

Compressibility of weft knitted reinforcement fabrics from glass yarn

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Abstract

Compression, and relaxation of a reinforcement fabric during composite manufacturing dictates mold design, resin flow, and fiber volume fraction of resultant composite; and single layer fabric architecture, and numbers of layers in a fabric stack change the compressibility character of overall reinforcement material. This study dealt with the effect of knit architecture and number of layers on dry compression and relaxation responses of weft knitted fabrics from glass yarn. Fabric architectures of 1x1, 2x2, English, and Fisherman ribs were selected. The thicknesses of single-, double-, and triple-fabric layers from same knit architectures were measured under compression and recovery pressures ranging from 2 to 200 kPa. Areal densities of single layer fabrics were measured. 2x2 and fisherman rib fabric architectures exhibited higher thickness, areal density and fiber volume fraction than 1x1 and English rib fabric architectures due to their nested and compact structures. Due to nesting between adjacent layers; multi-layer fabrics demonstrated higher fiber content than single layer fabrics. The difference between the compression and recovery thicknesses proved the existence of dissipated energy. Compression curves – the relationship between fiber volume fraction and compression pressure - classified by number of layers were fitted by square equation with fairly high determination of coefficients (R^2).

Keywords: fabric compressibility, fabric relaxation, glass yarn, reinforcement fabric, weft knitted fabric.

1. Introduction

Having knowledge about single and multi-layer compressibility of a reinforcement fabric is crucial to design a stable mold, to model resin flow, and to estimate fiber content of final composite product. This research is about the effect of knit pattern and number of layers on compression and recovery responses of weft knitted fabrics from glass yarn, and the literature review within this context is given below.

Pearce and Summerscales [1] monitored compressibility and repetitive relaxation responses of single and multiple (2, 3, 4, and 5) layers plain woven fabric from glass tow at maximum compression pressure levels of 100, 200, and 300 kPa. Specimen surface area exposed to compression was also varied as 50x50, 71x71, and 100x100 mm². The relationship between fiber volume fraction and compression pressure for initial loading was drawn on log-log scale and modeled by power-law equation. Single layer fabrics exhibited higher fiber volume fraction and lower exponent in power-law equation than multiple layer fabric stacks. Thickness - measured at maximum compression and normalized by number of layer - increased with number of layers, which indicated the lack of nesting between adjacent layers. Strain energy stored in compressed fabric (stack) dissipated during relaxation that reduced the pressure on the plates. Repetitive relaxation and reloading to maximum compression pressure improved fiber volume fraction. No lateral spreading of fabric was observed during compression test that verified the absence of areal density change.

Robitaille and Gauvin [2] reviewed published theoretical and experimental data on compression and relaxation



behavior of commercial random mats and woven reinforcement fabrics from glass fiber. They listed parameters of compression and relaxation processes as; fabric architecture of reinforcement material, number of fabric layers, stacking sequence, presence of a lubricant, compression velocity, maximum compression pressure, number of compression cycles. The researchers underlined that due to complex internal structures of textile fabrics; theoretical compressibility studies failed to model the behavior textile reinforcements accurately. Compression curves obtained from experimental works were modeled by Equation 1 (power-law). The researchers assumed no in-plane global deformation during compression and relaxation that was parallel with the results of Pearce and Summerscales's study [1].

$$v_f = A * P^B \quad (1)$$

Where v_f is fiber volume fraction, A is fiber volume fraction for a compaction pressure P equals to 1 Pa, P is compaction pressure (Pa), B is compaction stiffening index ($B < 1$).

The main findings of Robitaille and Gauvin's study [2] for compression curves of woven fabrics and random mats from glass fiber were;

- While number of fabric layers increased rigidity of the stack (M), and initial fiber volume fraction (A); it lowered stiffening index (B), and representative fiber volume fraction (Rv_f).
- While number of compression cycles increased rigidity of the stack (M), initial fiber volume fraction (A), and representative fiber volume fraction; it lowered stiffening index (B)
- While compression speed slightly reduced rigidity of the stack (M), and initial fiber volume fraction (A); it slightly increased stiffening index (B), and increased representative fiber volume fraction (Rv_f).

Similar to the findings of Pearce and Summerscales [1]; Robitaille and Gauvin [2] emphasized the importance of repetitive relaxation and reloading to maximum compression pressure to enhance rigidity and fiber volume fraction of overall fabric stack.

Luo and Verpoest [3] investigated the compressibility of a new sandwich fabric, Multimat, and its components, a mat and a weft knit with a woven fabric as comparison. The relaxations of the fabrics were tested. The fabric compression tests were done on varying number of fabric layers, by taking the relaxation behavior of the fabrics into account. The compressibility data are compared with the actual clamping pressure and a simple model was established. They mentioned that the relaxation of the knit was negligible in terms of volumetric dissipation energy and fabric stiffness; the fabric compression curves gave an idea of the practical range of fiber volume fraction in resin transfer molding, and the multi-layered knit preforms were easier to compress than the single-layered ones, whereas the number of layers did not influence the compressibility of other fabrics.

Weft knitting is a rapid, low-cost and versatile fabric manufacturing technique. Complex internal structure of weft knitted fabrics - created by interlocked stitches - make them unique among reinforcements family. They are stretchable, and shapeable that enables the direct production of intricate 2D or 3D near-net-shape preforms. Due to three dimensional interlacement of stitches within a layer and allowable nesting between porous layers; knitted fabrics exhibit better impact resistance than other textile forms as they are converted into layered composites. However, low load carrying capability arising from loose structure, and low fiber content of weft-knitted fabrics are disadvantageous as they are considered for in-plane reinforcement [4-7]. This disadvantageous character of weft knitted fabrics renders their compressibility and relaxation responses critical to improve their in-plane fiber volume fraction. To the best knowledge of the authors of this study; no special attention was devoted to characterize compression and recovery response of weft knitted fabrics from glass yarns. Focuses in previous studies were directed to mat and woven fabric materials. This study revealed the effect of two important material parameters -knit pattern, and number of fabric layers – on compression and recovery response of weft knitted fabrics.

2. Methods and methods

Three-ply 133 tex, E-glass multi filament yarn was consumed to manufacture fabrics on Brother KH-864 manual, flat weft knitting machine with a fineness of 5 gauges. Table 1 indicates the experimental plan of our study. Two input variables; knit architecture, and number of fabric layers were considered; in total 12 (4x3) different samples were considered. Figure 1 indicates technical notations (needle diagrams), three dimensional drawings, actual knit-fabric architectures both on the machine under tension in wale direction, and on the table in relaxed equilibrium state.

Table 1. Experimental Plan

Variables:	Knit architecture	Number of fabric layers
Levels:	1x1 Rib	1
	2x2 Rib	2
	English Rib	3
	Fisherman Rib	

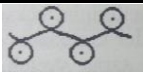



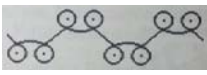

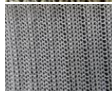









Name	Technical notations	3D drawings	On the machine	On the table
1x1 rib				
2x2 rib				
English rib				
Fisherman rib				

Figure 1. Technical notations, 3D drawings [8] [9], actual fabric images on the machine under tension, and on the table in relaxed state of the knit architectures

Knitted fabric swatches were laid on anvil of digital thickness gauge with a pressure foot diameter of 21.15 mm. The pressure foot that has a compression pressure of 2 kPa (due to its weight) was lowered on the fabric. After 30 seconds waiting time, once the display of the gauge stabilized, the thickness was recorded as compression thickness at 2 kPa. Then additional weights were successively added on pressure foot to achieve compression pressures of 5, 10, 20, 50, 100, 150, 200 kPa, respectively. After addition of each weight, 30 seconds were waited to record the thickness shown on the stable display of the thickness gauge. Once compression cycle was finalized at 200 kPa compression pressure, the weights on the pressure foot were gradually removed, and recovery thicknesses starting at 150 kPa pressures were recorded until recovery pressure of 2 kPa was achieved. This procedure was repeated five times from different spots of a fabric swatch for all knit architecture and number of fabric layer combinations. In total, 900 (12x5x15) thickness measurements were performed; 480 of them at compression pressures, and 420 of them at recovery pressures. For each measurement cycle; one compression and recovery curve couple was drawn; in total, 60 different compression and recovery curve couples were drawn. The areal densities of 5x5 cm² single layer pieces cut from fabric swatch were measured on the precision balance according to ASTM [10]. Six areal density measurements were completed for each different knit pattern.

3. Results

3.1. The Relationship between Number of Layers and Normalized Thickness

To reveal the presence of nesting between adjacent layers, we normalized all thickness measurements by their matching number of layers, and drew the graph of normalized thickness versus number of layers (Figure 2). Normalized thicknesses grouped by number of layers did not show statistically significant difference at significance level of 0.05 (Table 2) that indicated the lack of nesting between adjacent knitted fabric layers. Wale-on-wale and course-on-course placement of fabric layers impeded nesting between adjacent layers. However, the decrease in thickness as number of layer was increased showed a tendency in nesting that could have been revealed at compression pressures higher than 200 kPa. Thus, the difference between normalized thicknesses of single and two layers fabric stack was found as statistically significant.

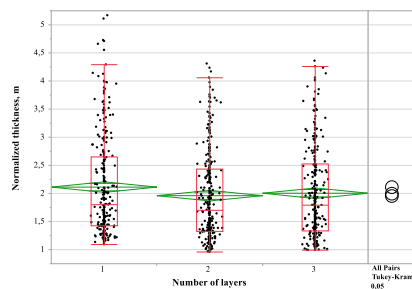


Table 2. Number of layers versus normalized thickness report

Number of layers		mean mm	sd mm	LL mm	UL mm
1	A	2,11	0,88	2,01	2,21
2	A	1,96	0,80	1,87	2,05
3	A	2,00	0,80	1,91	2,10

Note: levels not connected by same capital letter are significantly different. **sd:** standard deviation, **LL:** lower limit, **UL:** upper limit. Limits are based on 95% confidence level.

Figure 2. The relationship between number of layers and normalized thickness

Note: The top and bottom of each green diamond represent the 95% confidence interval for each layer level. Comparison circles (given on the right column) representing means those are significantly different either do not intersect, or intersect slightly. The height of red box - a quantitative indication of variation - is called interquartile range of mean.

3.2. The Effect of Compression and Recovery Pressures on Thickness

Comparison of thicknesses classified by compression and recovery pressures showed that recovery pressure thicknesses were significantly lower than compression thicknesses (Figure 3, Table 3). Compressed knitted fabrics could not recover to their initial thicknesses once the pressure was removed, which is advantage in the case of composite production. Because in many composite production technique, dry fabric is initially compressed before resin infusion, and later compression pressure on the fabric is offset by resin during infusion. Lack of complete recovery from compression lowers the final thickness of composite that enhance fiber volume fraction and mechanical properties of resultant composite. Lack of complete recovery also is an indication of dissipation of energy that was transferred to fabric during compression. Dissipated energy lowers the load on platens of two-sided mold that enhance the life of the mold.

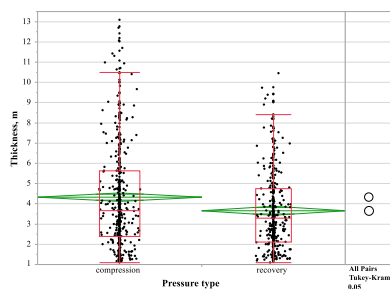


Table 3. The effect of pressure type on thickness

Pressure type	mean, mm	sd, mm	LL, mm	UL, mm	p-value
compression	4,33	2,61	4,10	4,56	<0,0001
recovery	3,66	1,99	3,47	3,85	

Figure 3. The effect of pressure type on thickness

3.3. The Effect of Knit Pattern on Thickness, Areal Density, and Fiber Volume Fraction

Two adjacent wales of face loops followed repeatedly by two adjacent wales of back loops enhanced internal tension in course direction of fabric that shortened the knit pattern of 2x2 ribs in width direction more than the other knit patterns. Therefore, due to shortening in width direction more than the other knit architectures; 2x2 rib structures exhibited the highest thickness. The only statistically significant thickness difference was observed between knit

patterns of 1x1 and 2x2 ribs (Figure 4 and Table 4). Similar trends were observed for the effects of knit patterns on areal density and fiber volume fraction (Figures 5 and 6, Tables 5 and 6, respectively).

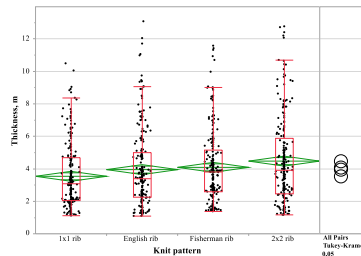


Figure 4. The effect of knit pattern on thickness

Table 4. The effect of knit pattern on thickness

Knit pattern		mean, mm	sd, mm	LL, mm	UL, mm
2x2 rib	A	4,48	2,66	4,13	4,82
Fisherman rib	A B	4,09	2,23	3,80	4,38
English rib	A B	3,95	2,42	3,63	4,27
1x1 rib	B	3,54	2,01	3,28	3,80

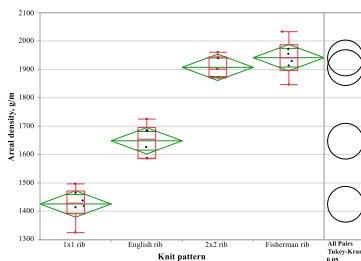


Figure 5. The effect of knit pattern on areal density

Table 5. The effect of knit pattern on areal density

Knit pattern		mean g/m ²	sd g/m ²	LL g/m ²	UL g/m ²
Fisherman rib	A	1941,67	62,41	1876,2	2007,2
2x2 rib	A	1907,73	36,01	1869,9	1945,5
English rib	B	1648,80	57,90	1588,0	1709,6
1x1 rib	C	1426,27	58,12	1365,3	1487,3

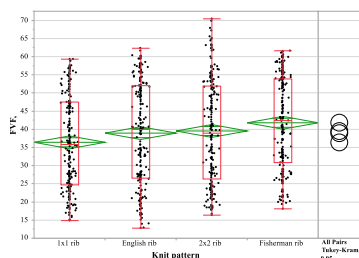


Figure 6. The effect of knit pattern on fiber volume fraction

Table 6. The effect of knit pattern on fiber volume fraction

Knit pattern		mean %	sd %	LL %	UL %
Fisherman rib	A	41,79	12,66	40,13	43,46
2x2 rib	A B	39,54	14,37	37,65	41,43
English rib	A B	38,95	14,11	37,10	40,80
1x1 rib	C	36,42	12,75	34,75	38,10

3.4. The Effect of Number of Layers on Fiber Volume Fraction

Number of layers increased fiber volume fraction of knitted fabrics. Nesting between adjacent layers in multiple fabric stacks lowered thickness and enhanced fiber content of knitted fabrics (Figure 7, Table 7).

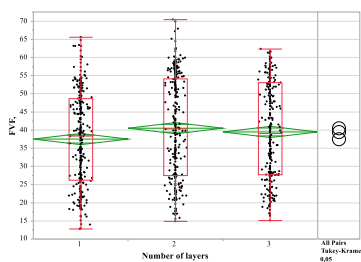


Table 7. The effect of number of layers on fiber volume fraction

Number of layers		mean %	sd %	LL %	UL %
2	A	40,52	14,15	38,91	42,12
3	A B	39,48	13,60	37,94	41,03
1	B	37,52	12,92	36,06	38,99

Figure 7. The effect of number of layers on fiber volume fraction

Figure 8 shows the compression curves of knitted fabrics with different number of layers. Fiber volume fraction improvement was observed again as the number of layer was increased. The compression curves were fitted by quadratic equation with fairly high coefficient of determinations, R^2 (Table 8).

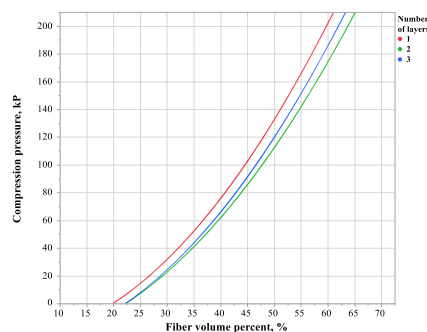


Figure 8. Compression curves grouped by number of layers

Table 8. Parameters of compression curves

Number of layers	R^2	Equation
1	0,82	$y = -24,73 + 0,063x^2$
2	0,86	$y = -27,57 + 0,056x^2$
3	0,90	$y = -29,35 + 0,060x^2$

4. Conclusion

This study revealed the effect of fabric architecture and number of fabric layers on compressibility and recovery from compression response of knitted fabrics from glass yarn. The onset of nesting between adjacent layers of multilayer fabric stack was indicated by number of layers versus normalized thickness graph. Lower recovery thicknesses than compression thicknesses showed the presence of dissipated energy during recovery that enhanced fiber volume fraction of the fabric stack and life cycle of the two-sided mold. Knit architecture emerged as a significant parameter to manipulate thickness, areal density and corresponding fiber content of the fabric. Due to internal course-wise tension that shortened the width of the fabric, once it was removed from the machine; 2x2 rib architectures demonstrated higher thickness, areal density and fiber volume fraction than other knit architectures. Fiber volume fraction increased by number of fabric layers. For future studies individual compression and recovery curves would be drawn and the effect of knit architecture and number of layers on dissipated energy would be revealed.

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