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The Compressive Behavior of 3D Weft Knitted Spacer Fabrics Designed for Cushioning Applications ⋆

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Abstract

In this research work, the effect of various construction parameters and structural characteristics of weft knitted spacer fabric on the compressive behavior and energy absorption capability was studied. The potential compression mechanism of the fabric was identified with support of the compression stress-strain curve, work done and efficiency at different compression stages. The results show that the compressive stress at the same compressive strain increases with the fabric density, and the stress-strain curves of spacer fabrics with different densities were all composed of initial, elastic region, plateau region and densification region. Third order polynomial regression model was used to establish the elastic deformation properties to obtain the compression results. The spacer fabrics ideal energy-absorption efficiency curves were obtained from their stress-strain curves and all findings show that stress corresponding to at the peak of the energy-absorption efficiency was closed to the densification stress of material. Advance statistical evaluation and one-way analysis of variance is used to analyze the significance of various factors such as thickness, spacer yarn diameter and surface structures on energy absorption at maximum compression load and deformation. These findings are important requirements for designing weft knitted spacer fabrics for cushioning applications in car seats, mattress, shoe insoles etc.

Keywords: Weft Knit Spacer Fabrics; Compression Stress; Compressive Energy Absorption; Efficiency

1 Introduction

Cushioning materials are used to dissipate the kinetic energy of the impacting mass while keeping the maximum load (or acceleration) below some limit [1]. They generally absorb kinetic mechanical energy under compression actions at a relatively constant stress over a large range of displacement. The works done by compressing these kinds of materials are equivalent to the kinetic energies of a mass that might impact on them. There are a number of materials and

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structures with the abovementioned feature for cushioning applications. Airbags, bubble films, rubberized fibre cushioning, and polymer-based foams are just a few typical examples. Foam is an important engineering material used in cushions of mattress, car seats, insole, pillows, packaging, acoustic absorption and upholstery [2]. Foams are typically used under compression, but it is very likely that also shear loading will occur in the foam components of the cushions. It is the primary means used in most modern seats, mattress and insole to achieve static comfort and vibration isolation which also happens to be the application area. It is non-linear and viscoelastic in nature. Its increasing importance as an engineering material has led to a detailed study of its structure and properties [3, 4]. The foam has a relatively complex geometry, with curved surfaces and varying thickness in order to provide the desired properties for support and cushioning.

Blair et al. [5] investigated the effect of chemical structure of Polyurethane (PU) foam on dynamic and static characteristics of the seat cushions and concluded that cushions with moderate hardness and high thickness yield lowest vibration transmissibility at low frequencies and near the resonance frequency. It has been further shown that thick PUF cushions yield lower stiffness and higher deflections [6]. However, the hysteresis loss for a thicker PUF sample was observed to be less than that of the thin foam, which led to higher vibration transmissibility.The PU foam, thanks to its specific characteristics, is the key element of the multilayer fabric in terms of comfort and mechanical behavior especially for the compression ones. The main issue with PU foam is partly the toxic gases it generates during its manufacturing process and recycling [7]. In fact, the recycling processes of such products require a delamination step of the different layers (PET, PU, PA). This operation is not optimal because some PU foam remains on the textile fabrics. It is also important to note that the machines used for the recycling are very expensive. The PU foam has many serious drawbacks such as flammability and gases emissions due to the laminating processes. These problems lead to the question of its replacement by a new product. Hence in order to overcome all these drawbacks in cushioning application, 3 dimensional spacer fabrics grab the attention of researchers in this decade.

Spacer fabrics are 3-dimensional (3D) textile structures formed of two fabric layers which are joined together and kept apart by spacer yarns. It has better mechanical and thermal characteristics compared to conventional ordinary fabric due to their wonderful 3-D sandwich structures and porous nature. [8, 9]. Spacer fabric in which its third dimension (thickness) is significant. Components in spacer fabrics differ depending on the yarn type and production method. [10]. There are two types of spacer fabrics such as warp knitted spacer fabric and weft-knitted spacer fabric. The first type is knitted on a rib raschel machine having two needle bars [11, 12], while the second is knitted on a double jersey circular machine having a rotatable needle cylinder and needle dial [13]. The Properties of spacer fabrics such as 3D fiber location, possibility to use different materials and production in one step, provide the spacer fabrics to use in different application areas. The major application areas are automotive textiles, medical textiles, geotextiles, protective textiles, sportswear and composites. Knitted Spacer fabrics are lightweight and breathable structures [14, 15]. Their compression characteristic is also better than conventional textile structures. Compression resilience is an important attribute of spacer fabrics, which is related to sensation of mechanical comfort. Modern consumers consider compression as one of the most important attributes in the comfort sensation. Compression characteristic of knitted fabrics has been studied by various researchers [15-17]. Postle (1974) indicated that bulk density or compression property of knitted structures is related to the effective diameter of the yarn inside of the fabric and also to the fabric thickness [14]. Xu-honget. al., analyzed the stress-strain behavior of warp knitted spacer fabrics when compressed [18]. MecitArmakanet. al., investigated

the compression characteristic of warp knitted spacer fabrics on the basis of spacer yarns in their structure [15]. They noted that, the material, pattern and threading of the spacer yarns have significant effect on compression characteristic of the fabrics. It was also observed that the location angle and the amount of the spacer yarns influence the compression behavior of fabrics. Arumugam et al. were studied the compression and energy absorption behavior of weft knitted spacer fabrics [19]. They have discussed effect of structural parameters and suggested that the spacer fabrics have ability to absorb high compression energy.

The lack of comprehensive studies on the characteristics especially on compressive behavior and energy absorption during loading of weft knitted 3D spacer fabrics are sound basis for this research.In the present study, the paper reports that the compression behavior of weft-knitted spacer fabrics specially developed for cushioning applications. With an attempt to increase the energy absorption during compression and efficiency of the cushioning material, various structural parameters such as structure, thickness and spacer yarn liner density are varied during development of spacer fabrics. At the end, the effect of all these factors on compressibility and energy absorption of different samples were carefully compared and analyzed using advance techniques. It is expected that a clear picture for tailoring a weft-knitted spacer fabric with promising cushioning properties for car seats, pillows, mattress, insole etc.

2 Materials and Methods

Six different types of spacer fabrics were developed using computerized Mayer & Cie, OVJA 1.6 E 3 WT knitting machine. These fabric samples were classified into two groups for convenient analysis of results, the first group has been developed using Polyester/Polypropylene blend with three different proportions and second group with Polyester/Polypropylene/Lycra blend having another 3 different compositions. The structure and knit pattern of the weft knitted spacer fabrics is given in Fig. 1. As a spacer yarn, three different types of 88 dtex Polyester monofilament yarn and Polyester multifilament yarns (167 dtex and 14.5 tex) were used. 14.5 tex Polypropylene yarn was used on both the surfaces in group 1 samples. In group 2 samples polypropylene (14.5 tex), without and with lycra (44 dtex) were used for the top and bottom surface of the spacer fabrics (Table 1). The loop length of the fabric without lycra (WES 1) was 2.46 mm and samples (WES

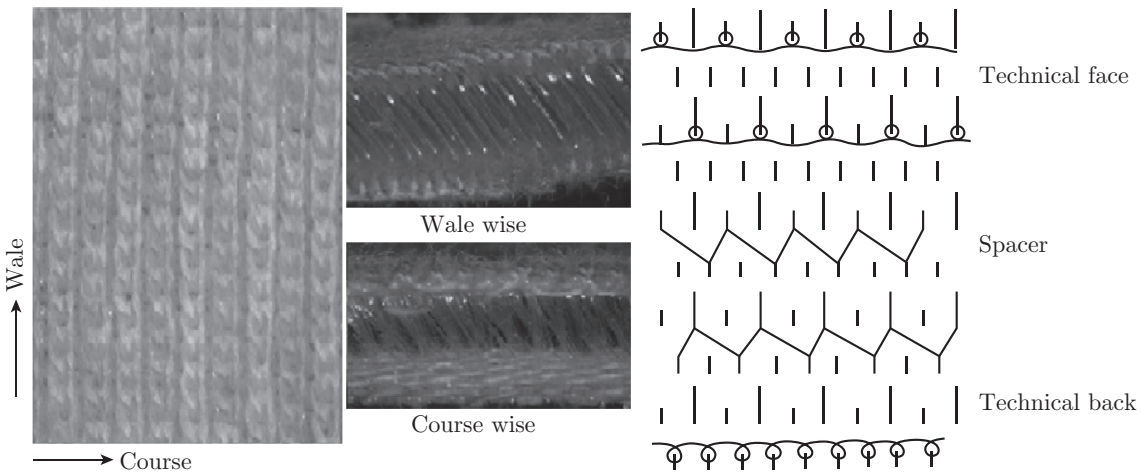


Fig. 1: Structure and knit pattern of weft knit spacer fabric

Table 1: Fabric Particulars

Fabric sample No.		Type of yarns and linear density				Type of yarns and linear density		
Fabric layers		S1	S2	S3		S4	S5	S6
Technical face	Group 1- Without Lycra	Polypropylene (POP)-14.5 tex	Polypropylene (POP)-14.5 tex	Polypropylene (POP)-14.5 tex	Group 2- With Lycra	Polypropylene (POP)-14.5 tex Lycra-44dtex	Polypropylene (POP)-14.5 tex Lycra-44dtex	Polypropylene (POP)-14.5 tex and Lycra-44dtex
Spacer		Polyester monofilament (PES monofil)-88 dtex	Polyester (PES)-14.5 tex	Polyester (PES)-167 dtex		Polyester monofilament (PES monofil)-88 dtex	Polyester (PES)-14.5 tex	Polyester (PES)-167 dtex
Technical back		Polypropylene (POP)-14.5 tex	Polypropylene (POP)-14.5 tex	Polypropylene (POP)-14.5 tex		Polypropylene (POP)-14.5 tex	Polypropylene (POP)-14.5 tex	Polypropylene (POP)-14.5 tex
Fiber composition (%)		58% POP 42% PES monofilament	45% POP 55% PES	41% POP & 59% PES		55%POP 39%PES monofilament 6% Lycra	42% POP 52% PES 6% Lycra	39% POP 55% PES 6% Lycra

Table 2: Characteristics of Spacer Fabrics

Weft Spacer	Areal Density ($g \cdot m^{-2}$)				Thickness (mm)				Density	Stitch Density (Stitches/cm^2)			
Samples	Mean	ME	LL	UL	Mean	ME	LL	UL	($kg \cdot m^{-3}$)	Mean	ME	LL	UL
WES 1	493	0.16	492.84	493.16	4.4	0.88	3.52	5.28	112	200	0.1	199.9	200.1
WES 2	443	0.12	442.88	443.12	2.62	1.1	1.52	3.72	169.1	150	0.04	149.96	150.04
WES 3	477	0.2	476.8	477.2	2.74	0.61	2.13	3.35	174.1	150	0.12	149.88	150.12
WES 4	632	0.1	631.9	632.1	4.4	0.55	3.85	4.95	144.8	350	0.06	349.94	350.06
WES 5	657	0.12	656.88	657.12	3.5	0.86	2.64	4.36	187.7	280	0.1	279.9	280.1
WES 6	695	0.22	694.78	695.22	3.4	0.45	2.95	3.85	205.4	280	0.1	279.9	280.1

2 and WES 3) were 2.78. The loop length weft knit spacer fabrics with Lycra on the surface (WES 4) was 1.28 mm and for samples (WES 5 and WES 6) were 1.52 mm.

Structural properties including the yarn linear density and fabric weights per unit area were determined according to ASTM D1059 standard using electronic weighing scale [14]. The thickness of the fabrics was measured according to ASTM D1777-96 standard with the SDL digital thickness gauge at a pressure of 200 Pa [15]. The Stitch density was calculated from wales per centimeter (WPC) and course per centimeter (CPC) with the help of optical microscope. The density (D) of the fabric was calculated was calculated using the relationship (1)

$$D = \frac{W}{t} kg \cdot m^{-3} \tag{1}$$

where, W is areal density (weight per unit area), t is thickness. All these spacer fabric characteristics have been mentioned in Table 2. All the experiments were carried out under standard ambient condition and as per standard.

2.1 Evaluation of Compression Behaviour

The speed of compression had been chosen at 12 mm/min in accordance to the ASTM d 575 (Test methods for rubber properties). The test performed is a compression one and the machine is equipped by 2 strictly parallel plates with a diameter of 150 mm and a smooth surface and the samples were cut with dimensions of 100 mm × 100 mm. All the spacer fabric specimens are compressed up to 80% of the initial thickness in an atmospheric condition of 20°C and 65% relative humidity [19, 20]. Five tests were carried out for each sample under each testing condition and the average compression stress-strain cure are presented throughout this paper.

Overall compressive stress-strain trend of the spacer fabric samples are presented in the Fig. 2. Normally the compression behavior of spacer fabrics are classified into four stages with respect to changes in the slope. The four stages are (1) initial, (2) elastic, (3) plateau and (4) densification (4). In the first stage, the surface layer of spacer fabric undergoes compression, a smaller slope is observed for loose/open structures and slope increases with increase in stitch density. The spacer yarns have very low contribution in constraining the deformation during initial compression.

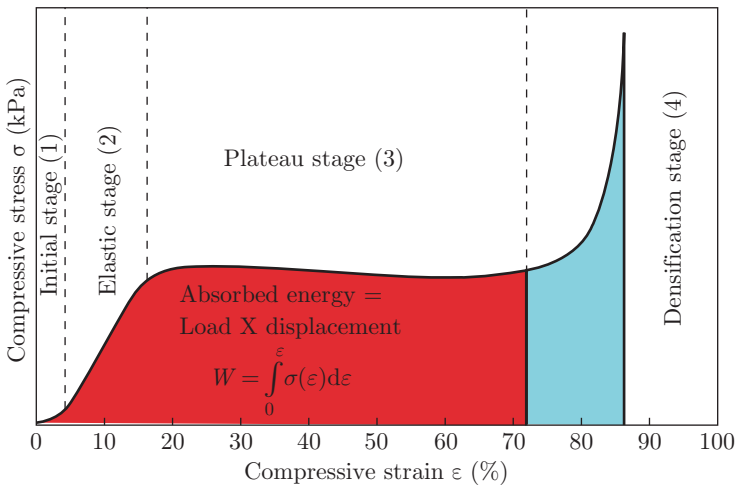


Fig. 2: Compressive behavior of 3D spacer fabrics

Further compression (2nd stage) leads to rapid increase in stress; it might be due to jamming of surface yarns which allows monofilaments to buckle to a larger extent. In spacer fabrics, third stage is quite complex because the compressive stress and strain have been affected by buckling, shearing and inter-contacting of spacer yarns. A faster increase in stress occurs in 4th stage because the fabric achieves a very high density.

2.2 Energy Absorption During Compression of Spacer Fabrics

It is necessary to evaluate and analyze the spacer fabrics energy absorbing ability during compression. it would be more useful to get a better understanding on the cushioning behavior of the spacer fabric. The compression curves reveal long deformation plateaus, suggesting that all spacer fabrics samples may potentially be good energy-absorbing materials. The area under the load-displacement curve represents the total energy absorbed and it can be calculated by multiplying the area under the stress-strain curve by the volume of the sample. The energy absorption capacity per unit volume, W, can be calculated by integrating the compression stress-strain curve, as given by Eq. (2) [21].

$$W = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \tag{2}$$

where, σ is the compression stress, $\mathcal{E}$ is the compression strains where $\mathcal{E}$ is the strain at the end/beginning of densification stage. In order to better understand the energy-absorption capacity of a cushioning material, the energy-absorption efficiency E can be used to analyze its energy-absorption process. The efficiency E is defined as the ratio of the energy absorbed by a real cushioning material compressed to a given strain and energy absorbed by an ideal cushioning material that transmits a constant stress of the same value at the same given strain. It is useful to plot the efficiency as a function of the stress to obtain the indication for optimum usage. The efficiency E is expressed by Eq. (3):

$$E = \frac{Ah \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon}{Ah\sigma} \tag{3}$$

where A — area, h — thickness, σ — stress at the strain ε. The energy-absorption and efficiency of all the spacer fabrics are compared and nalysed to find the suitable material for cushioning applications.

2.3 Statistical Analysis

Statistical analysis software, QC Expert-Trilobyte was used to conduct all the statistical tests mentioned in this work. Advance statistical evaluation and two-way analysis of variance was used to analyze the significance of various factors on required properties of weft knitted spacer fabrics. Also, differences in means between various groups were examined for statistical significance using one-way ANOVA followed by pair comparison using Scheffe's method. For all the statistical tests, differences were considered significant at $P < 0.05$. Data were reported as mean ± standard error of mean, unless otherwise stated.

3 Results and Discussions

3.1 Effect of Fabric Characteristics on Compression Behavior of Weft Knit Spacer Fabrics

As shown in Fig. 3, the compressive stress-strain curve reveals that the compressive resistance of spacer fabric without lycra made up of monofilament yarn is low in linear and elastic stage, but sudden increase in compressive stress observed in plateau and densification stage. From Fig. 3, spacer fabrics with lycra made up of monofilament spacer yarn constantly offers high compression resistance in all four stages. Among the fabrics made up of multifilament spacer yarn, the compressive stress — strain curve showed that, compressive resistance has indirectly proportional to thickness of the spacer fabrics. It was observed that the denser fabrics require higher compressive stress to undergo same compressive deformation than the fabric with low density. It was also observed that the thicker fabric has ability to undergo larger deformation under low loading condition. The thickness of the fabric should be selected according to the amount of the energy to be absorbed and the allowed stress level. In both the set of spacer fabrics (without lycra and with lycra), two types of spacer yarn such as monofilament and multifilament spacer yarns were used for convenient analysis of its effect on compression. Normally the monofilament spacer yarns act as a linear spring which offers more resistance towards compression as compared to other type of materials in cushioning applications.

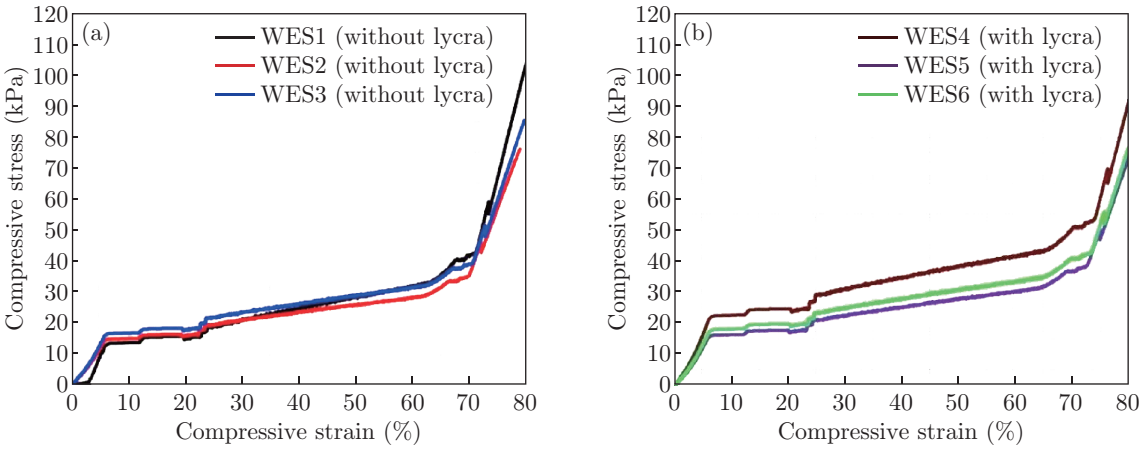


Fig. 3: Influence of thickness on compressive behavior of weft knit spacer fabrics

From the Fig. 4, it is observed that, the compressive resistance is high for the fabrics with monofilament yarn for both the groups than that of fabric with multifilament spacer yarn. In plateau region (3rd stage), the marginal differences has been observed between the fabrics made up of monofilament spacer yarn (WES 1 & WES 4) in both the groups. It might be due to the fact that the large differences in density between these two samples. But the fabrics with multifilament spacer yarn (WES 2, 3 & WES 5, 6) don't show significant differences in compressive strength because the densities of these samples have almost closer to each other. It has also been found that the outer layer structures could affects the stitch density of the fabrics. The stitch density on the surface layer directly affects the compressive strength of the spacer fabrics. The compressive resistance increases with increase in stitch density. The lower stitch density on the surface of the fabric results in large surface deformation. In stage 4, the lower deformation was observed in the

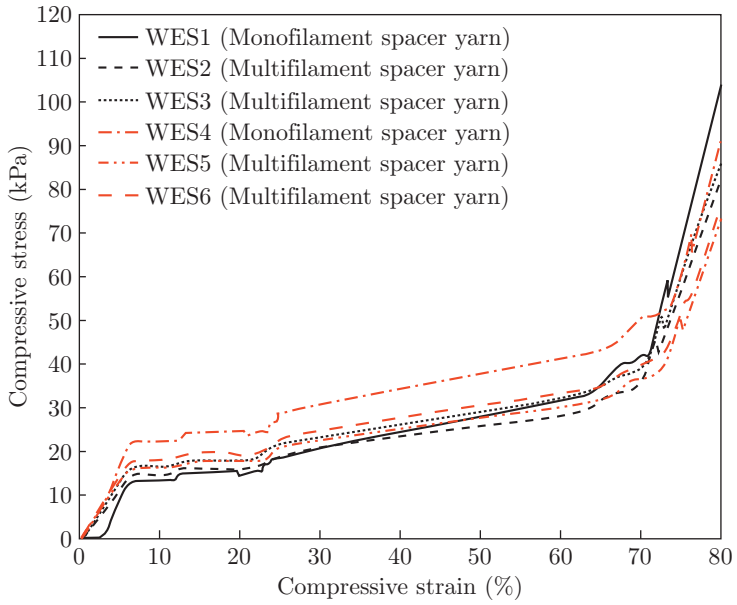


Fig. 4: Influence of spacer yarn on compressive behavior of weft knit spacer fabrics

fabrics with monofilament spacer yarn than the fabrics made up of multifilament spacer yarn. It might be the fact that the spacer yarns have comes in to contact with each other and also makes locking effect with surface structure as quick as possible.

3.2 Compressive Energy Absorption of Weft Knit Spacer Fabrics

Fig. 5(a) & (b) presents the work done of all spacer fabrics under compression load and also it compares the response compressive stress with effect of deformation and structural characteristics. The figures reveal that thicker spacer fabrics with monofilament spacer yarn have higher work done than that of thin fabrics with multifilament spacer yarn when it undergoes compression. Irrespective of the structural variations, the compressive work done shows same trend for all the

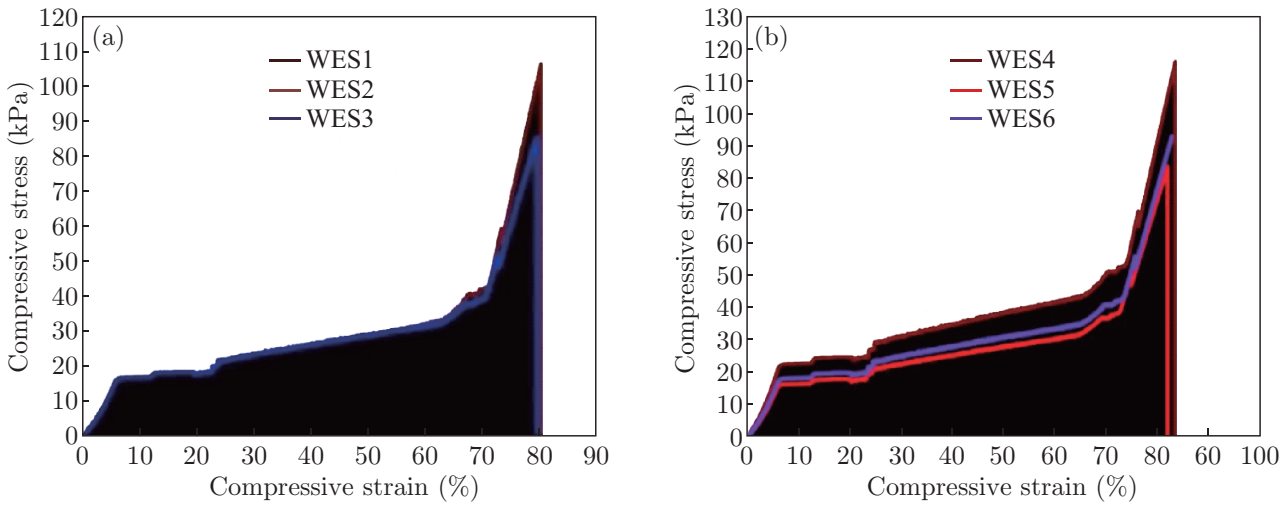


Fig. 5: Compressive energy absorption of weft knit spacer fabrics

samples. In both the groups, over all work done values are higher for the spacer fabrics made (WES 1 & WES 2) up of monofilament yarn. The density of spacer fabric also plays a vital role in compressive behavior, negative linear correlation was observed between density and compressive work done.

Fig. 6 presents the graphical analysis of compressive stress – absorbed energy — efficiency. It is observed from the figure that the absorbed energy of weft knit spacer fabrics (WES 1—WES 6) linearly increases with the stress in the initial stage of compression. The marginal differences in energy absorption between the samples can be seen when the compressive stress reaches towards the third stage for both the groups. At the start of densification stage, the rapid increases in stress results in small deformation and energy absorption. From the energy absorption graph, it is easy to find the stress associated with the required amount of energy to be absorbed. So, it is more convenient to select the suitable spacer fabrics for cushion application with optimum compressive performance. As noticed from the Fig. 6, in the densification stage, efficiency decreases with rapid increase in stress level. It is also because of dramatic increase in volume density of the spacer fabrics. The point at the maximum energy-absorption efficiency can also be considered a critical point between the plateau zone and the densification zone. Overall it is observed that the compressive energy and efficiency is higher for the thicker fabrics made up of monofilament spacer yarn with low density. Also it is found that fabrics with finer spacer yarns undergoes large amount of work done as well as high efficiency during compression mechanism.

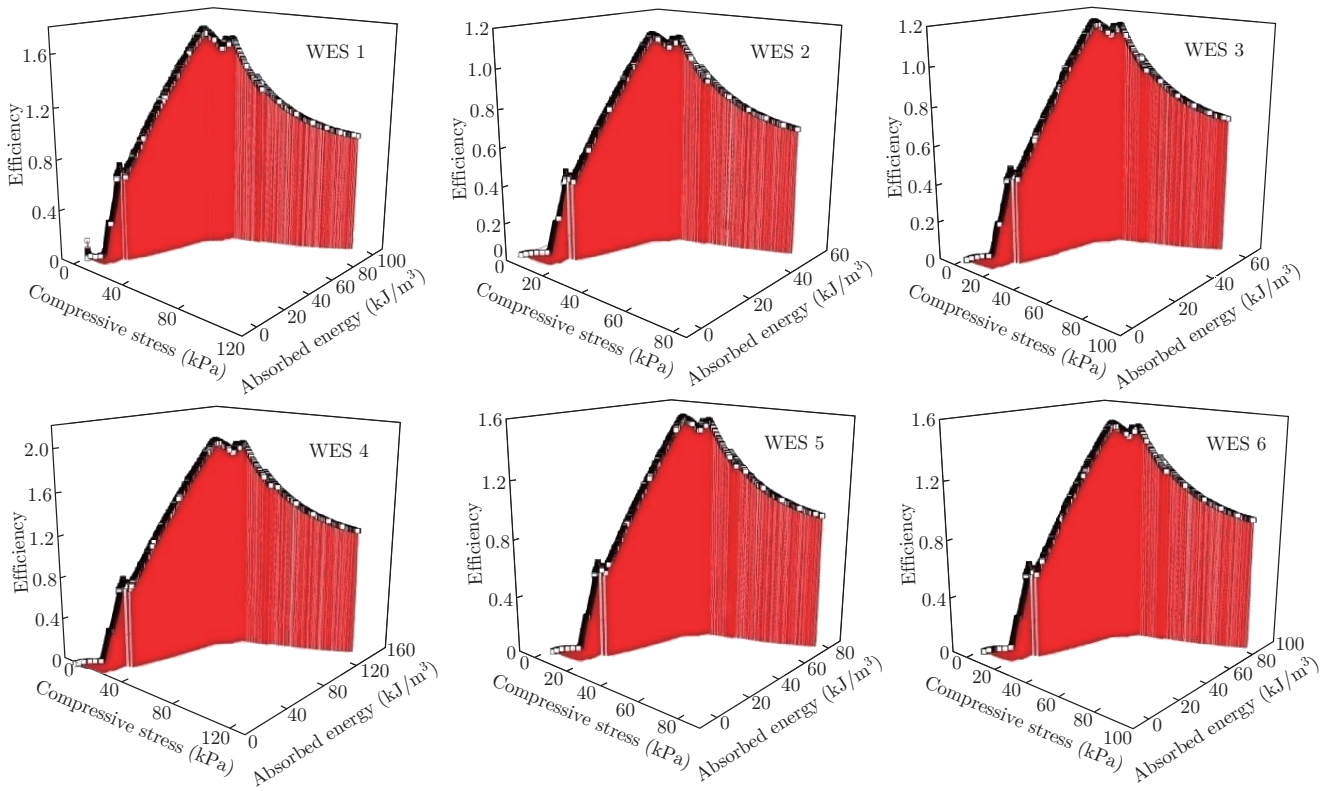


Fig. 6: Energy absorption and efficiency of weft knit spacer fabrics

3.3 Regression Model for Compressibility of Weft Knit Spacer Fabrics

The average of compressive stress responses against strain obtained for each spacer fabrics samples was fitted in the general form of third order polynomial (Fig. 7). Response fit analyses, regression coefficient estimations and model significance evaluations were conducted. The estimated regression coefficients of the fitted polynomial equation as well as the correlation coefficients for each model are given in Table 3. The adequacy of the models was tested using residuals sum of squares and adjusted coefficient of determination (R^2).

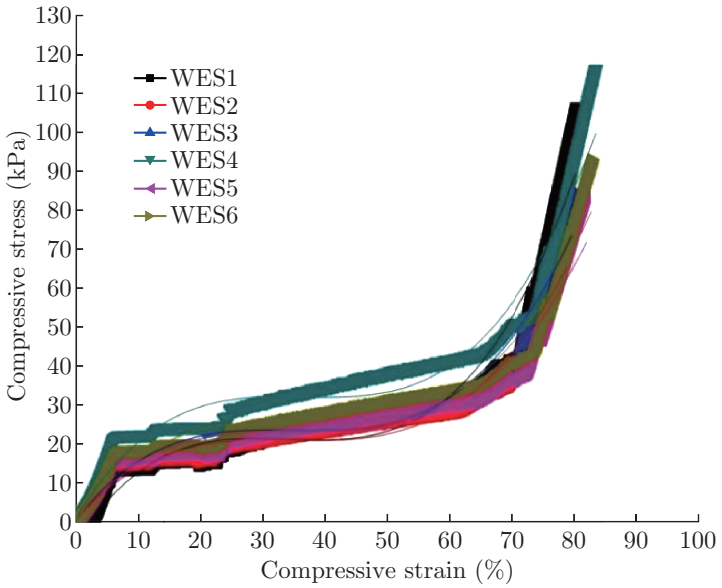


Fig. 7: Third order polynomial regression fit for compressibility of weft knit spacers

3.4 Statistical Evaluation for Compressive Behavior Response of Weft Knit Spacer Fabrics

In this section, one-way ANOVA is analyzed and the selected value of significance for all statistical tests in the study is $\alpha = 0.05$ levels. The degree of freedom is 1, 8, the Fcritical is 5.318, and degree of freedom 3, 16, the Fcritical is 3.239. If the statistic is smaller than the critical value, we retain the null hypothesis because the p-value must be bigger than α, and if the statistic is equal to or bigger than the critical value, we reject the null hypothesis because the p-value must be equal to or smaller than α. Also pair wise comparison using Scheffé's method and Z score was calculated and presented in Table 4. The results of the ANOVA are listed in Table 4, which analyses the effect of groups of thickness and surface characteristics and types of spacer yarn of spacer fabric samples with compressive stress.

The value of $F_{critical} < F_{actual}$ proves that the changes in the thickness, types of spacer yarn and surface layer structure (stitch density) of weft-knitted spacer fabric have significant influence on the above-mentioned fabric compressive stress. The insignificant difference in compressive stress is obtained between the pair, sample made up of multifilament spacer yarn without lycra on surface and with lycra. But the quite significant values are obtained in compressive stress between the other samples with multifilament spacer yarn.

Table 3: Prediction of compressive stress of weft knit spacer fabrics using polynomial regression model

Model			Polynomial				
Equation			y=Intercept+B1x+B2x^2+B3x^3				
Weight			No Weighting				
Sample Nos			Value	Standard Error	Residual Sum of Squares	F Value	Prob>F
Compressive Stress	WES 1	Intercept	−5.123	0.413	56756.200	12126.8	0.000
		B1	2.450	0.044			
		B2	−0.073	0.001			
		B3	0.001	0.000			
	WES 2	Intercept	0.473	0.270	24157.850	12940.4	0.000
		B1	1.835	0.029			
		B2	−0.054	0.001			
		B3	0.001	0.000			
	WES 3	Intercept	0.531	0.303	30483.590	12940.4	0.000
		B1	2.040	0.033			
		B2	−0.059	0.001			
		B3	0.001	0.000			
	WES 4	Intercept	0.722	0.412	56274.350	12940.4	0.000
		B1	2.644	0.042			
		B2	−0.073	0.001			
		B3	0.001	0.000			
	WES 5	Intercept	0.520	0.296	29172.620	12940.484	0.000
		B1	1.939	0.031			
		B2	−0.055	0.001			
		B3	0.001	0.000			
	WES 6	Intercept	0.578	0.329	36015.580	12940.484	0.000
		B1	2.132	0.034			
		B2	−0.059	0.001			
		B3	0.001	0.000			

Table 4: Statistical Evaluation for Compressive Behavior of Weft Knit Spacer Fabrics

One Way Anova - Influence of various factors on compression stress of weft knit spacer fabrics									
Test of factor influence: Influence of monofilament spacer yarn between both the groups									
		F_{cri}	F_{cal}	Prob.	Conclusion	Z-score (95% interval)	Pairwise comparison (Scheffé's method)		
							Compared Pair	Prob.	Significance
a	Without Lycra	5.318	30.520	0.0006	Significant	-2.859	a-b	5.57E-04	Significant
b	With Lycra					3.126			
Test of factor influence: Influence of multifilament spacer yarn between both the groups									
a	Without Lycra (Thickness-2.62 mm)	3.239	92.238	2.03E-08	Significant	-1.974	a-b	4.98E-05	Significant
b	Without Lycra (Thickness-2.74 mm)					2.217	a-c	0.000561	Significant
							a-d	2.22E-08	Significant
c	With Lycra (Thickness-3.5 mm)					-2.169	b-c	0.614266	Insignificant
d	With Lycra (Thickness-3.4 mm)					2.410	b-d	0.000637	Significant
							c-d	5.59E-05	Significant
Test of factor influence: Influence of types of spacer yarn within the group - Without Lycra									
a	Monofilament Spacer Yarn (Thickness-4.4 mm)	5.318	409.016	3.73E-08	Significant	3.138	a-b	3.73E-08	Significant
b	Multifilament Spacer Yarn (Thickness-2.62 mm)					-2.248			
Test of factor influence: Influence of types of spacer yarn within the group - With Lycra									
a	Monofilament Spacer Yarn (Thickness-4.4 mm)	5.318	187.617	7.78E-07	Significant	3.215	a-b	7.78E-07	Significant
b	Multifilament Spacer Yarn (Thickness-3.4 mm)					-2.572			

4 Conclusion

Compressive behavior, energy absorption and efficiency of weft -knitted spacer fabrics were studied. The compression deformation mechanism of the fabric was identified based on the analyses of the load-displacement curve. The results showed that the 3D spacer fabrics are more resilient towards compression stress. Thick spacer fabrics with monofilament spacer yarn have higher work done than that of thin fabrics with multifilament spacer yarn when it undergoes compression. Irrespective of the structural variations, the compressive work done shows same trend for all the samples. On the other hand, it has been shown that the spacer fabrics dissipate more energy during compression. The stitch density on the surface layer directly affects the compressive strength of the spacer fabrics. The compressive resistance increases with increase in stitch density. The lower stitch density on the surface of the fabric results in large surface deformation.

Overall it is observed that the compressive energy and efficiency is higher for the thicker spacer fabrics with low density. Also, the fabric with monofilament spacer yarns undergoes large amount of work done as well as high efficiency during compression mechanism. The spacer fabric with large compressive deformation, high efficiency and energy absorption until plateau stage is the suitable finding cushioning applications.

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