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Design of Warp Knit Spacer Fabrics: Recent research insights on technical applications

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ABSTRACT

Warp knit fabrics are recently being used in technical applications. This paper critically reviews the recent research trends in warp knit spacer fabrics intended for various technical applications. When considering areas of applications such as sofas, seat covers, and cushions, warp knit spacer fabrics could offer a good substitute for polyurethane foams due to their advantages of combining compressive characteristics, air permeability, and thermoregulation arising out of their 3D structure. The compressive behavior of warp knit spacer fabrics has been analyzed under both static and dynamic conditions so as to determine their suitability for protective applications. The sound absorption behavior of both warp and weft knitted fabrics have been studied. The study reveals that fabric surface structure and thickness, spacer yarn type and their connecting ways, fabric combinations and their arrangement methods have significant influence on the sound absorbability. The findings also show that good sound absorbability could be achieved by using knitted spacer fabrics when suitable fabric structures and combinations are used. Attempts have been made to study the relationships among the stab resistance and fabric density, thickness and the spacer structure. The results indicate that the thickness and the density of warp knitted spacer fabric and the compressive of the spacer layer structure are the main influencing factors on the stab resistance. The three layer composite structure of warp knitted spacer fabric was able to resist the penetration by stages during the penetration process and thereby achieved the objective of multiple protection through the knife self-locking, energy dissipation and friction damping.

Keywords: Warp knit, Spacer fabric, Protective application, Cushion, Noise absorption, Stab resistance

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1. Introduction

Spacer fabrics have been developed into a variety of special textile products by varying their structure design and finishing methods for a wide range of applications, such as sound absorption moisture transport, functional bra support, comfort property enhancement car seats and composite reinforcement [1-8]. As a kind of the sandwich structure, the applications of spacer fabrics are largely dependent on their compression properties. Warp knitted spacer fabrics (WK spacer fabrics) are able to conform under the category of technical textiles and they are very interesting structures, which could be used to substitute conventional PU foam used in seats, sofas and mattresses, etc. [9-11]. The advantage of WK spacer fabrics consists in the combination of good compressive characteristics, air permeability, and thermoregulation by their unique 3D structure. The use of warp-knitted spacer fabrics as cushioning material in personnel protective clothing and equipment against impact has attracted great attention in recent years [12–14]. In addition to the requirement in comfort, the capacity of the material for energy absorption and impact force attenuation is also very important to protect the human body from injuries [15]. As a kind of porous material, textiles such as nonwoven, woven, and knitted fabrics have recently attracted great attention for sound absorption application due to their low-cost and low environment impact [16–18]. Knitted fabric was seldom commended to be used as stab-resistant materials since it was penetrated by knifepoint easily and was prone to take deformation while receiving puncturing. But studies have also pointed out that the protective material based on knitted structure had the features of low weight, better designability, fulfilling wide-area protection etc. [19]. Flambard and Polo reported that the multi-layer knitted fabric could absorb penetration energy, and possessed a fairly well shearing resistance, of which stitches locked the knife to stop penetrating before the fabric was destroyed completely [20]. Yao Xiaolin and Qiu Guanxiong [21] proclaimed that weft-knitted structure could resist stronger penetration force through the deformation of weft loops and self-locking, anyhow, it was self-evident that fabric had a larger deformation, and a deeper penetration. Li Lijuan et al. [22] investigated the structure and property of stab resistant warp-knitted single-face fabric. The study found that the underloop structure peculiar to warp-knitted fabric could stabilize the stitch, and added the yarn’s agglomeration around knife edge, which had an obvious advantage in penetration force and yarn strength efficiency.

2. Design for cushioning applications

Overview

For the purpose of cushion application, six warp knit spacer fabrics have been knitted on a warp knitting machine having two needle beds and six yarn guides. The fabrics have been compared with polyurethane foam with regard to pressure distribution, air permeability, and heat resistance [23]. The warp knit spacer fabrics exhibit better performance in these properties in comparison with polyurethane foams and also enable easier recycling. The compression characteristic of warp knit spacer fabrics intended for cushioning applications have been studied by means of stress strain and efficiency diagrams. The influences of various structural factors such as spacer yarn inclination angle and fineness, fabric thickness and outer layer structure have been analyzed. 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 fabrics are well suited in 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 of the fabrics 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 parameters of the spacer fabric affect the compression behavior and cushioning performance. The spacer fabrics having 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. On the other hand, the fabrics with higher spacer yarn inclination angle, smaller fabric thickness, coarser spacer yarns, and smaller size mesh of the outer layers can be used to absorb higher energy with higher efficiency. Hence in order to design a warp knit spacer fabric of desired compression behavior, it becomes crucial in choosing appropriate structural parameters.

Technical aspects

A WK spacer fabric consists of two surface layers and a layer of the yarns called as spacer yarns. The spacer yarns connect two surface layers to form a special 3D structure. In the case of cushioning application, the spacer yarn prevents the crushing of the 3D structure under body pressure. In the design of the spacer fabric structure selection of spacer yarn with proper bending rigidity and connecting method between two surfaces become crucial. Different methods are available for connecting the two surface layers. The different inclination angles of the spacer yarns can be obtained by changing the underlap amounts of the spacer yarns in order to satisfy varied end-use requirement [23]. It is evident that the bigger underlap will lead to higher inclination of the spacer yarns. Besides different connecting methods, the two surface layers of a spacer fabric can be knitted with same or different structures. For the commonly used spacer fabrics, two surface layers are normally knitted with same structures. The surface structures can be plain structures or meshes with different opening sizes. A mesh structure with pillar and laying in yarns is commonly used in warp knit spacer fabrics, as it not only gives good structural stability but also good air permeability. Also the space between the two spacer layers is an important structural aspect to be considered. Greater fabric thickness is required in cushioning applications. The thickness of cushions varies between 10 – 100mm or above based on the varied application needs. However, the thickness of WK spacer fabrics is limited by the distance between the two needle-beds of the warp knitting machine. The thickest spacer fabric currently produced on the warp knitting machine is about 65 mm. For some cushion application situations, two or more layers of WK spacer fabrics are needed to be put together to obtain higher thickness, because the spacer fabrics with very high thicknesses are more difficult to be knitted. Although the PU foam has smaller average pressure than all the spacer fabrics, the peak pressures of all the spacer fabrics are lower than that of the PU foam with higher thickness. This means that the spacer fabrics developed have better property for the reduction of the pressure concentration, and they can be used in seat, sofa, and mattress to substitute PU foams for special applications where the relief of the body pressure is highly required. Experimental trials have shown that among all the spacer fabrics developed, the fabrics knitted with finer spacer yarns (0.18 mm) have lower peak pressure and average pressure values than the fabrics knitted with thicker spacer yarns (0.22 mm). For the fabrics knitted with the same spacer yarns, but with different inclination angles, the difference for peak pressures and average pressures exist, but is not so significant.

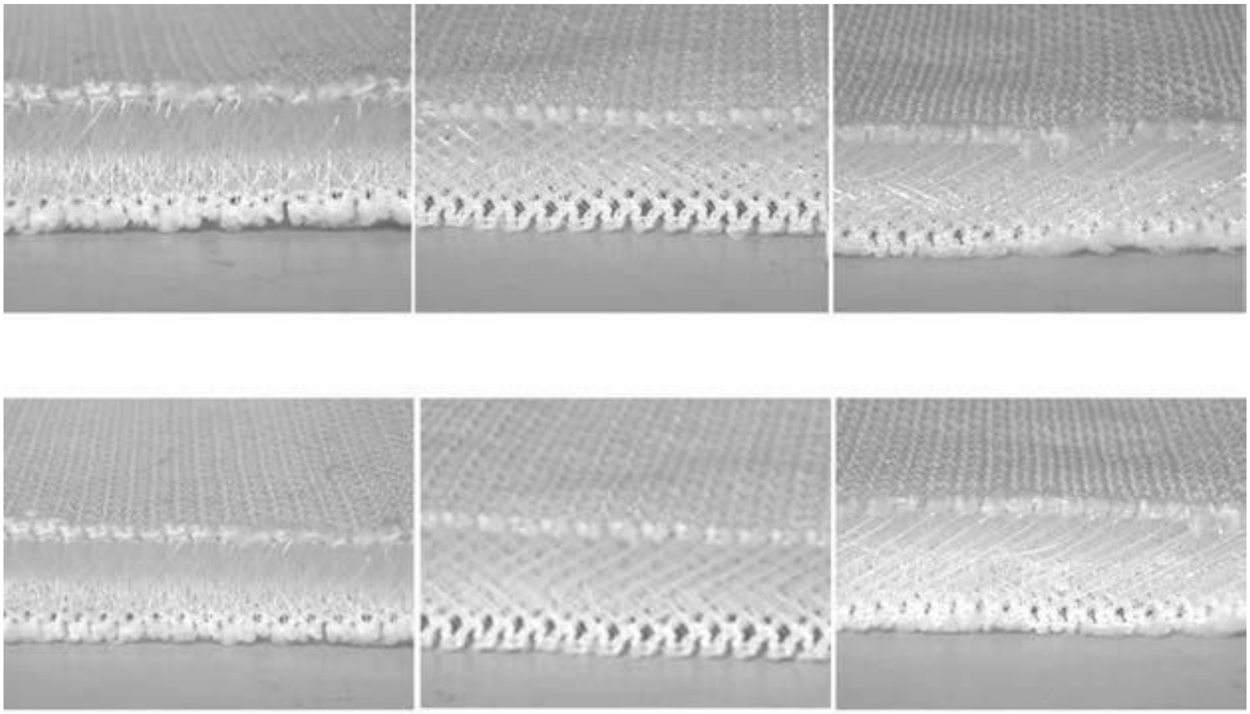


Figure – Fabrics for cushioning applications [41]

Relating the properties

The materials used for cushion applications must be soft and flexible. Besides this, the concentration of the 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 on a wheelchair always bears the pain caused by the pressure on the injured body. Bedsores or pressure sores are also caused by long-term downward pressure of the body on a support, especially when patients are immobile for hours in the same position [24]. Because of this, the evaluation of the pressure distribution under the body pressure is very important, especially in the case where the relief of the high pressure is required [25].

Air permeability and heat resistance are very important parameters for cushion application because they remarkably influence the comfort, especially for some application cases, such as car seats and medical mattresses. The testing results of air permeability and heat resistance are listed in Table 1.

Table 1. Comparison of air permeability and heat resistance of warp knit spacer fabrics an polyurethane foam [23]

Property tested	Warp knit fabrics						Polyurethane
	Thin spacer yarns			Thick spacer yarns			
	1	2	3	1	2	3	
Air permeability ($l/s/m^2$)	3588	3597	3604	3498	3523	3537	924
Heat resistance (m^2x K/W)	138	133	126	145	139	131	221

The results show that the WK spacer fabrics have very good air permeability. This is normal because the WK spacer fabrics were produced with open surface structures. Though the PU foam is a little thicker than spacer fabrics, air permeability for PU foam is much lower than those of spacer fabrics (about 25% of these of the WK spacer fabrics). Low air permeability can cause a big comfort problem for PU foam used in special application cases as above mentioned. Concerning the heat resistance, the tested PU foam has much higher value than WK spacer fabrics. This means that the PU foam has better capacity to keep the heat than spacer fabrics with same thickness. This may be an advantage for PU foams when they are used in a colder environment. However, the combination of lower air permeability and higher heat resistance always makes the PU foam too warm and uncomfortable in warm conditions.

3. Design for protective applications

Overview

During the recent times warp-knitted spacer fabrics have gained importance as cushioning material in personnel protective clothing and equipment against impact [26–28]. Besides the need for comfort, the ability of the material for energy absorption and impact force attenuation is also crucial in the protection of the human body from injuries [29]. They are proven to be ideal cushioning materials for such types of materials as pointed out by earlier researches on the compression and energy absorption [30]. But, the results from the earlier researches were only obtained from the static compressive testing condition. All other experimental and theoretical studies about compressive behavior of the spacer fabrics found in the literature also only focused on the static testing conditions [31-37]. Till recently, only few investigations have been carried out on the dynamic compressive behavior of warp-knitted spacer fabrics under impact [38]. Warp-knitted spacer fabrics have been tested on a drop-weight impact tester with predefined impact energy. Both the acceleration and transmitted force signals were measured and treated with a low-pass filter. Comparisons have been done on the peak contact force and transmitted force as a function of time, and the velocity and displacement of the striker calculated [39]. The impact compressive behavior of a typical fabric was analyzed based on both the contact force-displacement curve and energy absorbed-contact force curve. The effect of different structural parameters, including the spacer monofilament yarn inclination and fineness, fabric thickness, and surface knitted structures, on the impact compressive behavior of the warp-knitted spacer fabrics have been analyzed based on the contact force-displacement curves, energy absorbed-contact force curves and transmitted-time curves. The relationship between the peak transmitted force and peak contact force was established. The impact process of the warp knitted spacer fabric is complex, as pointed out by research findings. Both the acceleration of the striker and transmitted force as a function of time are important parameters that need to be measured in order to better analyze the impact process of the fabric. The whole impact process includes the impacting phase and rebounding phase. Also the peak contact force and peak transmitted force are different at their peak time and peak value. The peak transmitted force reaches its peak point with a time delay due to shock wave propagation. The peak transmitted force is much lower than the peak contact force. The impact behavior of spacer fabrics is considerably influenced by the spacer yarn inclination. Too vertical and too inclined spacer yarns can result in higher peak contact force and transmitted force. The peak contact force and peak transmitted force increase with decreasing the spacer monofilament fineness due to lower energy absorption capacity at the end of the plateau stage. The effect of the fabric thickness is more complicated than other structural parameters. With increase in fabric thickness the fluctuations of the contact force reduces. An optimized fabric thickness exists for obtaining better protective performance with lower peak contact force and peak transmitted force. The spacer fabrics knitted with large-size mesh structures for both top and bottom surface layers have higher peak contact force and higher peak transmitted force than the spacer fabrics knitted with small size mesh and close structures. A linear relationship exists between the peak contact force and peak transmitted force. The transmitting rate is about 66.84% and is nearly the same for all the warp-knitted spacer fabrics considered, irrespective of their structural parameters. Selection of suitable structural factors for human body protection, such as shoulder protectors and back protectors in sports and other strenuous conditions, can be done in using the warp knit spacer fabrics as effective material, considering a reduced peak transmitted force and a high energy absorption capacity.

As a cushion material, warp-knitted spacer fabrics have much better moisture transmission features [40] better pressure relief properties, higher air permeability, and lower heat resistance than polyurethane (PU) foam [41] thus, they have been widely used in areas such as automobile textiles (cushions3 or car seats4), sports textiles, [42] and foundation garments (bra cups, pads for swimwear), etc.[43]. Many studies have been conducted on warp-knitted spacer fabrics, which mainly focus on their static compression properties, as well as sound absorption behavior [44] pressure distribution, [41,45,46] air permeability, heat resistance, [40] etc. Studies on static compression behaviors of warp knitted spacer fabrics are as follows. Some effect factors, that is, material, pattern, and threading, as well as location angle and the number of spacer yarns, on the compression behaviors were investigated by Armakan and Roye.[47] Lateral compressive behaviors of spacer fabrics were explored based on Van Wyk's equation[48]. The indentation force deflection (IFD) properties of different warp-knitted spacer fabrics were studied in a paper by Miao and Ge [49]. Mechanical and the stress– strain model of single spacer yarn of warp-knitted spacer fabric were found by Chen Y13 and Chen HL [50]. Energy efficiency [40] and non-linear compression behavior [51] of spacer fabrics were investigated as well. The static compression properties of warp-knitted spacer fabrics have been investigated in many researches, as mentioned above. However, few of the researches [44–53] focus on the impact behaviors of spacer fabrics.

The impact behavior and damage characteristic after impacts of warp-knitted spacer fabrics for cushion material have been investigated. Four parameters, including peak force, absorbed energy, damage depth, and drop-off rate of residual strength, were involved to evaluate the two behaviors above of spacer fabrics with different structures. A spacer fabric with good protection performance was considered to have lower peak force, more absorbed energy, lower damage depth, and a lower drop-off rate of residual strength [54]. According to the experimental results and analysis, it has been found that the variation of force in an impact event is the result of the co-effect of two factors: displacement and failure of spacer yarns in the center zone. Also, force increases with the increasing of the former and decreases because of the latter. In the case of fabrics with the same needle bar distance (different surface structures and finenesses of spacer yarns), fabrics with coarser spacer yarns and close surface structure have several satisfying results, such as lower peak force, larger absorbed energy, and lower depth value, but higher drop-off rate of residual strength. While considering the specific impact method (flat-sphere), fabric with a mesh structure is body-fitted, for meshes can open and shut more freely according to the shape of wrapped objects. However, meshes that are too large on surface layers makes the mesh sides inclined to collapse and means that spacer yarns cannot be protected perfectly. In the case of fabrics with different needle bar distances (same surface structure and fineness of spacer yarns), fabric with higher thickness performs perfectly in the experiments (lower peak force, more absorbed energy, lower damage depth, and lower drop-off rate), but a person's body may feel uncomfortable if the protector is too thick. The balance between the protective performance and comfort should be taken into consideration by selecting a suitable thickness of fabric for the specific protective application. In the case of a fabric subjected to different energies, peak force, absorbed energy, and damage depth increase with the increasing of energy levels, while residual strengths approximate to each other.

Technical parameters

Warp-knitted spacer fabrics have been produced with varied fabric thicknesses, surface structures, spacer monofilament fineness, and inclinations so as to analyze the influence of structural parameters on their impact compressive behavior. The warp knit structures of interest include locknit, chain plus inlay, small-size rhombic mesh, and large-size hexagonal mesh for knitting the surface layers [54]. Three different spacer yarn inclinations have been used for linking the two surface layers. While the surface layers of all the samples were knitted with polyester multifilament, the spacer layer has been knitted with polyester monofilament. The dynamic compression tests were conducted on a drop-weight impact tester. The test method was based on the drop-weight principle using a low-energy, low-speed impact tester that is capable of measuring the changes in acceleration of the drop striker and the force transmitted from the top side to the bottom side of the specimen.

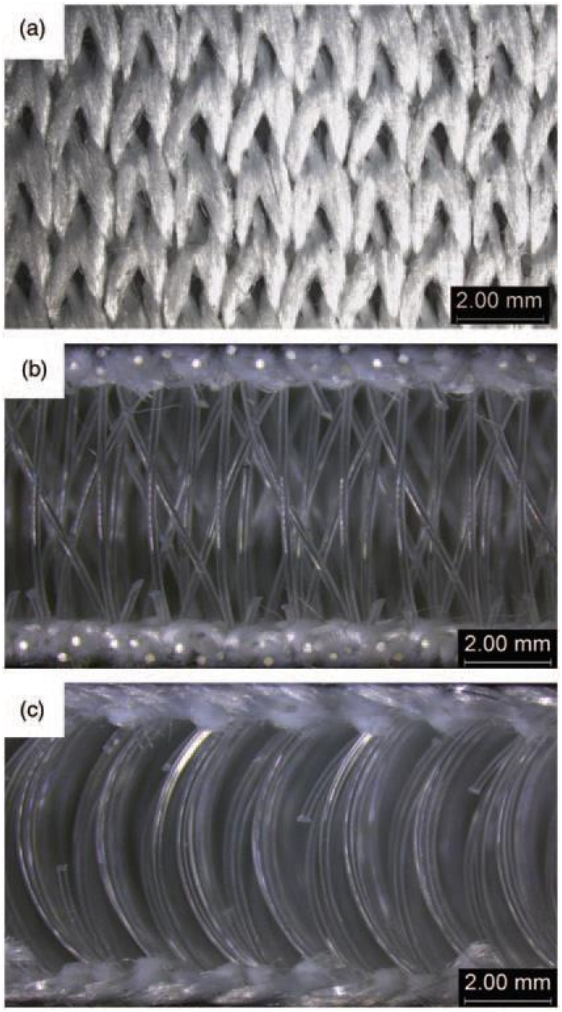


Figure – Fabrics for protective applications (3 different views) [54]

Relating the properties

The influence of the spacer yarn inclination on the impact compressive behavior of warp knitted spacer fabrics have been analyzed by use of a group of three fabrics with the same surface layer structure (chain plus inlay) and the same spacer monofilament yarn but with different spacer yarn inclination. The fabric thickness and stitch density of the surface layers are kept nearly the same. The contact force-displacement curves, energy absorbed-contact force curves, and transmitted force-time curves of warp knit spacer fabrics have been used to explain how the spacer yarns are able to withstand the contact force during impact process. It is necessary to point out that the compression resistance of spacer fabrics increases with decreasing the inclination of the spacer yarns, because the spacer yarns with lower inclination are more oriented to the direction of the impact [54]. Considering same thicknesses of warp knit spacer fabrics, the spacer yarn with lower inclination has the shorter length. Therefore, the fabric with lower inclination will have higher compression resistance during impact compression. However, if the spacer yarns become too vertical to the surface layers, the fabric structure will become less stable and the shear can easily take place between the two surface layers, because the spacer yarns tend to tilt along the course direction under the impact loads. On the other hand, if the spacer yarns are too inclined, they can easily be crushed under the contact force. As a result, the fabric will absorb less energy. At the same time, the fabric with higher inclined spacer yarns can be easier to densify under the impact.

Therefore, the fabric with lower inclination will have higher compression resistance during impact compression. However, if the spacer yarns become too vertical to the surface layers, the fabric structure will become less stable and the shear can easily take place between the two surface layers, because the spacer yarns tend to tilt along the course direction under the impact loads. On the other hand, if the spacer yarns are too inclined, they can easily be crushed under the contact force. As a result, the fabric will absorb less energy at the plateau stage. At the same time, the fabric with higher inclined spacer yarns can be easier to densify under the impact.

The above analysis shows that the spacer yarn inclination can significantly affect the impact behavior of spacer fabrics. Both the fabrics with lower inclination of spacer yarns (shifting one needle distance) and higher inclination of spacer yarns (shifting three needles distance) are not good for protective applications due to higher peak contact and transmitted forces. Fabric with higher inclined spacer yarns can result in higher peak contact force. However, as there are more spacer yarns within the fabric knitted with shifting three needles distance, it may be more difficult for the shock wave to go through its thickness. In this connection, its transmitted peak force is lower than that of the fabric knitted with shifting one needle distance.

Effect of the spacer monofilament fineness

The average level of the contact force at the elastic and plateau stages increases with increasing spacer monofilament fineness. This is due to the different moments of inertia of the spacer monofilament with different radii. While the fabric with the coarser spacer monofilament can absorb more energy at the elastic and plateau stages than the fabric with the finer spacer monofilament, because of the higher force level at these stages, the fabric with the finer spacer monofilament should absorb more energy at the densification stage [54]. Therefore, the contact force of the fabric with the finer spacer monofilament is much higher than that of the fabric with the coarser spacer monofilament at the densification stage. The different level of densification is also a reason for the peak contact force and peak transmitted force increasing with decreasing the spacer monofilament fineness. The contact and transmitted forces of the fabrics with different spacer monofilament fineness do not reach their peak points simultaneously. The spacer fabric with the finer spacer monofilament yarns first reaches its peak contact force point and peak transmitted force point during the impact process. This is because the higher acceleration at the densification stage of the fabric with finer spacer monofilament yarns can stop the striker in a shorter period of time. It is necessary to emphasize that the period of deceleration is essential to the impact protection, since the impact process should be as long as possible to minimize peak acceleration, which is directly related to the peak contact force and peak transmitted force.

From the above analysis, it can be found that the reduction of spacer monofilament fineness can considerably decrease the energy absorption capacity of spacer fabric and protective performance. But, the fabric stiffness increases with the fineness of spacer monofilament, and thereby reduce the comfort property of the fabric. Hence, the balance between the comfort and protective performance needs consideration through choice of suitable spacer monofilament fineness for a specific protective application.

Effect of the fabric thickness

The fluctuations of the contact force-displacement curves before rising to the peak force decrease with increasing the fabric thickness. The obvious plateau stage is obtained for the thicker spacer fabrics. The average level of contact force at the elastic and plateau stages decreases with increasing the fabric thickness, but the displacement at the plateau stage increases with the thickness. The thinner fabrics can absorb more energy before starting to rise to the peak force than the thicker fabrics, but at a higher contact force level. The same trend was found from the transmitted force-time curves, where the average level of the transmitted force decreases with increasing the fabric thickness at the elastic and plateau stages [54]. The peak contact force and peak transmitted forces firstly decrease and then increase with increasing fabric thickness. The above phenomena could be explained by the following reasons.

a) With increasing the fabric thickness, the spacer yarns get longer. If considering the spacer yarns as slender rods, their compression resistance will decrease with increasing their length. Thus, the thicker fabrics will become softer and their compression force level at the plateau stage will become lower than that of the thinner fabrics. At the same time, the softer fabrics can be easier to densify under impact, which can lead to a slow increase of the peak contact force at the densification stage with increasing the fabric thickness. On the other hand, the reduction of the spacer yarn length in a thinner spacer fabric makes it stiffer. If the fabric thickness is reduced to a certain level, the fabric can become very stiff. In this case, the reaction force between the fabric and the drop striker can considerably increase, which can result in an increase of the peak contact force. Thus, an optimized fabric thickness exists for obtaining a lower peak contact force.

b) It is normal that the displacement increases with increasing the fabric thickness, since there is more space between the surface layers in a thicker spacer fabric than in a thinner spacer fabric. With the increase of fabric thickness, the compression process of the fabric under impact becomes smoother, and

4. Design for stab resistance

Overview

Stab resistant fabrics are generally made of woven, knit and nonwoven fabrics and possess their own stab resistant characteristics [55-58]. But knits could be easily penetrated by knife point and got deformed. However, the protective knit fabrics had the advantage of low weight, better designability, fulfilling wide area protection, etc. [59]. The multi-layer knitted fabric could absorb penetration energy, and possessed a fairly well shearing resistance, of which stitches locked the knife to stop penetrating before the fabric was destroyed completely [60]. Weft-knitted structure could resist stronger penetration force through the deformation of weft loops and self-locking, anyhow, it was self-evident that fabric had a larger deformation, and a deeper penetration [61]. The structure and property of stab resistant warp-knitted single-face fabric has been studied and found that the under loop structure peculiar to warp-knitted fabric could stabilize the stitch, and added the yarn’s agglomeration around knife edge, which had an obvious advantage in penetration force and yarn strength efficiency [62]. The above studies revealed that the textile structure mainly suffered shearing and tensile action when the knife penetrated into the fabric. High-strength and good shearing-resistant fibers combining with tight textile structure contributed to a good stab resistance. Besides, the fabric distortion could absorb the penetration energy which could improve the stab resistance.

Warp-knitted spacer fabrics have been produced with UHMWPE fibers and tested by quasi-static stab tests. The stab-resistant characteristic of the warp-knitted spacer fabric and the influences of the fabric density and thickness on the stab resistance has been investigated. During the initial stage of stabbing, the stab-resistant law of warp-knitted spacer fabric is similar to the warp-knitted single-face fabric. During the subsequent phase, warp-knitted spacer fabric behaved an obviously different stab-resistant law from other textile structures. During the process of resisting knife puncturing, three deformations including tensile of surface knitted structure, shearing of yarns and compression of the spacer layer happened at the same time. Of these, the compressive deformation of the spacer layer played a pivotal role in stabbing [63]. The thickness and density of warp-knitted spacer fabric are the important factors affecting the stab resistance. Fabric density had the similar effect mechanism on the penetration force despite in different thicknesses. The increase in fabric density could effectively promote the penetration force and lower the penetration depth. The penetration force went down firstly and then ascended as the thickness of warp-knitted spacer fabric increased. But in a certain thickness, the fabric would reach the best comprehensive stab resistance. The stab-resistant characteristic of the warp-knitted spacer fabric could be applied into developing the soft stab-resistant material by making use of the compressive deformation of the spacer layer structure. However, this test measured the compressive property of the spacer layer merely from fabric thickness and density, for this reason, the quantitative relationship between the compressive property of the spacer layer and the stab resistance required further study in the future. The design of 3D structure of warp knitted spacer fabric can be used to effectively achieve the objective of multiple protection.

Technical parameters

The fibrous materials intended for the soft stab-resistant body armor possess properties such as high shearing endurance, dent resistance and high modulus. Some of the fibers under the category are ultra-high molecular weight polyethylene (UHMWPE), Kevlar and poly-p-phenylene benzobis-thiazole (PBO). UHMWPE fibers have low density and perform well under low-velocity stabbing when predominant forces were tension and shearing [64]. They are fluffy, high intensity and produce static electricity easily. The bundles may easily puff up and become tangled when warped and knitted, causing problems during manufacturing. Hence, the UHMWPE fibers are given a protective under-twist of 50 twists/m, which improve the cohesion of yarns without affecting their strength.

The warp knit spacer fabrics have been knitted on Rachel double needle-bar warp-knitting machine with six bars. Based on the result of the study on the structure and property of stab-resistant warp-knitted single-face fabric, sharkskin was adopted to knit the surface texture of the spacer fabric, the spacer yarns were arranged in the ‘‘>< ’’ shaped configuration.

The key factors to be considered are the distance of knock-over bar and the density of take down. They are also the pacing factors to influence the fabric thickness and density. Considering that the melting point of UHMWPE is widely different from polyester monofilament, no sizing has been done. The parameters considered are wale density, course density, thickness and mass. In the process of resisting stab, the fabrics behave differently based on their structures. The stab resistant property of the warp knitted spacer fabric has been investigated by selection of three comparative fabrics through the quasi-stab test. The specifications of the comparative fabrics are shown in Table 2

Table 2. Specifications of the comparative fabrics [63]

Fabric type	Fibrous Material (twist, fineness)	Manufacturing method	Fabric density	Mass (g/m^2)	Thickness (mm)
Warp-knitted Single face fabric	0 twist, 27.77 tex	Sharkskin warp knitted	11wales/cmx9 courses/cm	398	1.89
Woven fabric	350twist/m, 44.44 tex	Plain weave fabric	17ends/cmx10.5	315	1.54
Nonwoven Fabric	Fibrous reticulum	Spun bonded nonwoven fabric	-	282	0.82

Stab Resistance of Personal Body Armor [65], the quasi-static stab tester was developed from the. The bursting ball was replaced with a standard testing cutter. The fabric sample was cut into a circular specimen. Since the warp-knitted spacer fabric has a definite thickness, a fringe of spacer yarns, 8mm apart from the edge, were cut off to set the specimen into a pair of annular holders. The puncturing angle was adjusted such that the knife was parallel to the courses to avoid the influence of the angle variation on the test results. During the testing process, the knife was dropped at a constant speed of 20 mm/min to penetrate the specimen. The test ceased when the penetration force attenuated to 90% of the initial penetration force. A transducer was used to control the speed of the knife and record the curve of penetration force versus penetration depth, and penetration energy. The deterioration of the textile structure was also observed.

Relating the properties

The curves of the penetration force versus penetration depth obtained from the quasi-static stab test by the warp-knitted spacer fabric is shown in Figure 1.

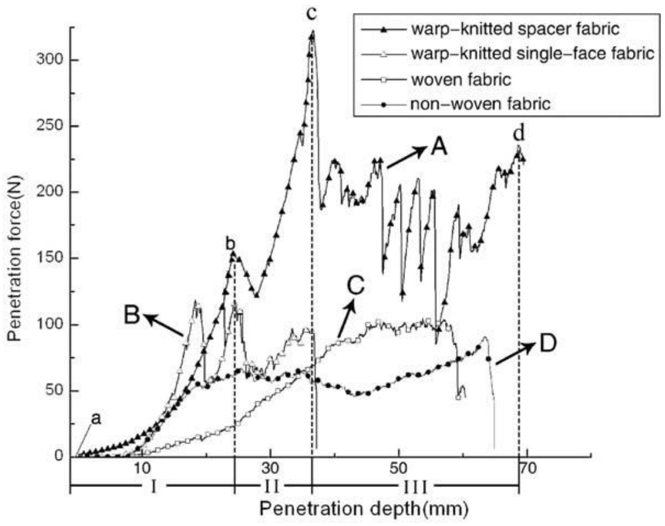
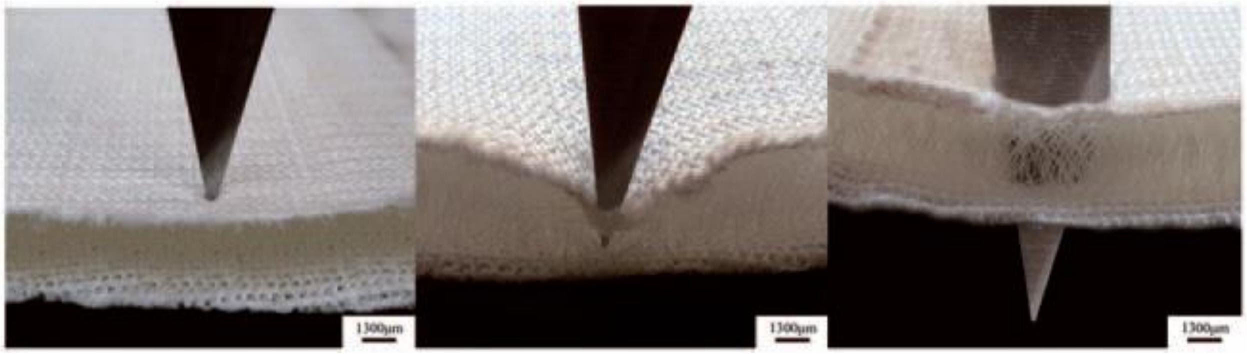


Figure 1. A comparison between the force vs displacement curves of woven fabric, nonwoven fabric, warp knitted single face fabric and warp knitted spacer fabric [63]

The fabrics considered are (a) Warp-knitted spacer fabric; (b) warp-knitted single-face fabric; (c) woven fabric; (d) non-woven fabric. According to the puncturing process of the warp-knitted spacer fabric (Figure1) during the penetration, the curve could be broadly divided into three stages:



(a) **(b)** **(c)**

Figure 2. The puncturing process of the warp knitted spacer fabric [63]

During the first stage, the knife tip smoothly penetrates the top surface of fabric owing to the easily deformed knitted stitch (Figure 2(a)). However, as the puncture opening increased in the fabric, stretched and sliding yarns gradually gathered around the knife edge. This considerably improved fabric resistance to knife as shown by the larger slope of curve in figure 1. At the same time, the pressure received by the upper surface of fabric was transmitted to the spacer layer and the monofilaments near the knife edge bent to absorb the penetration energy. Consequently, the depression of the surface fabric took place [66]. The gathering yarns had fully locked the knife as the penetration reached a certain depth, and the penetration force reached its first peak point b(Figure 2(b)). The blade would cut the nearest constrained yarns to further penetration.

During the second stage, the knifepoint was released with some fibers cut off, and the penetration force decreased. Due to the breaking down of the gathering yarns one after the other, the top surface of the fabric gradually opened up and the penetration force fluctuated.

At the same time, the spacer layer continued its compression to absorb the penetration energy. As the knife point touched the lower fabric surface, the deformation of stitches and stretch of yarns added the resistance to the knife. The penetration force rose markedly again until the knife was locked second time by the lower surface. The blade continued cutting the gathering yarns from the lower surface fabric. Meanwhile, the knife body was wedged by upper surface stitches (Figure 2(c)). In this case, the penetration force reached its second peak point c. During the third stage, the spacer layer was compacted, and the blade started to cut the lower surface yarns around it. The simultaneous out-break both of the upper and the lower surface yarns could cause a sudden drop of the penetration force. But, the newly gathering unbroken yarns of both surfaces continued to offer strong resistance to the knife. Hence the curve A showed a greater fluctuation in this stage until the upper and the lower surfaces were completely damaged and lost their effectiveness in the stab-resistance. It was found that the curve A of the warp-knitted spacer fabric was more complicated than the curves B, C and D of the single-face fabrics (Figure 1). The behavior of single-face warp-knitted fabric in the primary stage of the penetration was very similar to the warp-knitted spacer fabric during first stage. The stitches deformed and the yarns stretched and slipped, resulting in more number of yarns gathering around the knife to enhance the resistance. The penetration force increased and attained the peak point until that the knife was tightly locked. Subsequently, the penetration force bounded up and down with the yarns broken. But, the curve C of woven fabric and curve D of non-woven fabric reveal that the fabrics had mainly suffered the shearing effect of the knife during the whole puncturing process. So the penetration force increased relatively gently and peak point was not obvious on both curves. The warp knitted fabric having 3D structure, exhibited the characteristic which was not possessed by the single-face fabrics and offered better stab resistance in the tests. The compression deformation of the spacer layer, the yarns stretching and shearing deformation of both surfaces had a synergistic effect on the warp-knitted spacer fabric’s stab resistance. They may change their roles during the whole puncturing process. Also, the compression of the spacer layer consumed the penetration energy effectively and also increased the friction resistance to the knife’s penetration as well.

Fabric density versus stab resistance

The stitch density of the warp knitted spacer fabric is adjusted by the density of take down when the machine gauge is invariant. Also, the tightness of the upper and lower fabric surfaces is determined by the change of the take-down density, which influences the density of monofilaments in the spacer layer. The take-down density later influences the compressive property of the spacer layer. The relationships among penetration force, penetration depth, penetration energy and the density of take down have been investigated [63]. The maximum penetration force and the penetration energy increased regardless of the distance of knock-over bar, and the penetration depth decreased as the density of take down increased. As the density of take down increased, the stitch density of the upper and lower surfaces, as well as the tightness of cloth surface, was enhanced accordingly, which resulted in the increase of stab resistance. At the same time, the yarns around the knife edge would be cut under minimal penetration depth due to the decrease of tensile deformability of the stitches and yarns slippage [67]. The compression stiffness of the spacer layer has been strengthened by the increase in the number of monofilaments loading. Hence, the knife required consumption of more energy in the puncturing process. In view of the first two stages (not shown in figure), as the penetration force increased, the high-density curve showed a higher slope, and the first and the second peak values were higher. A larger curve slope indicated that the surface cloth was more difficult to be pierced. In this case, the value of penetration force was higher. Hence the warp knitted spacer fabric with higher density showed better stab resistance. A linear relationship has been shown between the penetration force and the density of take down. The areal density of fabric increases with the density of take down and the distance of knock-over bar increasing definitely. For a given thickness of the warp knitted spacer fabric, the maximum penetration force increased with areal density increasing unevenly. Specific force is a key factor of the armor weight, so it was calculated by maximum penetration force divided by areal density. In order to give more rational evaluation to different structures, specific force of each fabric has been compared, and the specific force of fabrics is found to be still higher. But, with the increase in knock over bar, the penetration force per weight reduced continuously. It is interesting that when the distance of knock-over bar increased to 14 mm, the penetration force of 14mm fabric increased obviously. But the specific force was less than that of 10mm and 8mm fabrics. This is because the content of polyester monofilaments increased significantly due to the increase of fabric thickness. Hence, the penetration force divided by areal density decreased as a result of the increase of fabric weight.

It has been found that the penetration depths per weight are all lower when the density of take down is 8.5 courses cm–1. Here, with the same structure of same weight, warp-knitted spacer fabric which has higher density of take down may have more efficient resistance to stab. Hence, considering penetration force and depth per weight, warp-knitted spacer fabric with moderate thickness and higher density would have the best stab resistance.

The density of take down could only increase to a certain degree due to the limitation of the machine model, machine gauge and the fineness of fibrous raw material. At the same time, both the warp-knitted spacer fabric areal density and its production cost would increase along with the increase of the take-down density, with even less fabric flexibility. In order to achieve the best balance stab resistance, production cost and flexibility, the density of take down should be reasonable.

Thickness of spacer layer versus stab resistance

Analysis of the compressive behavior of warp-knitted spacer fabric shows that the distance of knock-over bar determined the thickness of the spacer layer, and is considered to be crucial in influencing compressive property of the fabric [67]. The relation between the penetration force, penetration depth, penetration energy and the distance of knock-over bar has been investigated. Fabrics of various thicknesses in the same density have been selected to study the stab resistance of the spacer layer structure directly while ruling out the influence of the surface stitches on stab resistance. The penetration depth of different take-down densities all increased as the distance of knock-over bar increased. However, both the penetration force and penetration energy initially decreased, and then later increased.

Four types of fabrics have been investigated for the penetration force versus penetration depth. In stages I and II, the slope of the curve of higher knock-over bar distance was evidently lower as the penetration force increased. This suggested that the knife was easy to penetrate the spacer fabric [63]. On the other hand, the increase of the distance of knock-over bar caused the increase in the migration distance from the upper surface to the lower surface for the knife during the process of puncturing. Upon compression of the spacer layer, the spacer monofilaments bent more easily. Hence, the resistance of the spacer layer to knife penetration reduced through the decrease of the compression stiffness. Thus, the penetration force and penetration energy decreased when the distance of knock-over bar varied from 8mm to 12 mm. But an increase of penetration force and energy was observed when the distance of knock-over bar added up to 14 mm. The first peak point appearing at the moment that the knife was locked by the surface stitches in stage I was unclear. It revealed that the spacer layer has been compacted easily before the knife penetrated into the surface stitches, since the compression stiffness reduced as the thickness of spacer layer increased. Thus, the upper and lower surfaces were close to each other.

The warp-knitted spacer fabric was compressed to compact condition. The resilience force of the spacer fabric was released obviously. It led more fibers to undertake the puncturing process together. That is why the penetration force and energy had the trend to increase instead. However, the penetration depth was much higher when the second peak point of the penetration force appeared. At this stage, the knife has penetrated into the fabric, which did not make much sense for stabbing. Finally, in the present test specifications, the stab resistance decreased as the thickness of warp-knitted spacer fabric increased. It is due to the lesser effect of the compression of the spacer layer on resisting the penetration of the knife. Also, the increase of the fabric thickness caused the rise of fabric areal density and its volume, creating problems in its practical application.

5. Design for sound absorption

Overview

Textiles like nonwoven, woven, and knitted fabrics have gained importance for sound absorption application because of their economy and low environment impact [68–70]. Nonwoven fiber webs have been researched with regard to the noise-absorption properties and theoretically analyzed[71]. But it is hard to produce a textured surface on nonwovens even though their sound absorption characteristics are good and cost is economical. Thus nonwoven fiber webs are usually draped with a woven fabric [72]. Plain weft-knitted fabric was also proposed for application in sound absorption, but its noise absorption performance is poor [70]. In order to improve the noise absorption ability of knitted fabrics, spacer structures were first introduced by Dias et al. [73, 74]. Their studies focused on the sound absorption properties and theoretical modeling of weft knitted spacer fabrics, which are composed of two plain knitted surface layers and a spacer layer made of multifilament yarns through tuck stitches. They found that the sound absorbency of the weft-knitted spacer fabric is effective only from 2000 Hz onwards. Furthermore, they also studied the sound absorbency of the weft-knitted spacer fabric made of monofilament yarn as a spacer yarn, in combination with a uniform pattern of micro pores on the surfaces. Their work showed that this kind of fabric could provide reasonable absorbability at mid-high frequencies, but with a narrower absorption frequency range. Though knitted spacer fabrics are more expensive than nonwovens, their appearances and structures are designable and this characteristic can raise their added values. An investigation on the sound absorption behavior of both weft and warp-knitted spacer fabrics and their combinations has been done. The objective is to find out a sound absorber with improved sound absorbency at lower frequencies with a relatively wider absorption frequency range.

Warp and weft knit spacer fabrics have been analyzed and compared for sound absorption behavior. The influence of various fabric layers and arrangement sequences on the noise absorption coefficient have been analyzed and compared. The weft-knitted spacer fabric shows the typical sound absorption behavior of porous absorber, and the warp-knitted spacer fabric shows the typical sound absorption behavior of micro perforated panel (MPP) absorber [75]. In the case of both types of fabrics, the noise absorption coefficient (NAC) increases with increase of the frequency. Both the weft-knitted and the warp-knitted spacer fabrics backed with the air-back cavity exhibit frequency- selected sound absorption with a resonance form. The sound absorbability can be improved by laminating different layers of fabrics. For the weft-knitted spacer fabric, the NACs significantly increase from one layer to four layers and thereafter more layers are no longer effective. However, for the warp knitted spacer fabric, the NACs can continuously be improved with increase of the fabric layers, but with a shift of the resonance region towards the lower frequency side. The combinations of weft-knitted and warp-knitted spacer fabrics can significantly improve their sound absorbability, but their arrangement sequence has an obvious effect. In the case of warp knitted spacer fabrics backed with weft knitted fabrics, the NACs of the former are far greater than the latter, at higher frequencies. But, the NACs of the warp knitted spacer fabrics backed with weft knitted fabrics are far lesser than those of warp knitted spacer fabrics backed with weft knitted fabrics, at lower frequencies. In order to attain high NACs at low and middle frequencies, the air-back cavity can be substituted with multilayered warp-knitted spacer fabrics.

Technical parameters

The weft-knitted spacer fabric has been knit with nylon/spandex 70D/20D yarn as the outer layer yarns and 150Den/64F textured polyester multifilament as the spacer yarns.

This was a weft-knitted spacer fabric specially designed for sound absorption. In this fabric structure, both the top and bottom layers are produced with varied plain knitted structure and they are interconnected together with six separate spacer yarns through tuck stitches. The fabric has been subjected to steaming treatment. Lots of void pores between two outer layers are formed due to the interconnection of textured polyester multifilament yarns. Thus, this weft-knitted spacer fabric could be considered as a kind of porous sound absorber. In addition, the slits formed between the adjacent spacer yarns are good for sound waves to penetrate into the fabric [75].

The warp-knitted spacer fabric was produced on a double-needle bar Raschel machine. Different from the weft-knitted spacer fabric, the spacer yarn used in the warp spacer fabric was monofilament yarn. The fabric has been dyed. The holes in the elliptical form are regularly distributed on the fabric surface. The perforated ratio, which is defined as the ratio between the surface area of the holes and the total area, was 5.4%. As the minor axis of each hole is smaller than one millimeter, the fabric could be modeled as a micro perforated panel (MPP) absorber. Besides, the void spacer between the two outer layers could be considered as an air gap. All the fabric samples were conditioned for 24 hours at 20 °C and 65% relative humidity before testing. The structural details of two kinds of fabrics after being conditioned are given in Table 3. The air resistance and the fabric thickness was measured.

Table 3. Structural details of spacer fabrics [75]

Type of fabric	Air resistance(KPa-s/m)	Thickness(mm)	Porosity(%)	Density(kg/m^3)	WPC	CPC
Weft knit Spacer	0.513	7.480	89.068	150.868	9.2	24
Warp knit Spacer	0.013	4.324	90.958	124.774	10.0	16.5

Figure – Fabrics for sound absorption [75]

Relating the properties

Warp and weft knitted spacer fabrics have been compared for sound absorption behavior in terms of noise absorption coefficient. The single layer spacer fabrics and combined multilayered fabrics have been considered. The nose absorption coefficients have been determined in the following cases

a) Single layer spacer fabrics without air back cavity
b) Spacer fabrics with air back cavity
c) Weft knitted spacer fabrics laminated with different layers
d) Warp knitted spacer fabrics laminated with different layers
e) Different layers of warp knit backed with one layer of weft knit
f) Different layers of warp knit backed with two layers of weft knit
g) One layer of weft knit backed with different layers of warp knit
h) Two layers of weft knit backed with different layers of warp knit
i) Weft knit backed with air layer or eight layered warp knit fabric

The noise absorption coefficients (NACs) have been determined for single layer spacer fabrics without an air-back layer. It is found that the NACs of both weft knit and warp knit spacer fabrics increase with increase of the frequency (Table 4).

Table 4. NACs of warp and weft knit spacer fabrics at different frequencies [75]

Weft knit	NAC	Frequency - Hz
	0.06	500
	0.14	1000
	0.35	2000
Warp knit	0.035	500
	0.05	1000
	0.07	2000

The weft knit fabric exhibits a typical sound absorption behavior of porous material. In comparison, the warp knit shows lower NACs for all the frequencies. This is the typical behavior of MPP absorbers originating from combining different sizes of perforated holes. Due to the existence of slits like perforated holes, the weft knit can also be considered as a perforated panel absorber if the air-back cavity exists. The NACs of weft and warp knit with two different thicknesses (8 and 16 cm) of air-back cavity have revealed that the existence of the air-back cavity causes frequency-selected sound absorptions due to the frequencies is still very low without the use of air-back cavity.

It is hence proved that the single layer spacer fabric has low NACs at lower frequencies. Despite the fact that the use of the air-back cavity could improve the NACs, the frequency range became very narrow. Also, the use of the air-back cavity is suited in the practical application for spacer fabrics. Laminated absorbers with increased thickness is the generally adopted technique so as to improve the NACs at lower frequencies. The NACs of the sound absorbers laminated with the same kind of spacer fabric have been considered. For porous sound absorbers, the NACs depend on their thickness, porosity, airflow resistivity and appearance. In general, increasing the thickness can considerably enhance the NACs at low frequencies. But, the increase of the thickness does not significantly influence the NACs at high frequencies and lead to slight reduction in NAC on some occasions.

Also, the effect of increasing the thickness to enhance the NACs at low frequencies is limited, since the NACs no longer increase after the thickness reaches a critical value. This phenomenon has been confirmed, wherein the NACs of the porous sound absorbers laminated together with different layers of the same weft-knitted spacer fabric are shown. The two-layered spacer fabrics show a very significant improvement in the sound absorption capacity of the spacer fabric at low frequencies. But, the improvement becomes resonance of the system. Also, the presence of the air-back cavity leads to narrower absorption frequency ranges, but with higher NACs at lower frequencies if compared to the case where no air-back cavity is used [75]. The thickness of the air-back cavity also has the influence on the NACs. The increase of the air-back cavity makes the absorption frequency move toward the lower frequency side. The weft knit spacer fabric has better sound absorbability than warp knit spacer fabric for both cases of using and not using the air-back cavity due to higher thickness. However, its sound absorbency at lower slower after two layers, and the effect of increasing the thickness on the NACs is no longer observed after five layers. To further improve the NACs, other methods such as increasing the porosity, airflow resistivity and fabric surface smoothness or a combination of different kinds of fabrics, could be considered. For MPP absorbers, the NACs depend on the perforation ratio, dimension of the perforated holes, thickness of the panel and thickness of the air-back cavity. The MPP absorbers provide high absorbability at mid-high frequencies. But, their absorption frequency ranges are normally limited because of their nature as a resonator. To obtain a wider frequency range for sound absorption, the combination of multilayered MPP absorbers with different frequency characteristics or the use of a MPP absorber with different size of perforated holes are always adopted.

The NACs of the MPP absorbers formed with different layers of warp-knitted spacer fabrics have been studied. It has been found that the NACs significantly increase with the increase of fabric layers. In addition, the resonance phenomena are observed for all the fabric layers and their resonance region shifts towards the lower frequency side with an increase of the fabric layers. It has been predicted that the NAC will continuously increase with increase of the fabric layers. Thus, it is expected that an absorber with better sound absorbability can be obtained if enough layers are used. This behavior is different from that of the sound absorbers formed with different layers of weft-knitted spacer fabric, as explained before.

Based on the sound absorption principle of MPPs, it is possible to fabricate different kinds of warp-knitted spacer fabrics with different frequency characteristics. The lamination with different warp-knitted spacer fabrics or the use of different mesh size on the same fabric can be potential ways to achieve a broader absorption frequency range.

Multilayered sound absorbers consisting of both perforated panels and porous materials are widely used in broadband noise absorptions in the case of industrial applications [76]. Under this aspect, the sound absorption behavior of multilayered spacer fabrics laminated with different combinations of weft knit spacer fabric (porous material) and warp knit spacer fabric (perforated panel) have been investigated. Two cases have been considered, wherein weft knit spacer fabric was placed on the front or the back of warp knit spacer fabric. The NACs of different layers of sample warp knit spacer fabric backed with one layer of weft knit spacer fabric have been studied and compared. It has been noticed that the sound absorbability of the warp-knitted fabrics can be considerably improved by backing one layer of weft knit. Moreover, it can also be found that the resonance regions shift towards the lower frequency side when the layers of warp knit spacer fabric increase.

This phenomenon has already been observed in previous case. However, the NACs for the low frequencies under 500Hz are still less than 0.5, which is a critical value normally used to assess whether a sound absorber is good or not. As two-layered weft-knitted spacer fabrics already have a very obvious improvement of the sound absorption capacity at lower frequencies, the NACs of different layers of warp knit spacer fabric backed with two layers of weft knit spacer fabric were also investigated [75]. //////////////It has been observed that in this case the NACs for both lower and higher frequencies are further improved and a broader absorption frequency range has been achieved. It is also found that the NAC of 8B-2A at 500Hz reaches 0.5. The sound absorption behavior of the fabrics becomes more stable for the middle and high frequencies. If the layer number of weft knit spacer fabric continues to be increased, the NACs at low frequencies could be improved further, but this improvement should be limited it is confirmed that the NACs no longer increase when the thickness reaches a critical value. Besides, increasing the layers of the fabrics will result in an increase of material use and cost. At the same time, too high thickness of the sound absorbers is not convenient in practical application. By changing the arrangement sequence, i.e., by swapping the positions of weft-knitted and warp-knitted spacer fabrics, the sound absorption behavior gets quite different.

Investigations have been done on the NACs of one layer of weft knit spacer fabric backed with different layers of warp knit spacer fabric. When the NACs of different layers of warp knit spacer fabric are compared with backed with one layer of weft knit spacer fabric, it can be found that in this case the sound absorption capacity of the multilayered spacer fabrics at low frequencies show significant improvement with increase of warp knit spacer fabric layers, but the NACs for higher frequencies are much lower, though their values are greater than 0.5. The same phenomenon, i.e., the shift of the resonance regions towards the lower frequency side, is also observed. The small peaks around 1500 Hz are found due to resonance. Investigations have been done on the NACs of two layers of weft knit spacer fabric backed with different layers of warp knit spacer fabric. The NACs at low frequencies are improved further. Simultaneously, the curved wave forms for the middle and high frequencies become straighter. This situation is similar to that of the case with NACs of different layers of warp knit spacer fabrics backed with two layers of weft knit spacer fabric, but with lower values. The small peaks around 1500Hz due to resonance are still observed in this case. The above results show that the arrangement sequence has an obvious effect on the sound absorption. This is because the different positions of warp knit spacer fabric result in different sound absorption effects. As warp knit spacer fabric is placed before weft knit fabric, it functions as a resonator absorber, and improves the NACs for all the frequencies. In contrast, as warp knit spacer fabric is placed behind weft knit fabric, it functions as an air-back cavity and leads to an increase of the thickness of the system. In this case, the NACs of the system can be significantly increased at low frequencies, but with a cost of NAC reduction at high frequencies. Investigations have been done on the NACs of single/ double layers of weft knit fabric respectively backed with 4 cm air layer and eight layers of warp knit spacer fabric. In this case, the thickness of the air-back cavity (4 cm) is near to that of eight layers of warp knit spacer fabric (3.46 cm). It can be found that the curves between the same layered weft knit fabric backed with the air back cavity and eight layered warp knit fabric are nearly coincident when the frequencies are below 3000 Hz. The differences of the NACs above 3000 Hz are due to the minor thickness difference between eight layers of warp knit spacer fabric and the air-back cavity as well as the space occupied by warp knit spacer fabric. The findings show that multilayered warp-knitted spacer fabrics can substitute air-back cavity to result in high NACs at low and middle frequencies. Hence it is suitable for practical application.

Conclusions

Warp knit spacer fabrics have been compared with PU foam in cushioning applications. Fabrics have been developed and compared with PU foam with regard to pressure distribution, air permeability, and heat resistance, and it has been established the warp knit spacer fabrics could be used to substitute PU foams for cushion application where comfort and recycling are very much needed. The influence of various structural parameters such as spacer monofilament yarn inclination and fineness, fabric thickness and surface knitted structures on the impact compressive behavior for protective applications have been evaluated. Studies have been done in relation to contact force displacement, energy absorbed contact force and transmitted time. With a reduced peak transmitted force and a high energy absorption capacity, the warp knitted spacer fabrics can be used as a type of effective material by selection of appropriate structural parameters for human body protection like shoulder protectors and back protectors in sports and related applications. The impact behavior and damage characteristic after impacts of warp knitted fabrics have been studied with regard to cushioning applications. The factors considered are peak force, absorbed energy, damage depth, and drop off rate of residual strength, so as to evaluate the behavior of spacer fabrics with different structures. A spacer fabric with good protection performance has been considered to have lower peak force, more absorbed energy, lower damage depth, and a lower drop off rate of residual strength. The balance between comfort and protective performance has to be taken into account by choosing a suitable fabric thickness for the particular protective application. The compression behavior of warp knit spacer fabrics for cushioning applications have been investigated by utilizing the stress-strain and efficiency. The influence of the various structural factors such as spacer yarn inclination angle and fineness, fabric thickness, and outer layer structure has been studied. The energy absorption capacity of warp knit spacer fabrics can be easily tailored to meet specific end use requirements by just altering their structural parameters. In order to design a spacer fabric with required compression behavior, selection of suitable structural factors becomes crucial. The sound absorption behavior of both warp and weft knitted spacer fabrics have been analyzed and compared, by studying the influence of different fabric layers and arrangement sequences on the noise absorption coefficient. In the case of weft knitted fabrics, the noise absorption coefficients significantly increase from one layer to four layers and thereafter are no longer effective. But in the case of warp knitted fabrics, the noise absorption coefficients can continuously be improved with increase of the fabric layers with a shift of the resonance region towards the lower frequency side. At higher frequencies, the noise absorption coefficients of the warp knitted spacer fabrics backed with weft knitted fabrics are much higher in comparison with the weft knitted fabrics backed with warp knitted spacer fabrics. But the noise absorption coefficients of the warp knitted spacer fabrics backed with weft knitted fabrics are much lower than those compared with the weft knitted spacer fabrics backed with warp knitted fabrics, at lower frequencies. In order to achieve high noise absorption coefficients at low and middle frequencies the air back cavity in the spacer fabrics can be replaced with warp knitted spacer fabrics. The aforesaid discussions clearly establish the potential of warp knit spacer fabrics in a number of technical applications and hold promises for more areas of applications, of which design for shoe insole is one such prospect and is under active research.

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