

Analysis of the Compression Behavior of Warp Knit Spacer Fabrics for Evaluating Suitability in Cushioning Applications

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ABSTRACT

The article reviews the compression behavior of warp knit spacer fabrics intended for cushioning applications. An experimental study has been conducted on the compression behavior of a series of warp-knitted fabrics made for cushioning applications. The compression behavior of these fabrics and the effect of each structural parameter have been evaluated by the use of both the compression stress-strain curves and energy efficiency diagrams and the influence of each structural parameter analyzed. The findings show that warp knitted spacer fabrics are an ideal class of energy absorbers for cushioning applications, and their energy-absorption capacity can easily be tailored to meet specific end-use requirements by simply varying their structural parameters with the help of efficiency diagrams. The spherical compression behavior of warp knitted spacer fabrics has been studied by the development of a theoretical model to predict the spherical ball compression properties of the spacer fabric. The analysis results reveal that the spherical compression effects decrease with increasing ball radius and increase with increasing fabric thickness. It is expected that this study could help better understand the behavior of knitted spacer fabrics under spherical compression. The calculated values from the theoretical model have been compared with experimental measurements, and agreements were found between both. Based on the plane compression testing results, the validated model can be used to predict the spherical compression behaviors of knitted spacer fabrics compressed with different radii of the spherical balls.

Keywords: Cushioning application, efficiency diagram, energy absorption, spherical compression, warp knit, spacer fabric, theoretical model, experimental validation

Introduction

A number of materials and structures are available with special features for cushioning, of which airbags, bubble films, rubberized fiber cushioning, and polymer-based foams are some good examples. As a new class of three-dimensional textile

structures, warp-knitted spacer fabrics not only have much better moisture transmission property than PU foams but also have a similar cushioning performance if appropriate structural parameters are adopted [1]. As a type of sandwich structure, their applications are largely dependent on their

compression properties. Although several experimental and theoretical studies have been carried out on their plate compression properties, their spherical compression behaviors have not been deeply studied yet. A theoretical model is developed to predict the spherical ball compression properties of the fabric [2]. The non-dimensional parameters are introduced to analyze the effects of the fabric thickness and ball radius based on the theoretical relationship established between the compression force and compression strain at the maximal compression point. Based on earlier investigations, it is found that the compression stress-strain curve of a knitted spacer fabric can be divided into different regions and the compression stress-strain curve at each compression region can be approximately represented by a linear equation [3-6]. Based on the theoretical analysis, further study focuses on the comparison of the model with experimental results. The differences between the calculations and experiments have been highlighted based on the compression parameters selected [7].

Compression behavior for cushioning applications

When a mass is impacted on cushioning materials, the kinetic energy should be dissipated while maintaining maximum load/acceleration below certain limit [8]. When under compression, cushioning materials normally absorb kinetic mechanical energy at a relatively constant stress over a great displacement range. Cushioning material is capable of absorbing most of the energy, when designed suitably, having extended displacement and an appropriate level of the constant stress. Many materials and structures possess such features suited for cushioning applications, some of which are airbags, bubble films, rubberized fiber cushioning, and polymer-based foams, but are not so effective because of low cost, and inferior comfort properties, and hence unsuitable for human body protection. Warp-knitted spacer fabrics are 3D textile structures having two distinct fabric layers

joined together but kept apart normally by monofilament spacer yarns [9]. They have the advantages of low cost, high productivity, and wide structure variations, which render warp-knitted spacer fabrics very prospective for different applications [10–13]. More specifically, a combination of excellent transversal compressibility and high permeability renders them very suitable for multifunctional clothing and technical applications. Attempts have been made to study the compression properties of warp-knitted spacer fabrics. Most studies have focused on the overall compression load-displacement relationship, which is divided into three main stages, i.e., linear elasticity, plastic plateau, and densification, which represents the typical behavior necessary for a cushioning material in compression [8,10-13]. Even though the findings reveal warp-knitted spacer fabrics are a new option for cushioning applications, the plateau stage found in the literature is not notable and the zone of the plateau stage reported in the literature is too short as well [10,11-13]. In other words, the total energy absorbed in the plateau zone by these fabrics as reported is not sufficient to identify them as good cushioning materials. An investigation has been conducted on the compression behavior of warp-knitted spacer fabrics, specifically designed for cushioning applications. Efforts have been directed to enlarge the plateau zone and reasonably control the load levels at the plateau stage. For the purpose of this study, a series of warp-knitted spacer fabrics have been produced with varying structural factors including spacer yarn inclination angle and fineness, fabric thickness, and outer layer structure. It is expected that a clear picture for tailoring a warp-knitted spacer fabric with promising cushioning properties could be established from this study.

The compression behavior of the warp knitted spacer fabrics intended for cushioning applications has been studied using compression stress-strain curves and efficiency diagrams. Studies have been done on the influence of various structural factors like spacer yarn inclination angle and

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fineness, fabric thickness, and outer layer structure. The warp-knitted spacer fabrics are well suited for cushioning applications due to their high energy absorption capacity, which enables designs for satisfying specific end uses by mere variation in structural factors. In the evaluation of the cushioning performance of warp knit spacer fabrics, the efficiency proves effective. The efficiency diagram is suitable for choosing specific fabrics working at permitted stress levels, for absorption of a particular energy. The compression behavior and cushioning performance of spacer fabrics are influenced by all their structural aspects. Lower energy absorption with higher efficiency can be obtained with fabrics having lower spacer inclination angle, greater fabric thickness, finer spacer yarns, and larger mesh of the outer layers. Higher energy absorption with higher energy results can be obtained from higher spacer yarn inclination angle, lesser fabric thickness, coarser spacer yarns, and smaller mesh size of the outer layers. Hence the choice of appropriate structural factors becomes crucial in order to

design a spacer fabric with the required compression behavior.

Technical details

Twelve warp-knitted spacer fabrics have been considered (one fabric had finer spacer yarn). Four different structures - locknit, chain plus inlay, rhombic mesh, and hexagonal mesh have been used for knitting the outer layers. The fabrics have been knitted on a high-speed double-needle bar Raschel machine of six yarn guide bars with a machine gauge of 18. 300D/96F. Polyester multifilament was used to create the binding of the structure in the knitting process for the top outer layer and the bottom outer layer. The polyester monofilament of 0.2mm in diameter was used as spacer yarns to connect the two outer layers [1]. INSTRON device has been used to carry out the compression tests on the fabrics and obtain the compression stress-strain curves. The chain notations are as shown in table I and the chain notation for each movement is shown in table II below.

Table I. Chain notation of yarn guide bars for outer layers

Structure	Guide bar 1/guide bar 6	Guide bar 2/guide bar 5	Threading
Locknit (L)	1-0 0-0/3-2 3-3//	2-1 1-1/ 1-0 0-0//	Full
Chain+ inlay (CI)	0-0 0-0/ 5-5 5-5//	1-0 0-0/ 1-0 0-0//	Full
Rhombic mesh (RM)	1-0 0-0/1-2 2-2/ 2-3 3-3/2-1 1-1//	2-3 3-3/2-1 1-1/ 1-0 0-0/ 1-2 2-2//	1 full 1 empty
Hexagonal mesh (HM)	(1-1 1-0/ 3-3 3-2)x3 (4-4 5-4 /3-3 3-2)x3//	(4-4 5-4/3-3 3-2)x3 /(1-11-(4-4 5-4 /3-3 3-2)x3//	2 full 2 empty

Table II. Chain notation of yarn guide bars for spacer yarns

Lapping	Guide bar 3	Guide bar 4	Threading
I	1-0 2-1/2-1 1-0//	2-1 1-0/1-0 2-1//	1 full 1 empty
II	1-0 3-2/3-2 1-0//	3-2 1-0/1-0 3-2//	1 full 1 empty
III	1-0 4-3/4-3 1-0//	4-3 1-0/1-0 4-3//	1 full 1 empty

By considering different outer layer structures, different lapping movements of the spacer yarn guide bars, and different fabric thicknesses, 11 spacer fabric samples were produced. With one extra sample made with finer spacer yarn (0.16mm in diameter),

a total of 12 spacer fabric samples have been used in the investigation. Their wale stitch density during knitting was kept unchanged and was adjusted as 10courses/cm. The technical details of the fabrics used are given in table III.

Table III. Details of the spacer fabrics

Fabrics	Top outer layer	Spacer layer	Bottom outer layer	Thickness (mm)
1	Locknit	2	Locknit	7.52±0.06
2	Chain inlay	1	Chain inlay	7.57±0.08
3	Chain inlay	2	Chain inlay	7.59±0.10
4	Chain inlay	3	Chain inlay	7.40±0.06
5	Chain inlay	2	Chain inlay	5.64±0.03
6	Chain inlay	2	Chain inlay	8.45±0.09
7	Chain inlay	2	Chain inlay	10.62±0.10
8	Rhombic mesh	2	Chain inlay	7.20±0.05
9	Rhombic mesh	2	Rhombic mesh	7.76±0.06
10	Hexagonal mesh	2	Chain inlay	7.56±0.08
11	Hexagonal mesh	2	Hexagonal mesh	7.62±0.06
12	Chain inlay	3	Chain inlay	7.06±0.09

Continued...

Fabric	Areal density (g/m ²)	Bulk density (kg/m ³)	Stitches/ cm ²
1	1008.29±10.68	134.08±1.42	41.15
2	900.11±9.01	118.87±1.19	37.95
3	901.75±14.58	118.84±1.92	37.26
4	923.20±8.44	124.76±1.14	37.95
5	790.63±14.51	140.08±2.57	34.98
6	1022.08±13.38	120.96±1.58	43.50
7	1010.42±8.83	95.14±0.83	37.95
8	830.05±11.53	115.22±1.60	39.33
9	907.24±17.07	116.91±2.20	51.10
10	812.70±6.61	107.50±0.87	37.95
11	724.82±8.34	95.17±1.10	38.86
12	746.53±6.81	105.68±0.96	39.44

Relating compression stress-strain and cushioning behavior

In order to understand the compression behavior of the spacer fabric, the compression process is categorized into four steps – Initial, elastic, plateau, and densification. A lower slope is seen at the

initial stage due to the compression of the loose outer layers and their ineffective constraint for the monofilaments. There is a slight slippage of the monofilaments in the outer layers since each loose multifilament stitch around a monofilament cannot tightly constrain the monofilament at this stage [1].

As the fabric gets compressed further into the elastic stage, all the compressed multifilament stitches are changed to a fastened microstructure. In this stage, the monofilaments buckle at a larger scale, and they are better fastened by the multifilament stitches. As a result, a rapid increase of the compression stress, i.e., a stiffer mechanical behavior of the fabric is seen. During the plateau stage, an almost constant stress is reached. The deformation mechanism of the fabric in this stage is very complicated, which could be affected by the buckling, rotating, shearing, and inter-contacting of the monofilaments as well as the contacting of the monofilaments with the outer layers. The factor that strongly affects the fairly constant stress could probably be the inter-contacting of the monofilaments, of which the boundary conditions at their ends contacting with the outer layers are not constant. There is a drastic rise in the stress during the final stage of compression arising from the swift densification of the entire fabric and the monofilaments within the fabric collapse and contact each other, resulting in a very high stiffness. Such an analysis reveals that the spacer fabric has a good cushioning effect, due to almost constant compression stress in the third stage till the displacement reaches more than half the initial fabric thickness with 50% strain, and this aptly meets the need for an ideal energy absorber. As the fabric does not exhibit the same behavior at higher strain rates under impact, the absorbed energy calculated at a low strain rate can still be used as a good reference to optimize the cushioning performance of a warp-knitted spacer fabric. It is relatively equivalent to the absorbed kinetic energy of a mass that might impact on the fabric (First to third stage).

Hence, there are two criteria involved

- a) Amount of energy that needs to be absorbed by the impacted object
- b) Stress permitted with specific impact zone

The energy absorbed by the fabric is low in the densification stage, but the stress steeply increases (Figure 2). In this circumstance, for a specific application, it is preferable that the fabric dissipates all the

energy before reaching the densification stage in order to prevent the unpredictably increased reacting stresses in this insecure stage. In addition, it is necessary to ensure that the stress in the plateau zone of the fabric is lower than the maximal stress allowed to the protected object. The two key factors required to be optimized for a warp-knitted spacer fabric in order to satisfy the needs of a particular end use, are the amount of the energy absorbed before the densification stage and the stress level at the plateau stage. It should be noted that the determination of the energy absorbed by a spacer fabric under compression is important.

Energy-absorption diagram

Even though the stress-strain curve can directly show the energy-absorption behavior of a spacer fabric, the energy-absorption diagram is even more useful to get a better understanding of the cushioning behavior of the spacer fabric. An energy-absorption diagram is obtained by plotting the absorbed energy per unit volume as a function of the stress. The absorbed energy per unit volume is the area under the stress-strain curve. An ideal cushioning material could be defined as one that transmits a permitted constant force to the protected object over a given range of compression strains, and this is practically impossible to produce [1]. The energy-absorption efficiency can be used to analyze its energy-absorption process, to better understand the energy-absorption capacity of a cushioning material [8]. The efficiency is 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 allows for a plot of the efficiency as a function of the stress to obtain the indication for optimum usage.

From the beginning of compression, the absorbed energy steadily increases with the stress. A dramatic increase of the absorbed energy is seen when the stress approaches towards the plateau stress, while maintaining constant stress in this zone. The absorbed energy increases gradually with a

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rapid rising of the stress. The associated stress of fabric for a given amount of energy to be absorbed can be conveniently determined from the absorbed energy-stress curve. Hence it is convenient to choose a suitable fabric or to optimize the fabric performance for a specific application for which the amount of energy to be absorbed and the permitted stress level are predefined. A similar tendency can be seen until the commencement of densification stage, in the case of the efficiency-stress curve. At the end of the plateau stage, the optimum energy-absorption efficiency is achieved. The energy efficiency decreases since the fabric density rapidly increases due to the densification of the structure beyond this point. For a given stress the higher the efficiency-stress curve, the more the energy is absorbed. Both the efficiency-stress curves and contours of the energy absorbed prove to be very useful for the determination of the preferable working range of the fabric. Hence, for a defined amount of energy to be absorbed, higher cushioning performance for a spacer fabric should function at a lower stress level but with a higher efficiency. The efficiency diagram including efficiency-stress curves and the contours of the energy absorbed is user-friendly; it is used to investigate the effects of various structural parameters including the spacer yarn inclination angle and fineness, fabric thickness, and outer layer structure, on the compression behavior of the warp-knitted spacer fabrics for cushioning applications.

Influence of the spacer yarn inclination angle

The two surface layers of the spacer fabrics are connected by the spacer yarns, and their inclination angle and length depend on the number of needles underlapped between front- and back-needle bars of warp knitting machine. The microscopic C.S images of three fabrics seen from the walewise direction are shown in Figure 1.

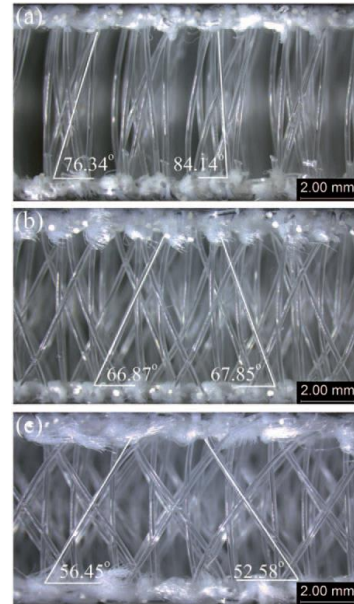


Figure 1. Microscopic views of the warp knitted spacer fabrics observed cross-sectionally from the walewise direction: [1]

- (a) Fabric with locknit structure in both layers and spacer layer with single lapping
- (b) (b) Fabric with chain inlay structure in both layers and spacer layer with double lapping
- (c) (c) Fabric with chain inlay structure in both layers and spacer layer with triple lapping

There are differences in spacer yarn angles which originate from the difficulty of producing the fabrics with exactly symmetrical spacer yarns in a complicated manufacturing and finishing process [1]. The spacer yarn inclination angle decreases as the number of needles underlapped increases. The biggest difference of the spacer yarn inclination angles between the left and right oblique spacer yarns was observed in fabric with chain inlay structure in both layers and single overlap in spacer yarns. This high difference in spacer yarn inclination angles makes the fabric asymmetric and unstable in structure, which leads to the occurrence of shearing between two outer layers along the coursewise direction under compression. As a result, the compression stress-strain curve

of the fabric has a sharp drop in the plateau zone. In order to avoid the influence of shearing, the outer layer surfaces of the fabric were stuck to the compression plates before testing.

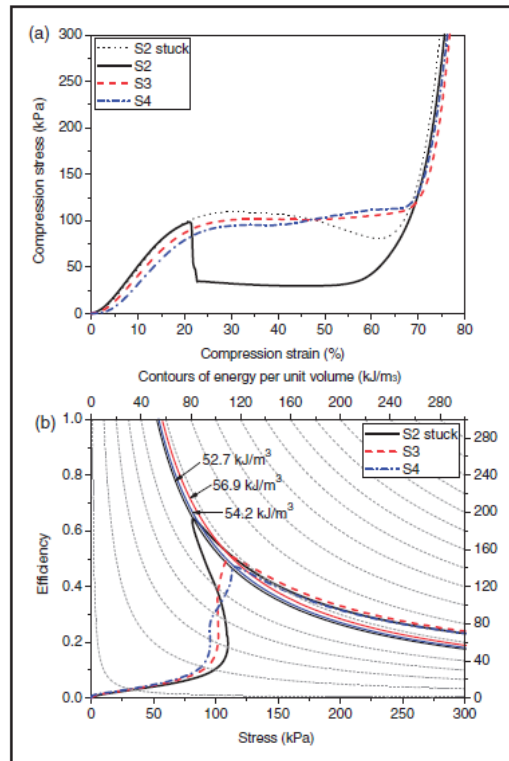


Figure 2. Influence of spacer yarn inclination angle on the compression behavior of spacer Fabrics [1]

- (a) Stress-strain curves
- (b) Efficiency diagram

The test result under this condition is also shown in Figure 5(a). As expected, the sharp drop disappears. The curves for samples S3 and S4 are also shown in Figure 5(a) for the comparison. With the decrease in spacer yarn inclination angle, the compression resistance of the spacer fabrics at the initial and elastic stages reduces. However, after the strain reaches about 47.5%, the situation is inverted. From this point to the end of the plateau zone, the stress of sample S2 has an obvious drop, but that of sample S4 has a slight increase. The stress of sample S3 remains nearly constant. The efficiency diagram, i.e., efficiency-stress

curves and contours of the energy absorbed per unit volume are shown in Figure 5(b). It is found that the maximum efficiencies of all these three fabrics are less than 0.7, which decrease with decreasing the spacer yarn inclination angle. The stress at the maximum efficiency point increases as the spacer yarn inclination angle decreases. The fabric with smaller spacer yarn inclination angle has a better cushioning performance at a low energy level, and fabric with higher spacer yarn inclination angle shows preferable cushioning property at a high energy level.

Influence of the fabric thickness

The compression resistance decreases as the fabric thickness increases. The thicker a fabric, the longer and lower the plateau zone observed. The thicker fabric can absorb a defined amount of energy in a larger deformation but at a lower stress level due to its low-value plateau [1]. The thinner fabric absorbs the same amount of energy in a lower deformation but at a higher stress level. Moreover, the thicker fabric reaches its maximum efficiency point at a lower stress and energy level, while the thinner fabric reaches its maximum efficiency point at much higher stress and energy level. Under such conditions, the fabrics having various thicknesses have various ranges of applications and are not directly comparable. The fabric thickness is chosen based on the amount of energy that needs to be absorbed and the permitted stress level. Hence efficiency diagram enables the efficiency of fabric to be optimized for a specific application.

Influence of the spacer yarn fineness

Two fabrics which have the same number of needles underlapped for the spacer yarns and the same outer layer structure but with two different diameters of spacer yarns (0.2 and 0.16 mm), have been selected to analyze the influence of the spacer yarn fineness on the compression behavior. The compression stress-strain behavior of these two fabrics reveals that the fabric made with coarser spacer yarn has higher compression resistance and a higher value plateau. From

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the efficiency diagram, it is found that the maximum efficiency can be achieved at lower stress and energy for fabric made with finer spacer yarns due to its lower plateau level. In the case of the fabric made with coarser spacer yarn, energy at the maximum efficiency is much higher compared to fabric made with finer spacer yarn, which indicates that fabric made with coarser spacer yarn can absorb more energy but at a higher stress level [1]. Hence, for a given energy to be absorbed, the associated stress of the spacer fabric can be varied by simply adjusting the diameter of the spacer yarns according to the maximum stress permissible for a protected object to achieve a high efficiency of energy absorption. Fabric from finer spacer yarn is suitable for lower energy absorption and lower stress level, and fabric from coarser spacer yarn is suitable for higher energy absorption and higher stress level.

Influence of the outer layer structure

Since the monofilaments in the spacer layer are bound by the multifilament stitches in the outer layer, the distribution, binding condition, and inclination angle of the spacer yarns can be affected by the outer layer knitted structure [1]. Six fabrics with the same number of underlapped needles for spacer yarns and almost the same thickness, but with different outer layer structures have been selected to study the influence of the outer layer structure on the compression behavior of the spacer fabrics. The outer layer structures can be divided into following types

- a) Both outer layers with a close structure
- b) The top layer with an open structure and
- c) The bottom layer with a close structure
- d) Both outer layers with an open structure

The close structures are comprised of locknit and chain plus inlay, and the open structures are comprised of rhombic mesh and hexagonal mesh. Such differences in compression behavior arise from the uneven distribution of the stitches, the changes in stitch density of the outer layers, and the spacer yarn inclination angle due to changing

outer layer structure. The rhombic mesh structure has better stability and is more suitable for absorbing higher energy. Also, the fabrics with close outer layer structures have moderate compression resistance and plateau values. The lowest and highest values of absorbed energy at maximum efficiency point are seen with open structures in both of outer layers, and the fabrics with close structures in one or two outer layers have intermediate values between the lowest and highest values. In the case of open structures, a large range of the variations in the energy absorbed for different applications can be obtained. The fabric with the hexagonal mesh structure in both outer layers can be used to absorb the energy at lower stress levels, and the fabric with the rhombic mesh structure can be used to absorb the energy at higher stress levels. Hence, another approach to choose the fabrics is the variation of the outer layer structure, which can absorb the same quantity of the energy, but with various stress levels for various end uses.

Spherical compression

By change of structure design and finishing techniques, spacer fabrics have been tailored for a wide range of applications, such as sound absorption, moisture transport, functional bra support, comfort property enhancement, car seats and composite reinforcement [13-21]. Since the spacer fabrics have a kind of sandwich structure, their applications are mainly based on their compression properties. The compression properties of spacer fabrics intended for apparel should be soft to handle, and they should be able to fit the shape of the body. Constructed with two separate knitted fabrics as the upper and bottom layers and flexible filaments as the inner layer, both weft, and warp-knitted spacer fabrics can be designed as a kind of soft spacer fabric structure to meet the need of special applications such as bra cups and flexible cushioning or padding materials [22]. Studies relating to physical and compression properties under low stress have been done on various knitted spacer fabrics used for intimate apparel [23,24]. Other studies have proved that the knitted

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spacer fabrics have better pressure distribution, air permeability, and heat resistance than those of polyurethane foams. Knitted spacer fabrics can more specifically be used as pressure release products like functional mattresses and wheel chairs for reducing peak pressure to avoid the pressure concentration on the body. An understanding of the compression properties of knit spacer fabrics under spherical compression conditions enables researchers to effectively evaluate the uses of the knitted spacer fabrics for various shapes of the body. Though considerable research has been done on the compression properties of knitted spacer fabrics, it has only focused on the compression behavior under plane compression conditions [25–32]. Even research reporting on spherical compression of the spacer fabrics though considering finite element simulation was lacking in analytical models for predicting the spherical compression behavior [33, 34]. In considering the spherical compression behavior of knitted spacer fabrics, two aspects are considered – theoretical analysis model based on spherical ball compression, and comparisons of the calculated results from the model with experimental measurements.

A thorough theoretical analysis has been carried out to establish a theoretical model that can be used to predict the spherical compression properties of knitted spacer fabrics. In this model, the compression constants have been derived from the compression stress–strain curve of a knitted spacer fabric under the plane compression condition. The constants (modulus and intercept) are needed for the theoretical calculation of its compression force–strain curve under the spherical compression condition. Earlier works, 2–6 have shown that the compression stress–strain curve of a knitted spacer fabric can be divided into various zones, and that the compression stress–strain curve at each compression zone can be approximately represented by a linear equation. The theoretical model analyzed is compared with experimental results. The plane compression stress–strain curves of

different spacer fabrics are first provided by the experiments to calculate the modulus and intercept using linear fitting methods. The total spherical compression force and compression strain curve for each fabric is calculated by use of the compression constants obtained. The calculated curves have then been compared with experimental ones to validate the model. The differences between the calculations and experiments have been explained based on the chosen compression factors.

The spherical compression behavior of warp knitted spacer fabrics has been evaluated theoretically from the basic assumptions from a prior trial. Evaluation has been done by ball compression on the shape of the fabrics deformed, and thus establishes the relationship between the total compression force applied by the spherical ball, and compression strain at the maximal compression point. The influences of both ball radius and fabric thickness have been dealt with based on the introduction of non-dimensional parameters. The findings reveal that there is a reduction in spherical compression effects with increasing the ball radius, and an increase in spherical compression with increasing fabric thickness. Five different knitted spacer fabrics have been tested under both plane plate and spherical ball compression conditions and their plane compression stress-strain curves are divided into three zones, and the curve segment in each zone is approximately represented by a linear equation. Based on the constants obtained, the compression curve under spherical ball compression of each fabric is calculated and compared with the experimental curve. For the purpose of comparison three compression parameters, including the maximal compression force and compression work at the compression strain of 0.70, as well as the linear degree, are also used for comparison. The calculations and experiments agree. The theoretical model is thus validated and can be used to predict the spherical compression behaviors of knitted spacer fabrics compressed with various radii of the balls from the results of plane compression testing.

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Technical details

Warp-knitted spacer fabrics with varied fabric thickness, surface structure, and spacer yarn fineness have been used to analyze their compression properties. These factors can significantly affect the compression properties of the spacer fabrics [2,7]. In order to render the study more

comprehensive, the fabrics with varied structural parameters have been chosen. The material used is polyester filaments. The plane plate and spherical ball compressions have been carried out on an Instron tester. The technical details of the warp knit spacer fabrics are given in Table 3.

Table 3. Technical details of test fabrics

Fabric	Thickness (mm)	Structure of outer layer	Diameter of spacer yarn (mm)
Test fabric 1	7.5	Locknit	0.20
Test fabric 2	7.5	Chain plus inlay	0.20
Test fabric 3	6.8	Hexagonal mesh	0.20
Test fabric 4	18	Hexagonal mesh	0.12
Test fabric 4	10	Hexagonal mesh	0.22

Typical plane compression stress–strain curves and linear fitting

Figure 3. depicts the typical plane compression stress–strain curves of all five fabrics. The compression stress–strain curves under the plane plate compression are non-linear, but can be divided into three linear zones (Figure 4). While the compression stress quickly increases with increasing the compression strain in the initial and final regions, an obvious plateau can be found for four fabrics in the second zone. The curve segment in each zone can be approximately represented by a linear equation. A compression stress–strain curve is divided into three linear zones by two critical compression strains. By linear fitting of the compression stress–strain curves, the correlation coefficients of linear fitting are all higher than 0.95.

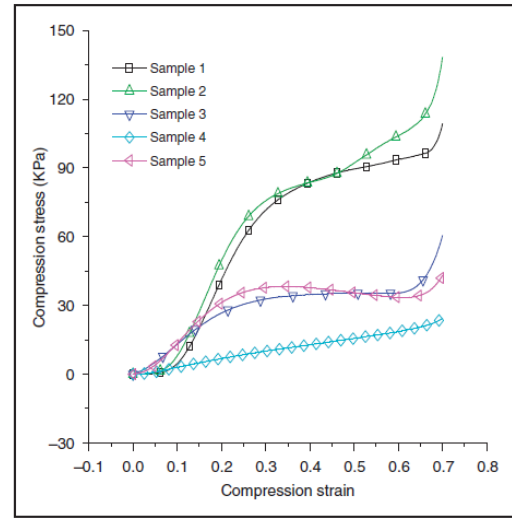


Figure 3. Typical plane compression stress strain curves of warp knitted spacer fabrics [7]

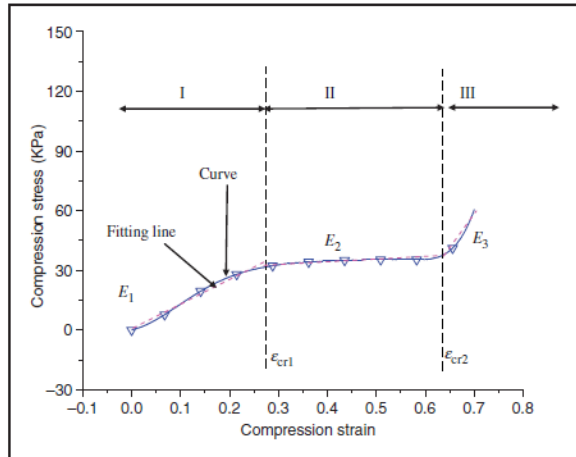


Figure 4. Representation of a plane compression curve by straight lines [7]

Calculation of spherical compression curves

The spherical compression curve for each knitted spacer fabric can be calculated using the obtained data and derived equations:

The following aspects have been considered:

- Total compression force applied to the fabric by the spherical ball
- Resultant force withstood by spacer filaments in the contacting area
- Resultant force withstood by spacer filaments in the expanding area
- Compression displacement
- Fabric thickness
- Curvature radius of the spherical ball
- Separating angle between the ball surface and knitted spacer fabric
- Expanding zone span width of the compression deformation

The choice of compression constants and critical strains is based on the zone in which compression strain is situated [1]. Hence, the critical compression strains can be used to determine the intervals of deformation zones.

The calculation of the resultant force withstood by spacer filaments in the contacting area has been performed in three cases. In the first case, the compression strain at the maximal compression point is smaller than the first critical compression strain. In

the second case, the compression strain at the maximal compression point is between the first and second critical compression strain. In the third case, the compression strain at the maximal compression point is bigger than the second critical compression strain.

Comparison between calculations and measurements

The spherical compression curves have been obtained by both calculations and measurements for knitted spacer fabrics (Figure 5).

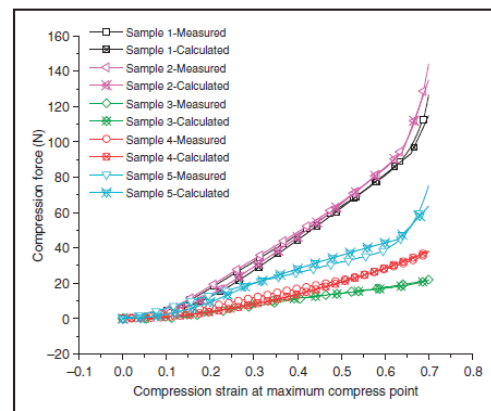


Figure 5. Comparison between calculation and measurements [7]

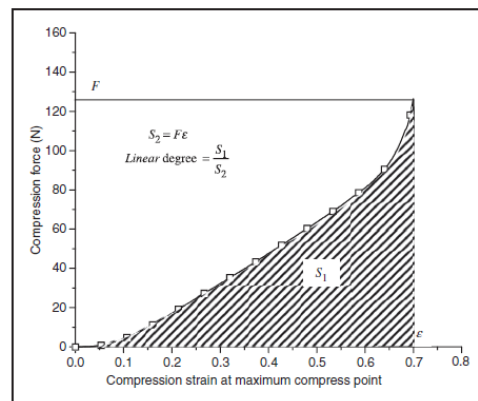


Figure 6. Definition of the linear degree of a curve [7]

The curves from calculations fit well with the experimental ones. For making a better comparison, three compression parameters have been chosen that can be used

to characterize the compression behaviors of knitted spacer fabrics - the maximal compression force, compression work at the compression strain of 0.70, and linear degree (Figure 6). The maximal difference between the calculations and measurements is less than 18.2%, which implies that the calculation results agree with the experiments. The theoretical model can be used to predict the spherical compression of the knitted spacer fabrics from the plane compression testing results.

Cushioning performance

Warp knit spacer fabrics have been compared with polyurethane foam in terms of pressure distribution for determination of suitability in cushioning applications [36]. The warp knit spacer fabrics have been found to exhibit better properties in comparison with polyurethane foams. The compression behavior of warp knitted spacer fabrics intended for cushioning applications have been studied by means of efficiency diagrams and stress-strain curves. Warp knitted spacer fabrics are well suited for cushioning applications as energy absorbers. The influence of the various structural factors such as the spacer yarn inclination and fineness, fabric thickness, and outer layer structure has been studied. The alteration of the structural factors enables energy absorption capacity of the spacer fabrics to be tailored to suit specific end uses. The cushioning performance can be evaluated by means of the efficiency diagram. The efficiency diagram can be used to choose particular fabrics working at the permissible stress levels for a given absorption of energy. All the structural factors of the spacer fabric affect the compression behavior and cushioning performance. The spacer fabrics with a lower spacer inclination angle, more fabric thickness, finer spacer yarns, and larger mesh size of the outer layers are meant for absorption of lower energy with greater efficiency. Fabrics with higher spacer yarn inclination angle, smaller fabric thickness, coarser spacer yarns, and smaller mesh size of the outer layers can be used to absorb higher energy with higher efficiency. Hence,

in order to knit a warp knit spacer fabric of desired compression behavior, it becomes crucial to choose appropriate structural parameters.

Distribution of pressure

The materials used for cushion applications must be soft and flexible. Besides this, the concentration of body pressure must also be avoided, especially for people sleeping on a bed or seated on a chair for a long time. For example, a patient seated in a wheelchair bears pain caused by pressure on the injured body on a support, especially when patients are immobile for hours in the same position [37]. Because of this, the evaluation of the pressure distribution under the body is very important, especially in the case where the relief of the high pressure is required [38].

Conclusion

The compression behavior of the warp knit spacer fabrics has been studied for cushioning applications using both compression stress-strain curves and efficiency diagrams. The effects of different structural parameters including the spacer yarn inclination angle and fineness, fabric thickness, and outer layer structure were examined. Warp-knitted spacer fabrics are an ideal class of energy absorbers for cushioning applications. Their energy-absorption capacity can easily be tailored to meet specific end-use requirements by simply varying their structural parameters. All the structural parameters have obvious effects on compression behavior and cushioning performance of spacer fabrics. The analysis results show that the spherical compression effects decrease with increasing the ball radius and increase with the increasing the fabric thickness. Agreements are obtained between the calculations and experiments. The theoretical model is thus validated and can be used to predict the spherical compression behaviors of knitted spacer fabrics compressed with different radii of the balls from the plane compression testing results.

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