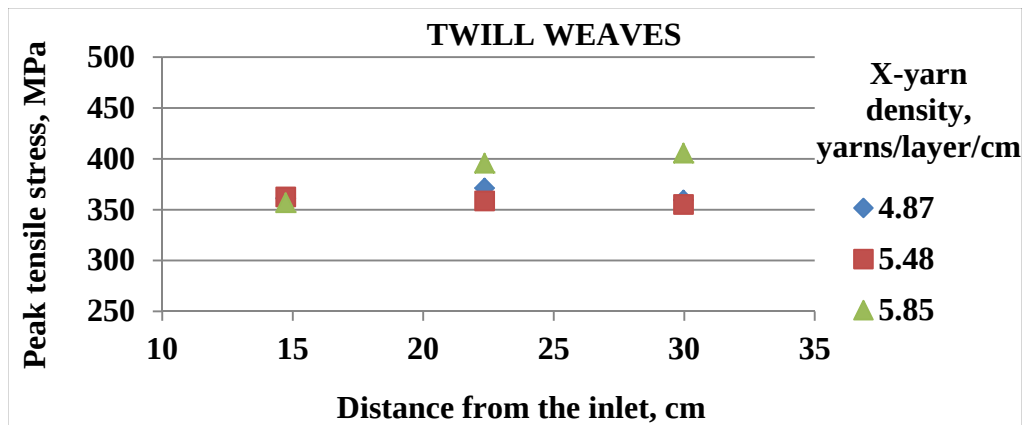
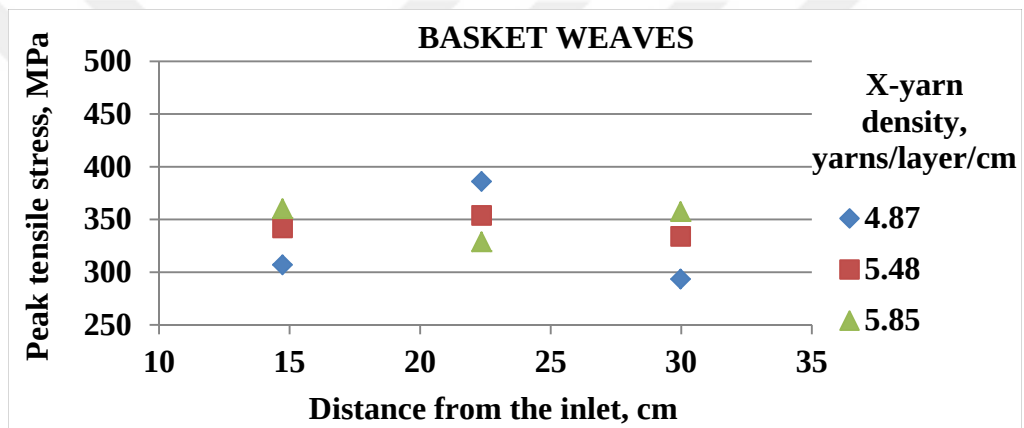
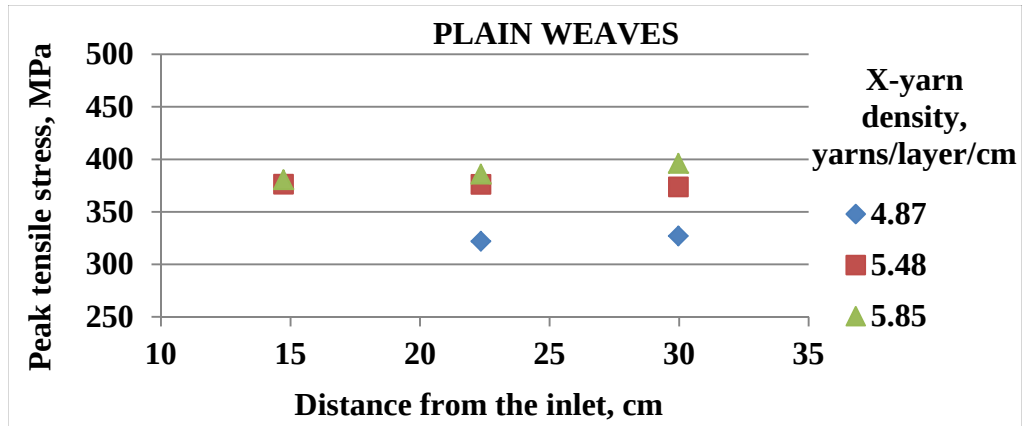


Figure J.3. Peak tensile stress profile in x-yarn direction of 4 layer composites manufactured at 75 kPa

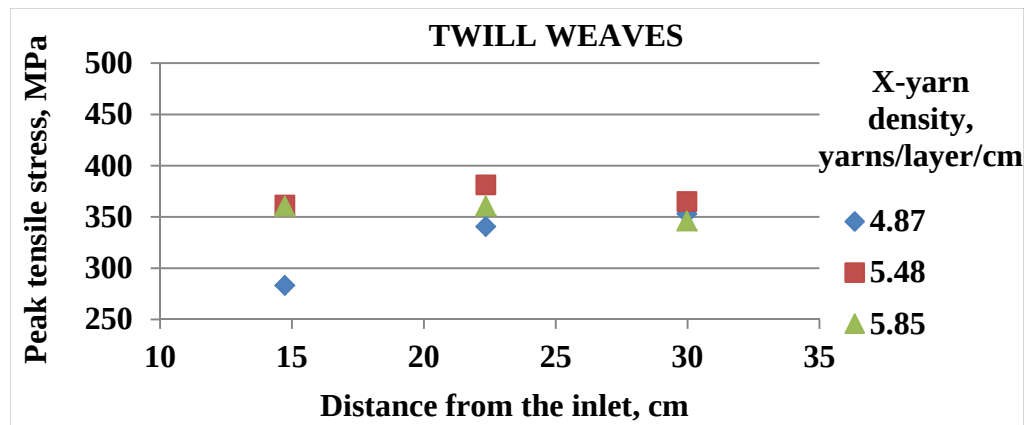
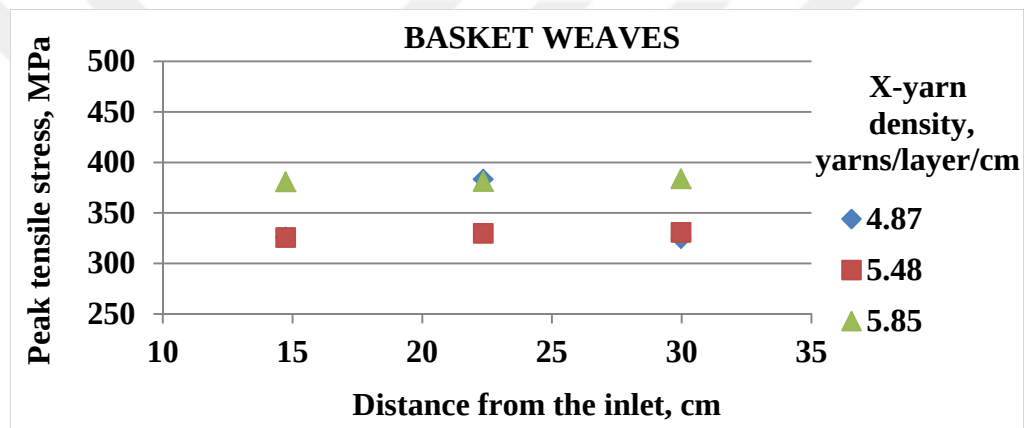
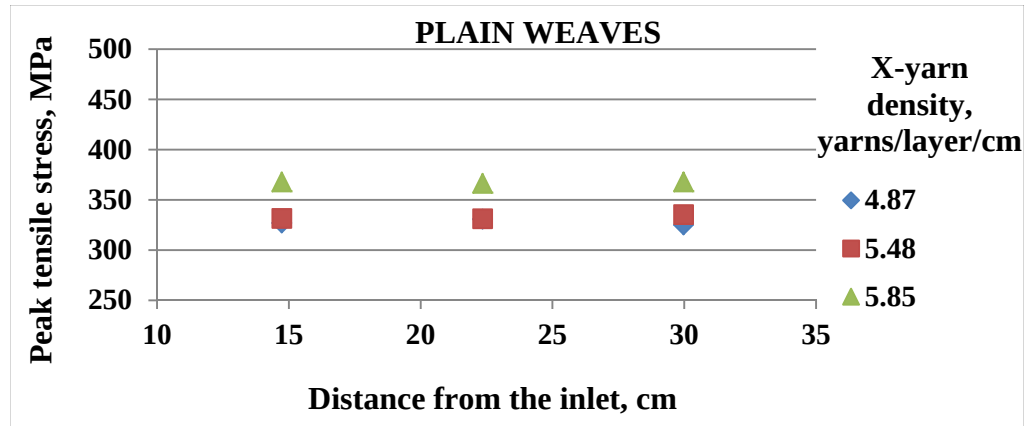


Figure J.4. Peak tensile stress profile in x-yarn direction of 4 layers composites manufactured at 100 kPa vacuums

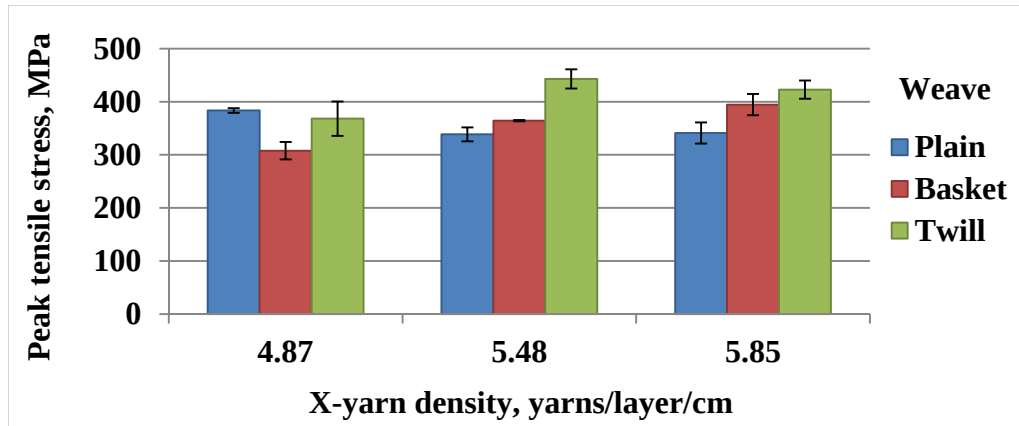


Figure J.5. Peak tensile stress in x-yarn direction of 2 layers composites manufactured at 75 kPa vacuums

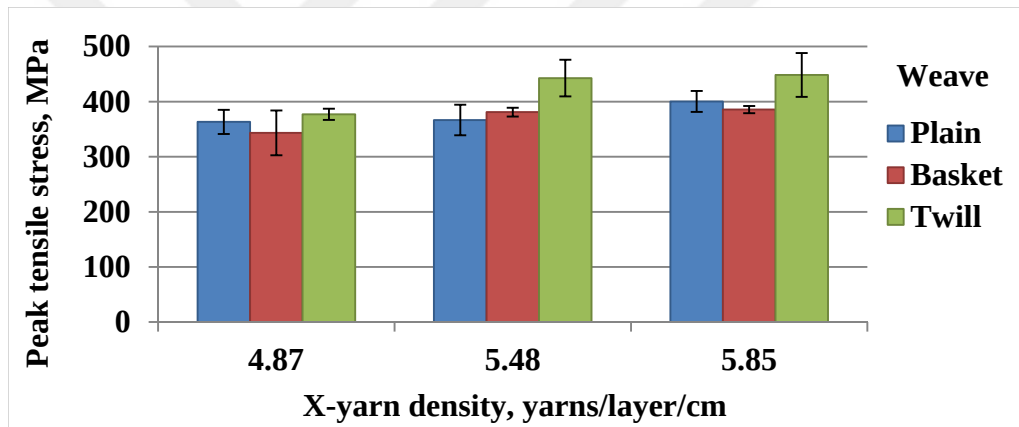


Figure J.6. Peak tensile stress in x-yarn direction of 2 layers composites manufactured at 100 kPa vacuums

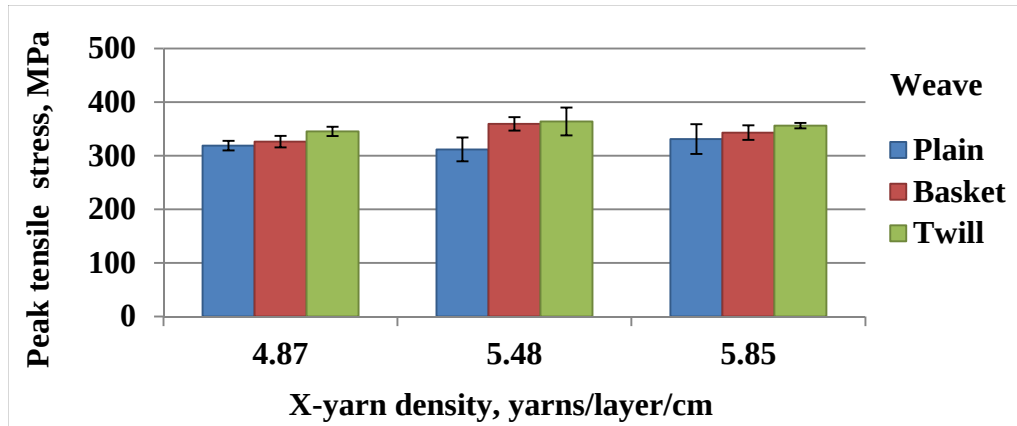


Figure J.7. Peak tensile stress in x-yarn direction of 3 layers composites manufactured at 75 kPa vacuums

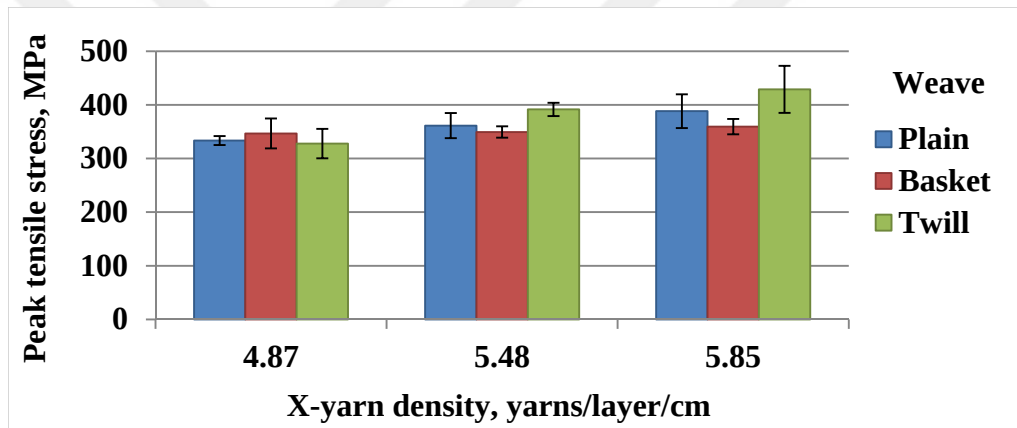


Figure J.8. Peak tensile stress in x-yarn direction of 3 layers composites manufactured at 100 kPa vacuums (error bars represent $\pm$ one standard deviation)

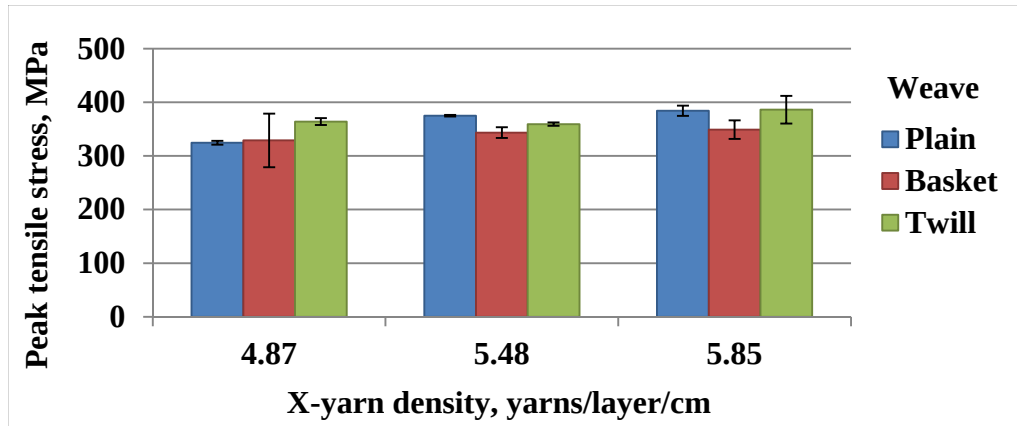


Figure J.9. Peak tensile stress in x-yarn direction of 4 layers composites manufactured at 75 kPa vacuums

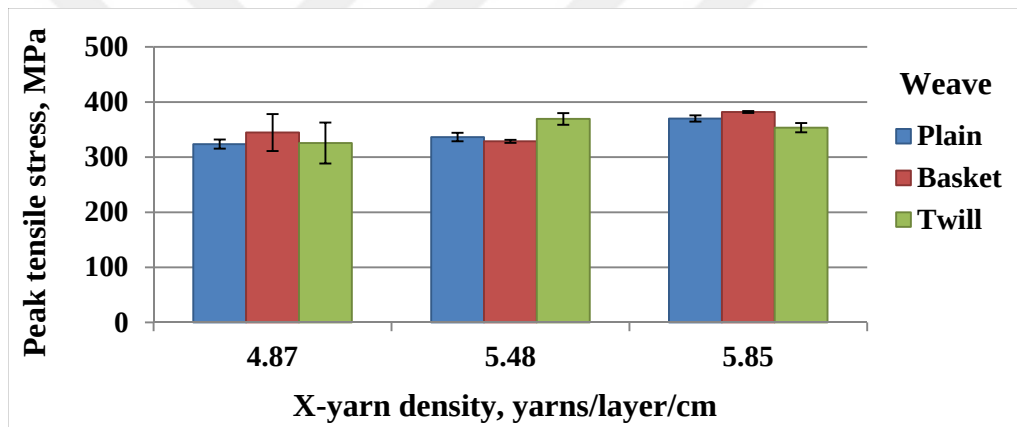


Figure J.10. Peak tensile stress in x-yarn direction of 4 layers composites manufactured at 100 kPa vacuums

APPENDIX K: Peak tensile stress in y-yarn direction

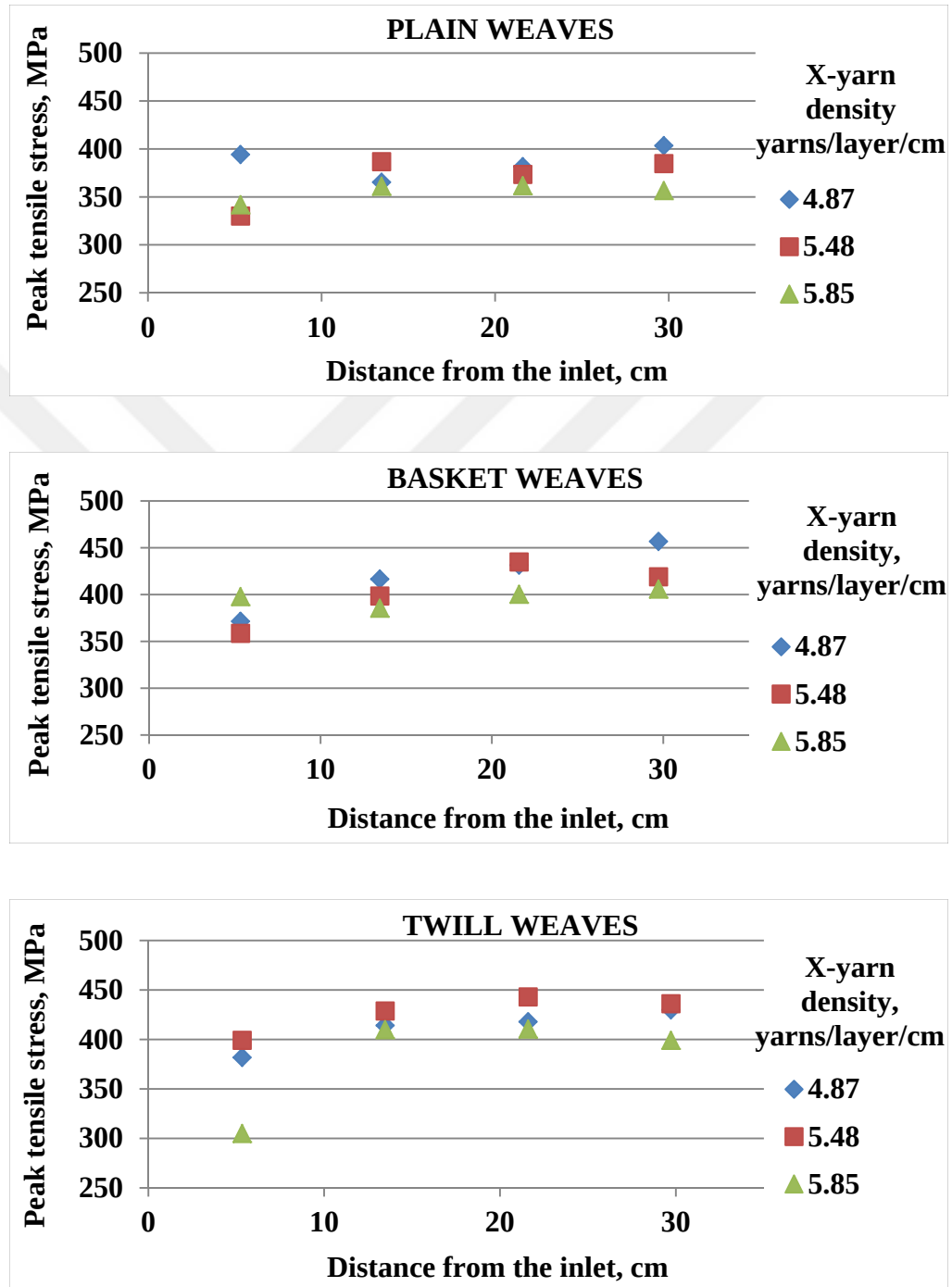


Figure K.1. Peak tensile stress profile in y-yarn direction of 2 layers composites manufactured at 75 kPa vacuums

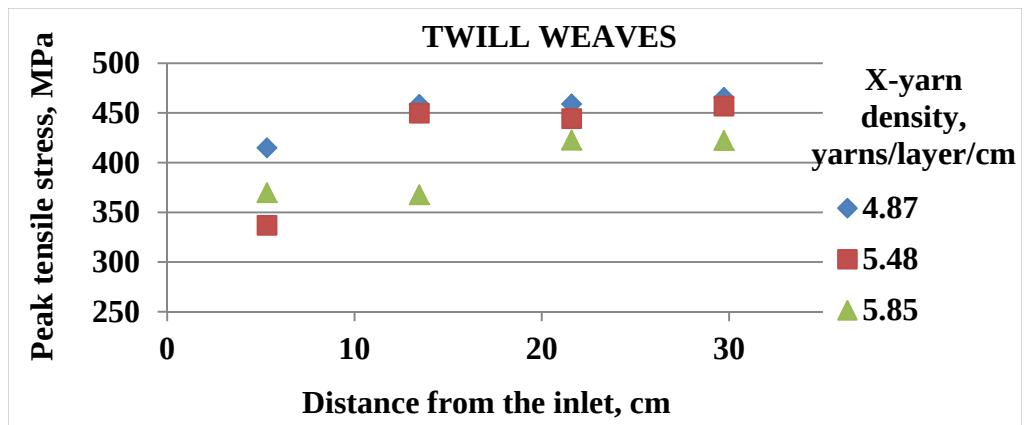
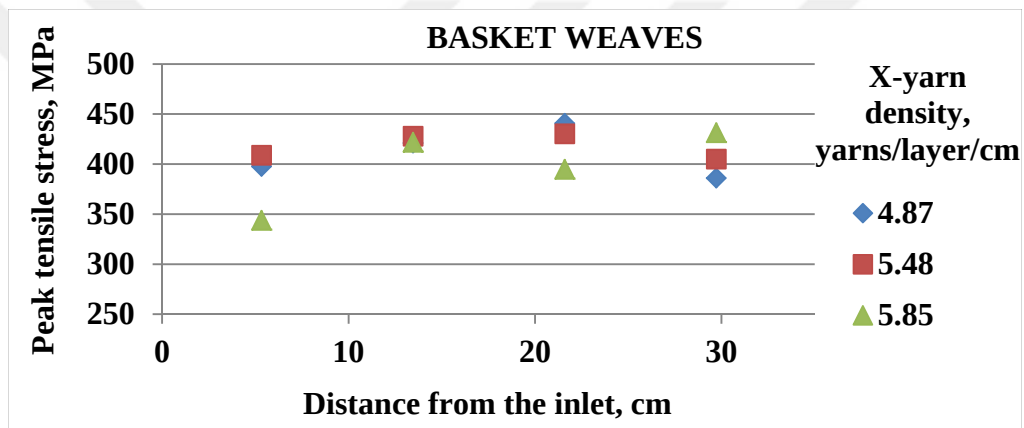
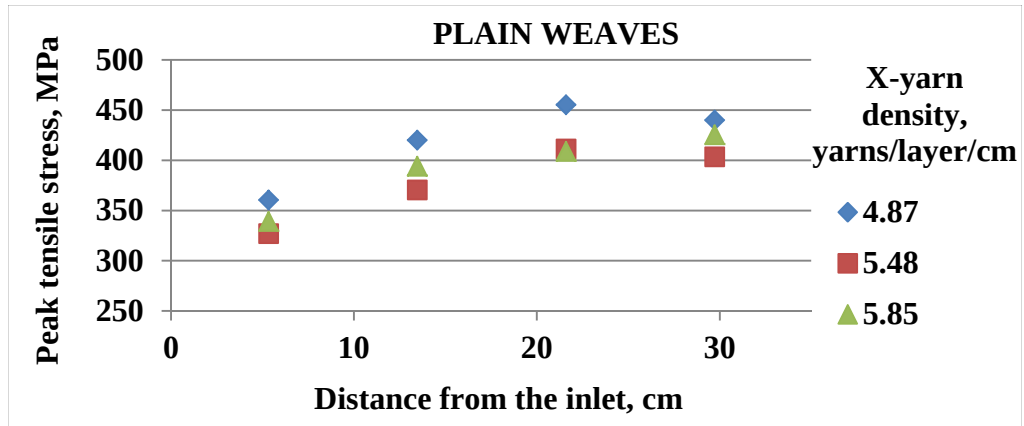


Figure K2. Peak tensile stress profile in y-direction of 2 layers composites manufactured at 100 kPa vacuums

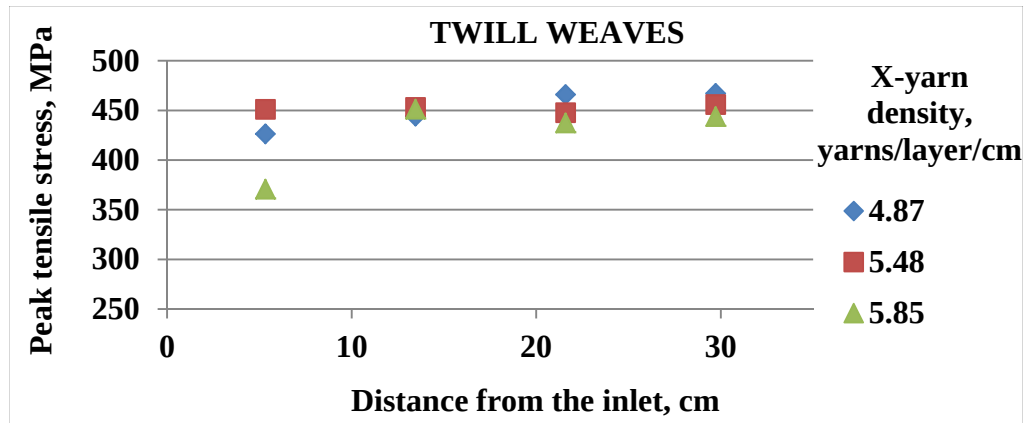
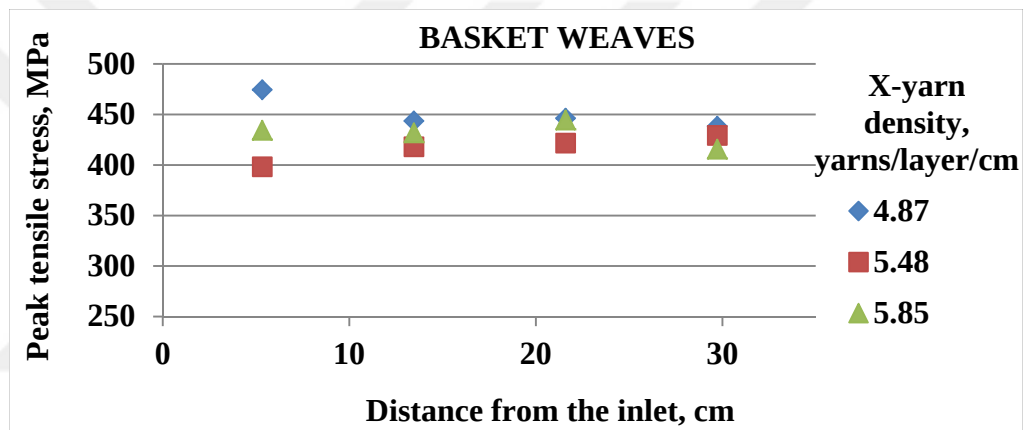
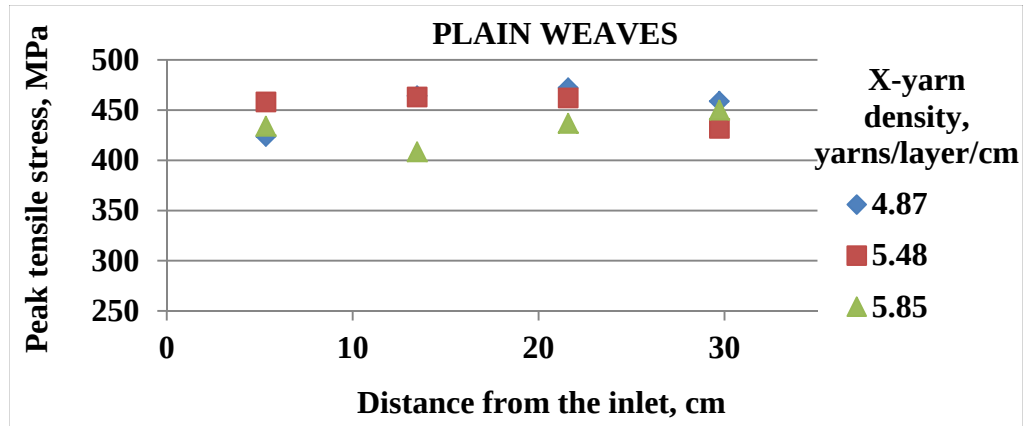


Figure K.3. Peak tensile stress profile in y-direction of 4 layers composites manufactured at 75 kPa vacuums

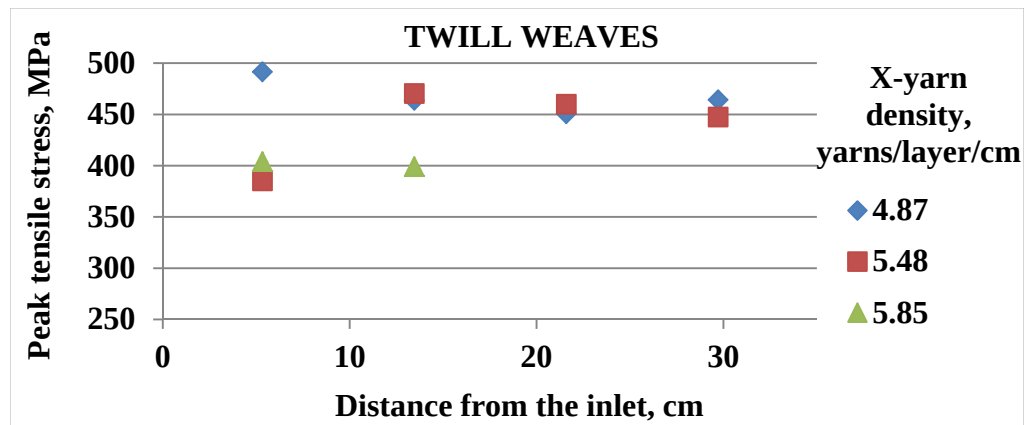
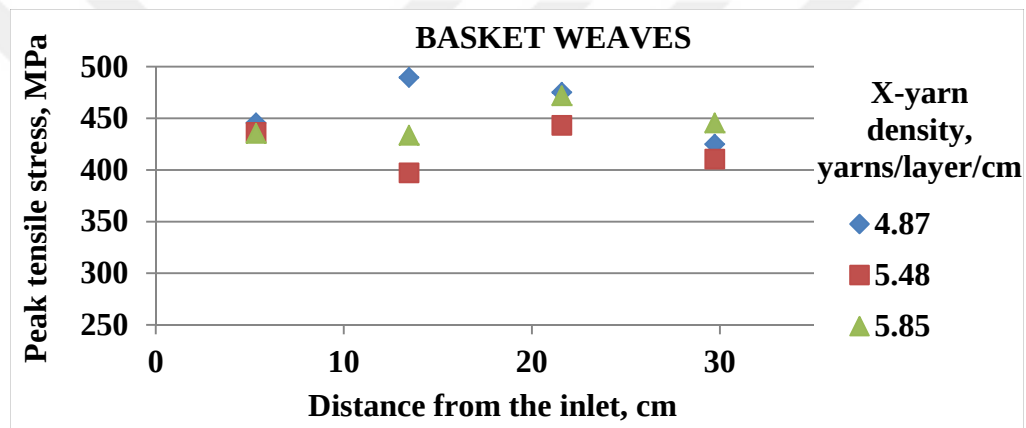
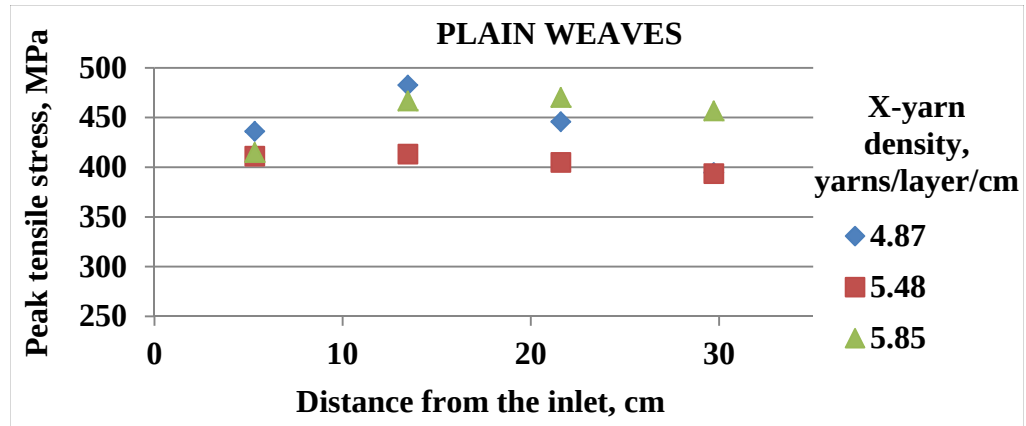


Figure K.4. Peak tensile stress profile in y-direction of 4 layers composites manufactured at 100 kPa vacuums

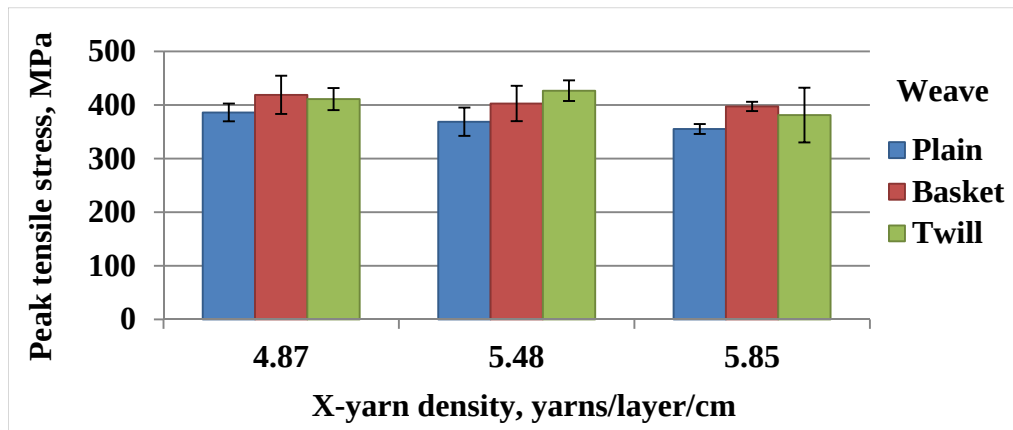


Figure K.5. Peak tensile stress in y-direction of 2 layers composites manufactured at 75 kPa vacuums
(Error bars represent $\pm$ one standard deviation)

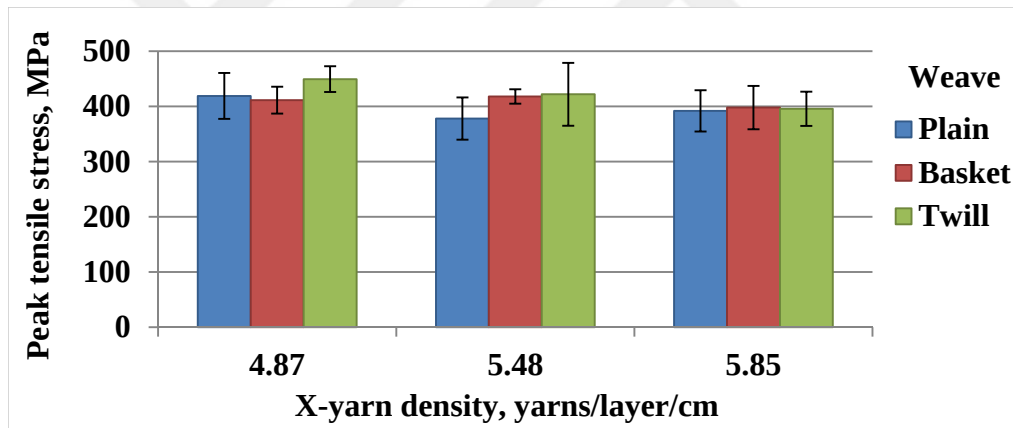


Figure K.6. Peak tensile stress in y- direction of 2 layers composites manufactured at 100 kPa vacuums

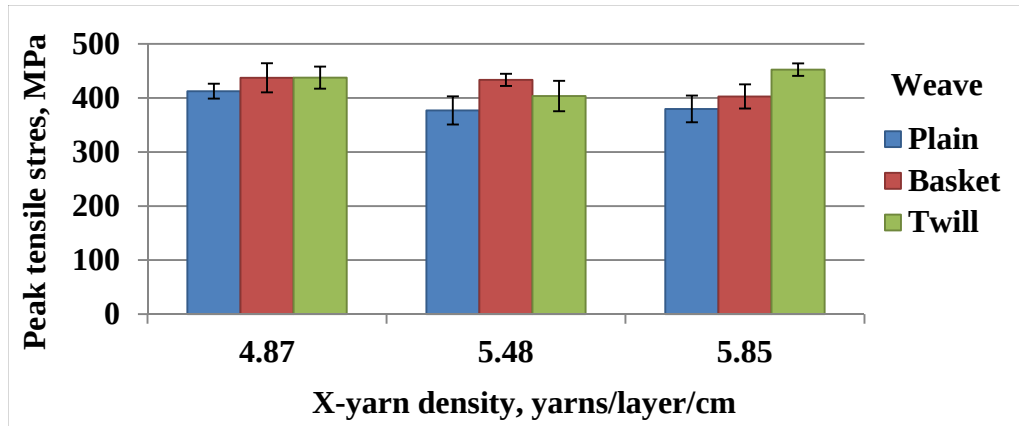


Figure K.7. Peak tensile stress in y-direction of 3 layers composites manufactured at 75 kPa vacuums

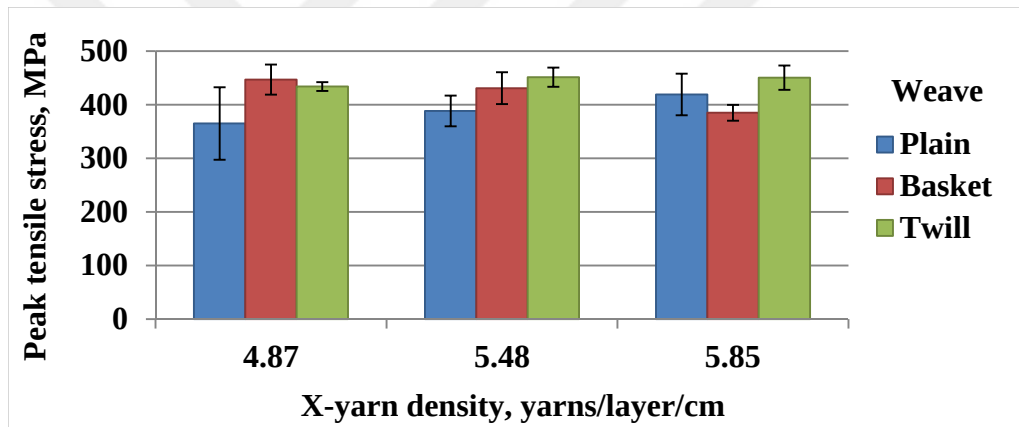


Figure K.8. Peak tensile stress in y-yarn direction of 3 layers composites manufactured at 100 kPa vacuums
(Error bars represent $\pm$ one standard deviation)

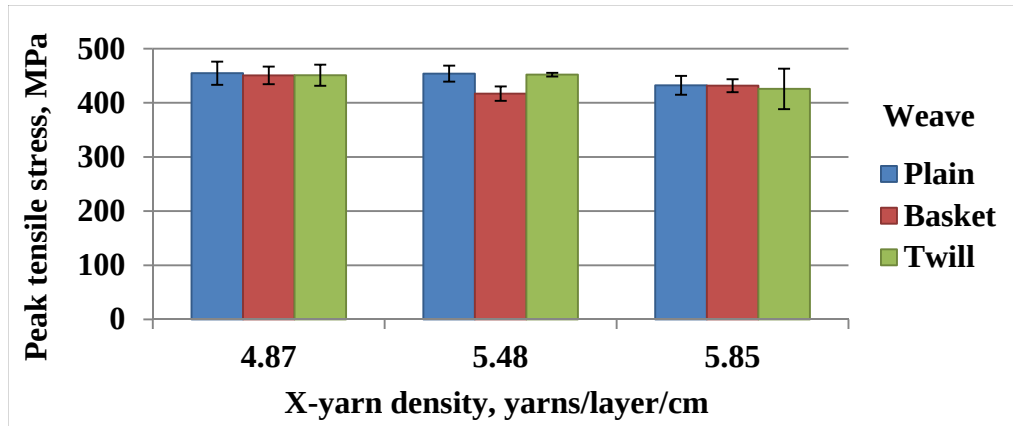


Figure K.9. Peak tensile stress in y-direction of 4 layers composites manufactured at 75 kPa vacuums
(Error bars represent $\pm$ one standard deviation)

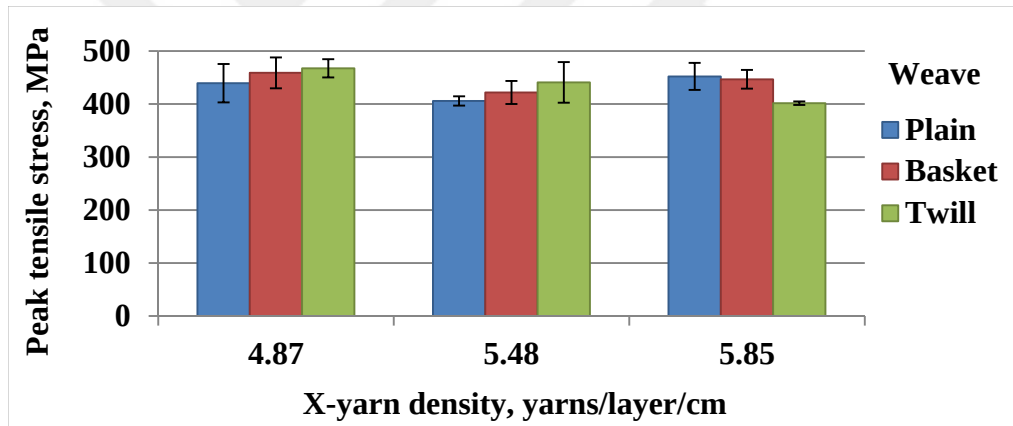


Figure K.10. Peak tensile stress in y-direction of 4 layers composites manufactured at 100 kPa vacuums

APPENDIX L: Peak tensile stress of balanced composites in x- and y-direction

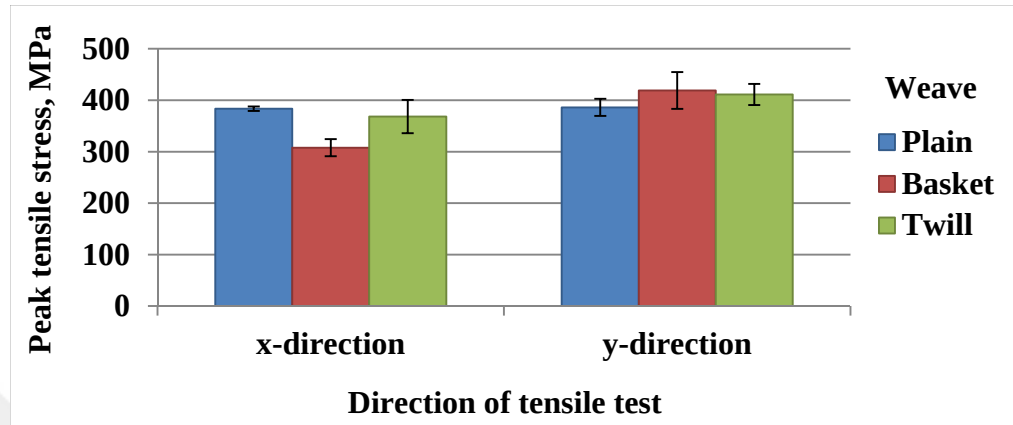


Figure L.1. Peak tensile stresses in x- and y-direction of balanced, 2 layers, 4.87 x-yarns/layer/cm composites manufactured at 75 kPa vacuums

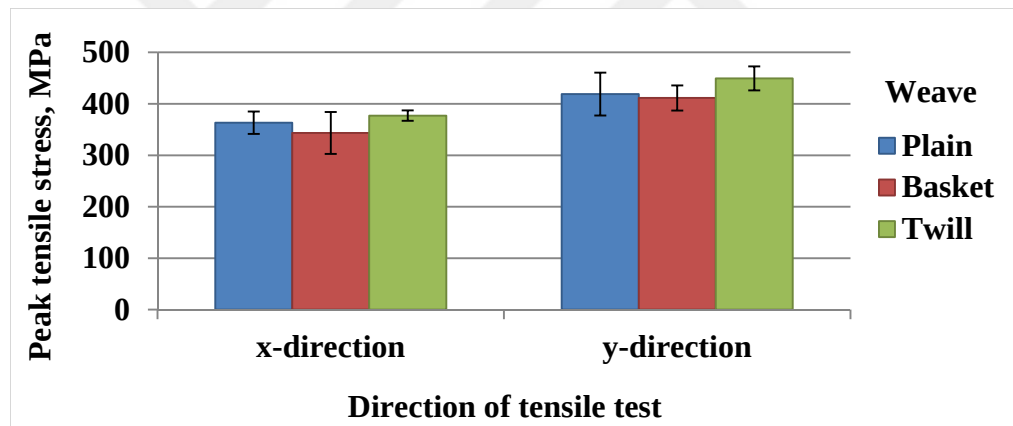


Figure L.2. Peak tensile stresses in x- and y-direction of balanced, 2 layers, 4.87 x-yarns/layer/cm composites manufactured at 100 kPa vacuums

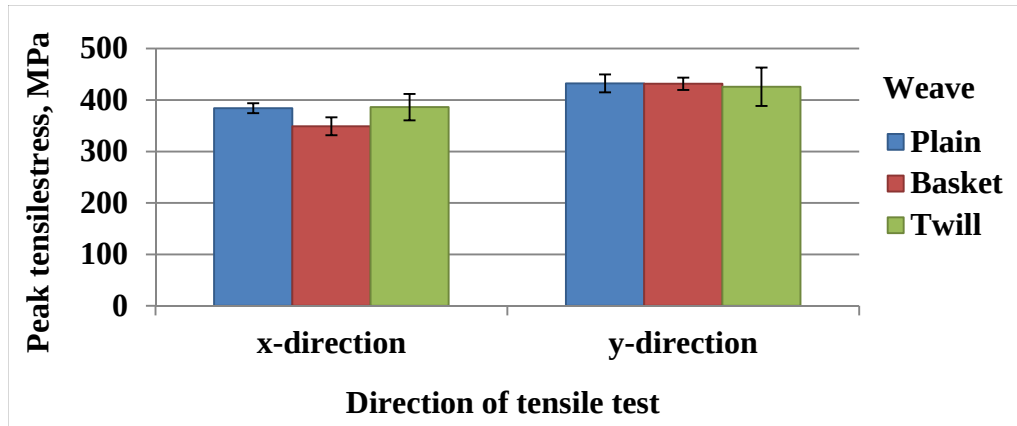


Figure L.3. Peak tensile stresses in x- and y-direction of balanced, 4 layers, 5.85 x-yarns/layer/cm composites manufactured at 75 kPa vacuums

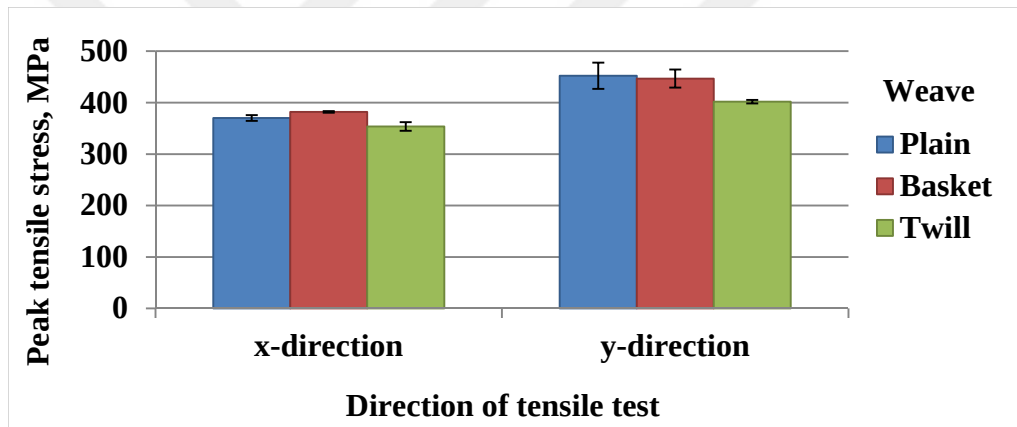


Figure L.4. Peak tensile stresses in x- and y-direction of balanced, 4 layers, 5.85 x-yarns/layer/cm composites manufactured at 100 kPa vacuums

APPENDIX M: Peak flexure stress in x-yarn direction

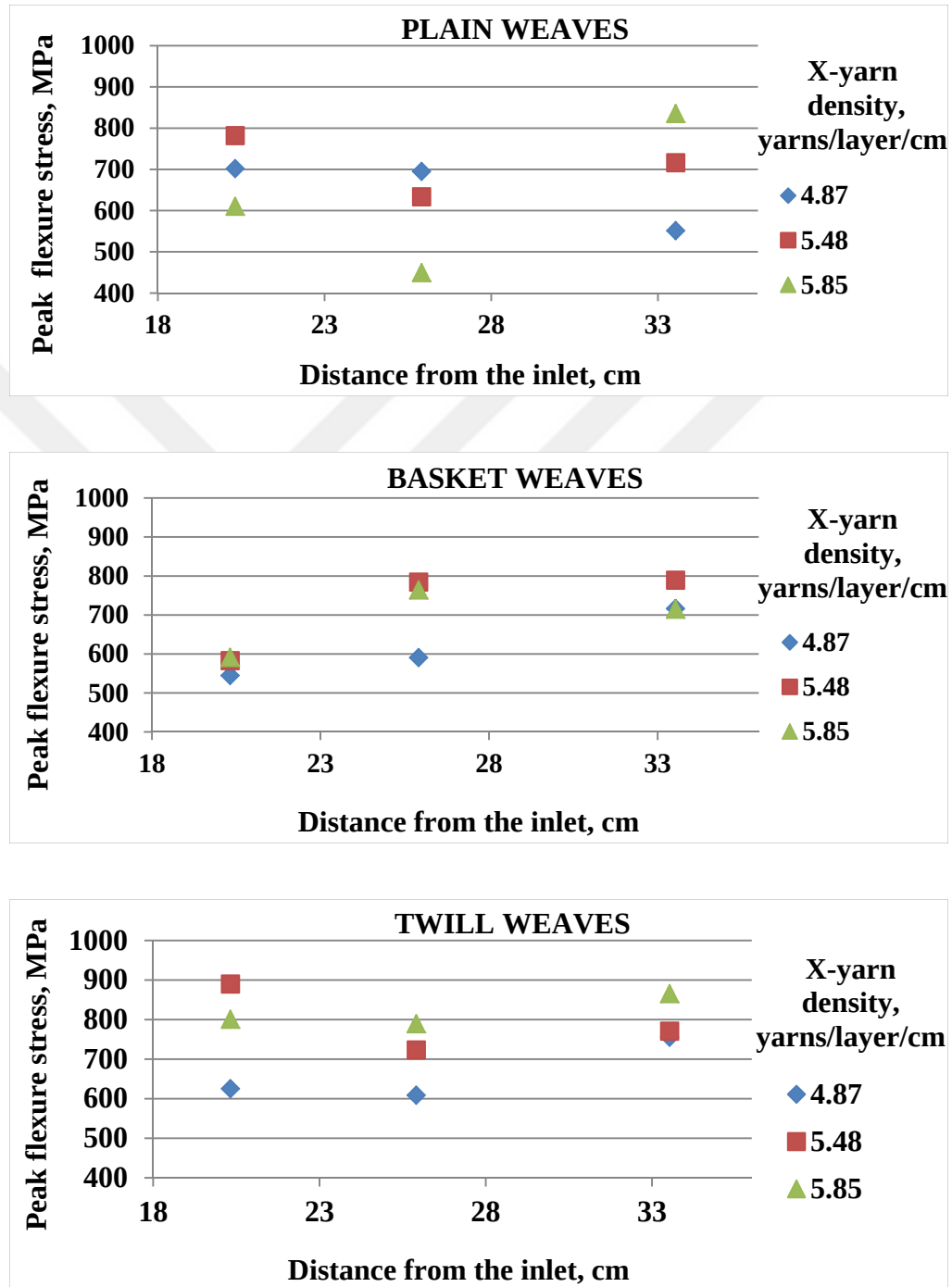


Figure M.1. Peak flexure stress profile in x-direction of 2 layers composites manufactured at 75 kPa

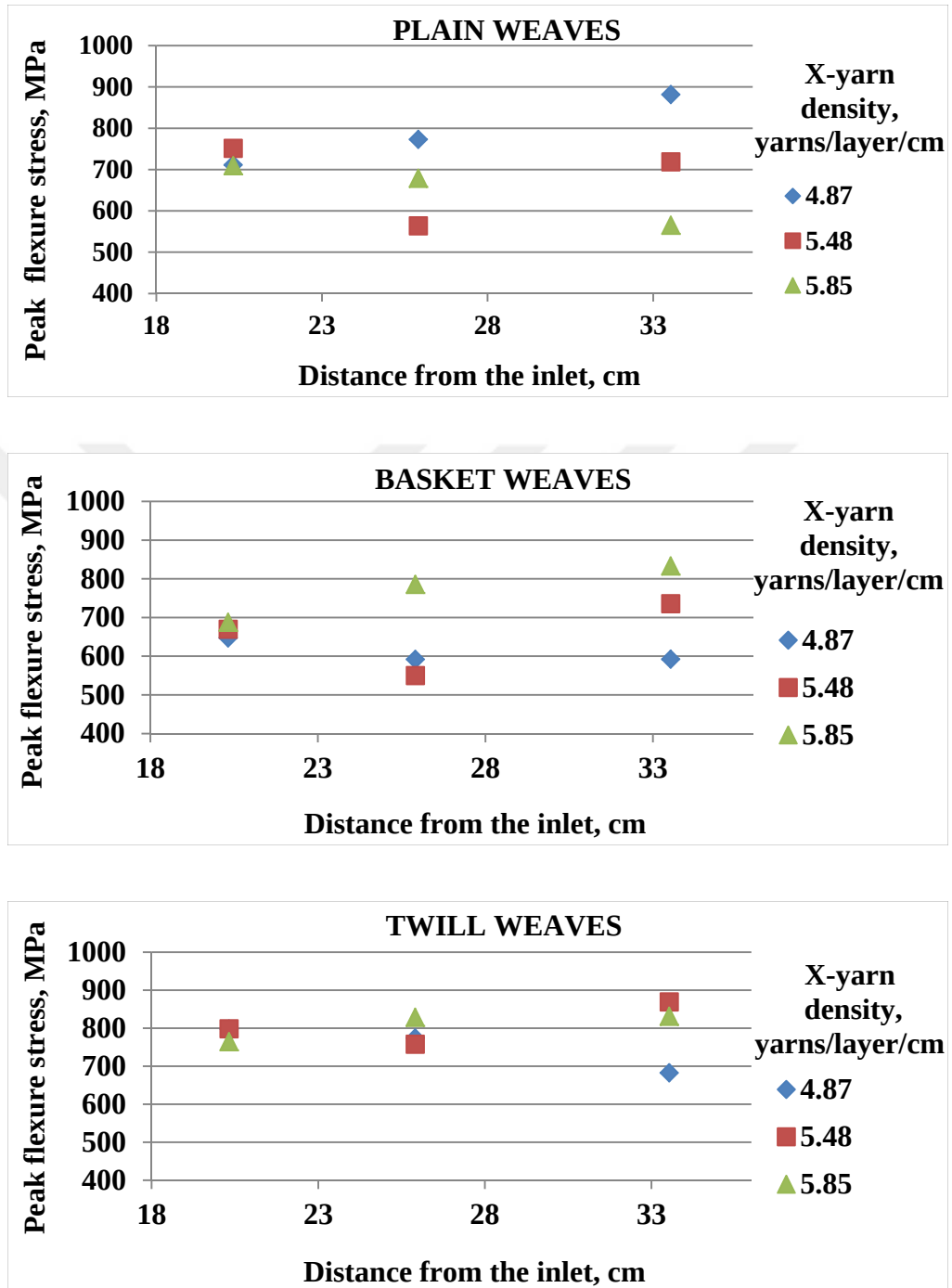


Figure M.2. Peak flexure stress profile in x-direction of 2 layers composites manufactured at 100 kPa vacuums

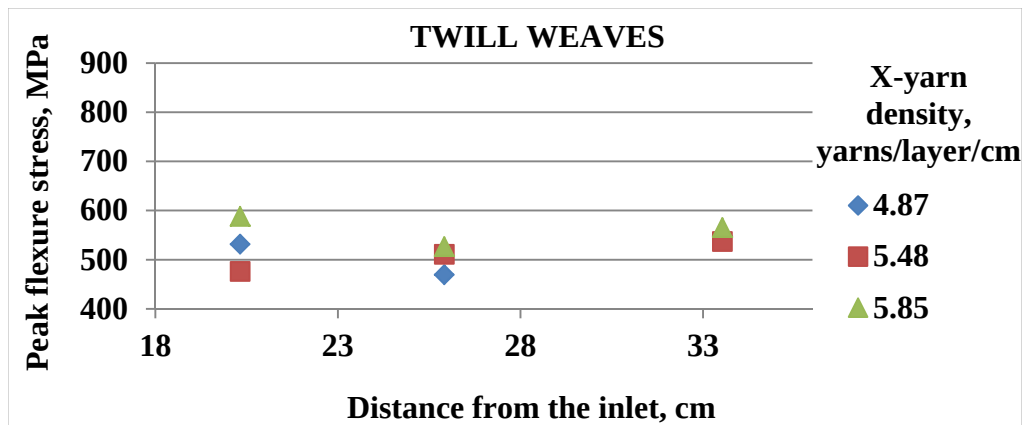
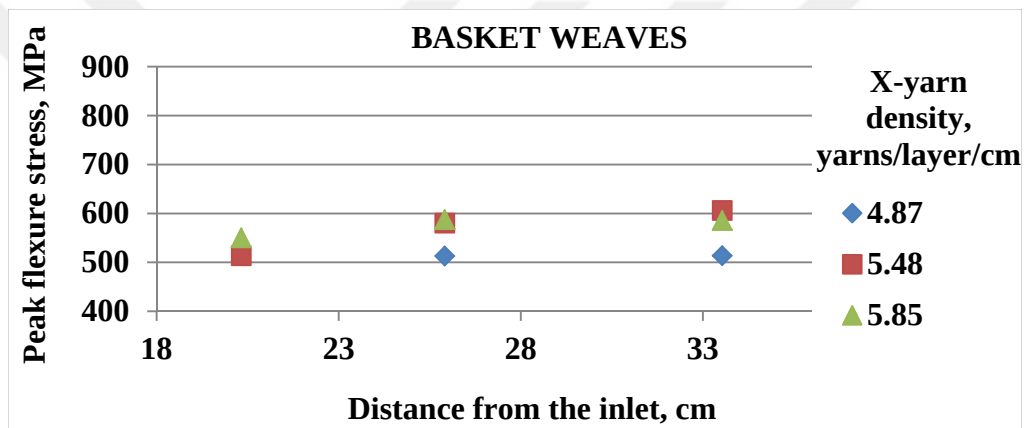
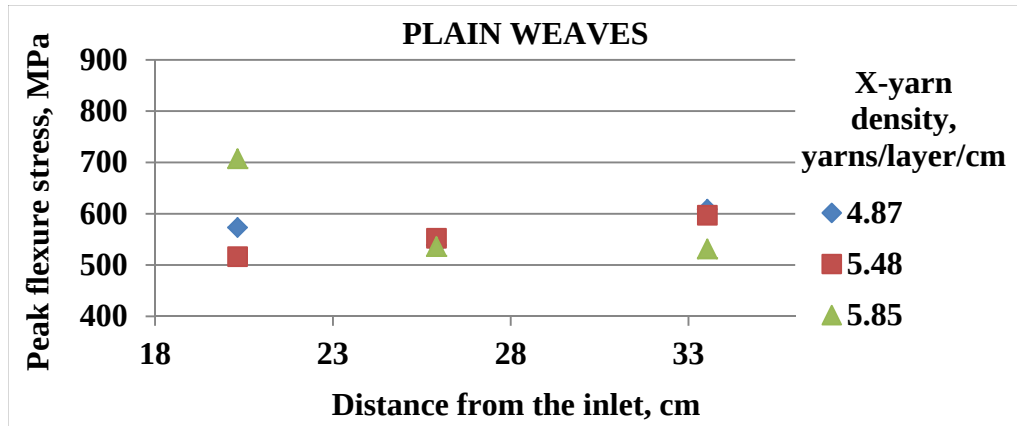


Figure M.3. Peak flexure stress profile in x-yarn direction of 4 layers composites manufactured at 75 kPa vacuums

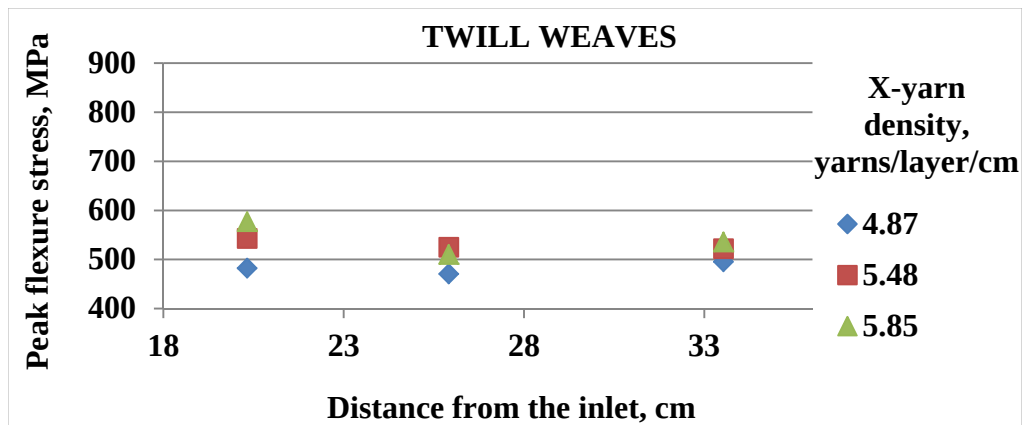
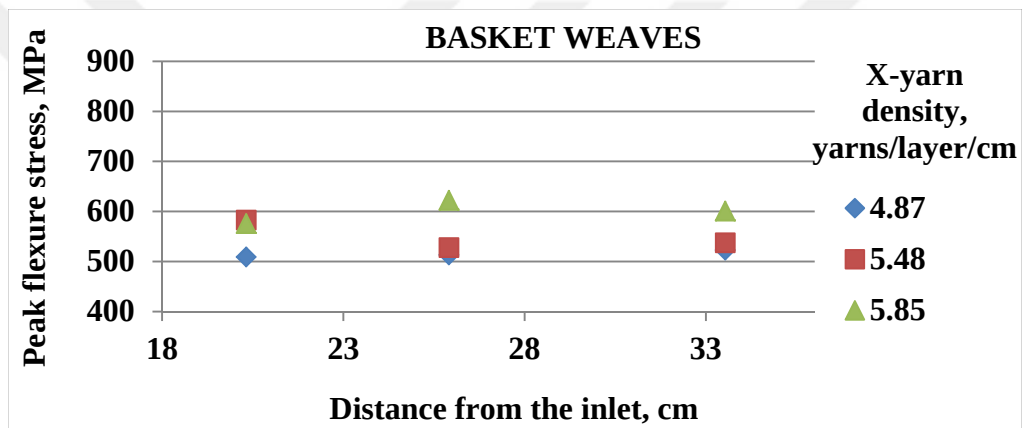
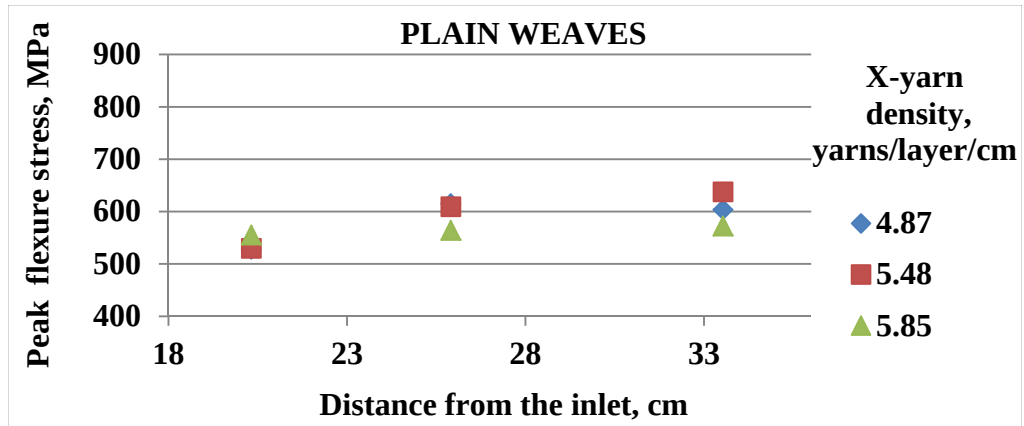


Figure M.4. Peak flexure stress profile in x-yarn direction of 4 layers composites manufactured at 100 kPa vacuums

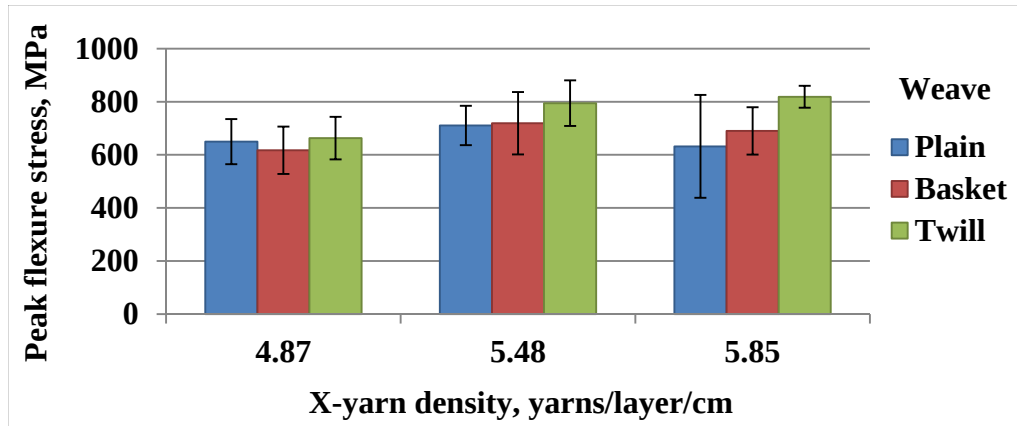


Figure M.5. Peak flexure stress in x-yarn direction of 2 layers composites manufactured at 75 kPa vacuums

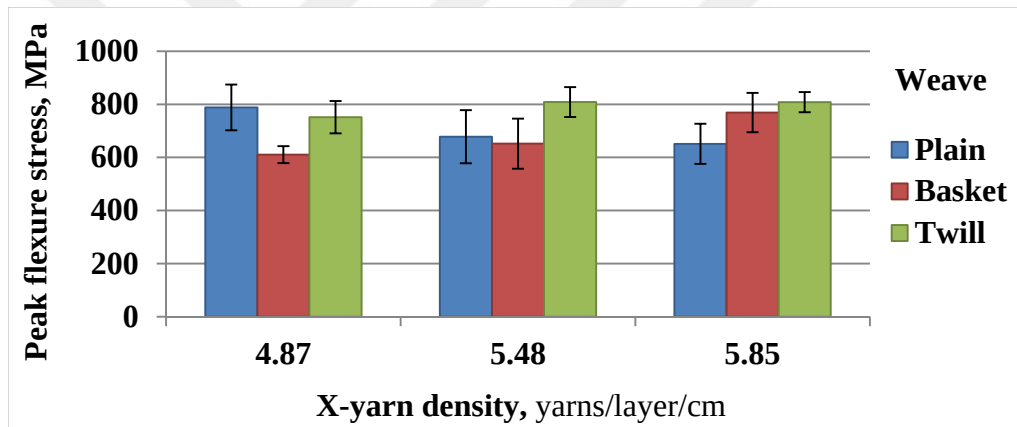


Figure M.6. Peak flexure stress in x-yarn direction of 2 layers composites manufactured at 100 kPa vacuums
(Error bars represent $\pm$ one standard deviation)

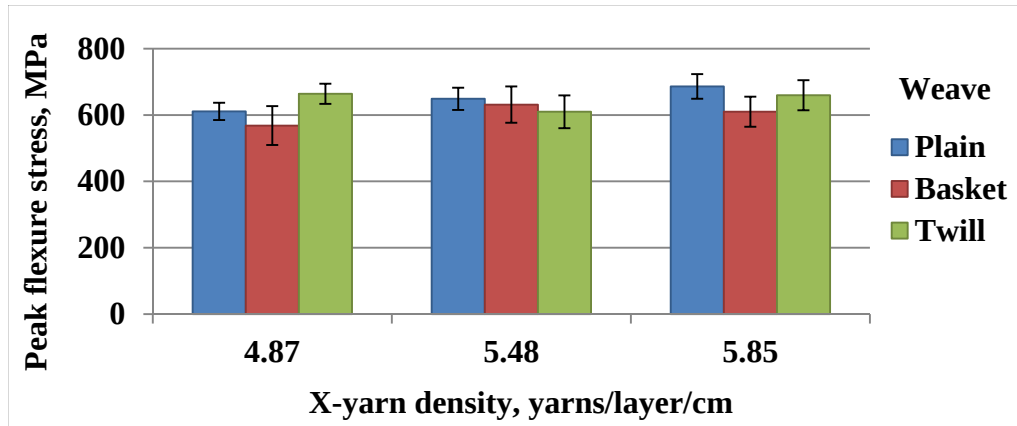


Figure M.7. Peak flexure stress in x-yarn direction of 3 layers composites manufactured at 75 kPa vacuums
(Error bars represent $\pm$ one standard deviation)

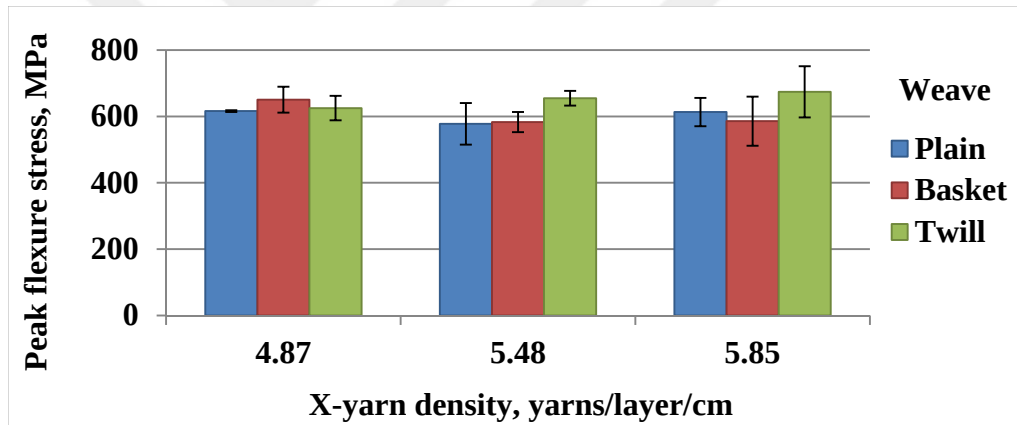


Figure M.8. Peak flexure stress in x-yarn direction of 3 layers composites manufactured at 100 kPa vacuums
(Error bars represent $\pm$ one standard deviation)

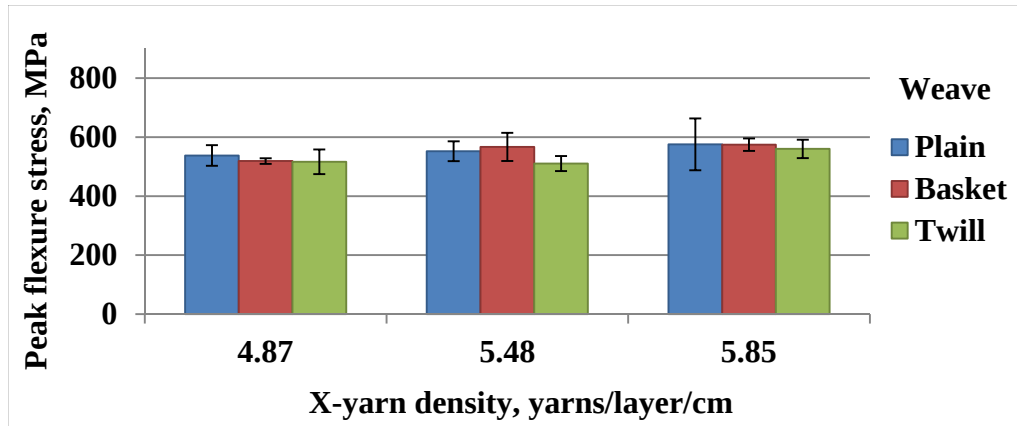


Figure M.9. Peak flexure stress in x-yarn direction of 4 layers composites manufactured at 75 kPa vacuums

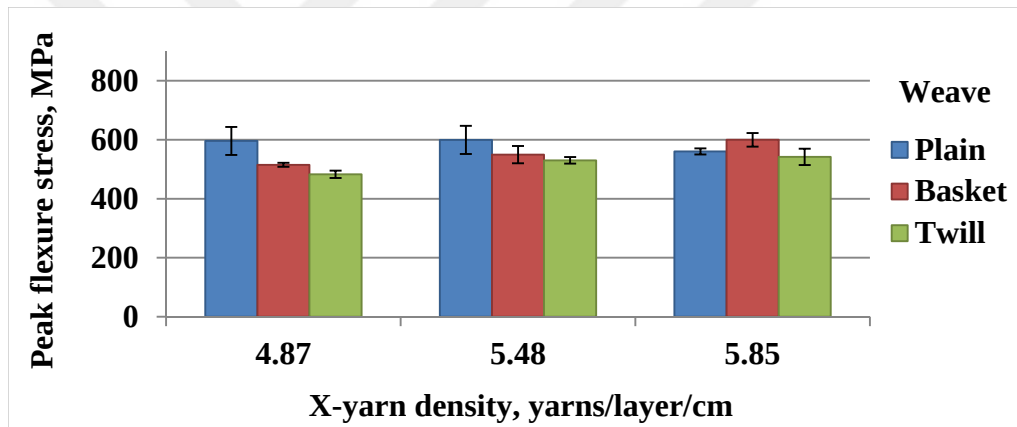


Figure M.10. Peak flexure stress in x-yarn direction of 4 layers composites manufactured at 100 kPa vacuums
(Error bars represent $\pm$ one standard deviation)

APPENDIX N: Peak flexure stress in y-yarn direction

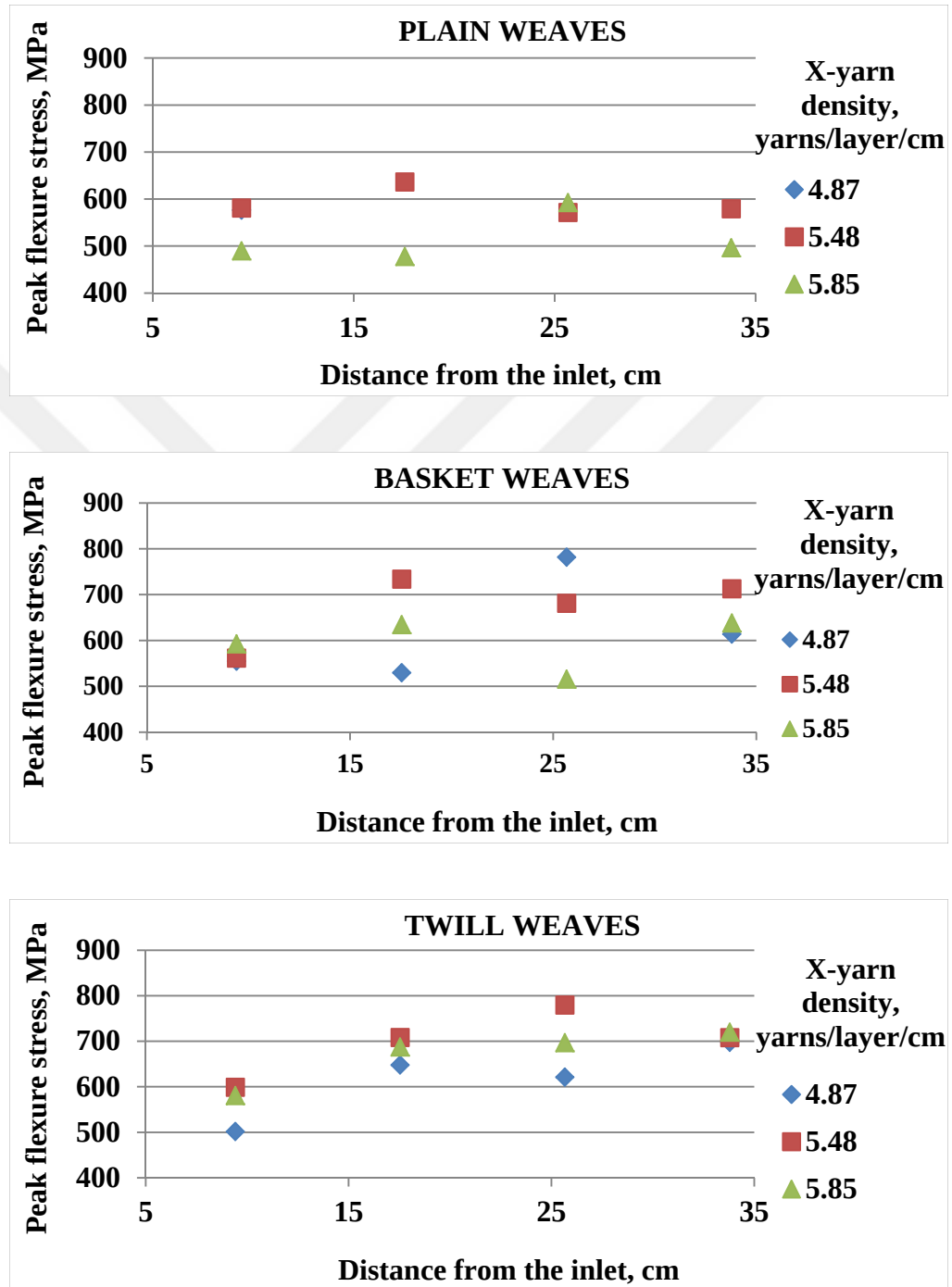


Figure N.1. Peak flexure stress profile in y-yarn direction of 2 layers composites manufactured at 75 kPa

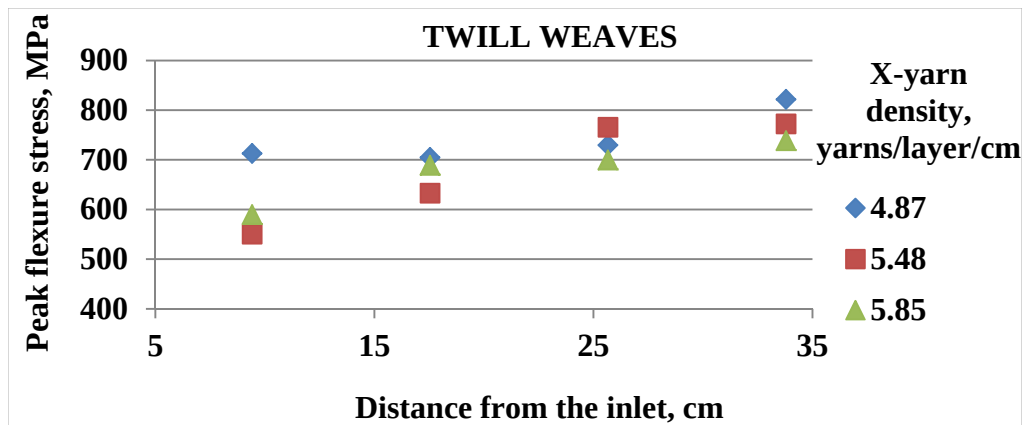
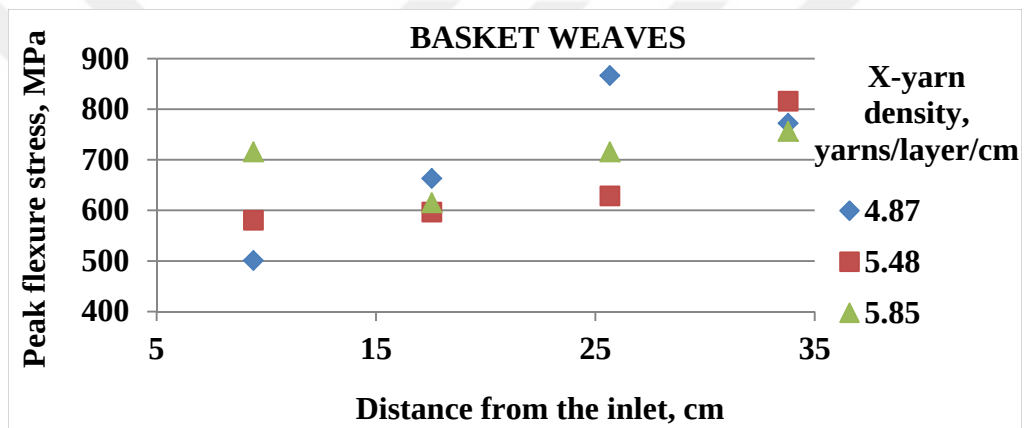
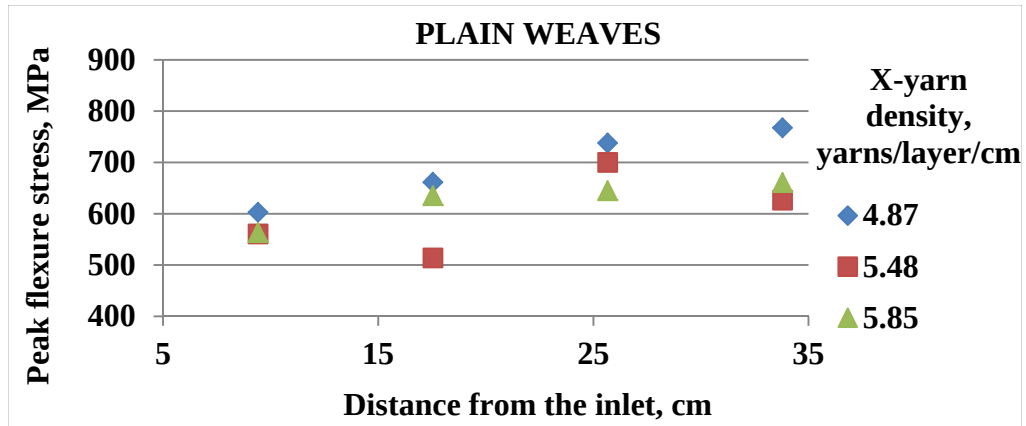


Figure N.2. Peak flexure stress profile in y-yarn direction of 2 layers composites manufactured at 100 kPa vacuums

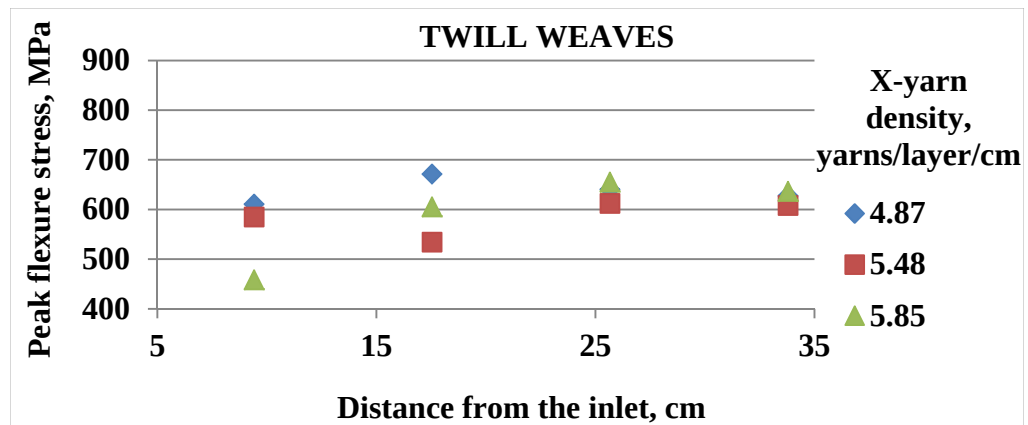
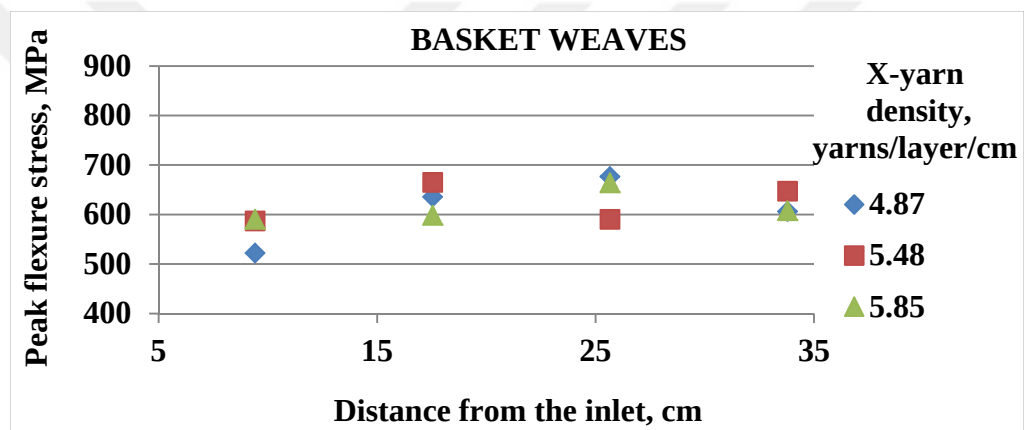
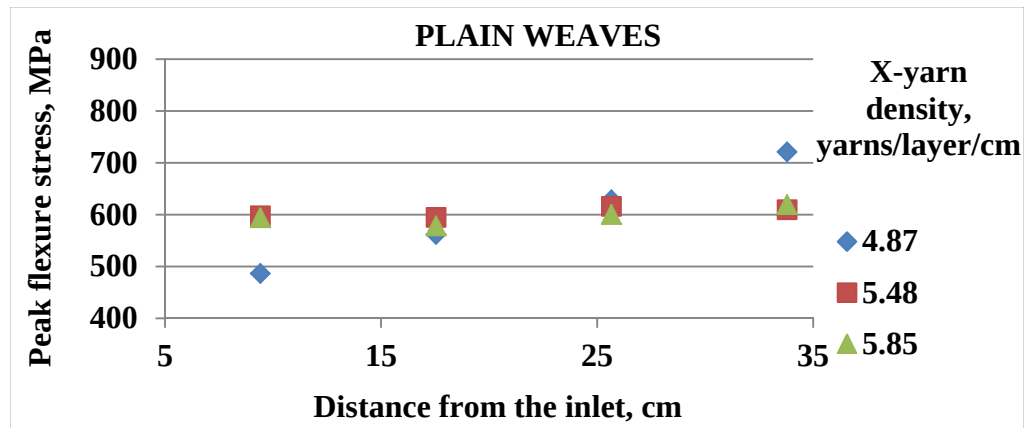


Figure N.3. Peak flexure stress profile in y-yarn direction of 4 layers composites manufactured at 75 kPa vacuum

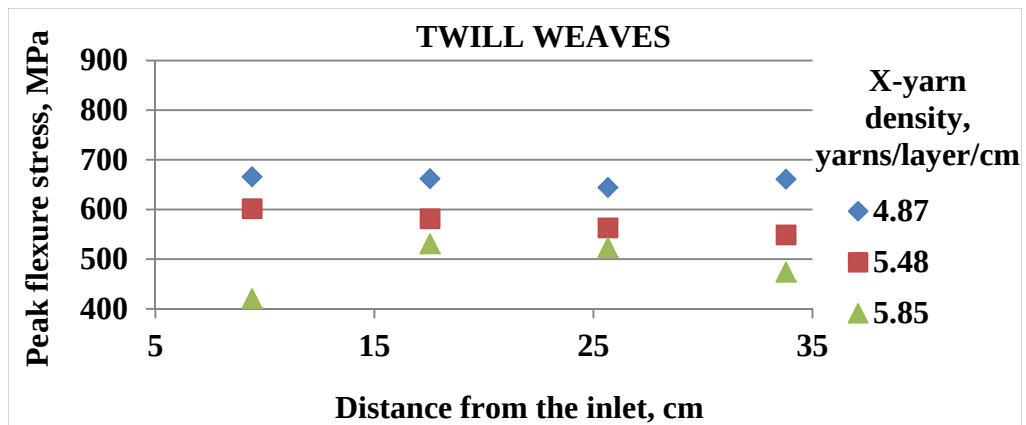
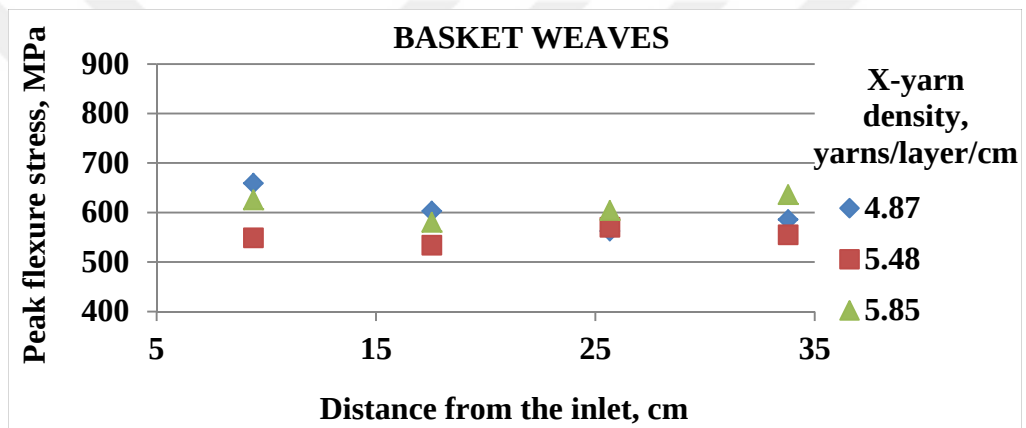
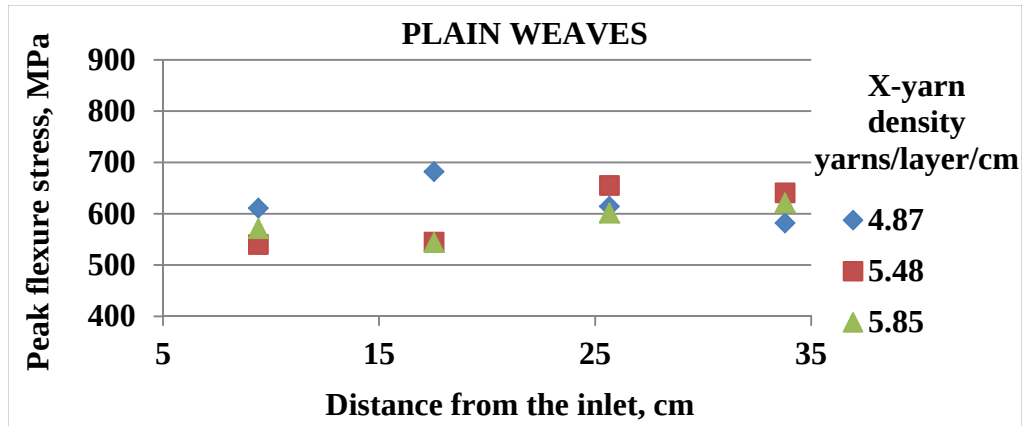


Figure N.4 Peak flexure stress profile in y-yarn direction of 4 layers composites manufactured at 100 kPa vacuum

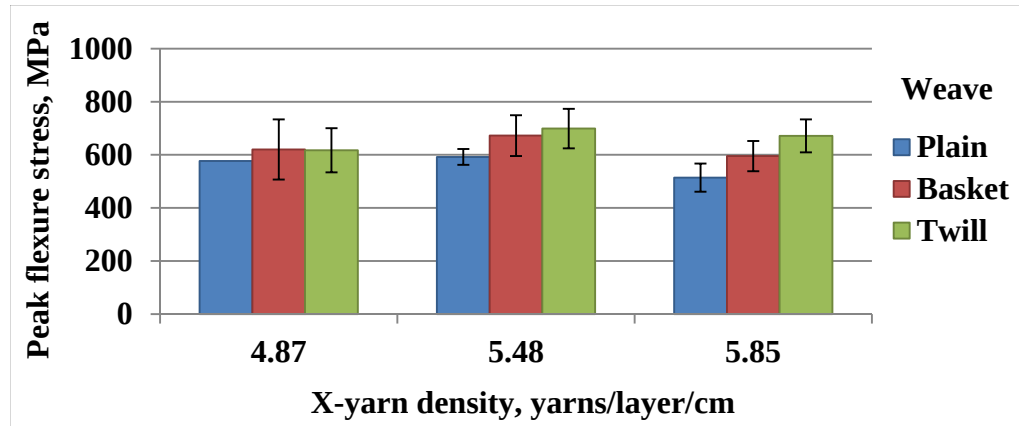


Figure N.5. Peak flexure stress in y-yarn direction of 2 layers composites manufactured at 75 kPa vacuums

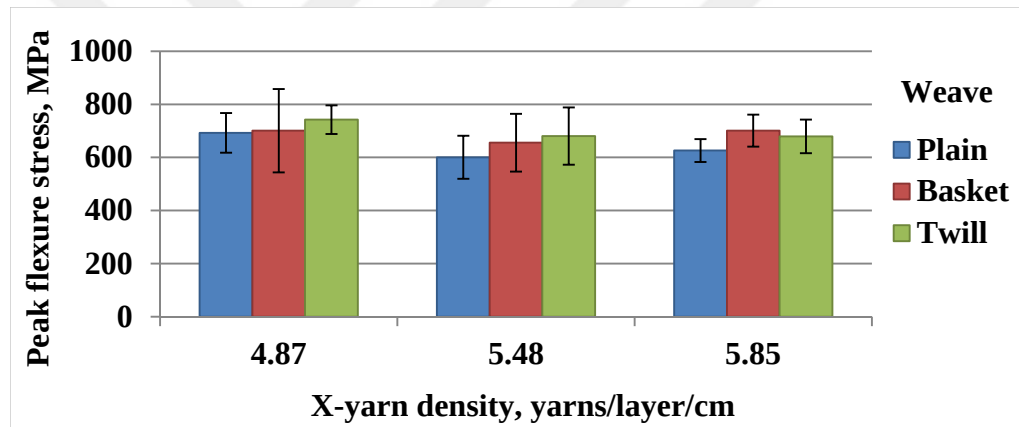


Figure N.6. Peak flexure stress in y-yarn direction of 2 layers composites manufactured at 100 kPa vacuums
(Error bars represent $\pm$ one standard deviation)

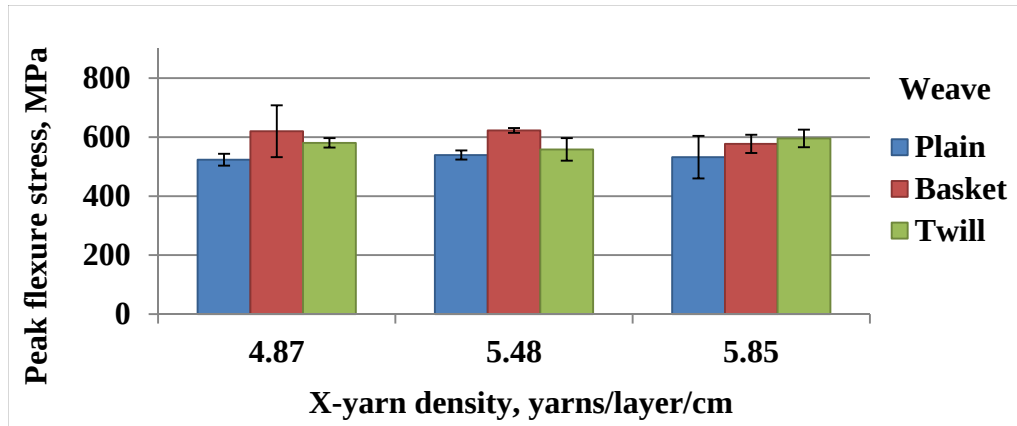


Figure N.7. Peak flexure stress in y-yarn direction of 3 layers composites manufactured at 75 kPa vacuums

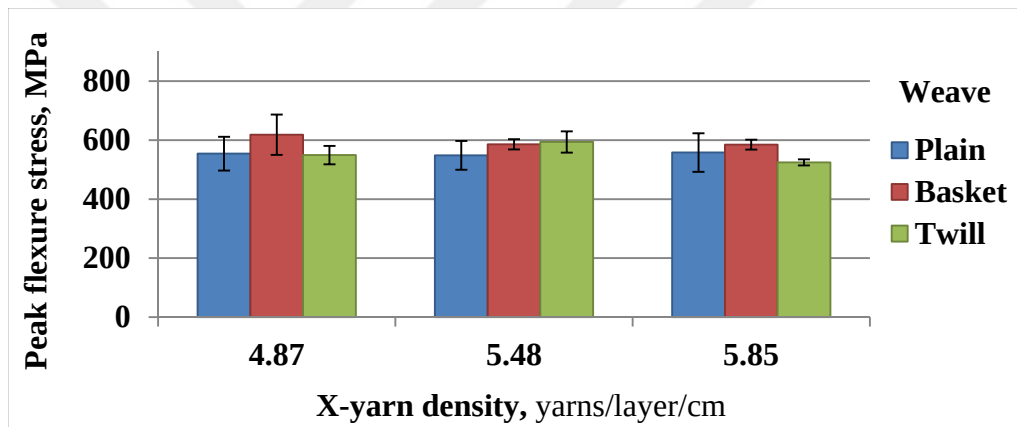


Figure N.8. Peak flexure stress in y-yarn direction of 3 layers composites manufactured at 100 kPa vacuums
(Error bars represent $\pm$ one standard deviation)

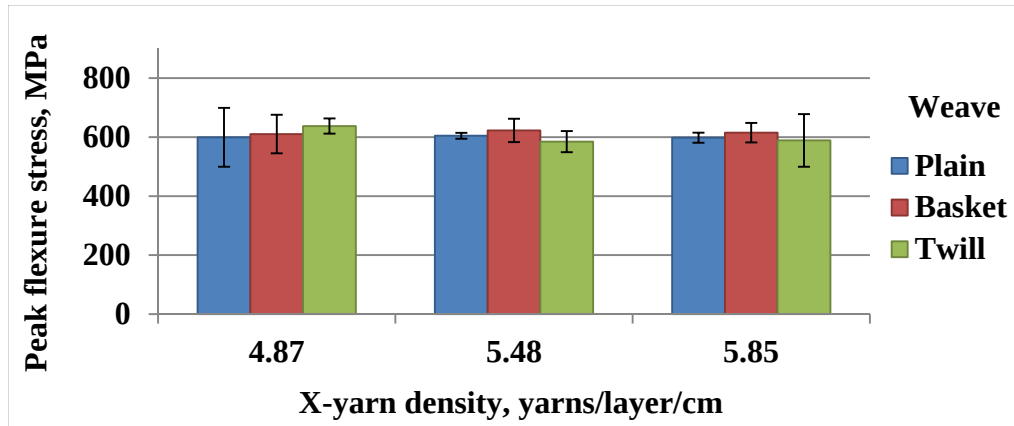


Figure N.9. Peak flexure stress in y-yarn direction of 4 layers composites manufactured at 75 kPa vacuums

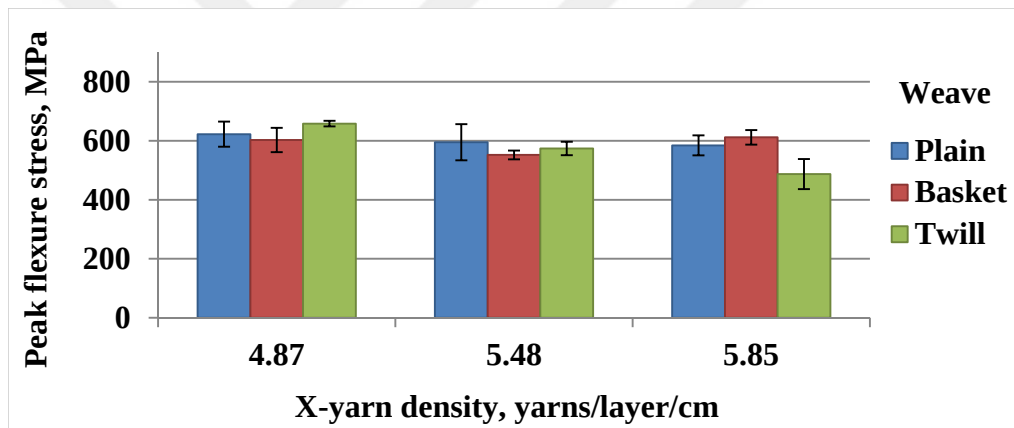


Figure N.10. Peak flexure stress in y-yarn direction of 4 layers composites manufactured at 100 kPa vacuums

APPENDIX O: Impact properties of composites

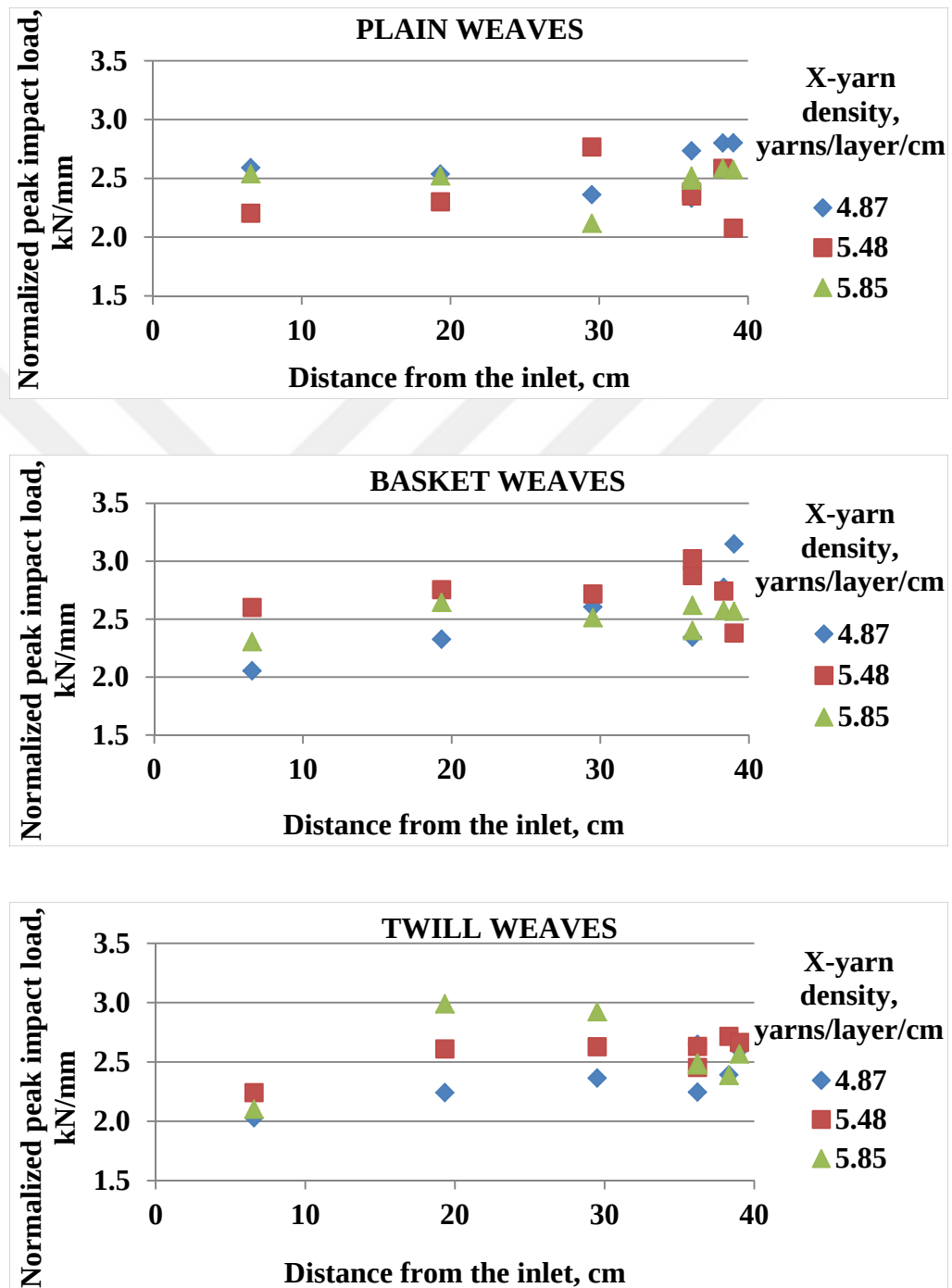


Figure O.1. Normalized peak impact load profile of 2 layers composites manufactured at 75 kPa vacuum

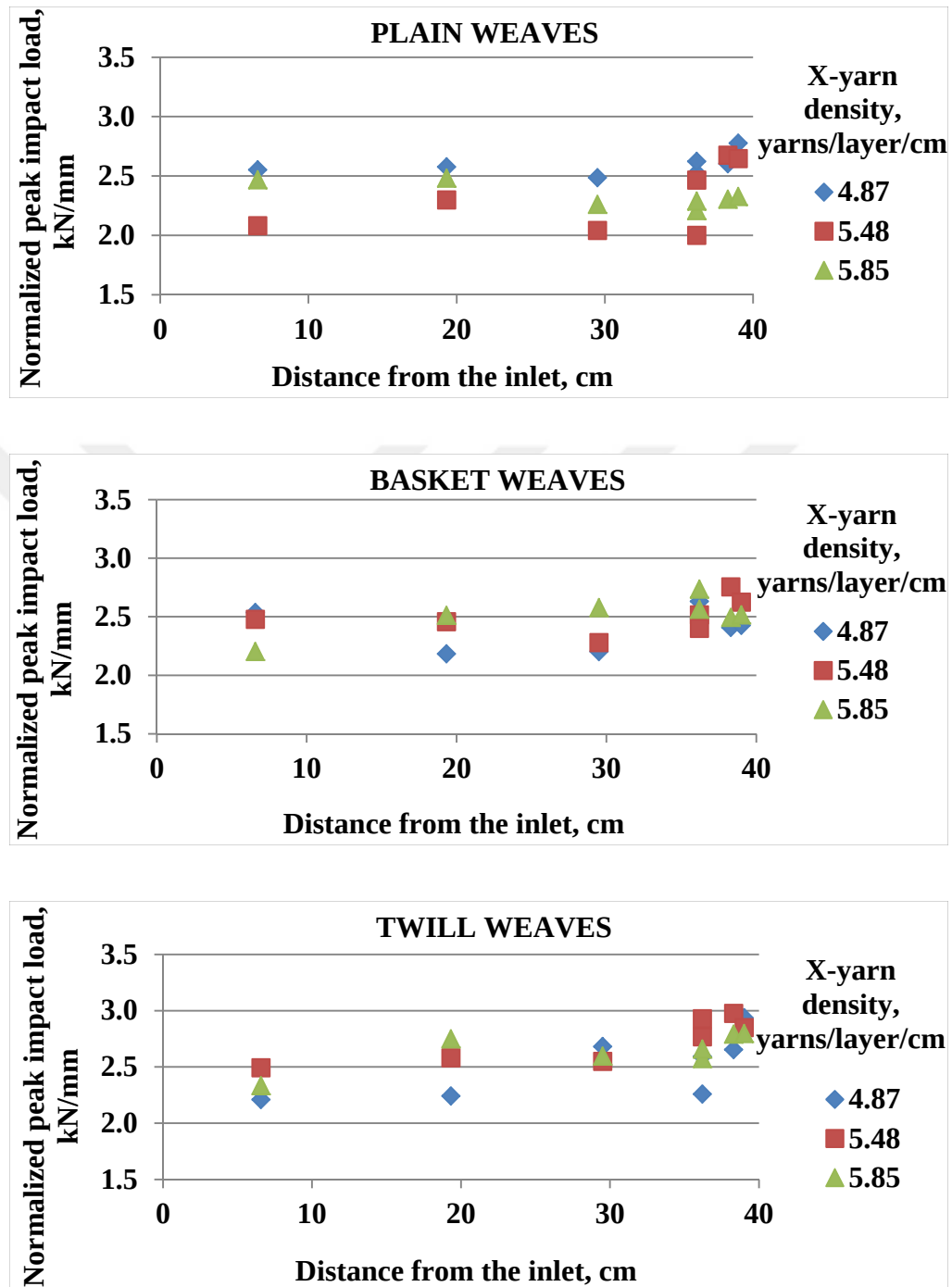


Figure O.2. Normalized peak impact load profile of 2 layers composites manufactured at 100 kPa vacuum

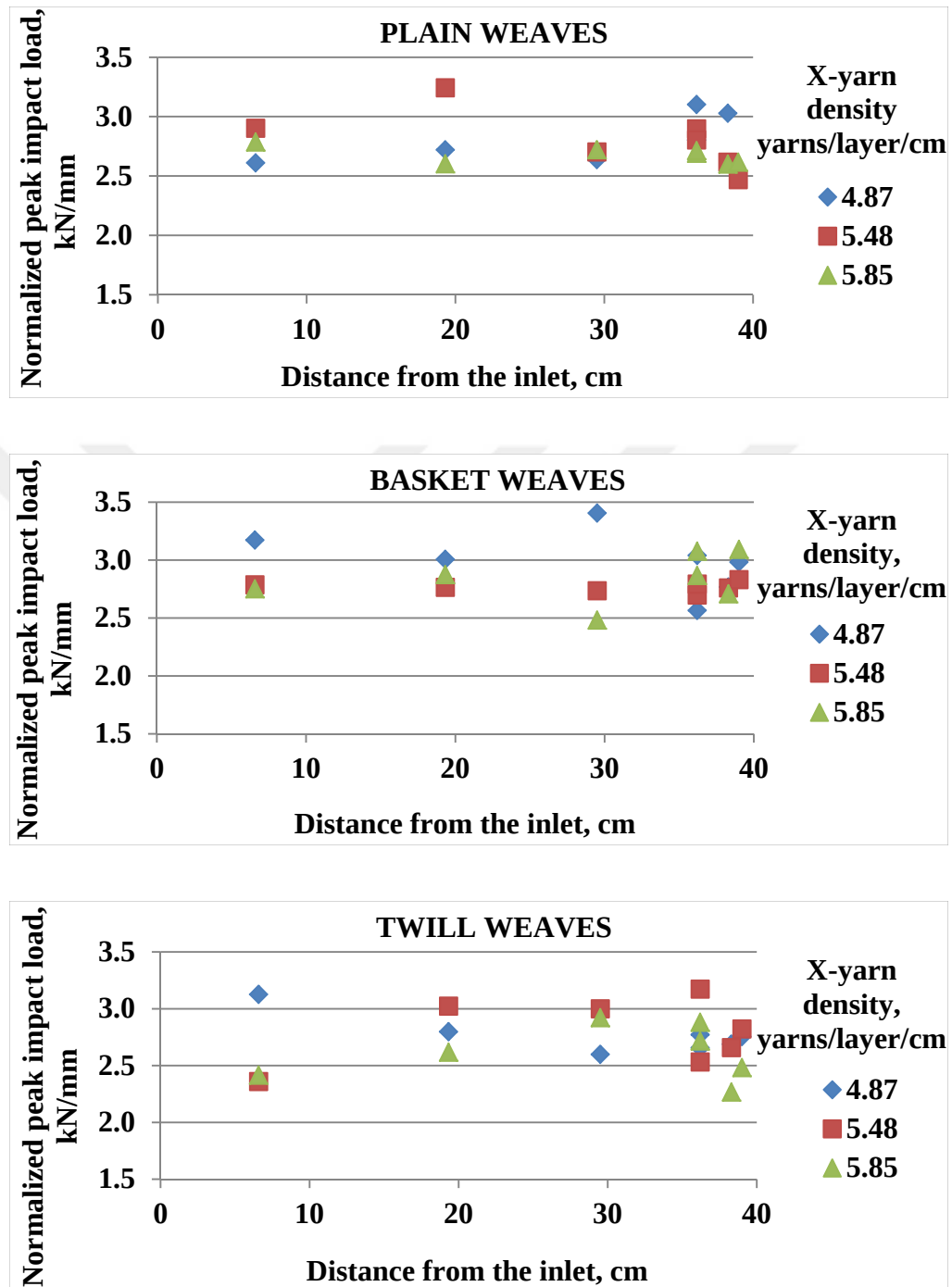


Figure O.3. Normalized peak impact load profile of 4 layers composites manufactured at 75 kPa vacuums

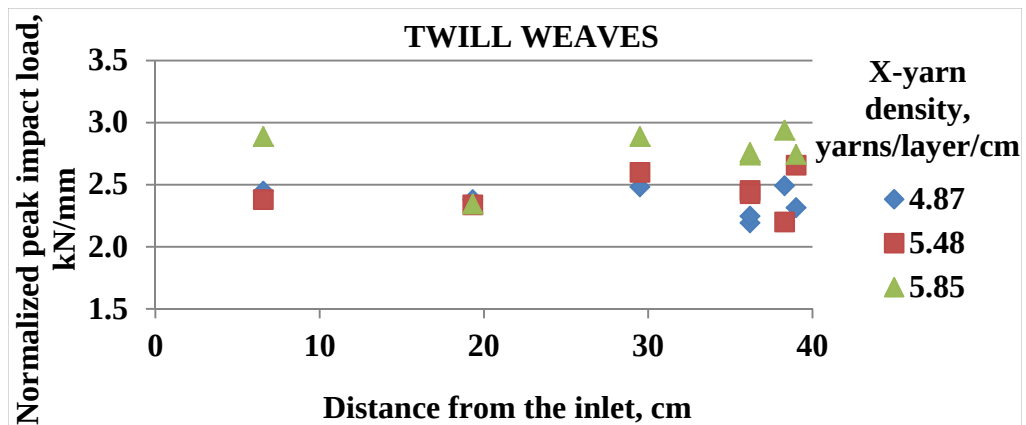
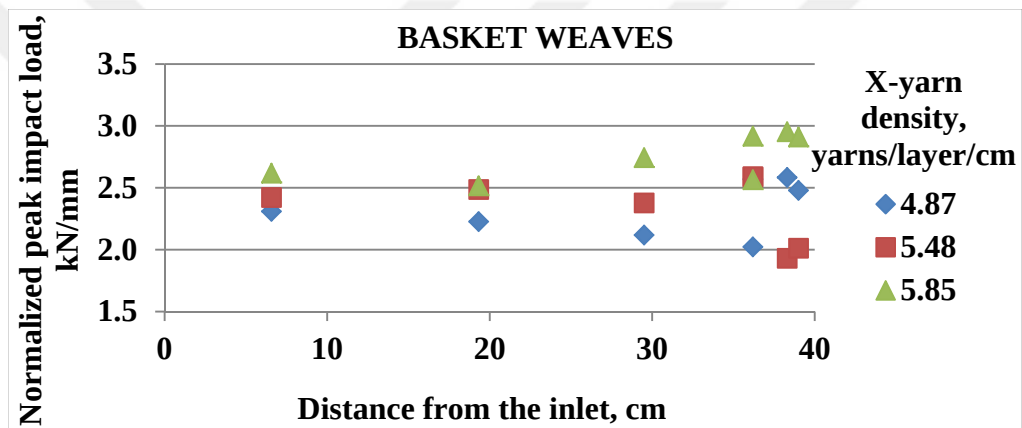
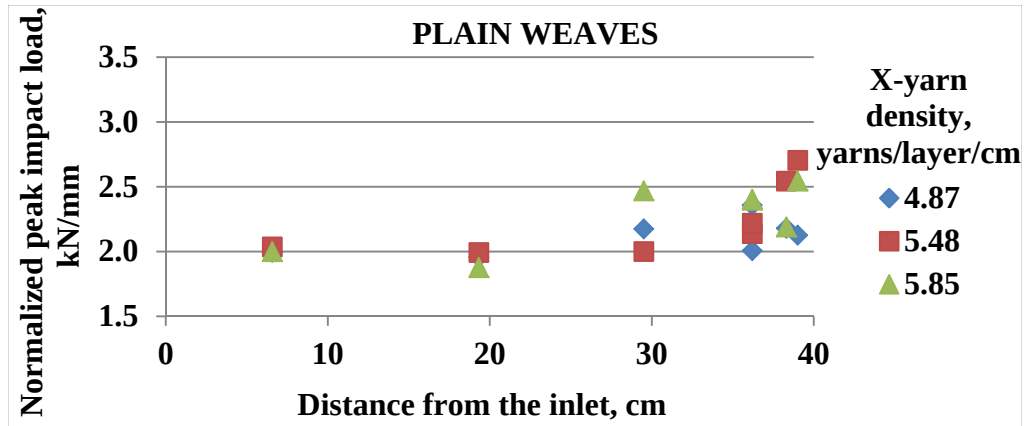


Figure O.4. Normalized peak impact load profile of 4 layers composites manufactured at 100 kPa vacuums

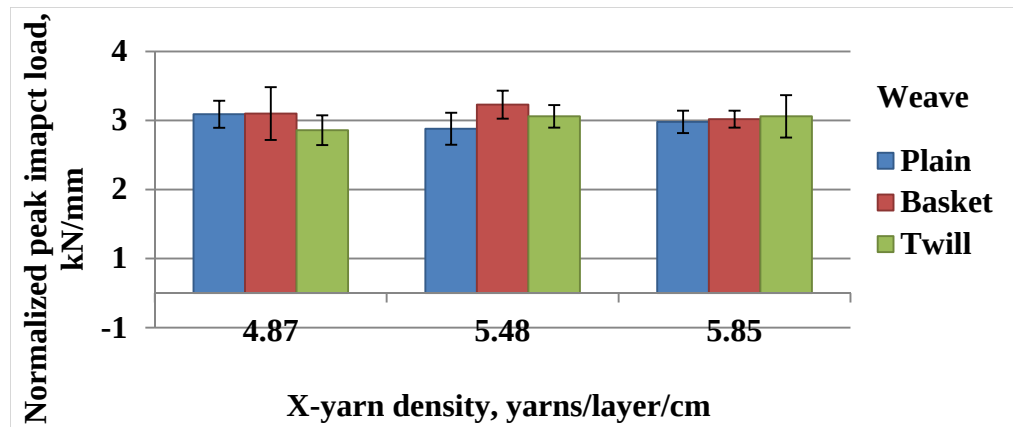


Figure O.5. Normalized peak impact load of 2 layers composites manufactured at 75 kPa vacuums

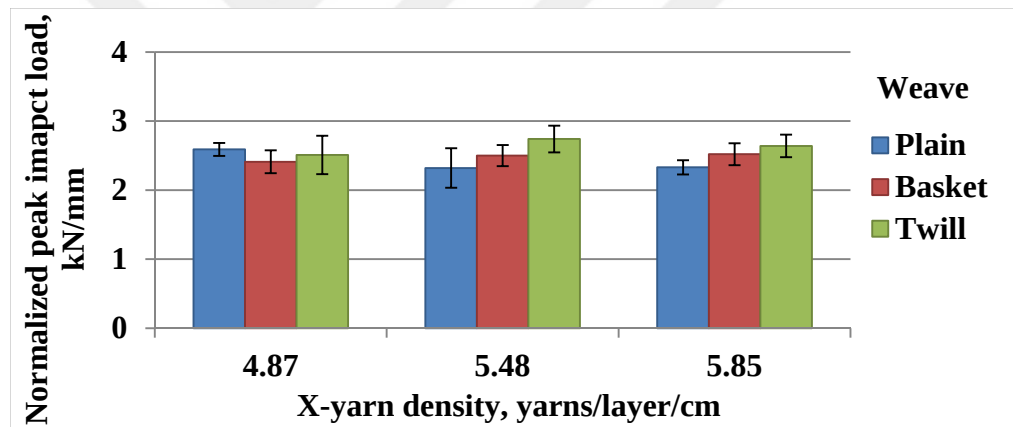


Figure O.6. Normalized peak impact load of 2 layers composites manufactured at 100 kPa vacuums

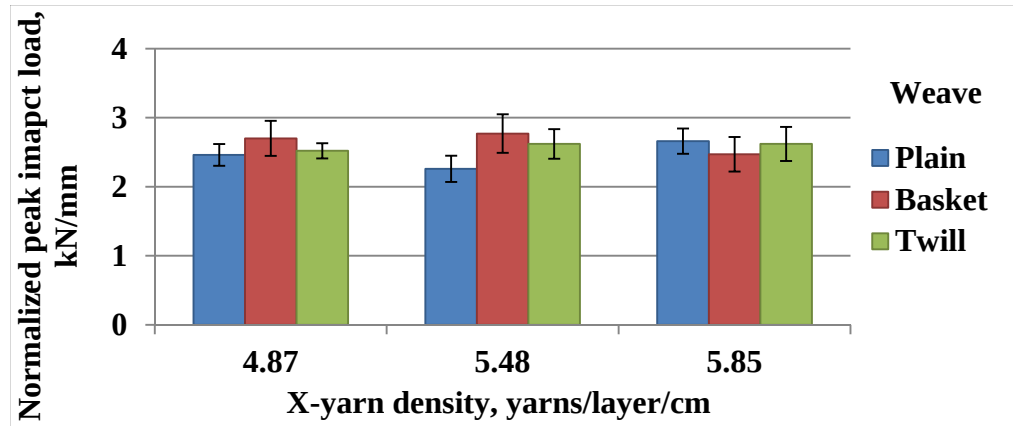


Figure O.7. Normalized peak impact load of 3 layers composites manufactured at 75 kPa vacuums

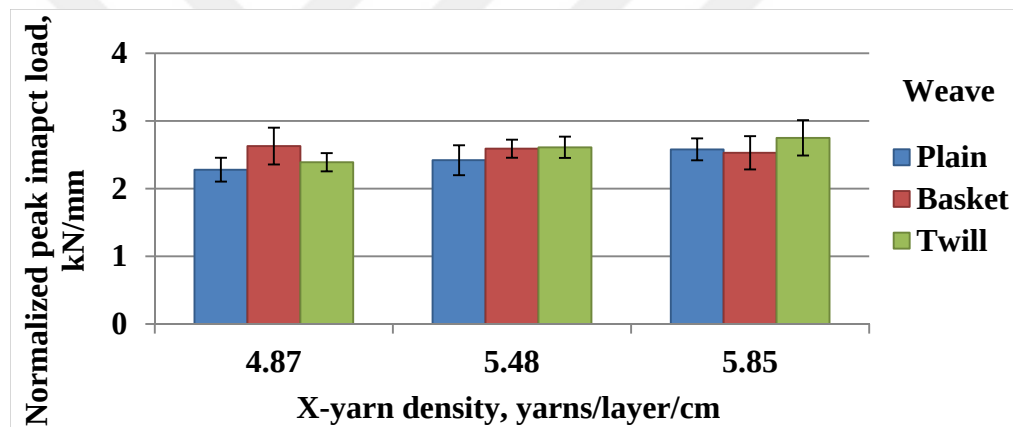


Figure O.8. Normalized peak impact load of 3 layers composites manufactured at 100 kPa vacuums

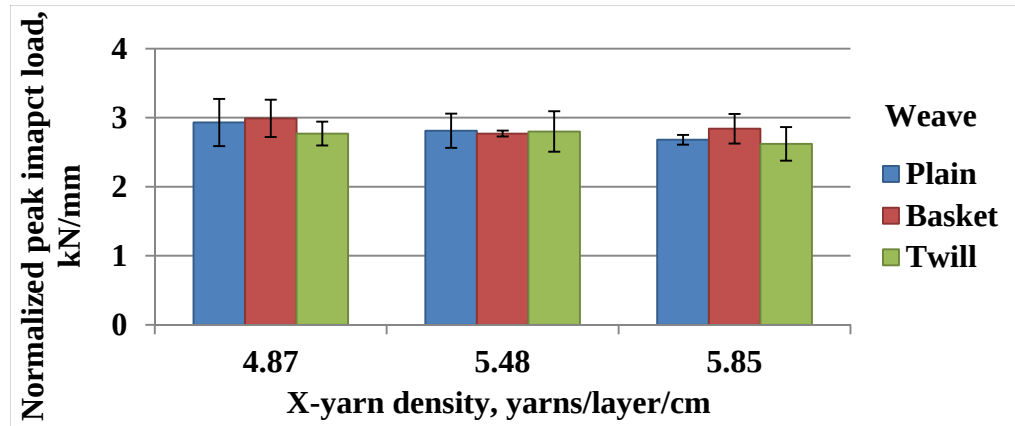


Figure O.9. Normalized peak impact load of 4 layers composites manufactured at 75 kPa vacuums

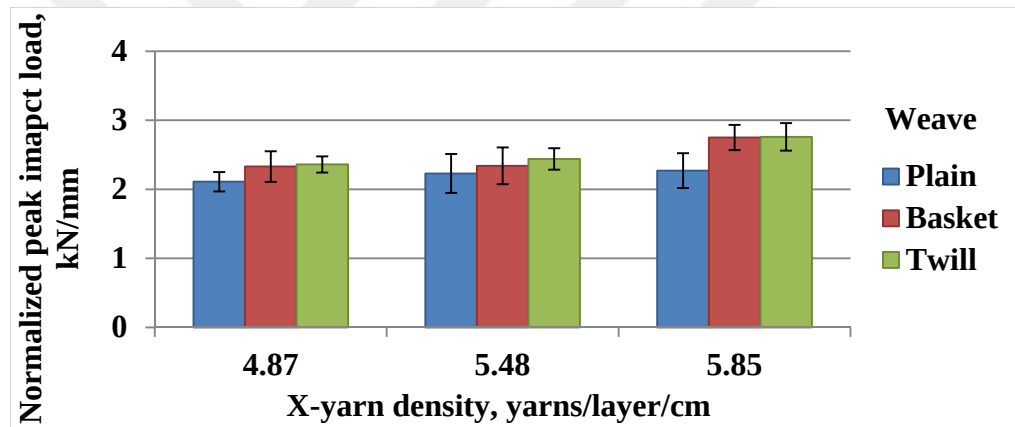


Figure O.10. Normalized peak impact load of 4 layers composites manufactured at 100 kPa vacuums

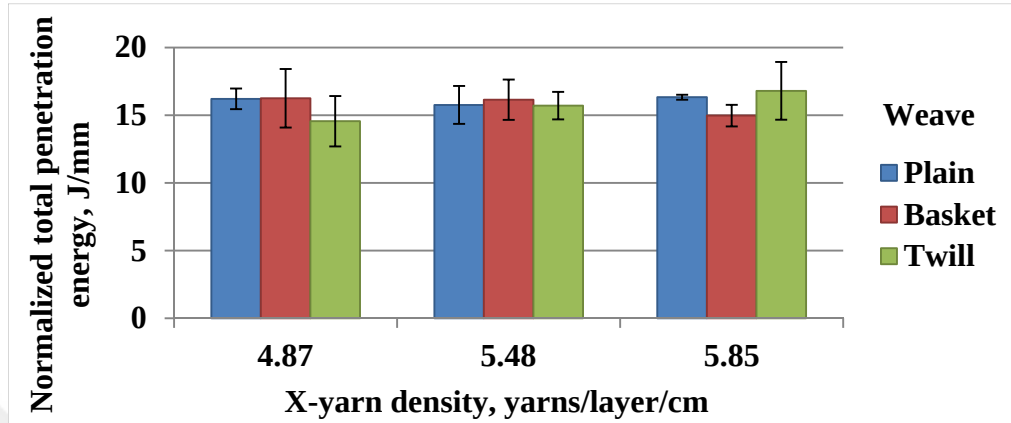


Figure O.11. Normalized total penetration energy of 2 layers composites manufactured at 75 kPa vacuums

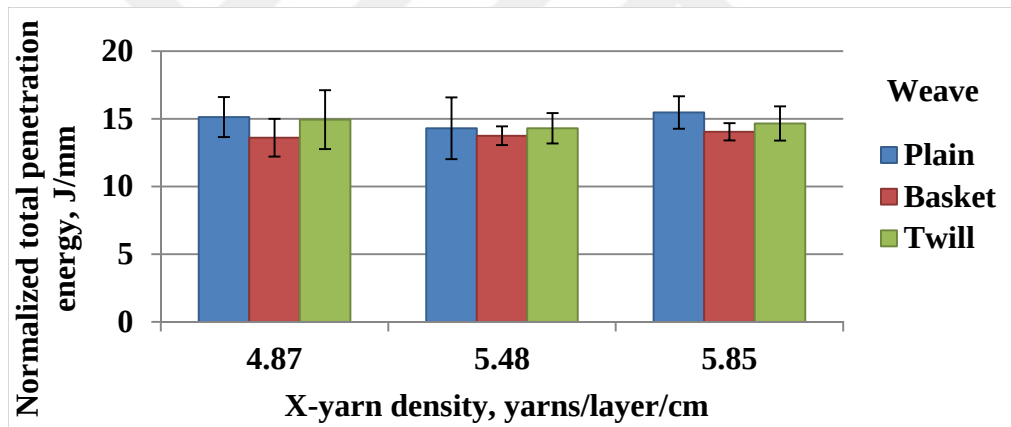


Figure O.12. Normalized total penetration energy of 2 layers composites manufactured at 100 kPa vacuums

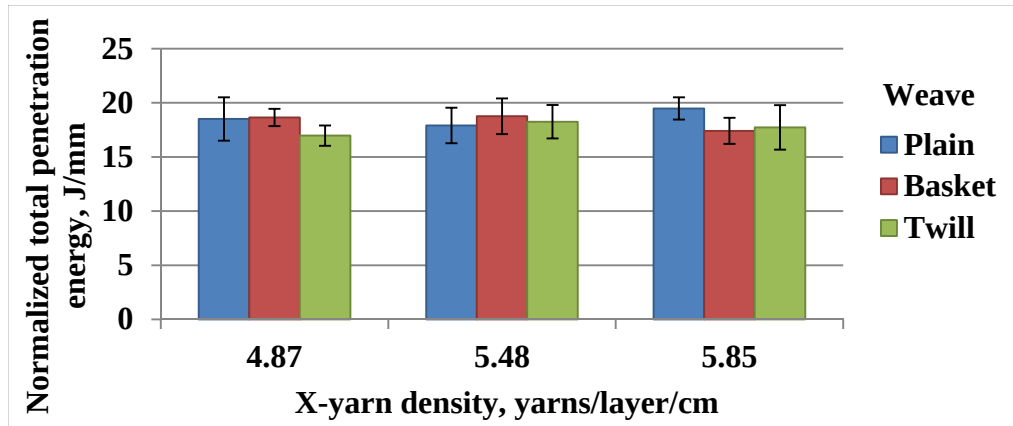


Figure O.13. Normalized total penetration energy of 3 layers composites manufactured at 75 kPa vacuums

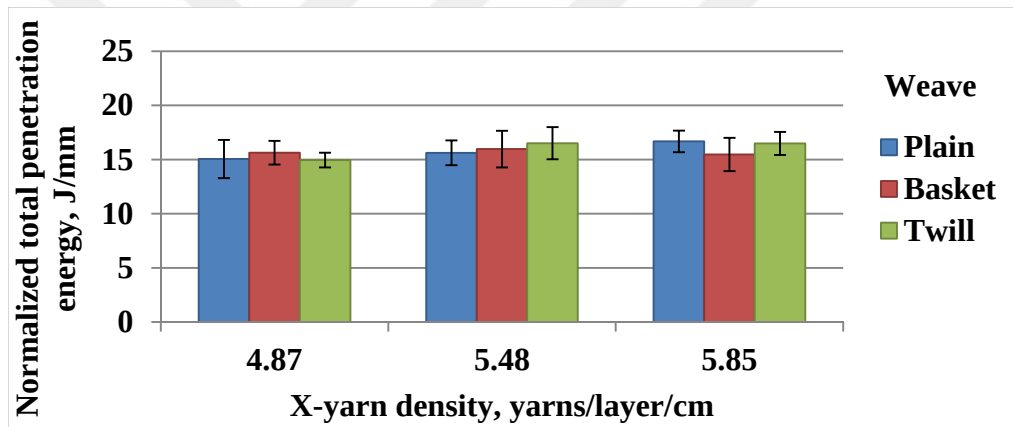


Figure O.14. Normalized total penetration energy of 3 layers composites manufactured at 100 kPa vacuums

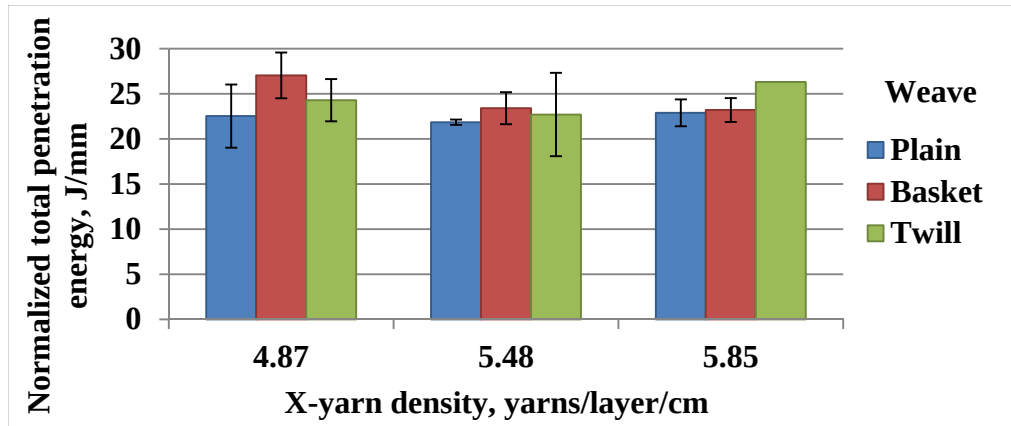


Figure O.15. Normalized total penetration energy of 4 layers composites manufactured at 75 kPa vacuums

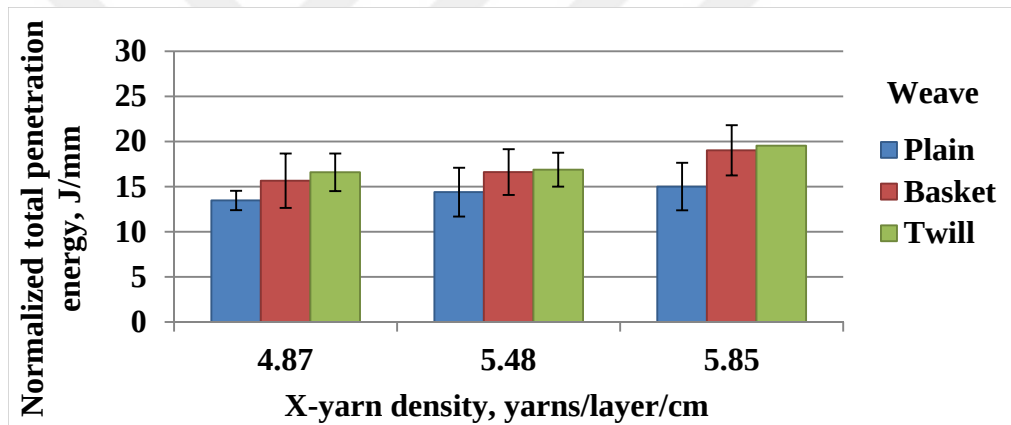


Figure O.16. Normalized total penetration energy of 4 layers composites manufactured at 100 kPa vacuums

APPENDIX P: Statistical analysis

Table P.1. Correlation matrix for volume-based thickness of composite

distance from inlet					
0.00	layers				
0.00	0.00	weave			
-0.00	-0.00	-0.00	xden		
0.00	-0.00	0.00	-0.00	pressure	
-0.13	0.95	-0.10	0.12	-0.03	cthick

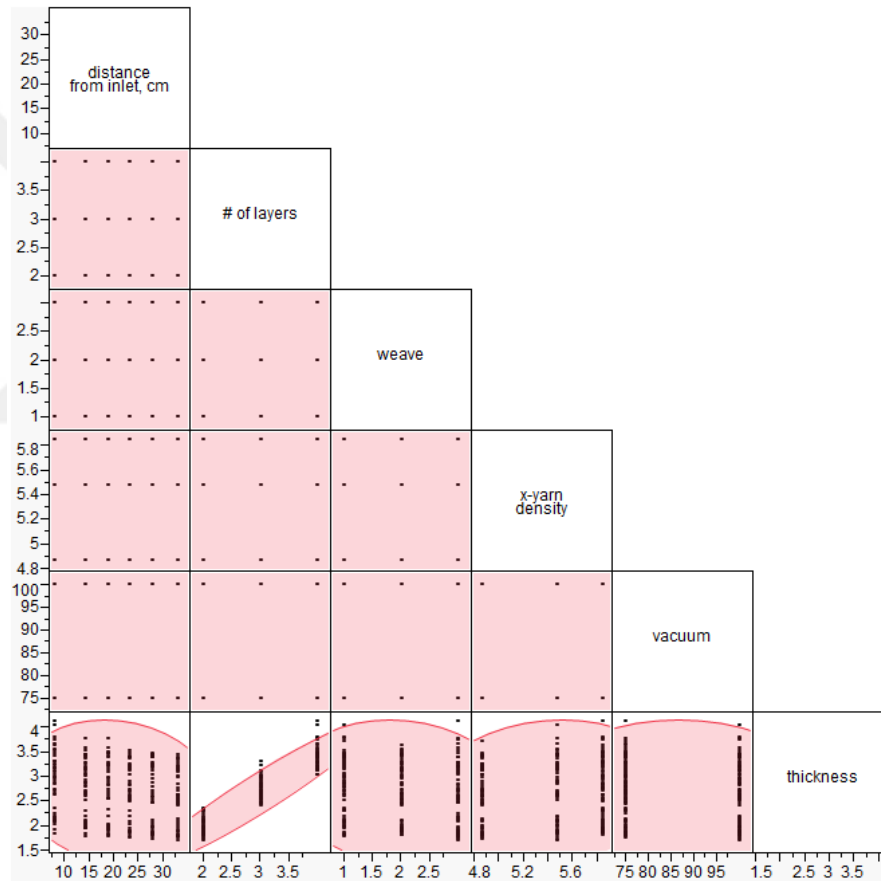


Figure P.1. Scatterplot matrix for volume-based thickness of composite

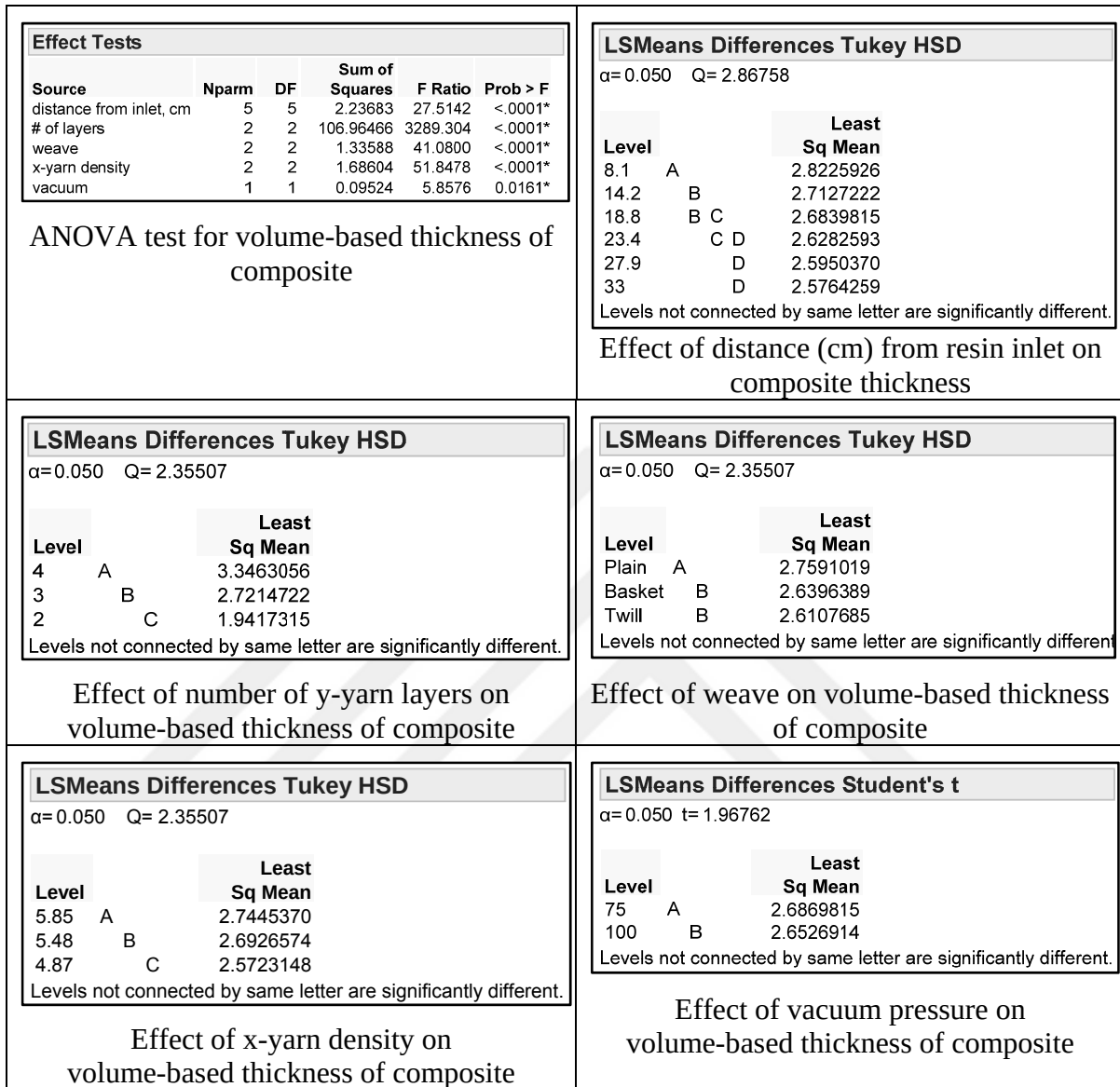


Figure P.2. ANOVA and Tukey multiple means comparison analyses for volume-based thickness of composite

Table P.2. Correlation matrix for composite total FVF

distance from inlet					
0.00	layers				
0.00	0.00	weave			
-0.00	-0.00	-0.00	xden		
0.00	-0.00	0.00	-0.00	pressure	
0.48	0.29	0.39	0.19	0.11	total FVF

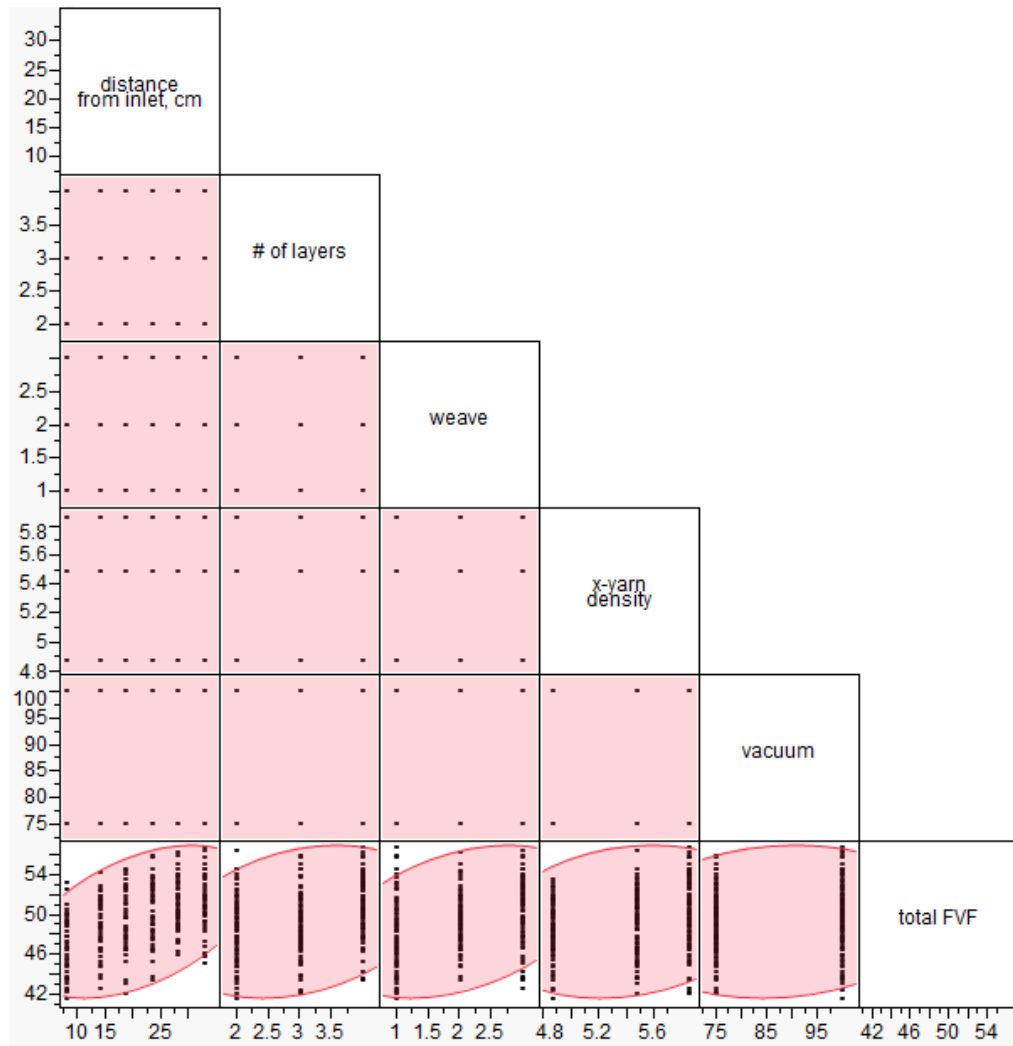


Figure P.3. Scatterplot matrix for composite total FVF

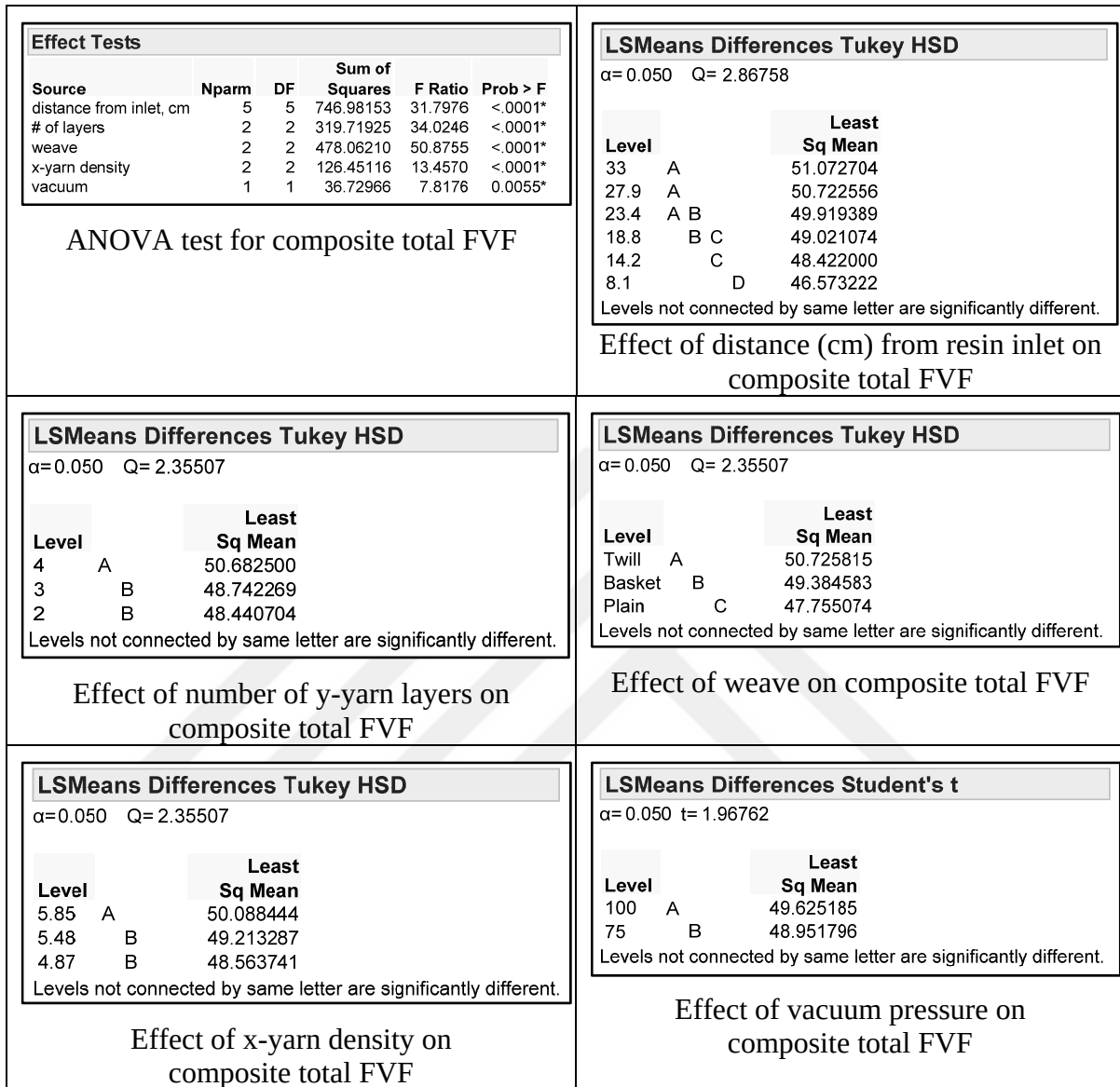


Figure P.4. ANOVA and Tukey multiple means comparison analyses for composite total FVF

Table P.3. Correlation matrix for composite void content

distance from inlet					
0.00	layers				
0.00	0.00	weave			
-0.00	-0.00	-0.00	xden		
0.00	-0.00	0.00	-0.00	pressure	
0.04	0.15	-0.32	-0.26	-0.22	void content

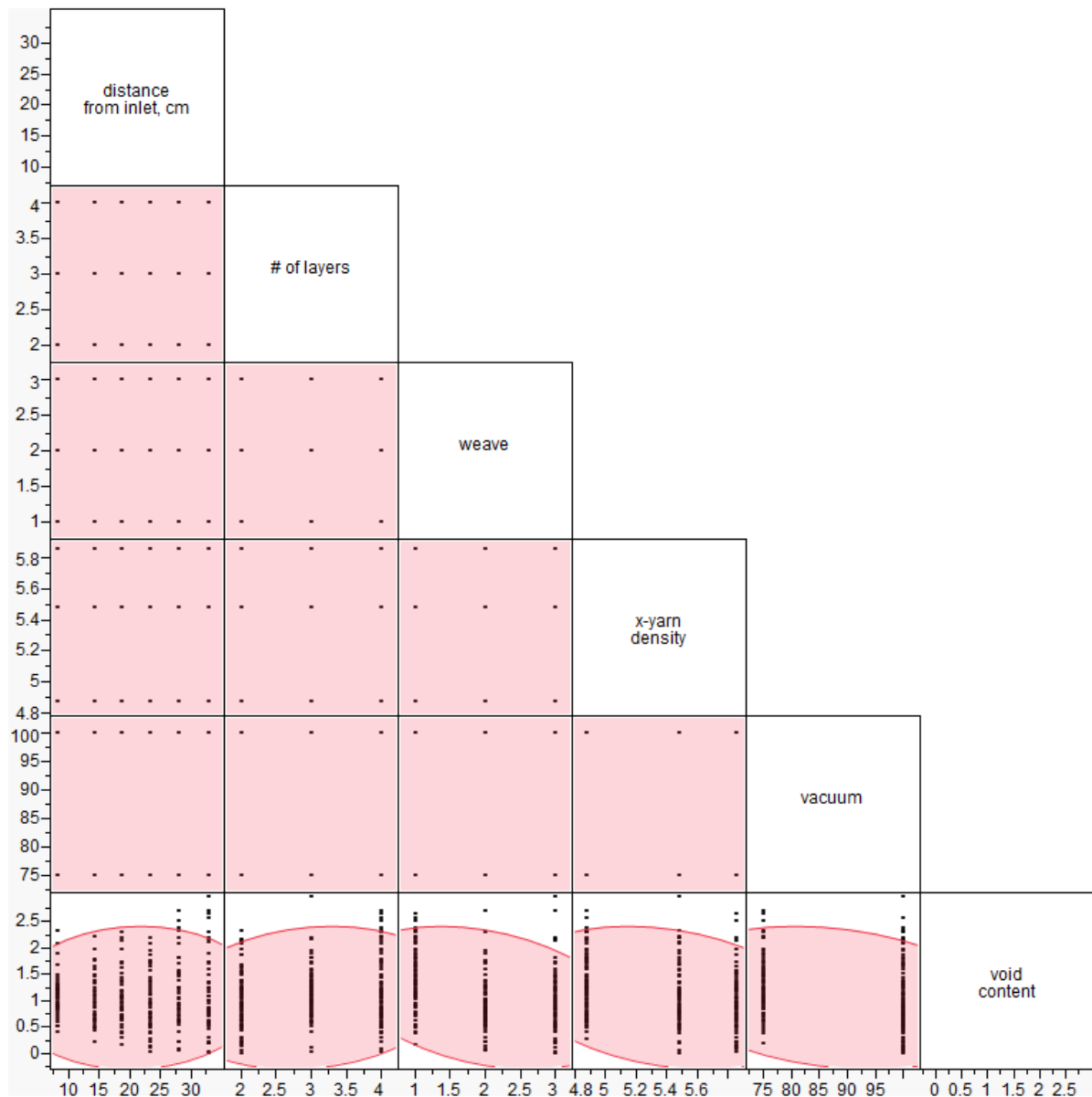


Figure P.5. Scatterplot matrix for composite void content

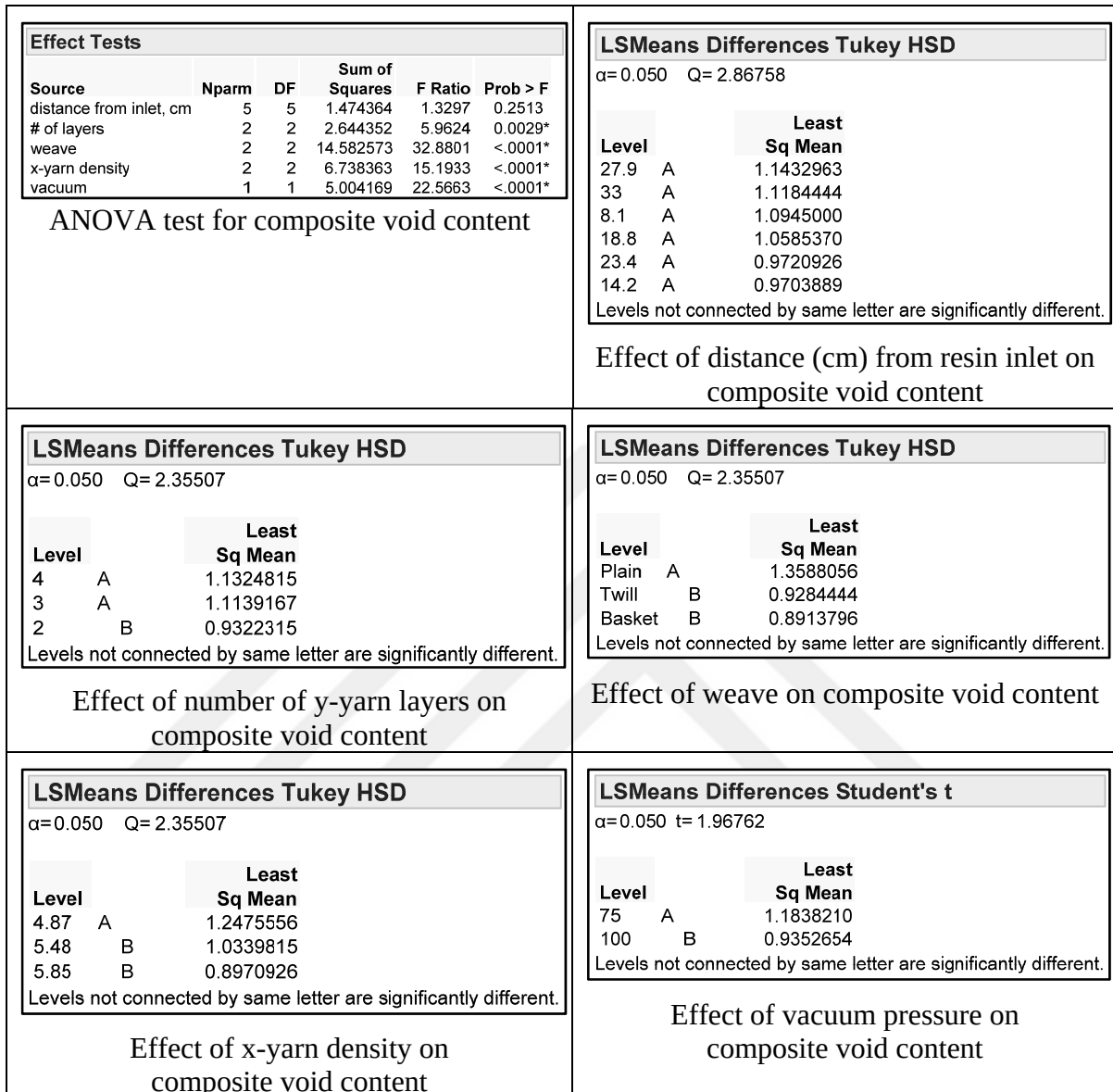


Figure P.6. ANOVA and Tukey multiple means comparison analyses for composite void content

Table P.4. Correlation matrix for peak tensile stress in x-direction

layers												
-0.00	xden											
0.00	0.00	weave										
0.00	-0.00	-0.00	pressure									
0.93	0.35	0.01	0.00	xweight								
0.98	0.14	-0.06	0.01	0.96	areal							
0.96	0.14	-0.10	-0.01	0.95	0.99	cthick						
0.12	0.01	0.37	-0.02	0.12	0.06	0.00	tfvf					
-0.76	-0.01	-0.19	-0.01	-0.71	-0.75	-0.74	0.28	zfvf				
0.48	-0.35	0.31	-0.02	0.33	0.38	0.32	0.85	-0.08	yfvf			
-0.20	0.36	0.36	-0.02	-0.05	-0.20	-0.24	0.88	0.49	0.50	xfvf		
-0.29	0.41	0.37	0.16	-0.12	-0.28	-0.36	0.29	0.30	-0.03	0.51	tensile-x	

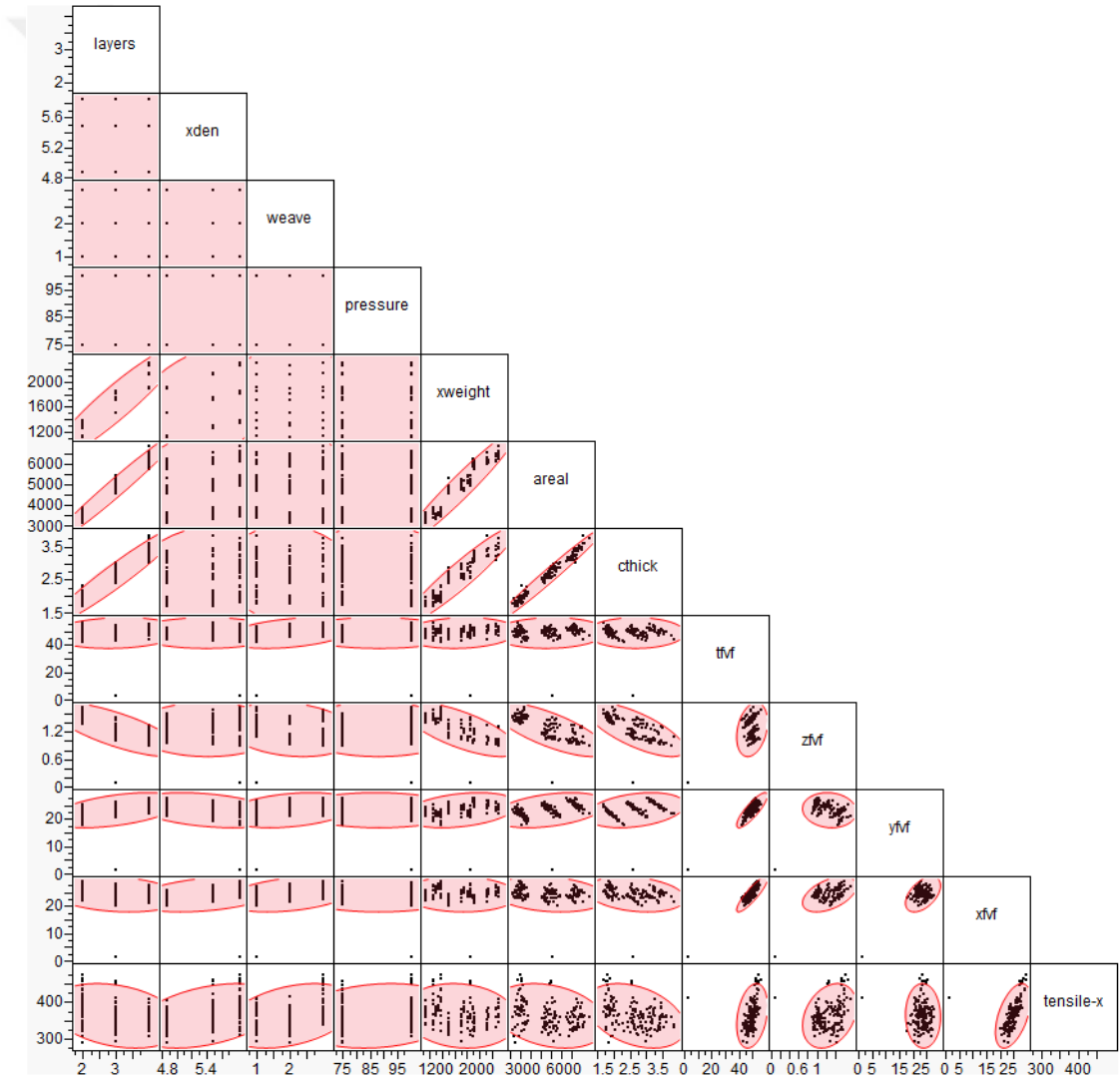


Figure P.7. Scatterplot matrix for peak tensile stress in x-direction

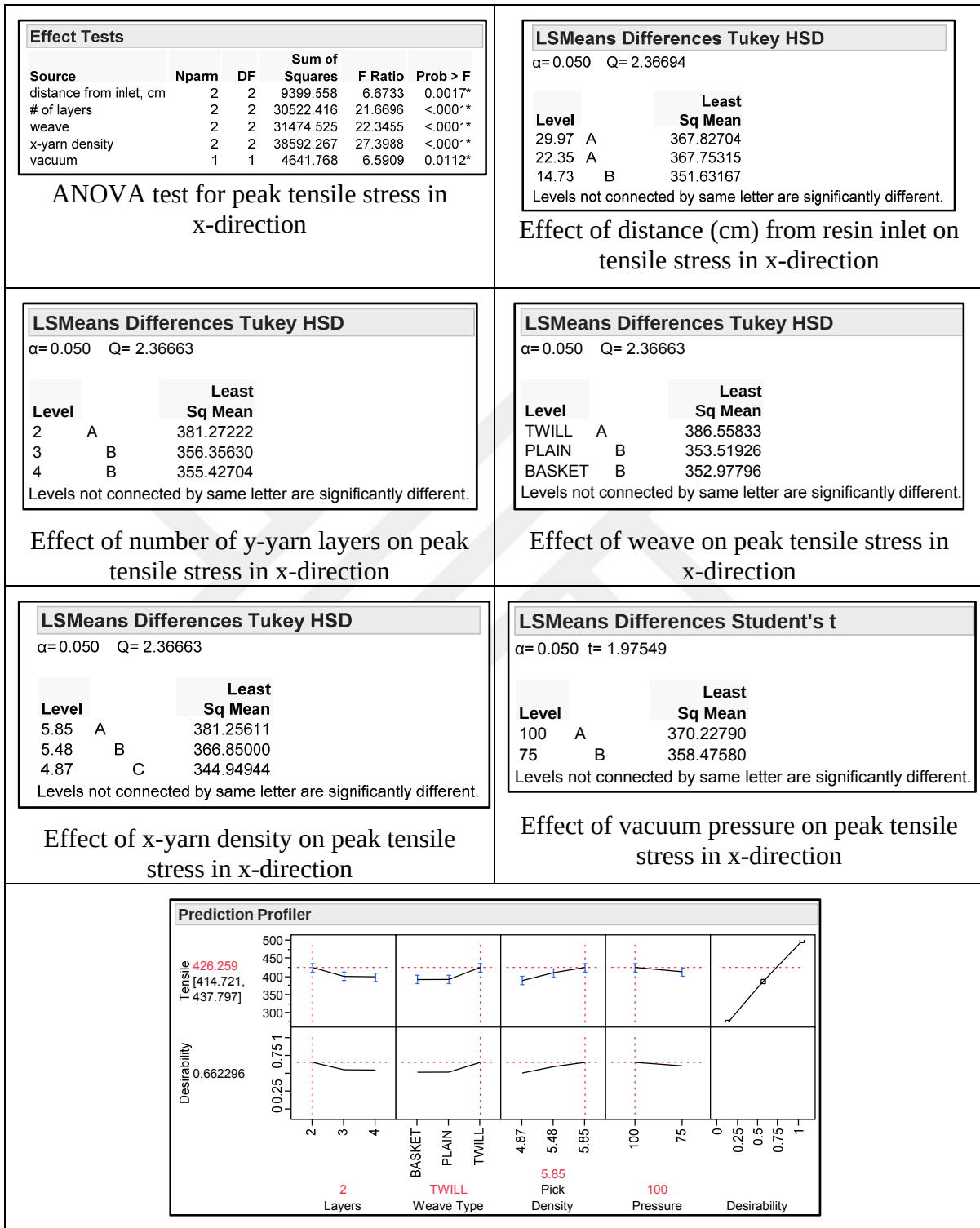


Figure P.8. ANOVA and Tukey multiple means comparison analyses for peak tensile stress in x-direction

Table P.5. Correlation matrix for peak tensile stress in y-direction

layers												
-0.00	xden											
0.00	0.00	weave										
0.00	-0.00	-0.00	pressure									
1.00	0.00	0.00	0.00	yweight								
0.98	0.13	-0.07	0.05	0.98	areal							
0.96	0.11	-0.11	0.01	0.96	0.98	cthick						
0.24	0.25	0.46	0.00	0.24	0.16	0.03	tfvf					
-0.80	0.07	-0.26	0.00	-0.80	-0.79	-0.80	-0.01	zfvf				
-0.21	0.65	0.37	0.01	-0.21	-0.21	-0.31	0.79	0.34	xfvf			
0.68	-0.29	0.34	-0.00	0.68	0.55	0.46	0.72	-0.48	0.15	yfvf		
0.43	-0.26	0.31	0.12	0.44	0.33	0.23	0.61	-0.29	0.19	0.78	tensile-y	

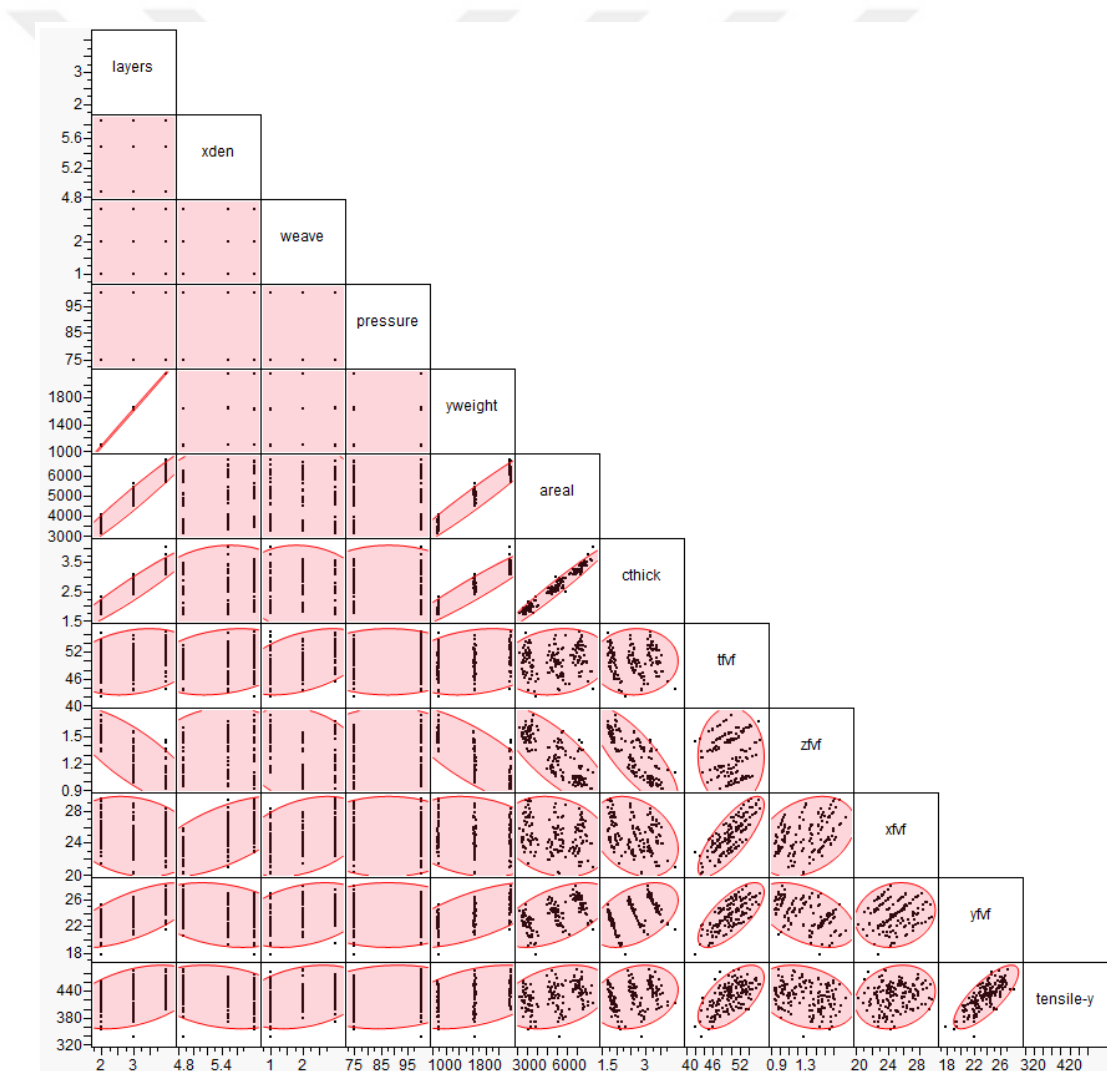


Figure P.9. Scatterplot matrix for peak tensile stress in y-direction

Table P.6. Correlation matrix for peak flexure stress in x-direction

layers												
-0.00	xden											
0.00	0.00	weave										
0.00	-0.00	-0.00	pressure									
0.93	0.35	0.01	0.00	xweight								
0.98	0.13	-0.06	0.00	0.96	areal							
0.96	0.12	-0.12	-0.02	0.94	0.99	cthick						
0.33	0.23	0.47	0.09	0.40	0.25	0.14	tfvf					
-0.79	0.06	-0.26	0.03	-0.71	-0.78	-0.77	-0.11	zfvf				
0.72	-0.30	0.33	0.06	0.57	0.60	0.52	0.73	-0.53	yfvf			
-0.16	0.65	0.40	0.07	0.09	-0.15	-0.24	0.77	0.28	0.14	xfvf		
-0.68	0.12	0.08	0.04	-0.60	-0.65	-0.68	-0.01	0.64	-0.41	0.34	flexure-x	

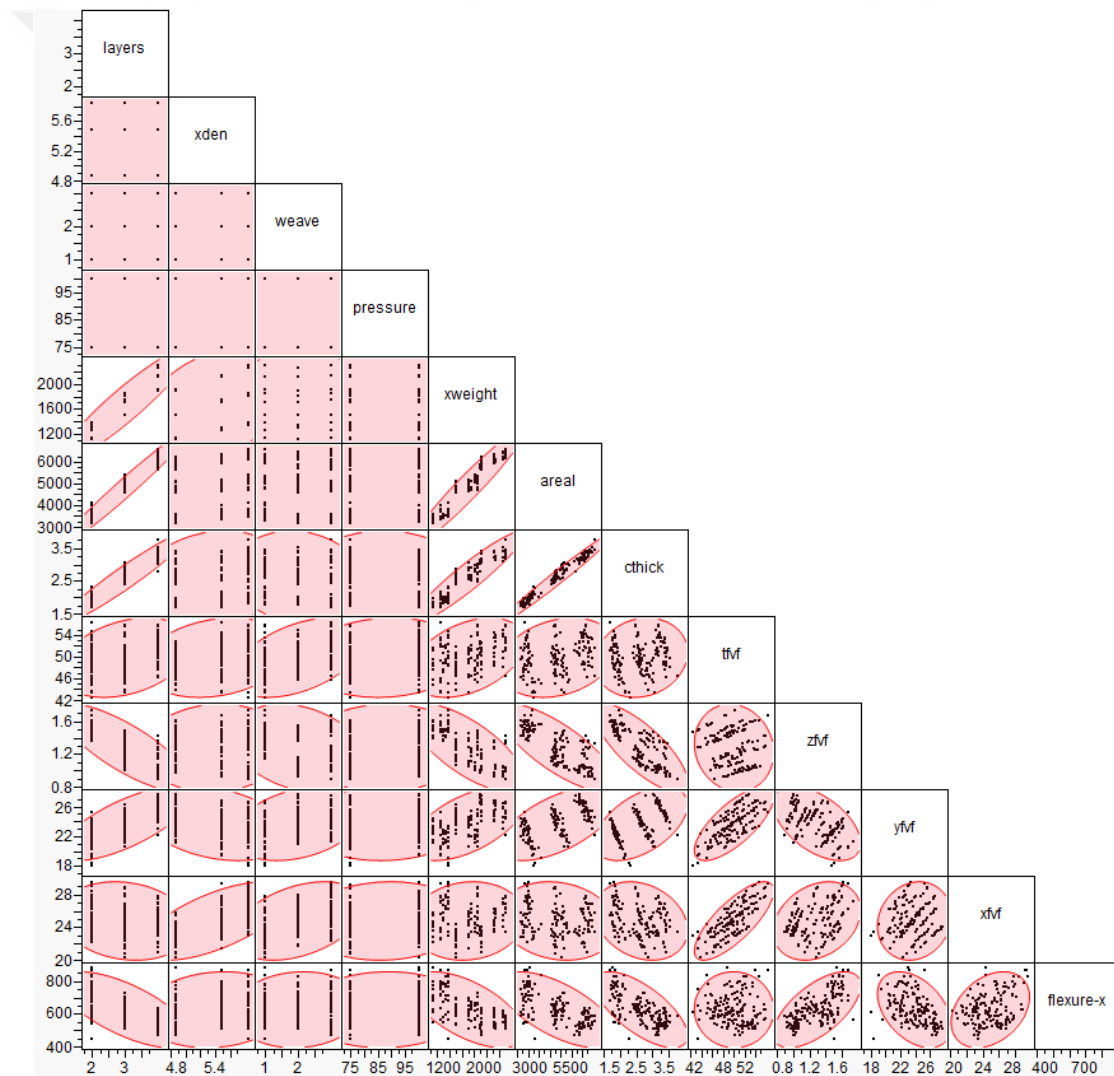


Figure P.11. Scatterplot matrix for peak flexure stress in x-direction

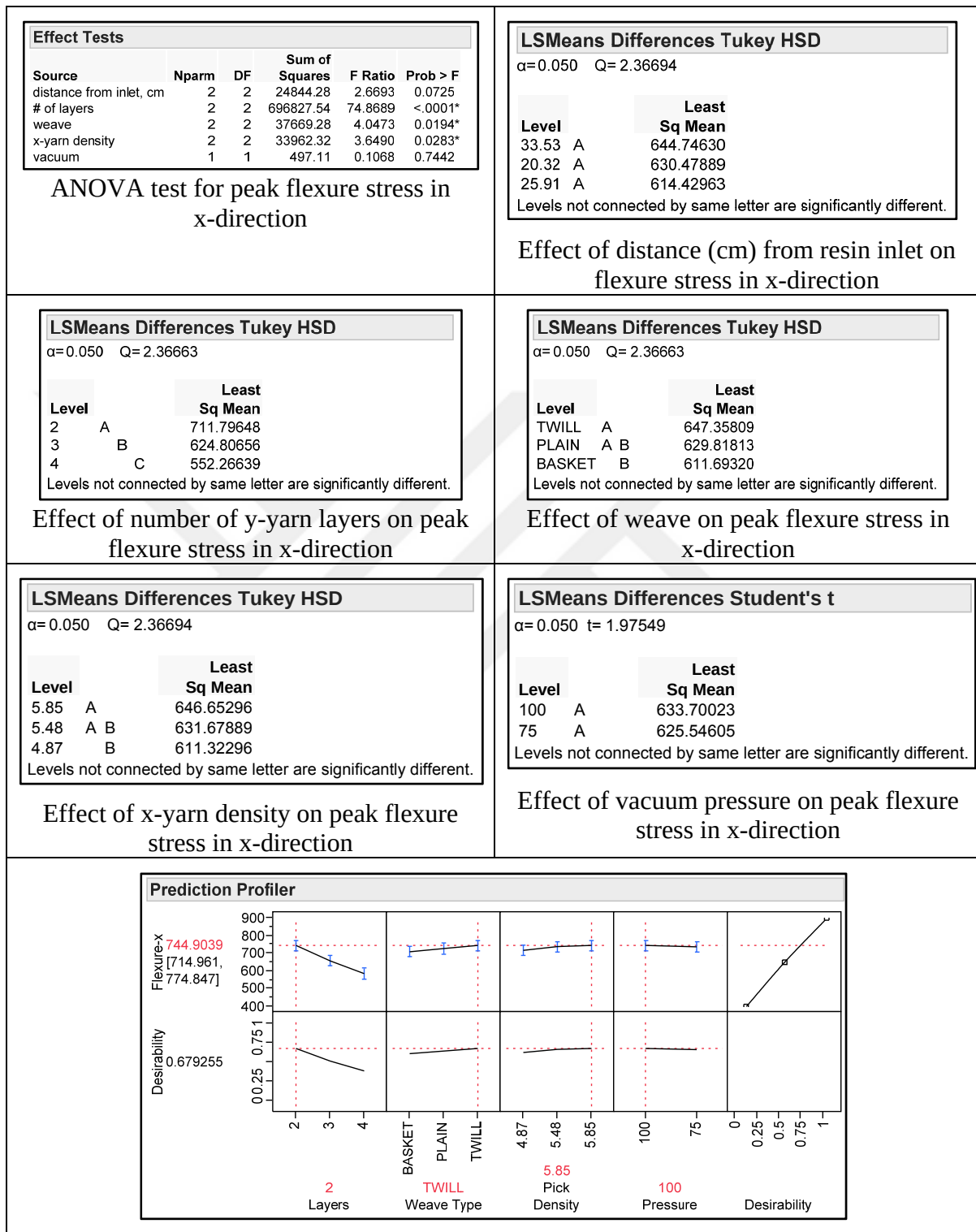


Figure P.12. ANOVA and Tukey multiple means comparison analyses for peak flexure stress in x-direction

Table P.7. Correlation matrix for peak flexure stress in y-direction

layers												
0.00	xden											
-0.00	0.00	weave										
0.00	0.00	0.00	pressure									
1.00	0.00	0.00	0.00	yweight								
0.97	0.12	-0.08	-0.00	0.97	areal							
0.96	0.10	-0.10	-0.02	0.95	0.99	cthick						
0.32	0.24	0.37	0.09	0.32	0.19	0.09	tfvf					
-0.78	0.08	-0.28	0.04	-0.78	-0.77	-0.78	-0.04	zfvf				
-0.13	0.64	0.33	0.08	-0.13	-0.18	-0.26	0.80	0.30	xfvf			
0.70	-0.26	0.28	0.06	0.70	0.54	0.47	0.76	-0.46	0.23	yfvf		
-0.27	-0.15	0.17	0.08	-0.28	-0.36	-0.44	0.38	0.33	0.37	0.20	flexure-y	

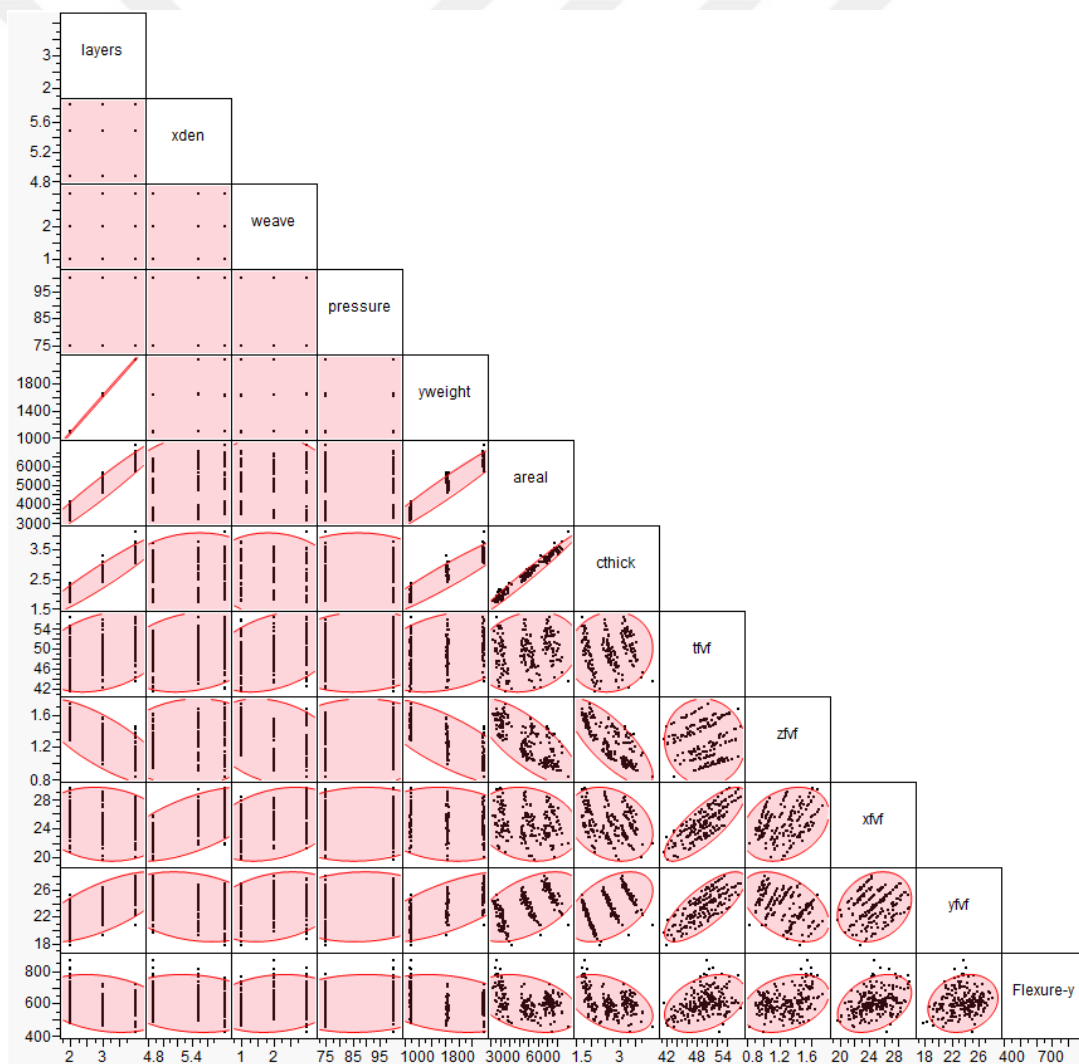


Figure P.13. Scatterplot matrix for peak flexure stress in y-direction

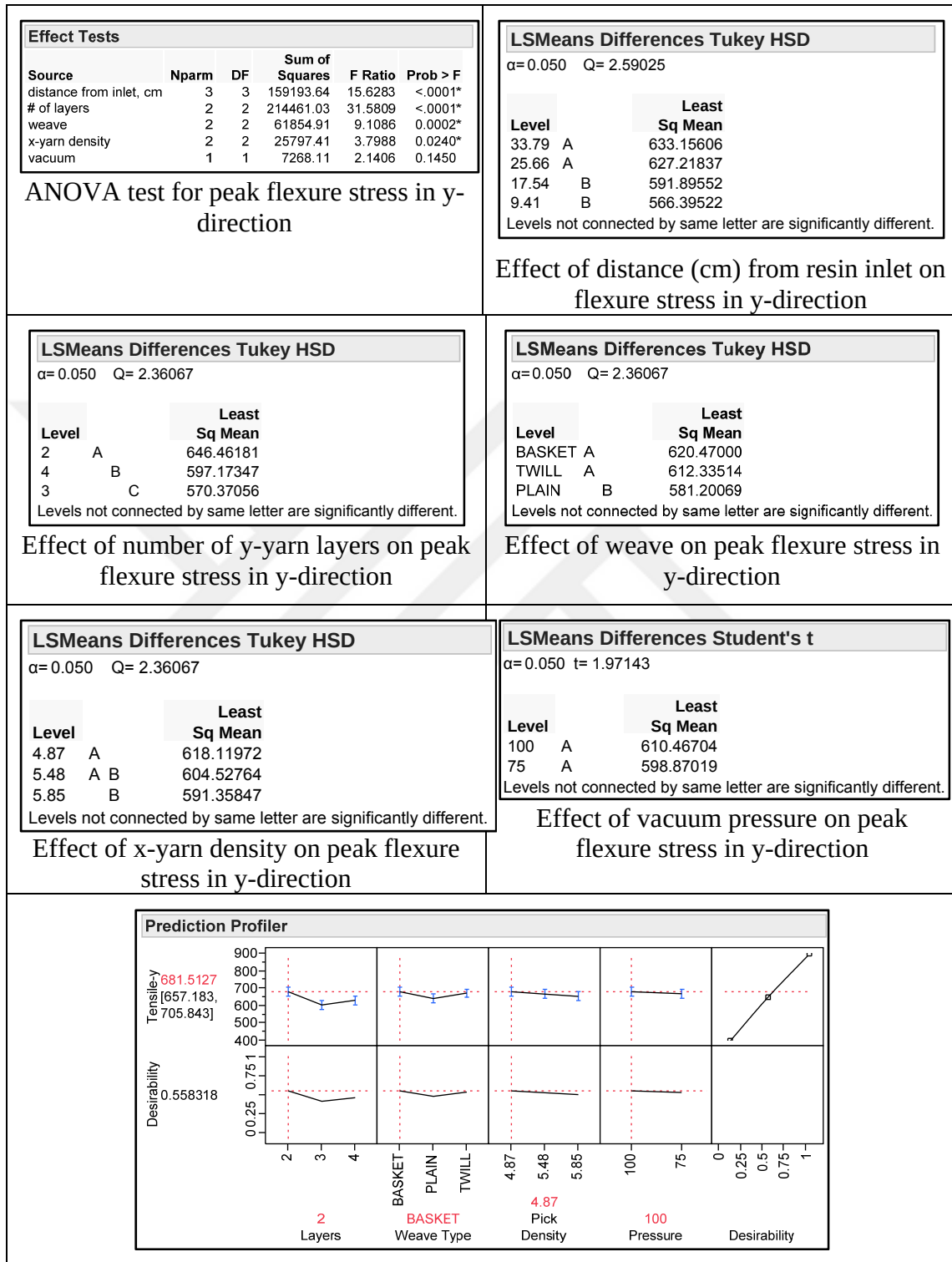


Figure P.14. ANOVA and Tukey multiple means comparison analyses for peak flexure stress in y-direction

Table P.8. Correlation matrix for normalized peak impact load

layers													
-0.00	xden												
-0.00	0.00	weave											
0.00	0.00	-0.00	pressure										
0.93	0.35	0.01	0.00	xweight									
1.00	0.00	0.00	0.00	0.93	yweight								
0.95	0.15	-0.02	0.00	0.95	0.95	areal							
0.91	0.14	-0.04	-0.03	0.90	0.91	0.95	cthick						
-0.23	0.51	0.24	0.07	-0.03	-0.23	-0.27	-0.38	xfvf					
0.57	-0.33	0.21	0.05	0.42	0.57	0.36	0.23	0.31	yfvf				
-0.77	0.03	-0.29	0.03	-0.71	-0.77	-0.77	-0.78	0.44	-0.24	zfvf			
0.16	0.11	0.25	0.08	0.19	0.16	0.01	-0.14	0.83	0.79	0.18	tfvf		
0.18	-0.32	-0.39	-0.28	0.06	0.19	0.17	0.18	-0.40	0.04	-0.02	-0.22	void	
0.13	0.07	0.21	-0.28	0.15	0.13	0.07	-0.08	0.34	0.36	-0.07	0.42	-0.01	impact load

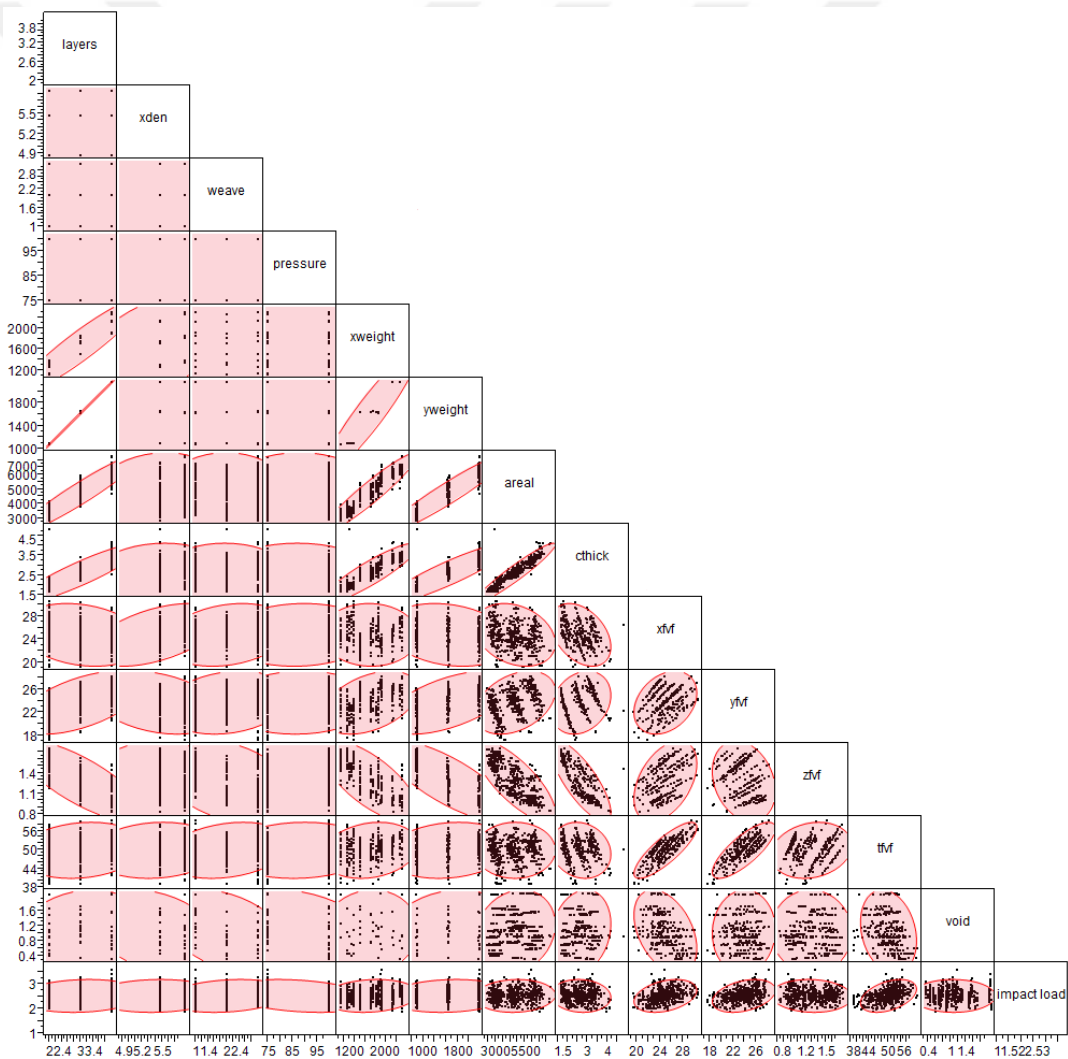


Figure P.15. Scatterplot matrix for normalized peak impact load

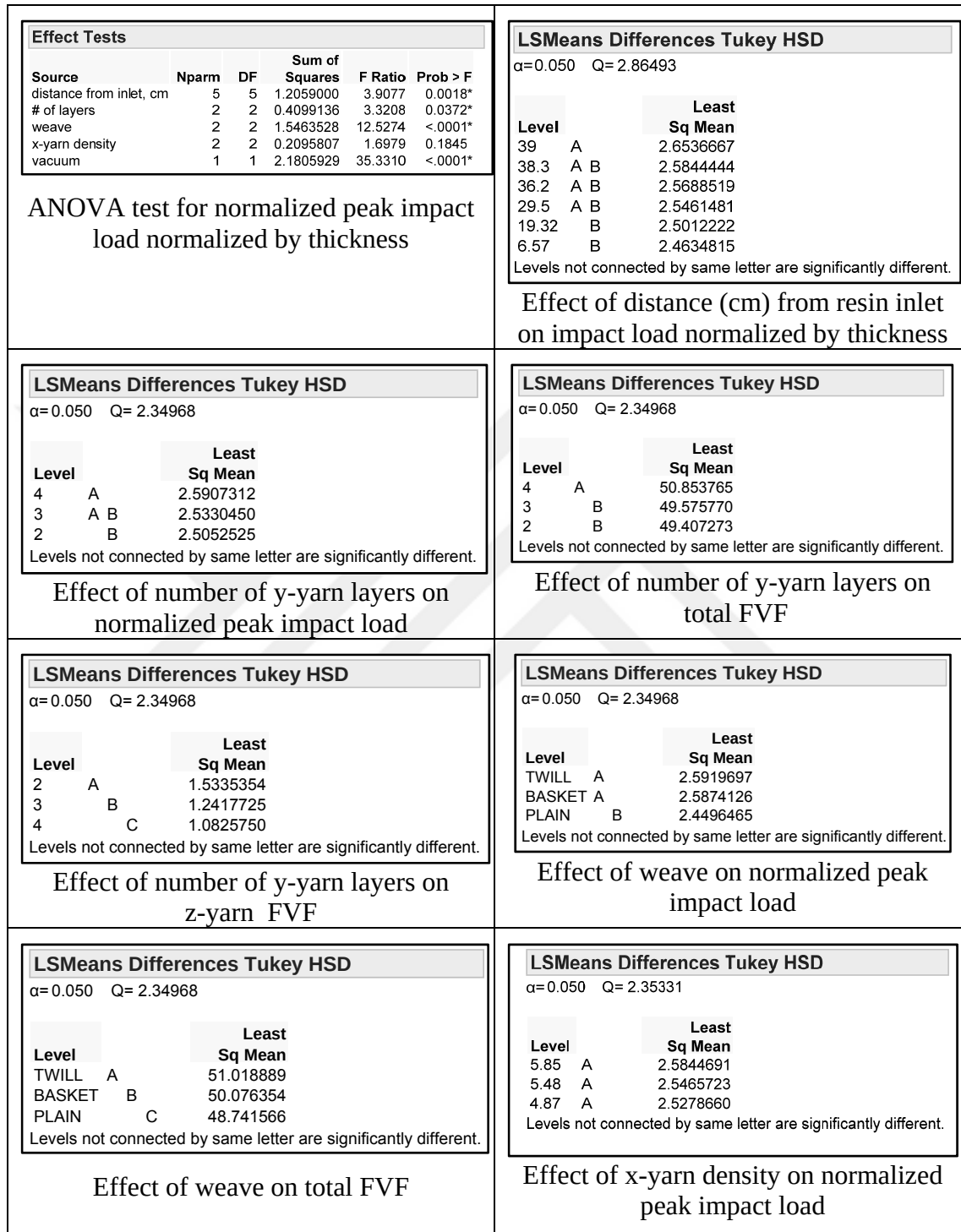


Figure P.16. ANOVA and Tukey multiple means comparison analyses for normalized peak impact load

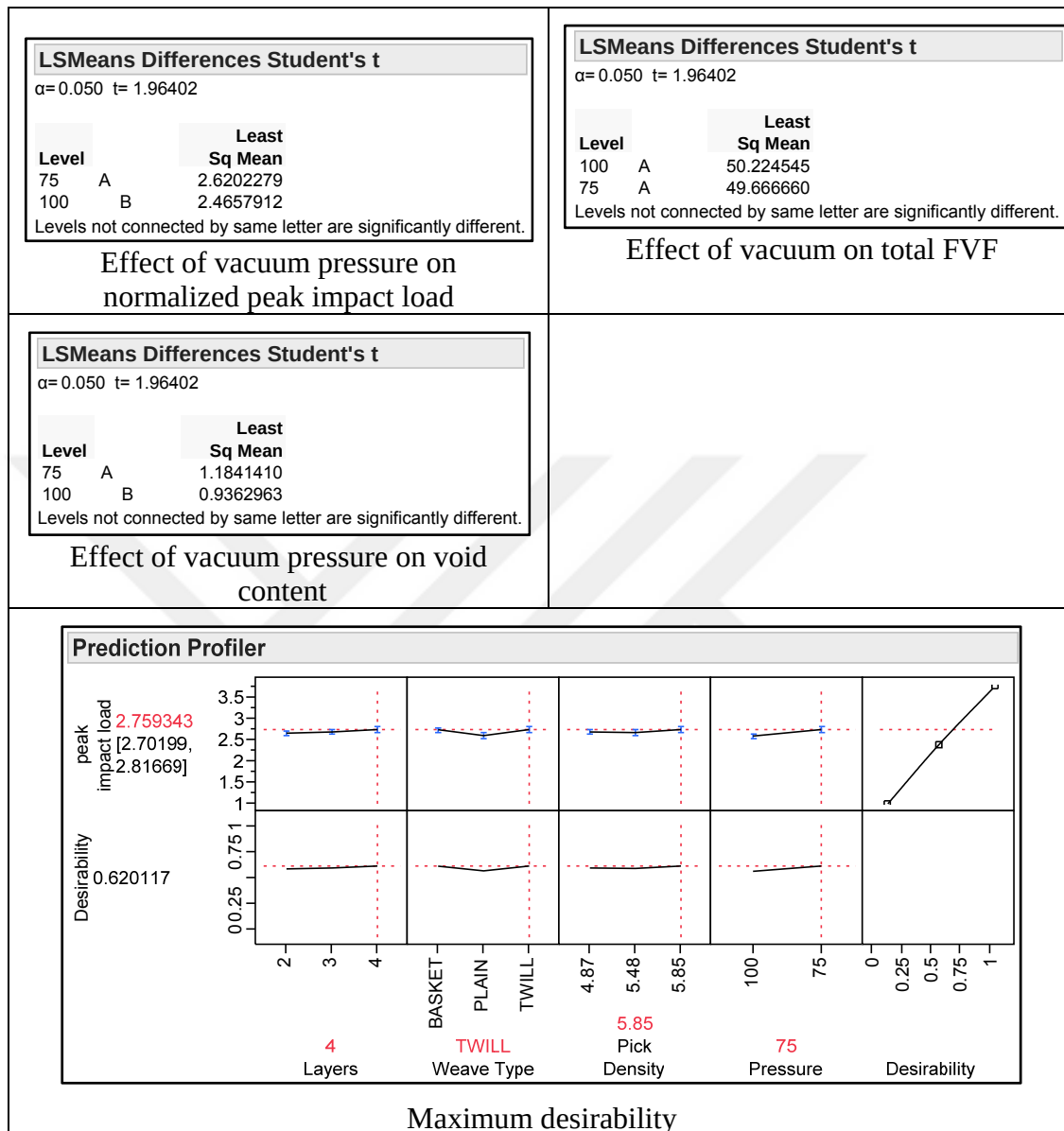


Figure P.16. ANOVA and Tukey multiple means comparison analyses for normalized peak impact load continued

Table P.9. Correlation matrix for normalized total penetration energy

layers														
-0.00	xden													
-0.00	0.00	weave												
0.00	0.00	-0.00	pressure											
0.93	0.35	0.01	0.00	xweight										
1.00	0.00	0.00	0.00	0.93	yweight									
0.96	0.15	-0.03	-0.00	0.96	0.97	areal								
0.92	0.15	-0.05	-0.03	0.91	0.92	0.96	cthick							
-0.22	0.53	0.23	0.08	-0.02	-0.22	-0.25	-0.35	xfvf						
0.60	-0.34	0.20	0.07	0.44	0.60	0.42	0.29	0.26	yfvf					
-0.77	0.03	-0.31	0.04	-0.71	-0.78	-0.77	-0.78	0.42	-0.30	zfvf				
0.19	0.12	0.25	0.10	0.22	0.19	0.06	-0.09	0.81	0.77	0.14	tfvf			
0.19	-0.32	-0.39	-0.28	0.06	0.19	0.16	0.17	-0.38	0.07	-0.01	-0.19	void		
0.56	0.05	0.10	-0.51	0.54	0.56	0.52	0.43	0.05	0.45	-0.41	0.28	0.30	energy	

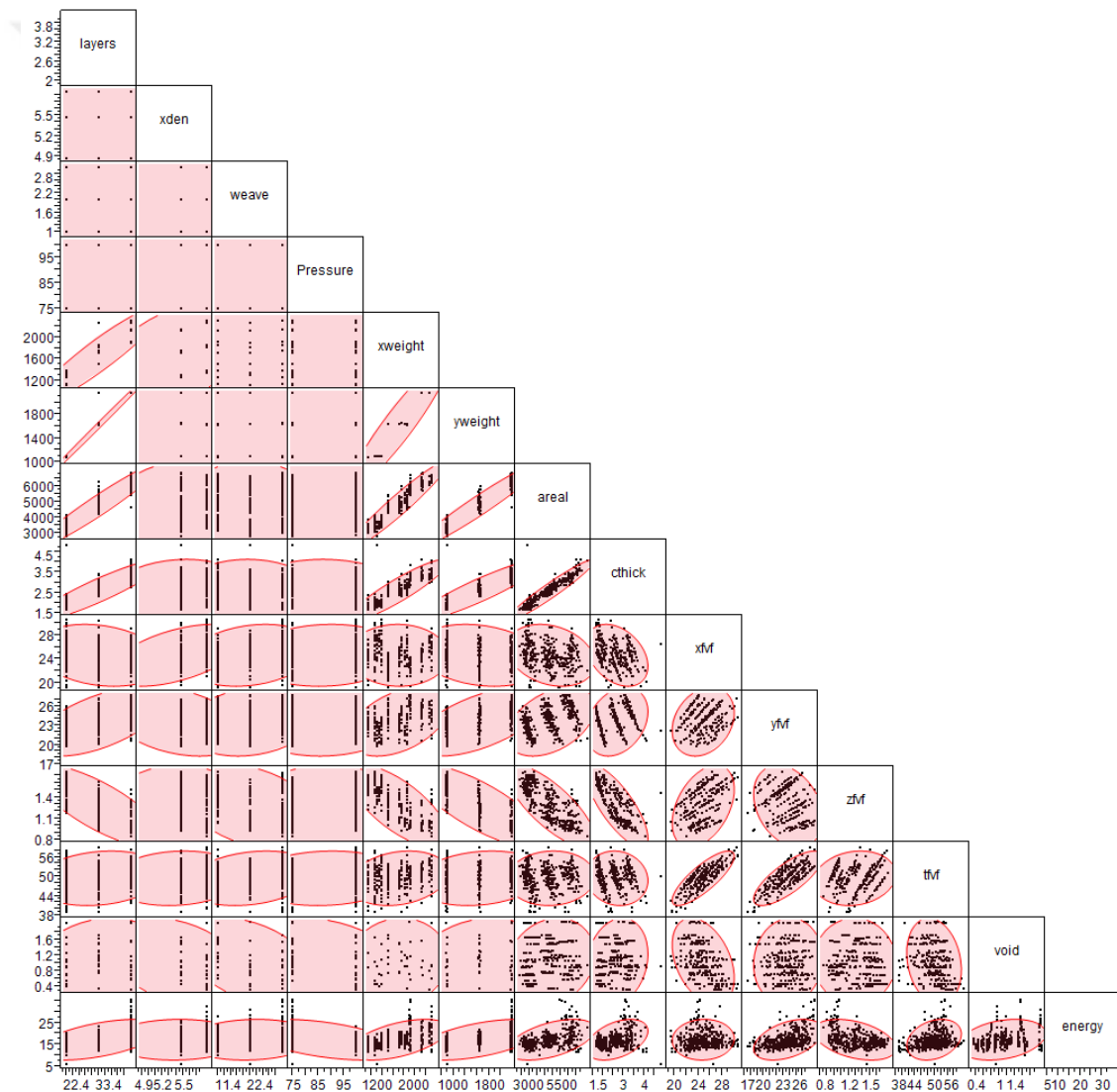


Figure P.17. Scatterplot matrix for normalized total penetration energy

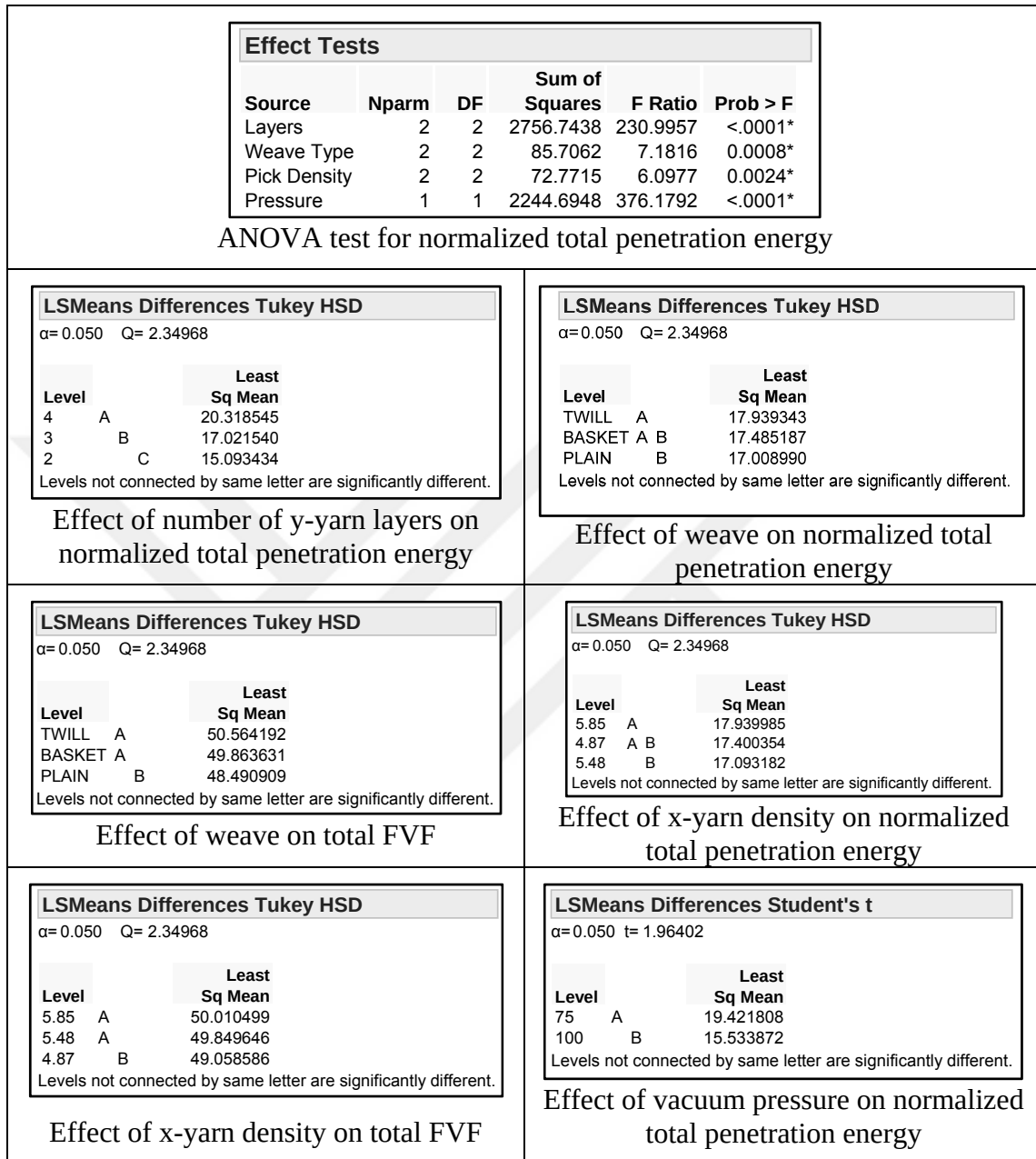


Figure P.18. ANOVA and Tukey multiple means comparison analyses for normalized total penetration energy

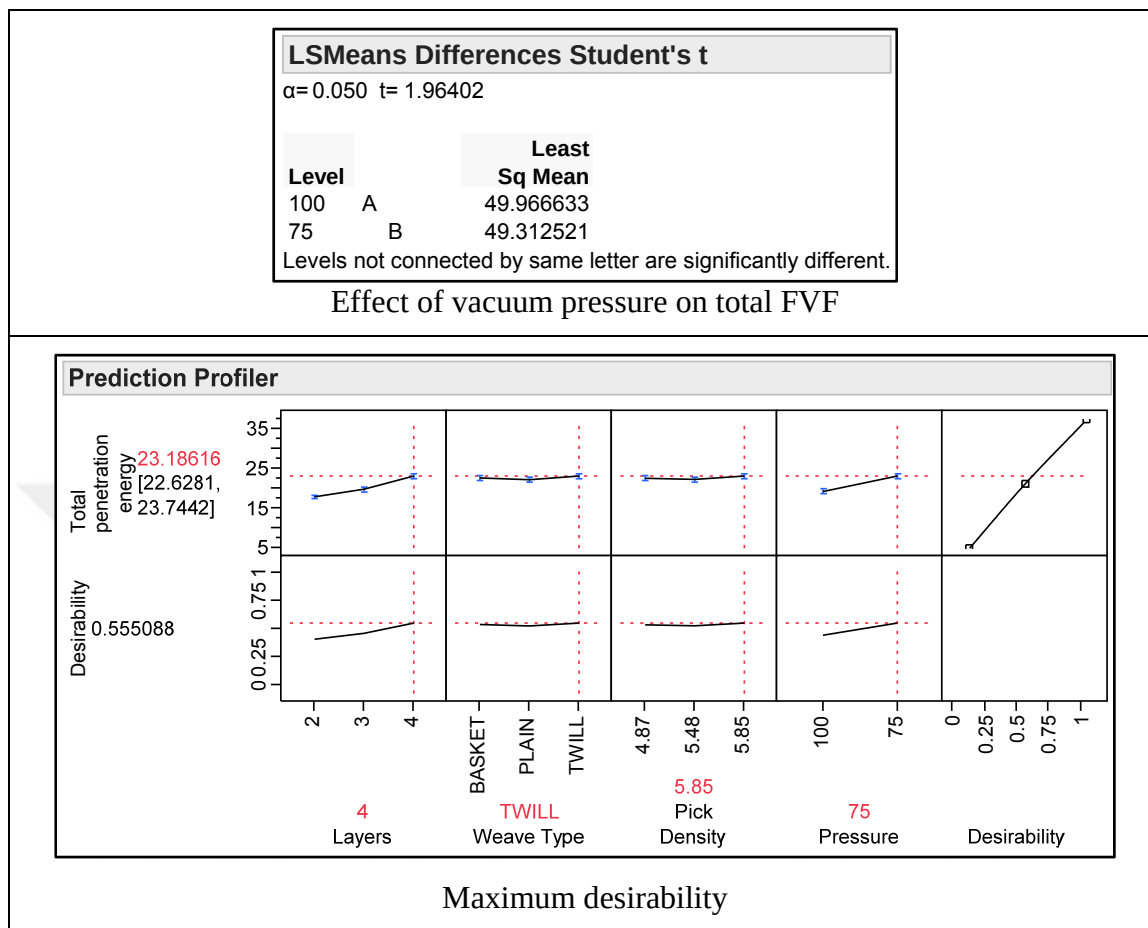


Figure P.18. ANOVA and Tukey multiple means comparison analyses for normalized total penetration energy continued