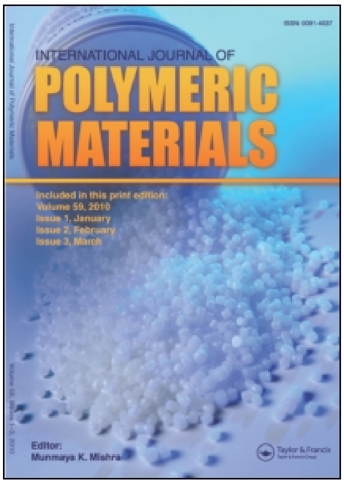

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Influence of Different Woven Geometry and Ply Effect in Woven Thermoplastic Composite Behaviour – Part 2

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Works on woven composite both thermoset and thermoplastic are numerous, however in most instances they involve the use of preimpregnated fabric. It is apparent that woven thermoplastic system has significant potential due to the combined properties such as better damage tolerence, recyclability, easy processing, storage, *etc.* Here work on woven thermoplastic composites based on Continuous Fiber Impregnated towpreg (COFIT) tape rather than conventional approach is reported. The influences of different woven geometry and ply effect were investigated. Correlations between different woven geometry and weave characteristics were also noted. In general, the woven composite properties are influenced by many process variables such as type of towpreg, woven geometry, number of plies *etc.*

Keywords: Woven geometry; ply effect; woven thermoplastic composite; mechanical properties; weave characteristics

1. INTRODUCTION

Woven composites are unique, with many advantages suitable for numerous engineering applications. These advantages include high impact resistance, better toughness, dimensional stability, low cost of fabrication, improved tensile strength and modulus, *etc.* [1,2].

As reported in previous work [3–5], the presence of additional effects coming from weave characteristics such as interlace points, unit cell,

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etc., plays an important role in composite properties. For example, the tensile properties of a single ply plain weave at any directions and positions are controlled by these factors, apart from the usual constituents of composite such as W_f, void content and so forth.

In this present work, the influence of woven geometry and ply effect on the properties of woven thermoplastic will be reported. As mentioned in part 1 of this report [5], several assumptions were made in view of the nature of the work, which was still preliminary in nature and many shortcomings may be present, particularly with respect to the testing, or characterization.

2. EXPERIMENTAL

2.1. Materials

Acrylonitrile Butadiene Styrene (ABS) resin of general-purpose grades was made into 30% w/w solution using Methyl Ethyl Ketone (MEK) as a solvent. The continuous E glass fiber which was manufactured by Central Glass Ltd., Japan and was supplied locally by EuroChemo-Pharma (M) Sdn Bhd were utilized throughout.

2.2. Preparation of COFIT Prepreg

COFIT prepregs or towpregs were prepared under similar prepregging conditions using the SIRNA prepregger system. The processing conditions were; dryer temperature, 80°C; die temperature, 220°C and pulling rate, 0.35 m/min. All prepregs were then characterized for their dimensions, specific gravity (S.G.) and also tensile properties.

2.3. Preparation of Woven System

To ensure the quality of the woven composite, only prepregs having acceptable properties such as dimensions, density and fiber fraction (W_f) were chosen. For the study of different woven geometries, the single ply laminate was prepared by manually weaving continuous fibers into basic 2-D woven geometric patterns such as plain, (2 ×2) basket, (2 × 1) twill and 4-end satin. Meanwhile, for the study of the ply effect, the thin laminate systems such as 1, 2 and 3 plies of plain and satin weave were prepared. These two woven geometries were selected due to the contradicting properties shown by these patterns in single ply laminate system. For example satin weave exhibits better properties but shows difficulty in handling characteristics, meanwhile plain weave exhibits slightly lower properties but shows excellent properties in handling stability. The single laminated woven plies were then stacked and subsequently compression molded under similar conditions of preheating at 220°C for 15 minutes and compressing at 12 MPa for 5 minutes. To prevent sticking and facilitate demolding, they were placed between TEFLON sheets. In this step no spacer or mold was used using an open mold. Finally, the samples were removed from the press and allowed to cool to room temperature under pressure so as to prevent warping. Then the woven laminated systems were cut into a certain specimen sizes to characterize physical properties of the woven system. The sample size of 220 × 50 mm was used for both tensile and flexural tests. The specimens were then tested according to tensile test (ASTM D638) and flexural test (ASTM D790).

3. RESULTS AND DISCUSSION

3.1. Different Woven Geometry

Woven geometry basically refers to woven pattern, which exhibit dissimilarities in appearance and also performance [6, 7]. These difference in woven geometry are basically attributed from the weave characteristics such as unit cell, interlace point, float length, *etc.*, which are different from one pattern to another pattern. By having many types of woven geometry, basically a wide diversity of composite properties and aesthetic value can be obtained. Previous studies [2, 3] have identified that the properties of different woven geometry are basically controlled by weaving characteristics of the system, however most of the studies were generally confined to woven fabric system. Based on this information, the main purpose of the present study was to identify the properties of basic 2-D woven prepreg patterns such as plain, basket, twill and satin in order to optimize the composites properties and satisfy the needs of specific structural applications. Here, the study is confined to a single ply system of 4 woven patterns produced from ABS, 12 towpreg and molded under same nominal conditions.

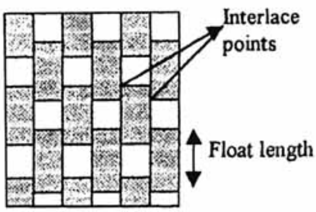
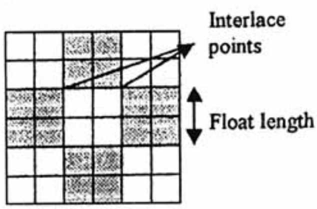
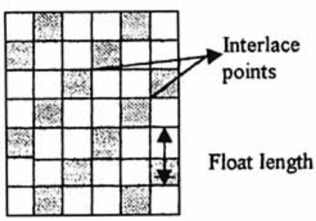
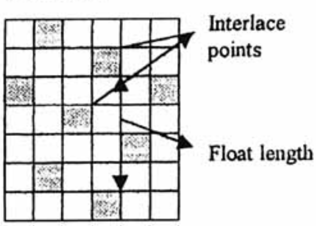
Table I summarizes the properties of basic 2-D weave patterns and some of the characteristics of these weave patterns are given in Table II. In general it is apparent that different woven geometry exhibit various weaving characteristics. This perhaps might result in different properties of the woven systems. However, it is interesting to note that the W_f of these four systems remains constant as noted with different types of towpreg in the previous report [5]. Meanwhile the void content of basket and satin was found lower than that of plain and twill, although they were molded under similar molding condition. Perhaps the difference in void content might be attributed to the presence of various weaving characteristics in these woven systems. For example by referring to the Table II, it is apparent that plain and twill exhibit higher quantity of interlace points per unit area compared to satin and basket. Perhaps voids might be present between the interlace points which are higher in these two systems than those of satin and basket. However there are many potential sources of void formation such as matrix-fiber interface, intraply space, *etc.*

The differences in physical properties and weave characteristics, normally might influence the mechanical properties as well [4, 5, 7]. It is therefore expected that the satin weave which exhibits lesser void content and interlace points, higher fiber count and smaller interlacing gaps shows higher 0° tensile strength property, followed by twill, basket and plain. However anomalies are observed in the case of basket and twill weaves under more or less similar molding condition and similar quantity of W_f. The basket weave contains lower void content, slightly reduced tensile strength but higher tensile stiffness. Meanwhile twill weave which contains slightly higher quantity of void content, shows high tensile strength but slightly lower stiffness. Instead of void content,

TABLE I Properties of single ply 2-D basic woven patterns

Properties	*Plain*	*Basket*	*Twill*	*Satin*
Thickness (cm)	0.12	0.14	0.15	0.14
W_f	0.84	0.85	0.86	0.84
Voids (%)	5.4	4.3	4.8	4.4
Type I, 0° TS_0 (MPa)	187	206	218	232
Young Modulus (GPa)	4.3	6.0	2.9	4.1
0° FS_0 (MPa)	30	46	40	64
Float Length (cm)	2	6	5	9
Fiber Count/unit cell (cm^{-2})	0.08	0.07	0.14	0.17

TABLE II The several weave characteristics and schematic illustration for a single, 2-D ABS, 12 tow woven system (based on similar area of 30 × 45 -cm)

Types of woven pattern	*Characteristics*
Plain 	-high number of interlaces per unit area -short float length, more or less a size of towpreg -very tight pattern, results to bigger gaps at 90° -less fiber counts per unit area due to tight pattern -symmetrical pattern
(2 × 2) Basket 	-fewer interlaces than that of plain weave -longer float length than that of plain weave -tight pattern but less than that of plain weaves -less fiber counts -symmetrical pattern
(2 × 1) Twill 	-more interlaces than basket but less than satin -float length is basically similar to basket -loose pattern -fiber count is less than that of satin -asymmetrical pattern
4-end Satin 	-fewer interlaces per unit area -the longest float length amongst 4 patterns -loose pattern, results to smaller gaps at interlaces -high fiber counts -asymmetrical pattern

the properties of woven geometry are dependent on many weaving characteristics. Thus, there are many possibilities that all these factors might contribute to different properties of these two weave geometries. Unlike these two systems, the properties of plain and satin are basically are more predictable.

Amongst other single ply woven patterns, satin weave exhibits better tensile properties. This can be related to its excellent weaving characteristics. For example it is a loose pattern, thus many towpreg tapes can be packed more closely together. These resulted in smaller interlacing gaps at interlace points and increased the fiber count of the system (as shown in Tab. I). Theoretically, a higher fiber count should increase the tensile properties because more fibers are able to carry the force which was applied to the system [8]. While smaller interlacing gaps will reduce the possibility of fiber distortion and formation of additional voids at this region during the molding process.

However in the case of plain weave, the respective lower properties can also be explained by the weaving characteristics. The situation in trend is, however, basically differed from that of satin weave. During the fabrication, it was realized that plain weave is a tight pattern, thus this characteristic can be related to lower fiber count. It was found easier to tighten the towpreg tapes at warp direction but not at weft direction. This resulted in the presence of interlacing gaps at weft direction, which relates to the fiber distortion and additional void content present between the fibers during the molding process. The combined properties of lower fiber count, bigger interlacing gaps at weft direction, *etc.*, basically explained why the properties of single ply plain weave are lower than those of other woven patterns which were investigated here.

Figure 1 shows the correlation between woven tensile strength with one of the weave characteristics, the fiber count/unit cell. From the above information, it is apparent that the fiber count influences the tensile properties of woven geometry. However from the figure, it is also clear that the tensile strength of different woven geometries is not only dependent on the of fiber count. For example basket and plain weave show marginal change in fiber count, but show higher differences in tensile strength that is with plain weave about 19 MPa lower than that of basket weave. Perhaps the reduction of plain weave tensile strength might be due to other factors such as void content and other weaving characteristics.

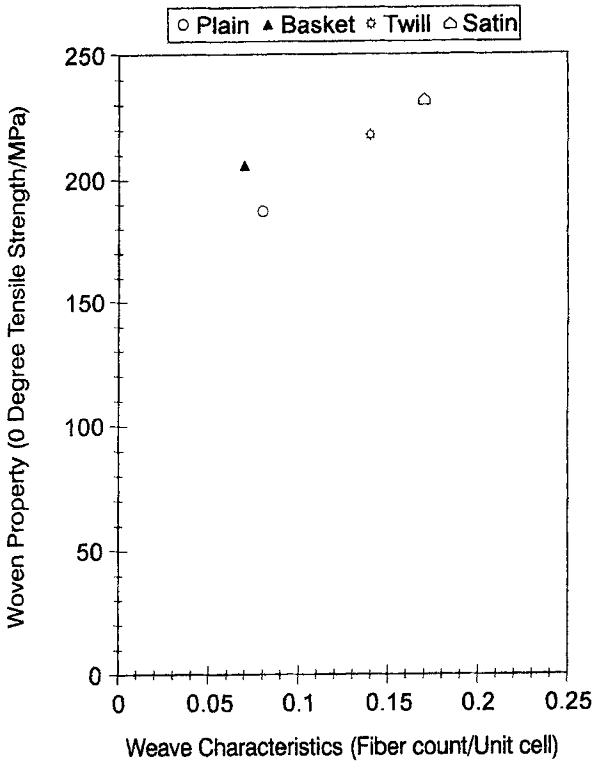


FIGURE 1 The correlation between woven tensile strength and fiber count/unit cell for different woven geometry where ply, type of towpreg, molding conditions remain constant.

In the case of flexure property, it is apparent that the satin weave shows higher flexure strength followed by basket, twill and plain weaves. A previous study attributes the ability of woven systems to exhibit high flexure properties with the float length [8]. Theoretically float length was reported to give the woven pattern more freedom of movement and thus enabling the system to better respond to bending stresses. Hence judging from the characteristics of woven system such as float length as shown in Figure 2, it is clearly shown that the flexure strength is dependent on the float length of the woven system.

Earlier studies [7] have identified that the weaving characteristics of different woven geometry might influence the heat transfer, resin flow and penetration of the resin within the woven plies. However since the

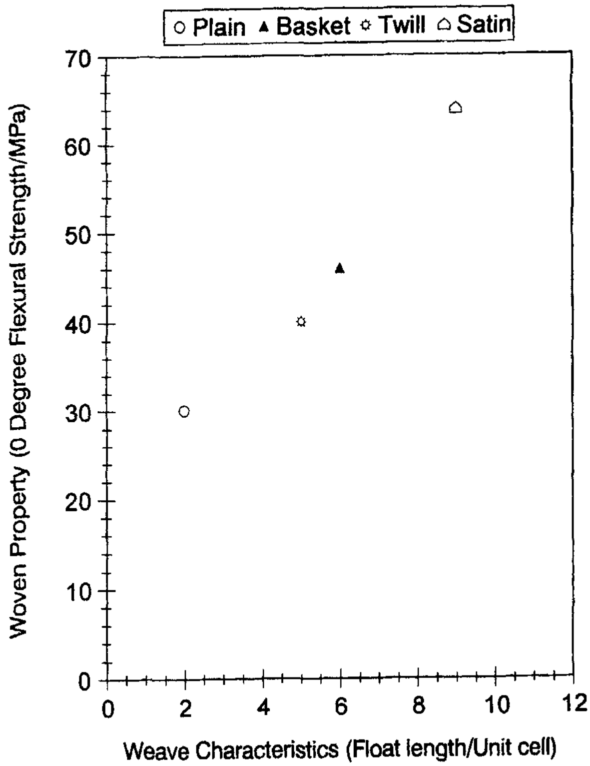


FIGURE 2 The correlation between woven flexural strength and float length/unit cell for different woven geometry where ply, type of towpreg, molding conditions remain constant.

system in discussion is a single ply, thus the effect is not really significant.

From our experiments, it is apparent that every weave pattern has its own advantages, that are governed by weaving characteristics of the system. Thus, the choice of weave system should be based on the properties needed in final composite system. For example if the final application needs higher bending properties such as in the beam system, there, the satin weave is the right choice. However the selection of the weave geometry can also be based on the weaveability and cost effectiveness of the system. For example, as noted by Heng [7], amongst the weave patterns, the plain weave exhibits an excellent handling stability by taking advantage of a tight pattern and also utilizing smaller amount of towpreg in preparing same size of laminate system followed by basket, twill and satin weaves. Satin weaves, with its looser pattern shows difficulty in handling and preparing during the fabrication process. Furthermore due to the loose pattern, it needs many towpreg tapes to occupy the same size of laminate system. Consequently, it can be concluded that the properties of woven composite are dependent on type of geometry, which in turn depends on the weaving characteristics such as interlace point, float length, fiber count, *etc*. And this can be summarized in the following equation.

$P_{\text{woven (Wf, V\%, TS)}} = \{f(\text{woven geometry}_{\text{(Wf, V\%, TS)}}); P_{\text{towpreg}}$, mold condition, ply, remain constant$\}$.

3.2. Ply Effect

A single layer of a laminated composite material is generally referred to as a ply or lamina. A single ply is basically too thin to be directly used in any engineering application [9], however it is still applicable depending on requirement. Thus, normally in composite application, several laminae are bonded together to form a structure termed as a laminate [10]. The closest example is in UD composite system, where the desirable properties are only in the direction of the fiber axis. By making multi-layered laminates in which the fibers in the various layers have different orientations, such composite with desirable properties in all directions can be obtained. Even though the behavior of the laminate is governed by the behavior of individual laminae, there are some parameters that need to be considered in predicting the properties of laminated composite such as ply thickness, stacking material, stacking orientation, *etc*. [11, 12].

By considering the importance of composite laminate system in the composite application, here the preliminary study of 12 tow ABS satin and plain weave with 1, 2 and 3 laminated system were chosen as a representative. The main aim here was to study the effect of different woven laminated system such as plain and satin weaves. Table III highlights some of the physical and mechanical properties of different laminated system of 12 tow, ABS satin and plain weaves.

It is interesting to note that for both weave system with laminate of 1, 2 and 3 plies, the W_f remain constant. In general, other physical properties of woven system such as thickness and void content increase

TABLE III Properties of various ply of 12 tow, ABS satin and plain weave laminate composite, molded under similar molding condition

Woven system	Properties	*Different laminate system* 1 ply	2 ply	3 ply
Satin Weave	Thickness	0.14	0.24	0.32
	W_f	0.84	0.88	0.89
	Voids (%)	4.4	6.7	9.2
	0°TS (MPa)	232	229	169
	Tensile Modulus (GPa)	4.1	4.1	3.8
Plain Weave	Thickness	0.12	0.21	0.30
	W_f	0.84	0.85	0.86
	Voids (%)	5.4	4.3	4.8
	0°TS (MPa)	187	197	227
	Tensile Modulus (GPa)	4.0	4.5	5.3

with increase the woven ply. As seen different woven laminated system exhibit different tensile properties, under similar molding conditions. For example, in single ply system, satin weave shows higher tensile properties than those of plain weave, but the trend was changed as the laminate increased to 3-ply system, where satin weave shows lower tensile properties than those of plain weave. It appears that due to the presence of different weaving characteristics and ply thickness, different molding conditions are required for different woven composite laminated system.

For more in depth discussion, Figures 3, 4 and 5 show the correlation between the number of woven laminate and the laminate thickness, void content and tensile strength. It is apparent that similar trend was shown for both woven systems where with the increase in laminate plyes results in increase in woven thickness, that amounts to about 0.01 cm per ply for both woven systems. A different trend however was shown in the void content, where the void content of single ply plain weave was observed higher than those of 2 and 3 plie systems. There are many possibilities that might contribute to the higher void content of single ply plain weave. Perhaps, voids might be present at interlacing gaps due to fiber distortion during the molding process, *etc.* In the case of higher ply laminates or thicker system, different trend of void content for these two systems was observed. The void content of higher ply laminate system in satin increases while those of plain weave shows reducing trend.

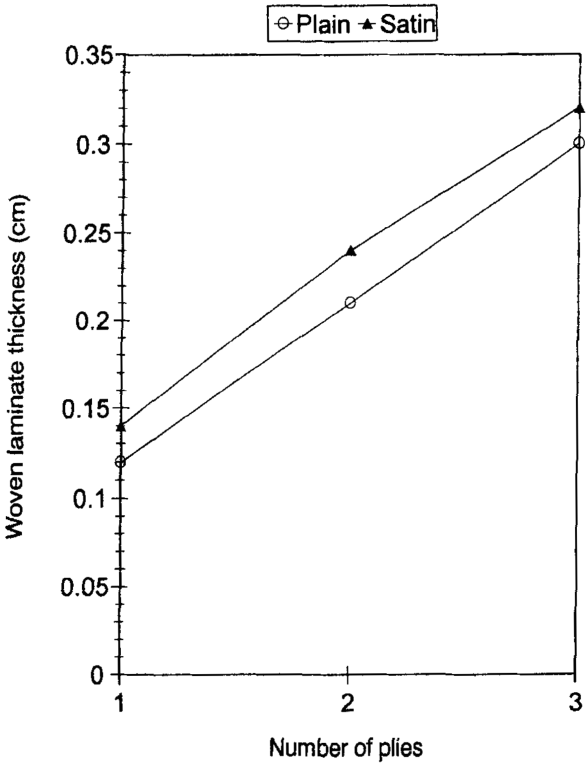


FIGURE 3 The correlation between woven thickness and number of plies for different laminate of plain and satin weave where type of towpreg, molding conditions remain constant.

The phenomenon of void content in thicker laminate systems, perhaps can be explained by referring to the differences in weaving characteristics between these two systems. As shown in previous section, it is apparent that the satin weave is a loose pattern, which leads to a higher fiber count. This results in a very packed structure because of smaller interlacing gaps between the towpregs and interlacing points. Theoretically, this phenomenon creates good properties for single ply system but not for thicker system. These characteristics reduce the heat transfer from outer layer to the middle layer and create difficulties for the resin to penetrate within the laminates. Consequently low resin impregnation and wetting of the composite occurred and this might increase interlamina voids. This phenomenon perhaps might be

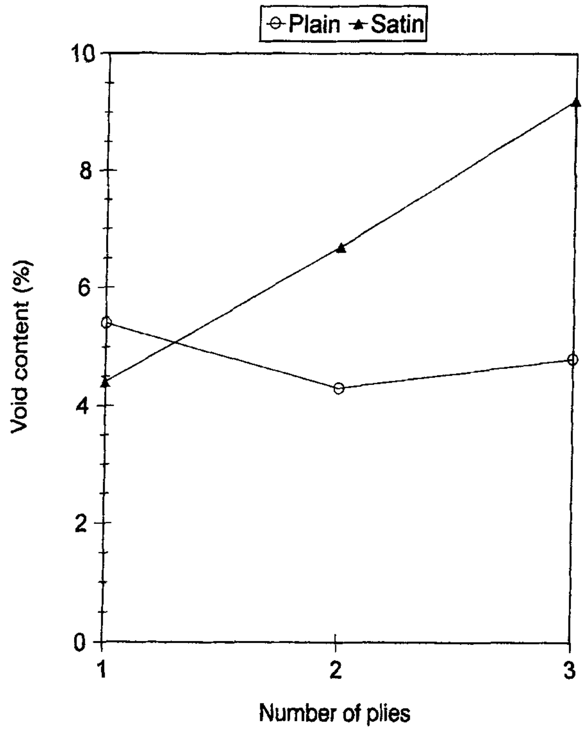


FIGURE 4 The correlation between woven void content and number of plies for different laminate of plain and satin weave where type of towpreg, molding conditions remain constant.

significant for thicker satin weave laminate system compared to those of single ply [7]. This effect is minimal in plain weave since it exhibits very tight pattern which results in a smaller fiber content, high interlacing gaps, *etc.* These factors result in better resin impregnation within plies and reduce the interlamina void content in higher ply laminate system.

From the above information, it is apparent that the properties of woven composite are governed by the weaving characteristics and number of laminate which in turn influence the thickness and molding condition of the system.

The correlation between woven properties and the effect of ply laminates can be shown by the following equation.

$P_{\mathrm{Woven(Wf, V\%, TS)}} = \{f(\mathrm{ply}_{\mathrm{(Wf, V\%, TS)}})$; P towpreg, molding condition remain constant$\}$.

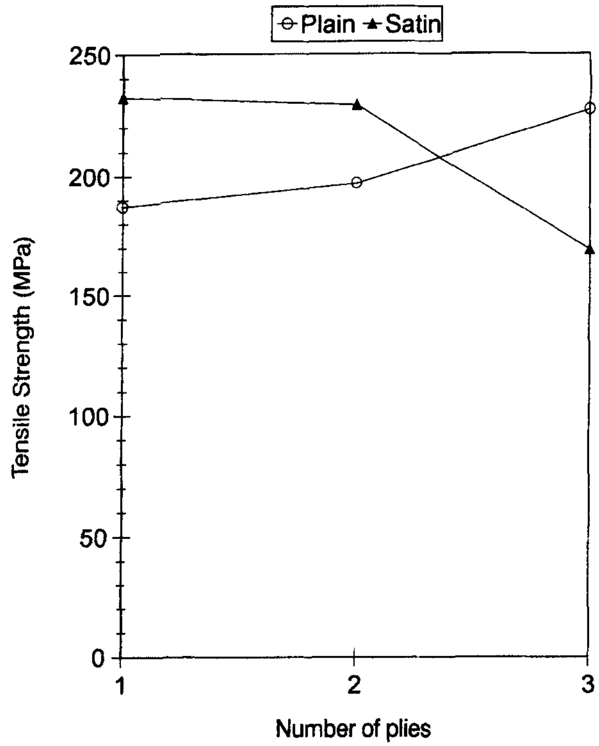


FIGURE 5 The correlation between woven tensile strength and number of plies for different laminate of plain and satin weave where type of towpreg, molding conditions remain constant.

4. CONCLUSIONS

From the above discussion, a few conclusions on controlling factor of woven thermoplastic composite can be made. They can be summarized as follows:

(a) Among the various woven geometry of single ply laminated system, the satin weave seems to impart overall superior properties such as tensile and flexure by taking advantage of weave characteristics such as float length, fiber count, unit cell, interlace point, *etc.*

(b) The woven composite properties are strongly dependent of the selection of woven geometry or pattern. This might be due to different weaving characteristics present in each of the woven pattern. For example, satin weave exhibits the best flexure and tensile properties, which is due to weave characteristics such as longer float length, higher fiber count, *etc*. Besides the mechanical properties, the selection of the woven patterns should be based on the cost effectiveness, weaveability, *etc*., by taking advantage of certain weave characteristics.

(c) The properties of the woven system are controlled by number of ply being used in the laminate system. Apparently the single ply laminate system exhibits different properties than those of thicker laminate system due to the presence of interply effect, laminate thickness, *etc*.

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