AIMS Materials Science

http://www.aimspress.com/journal/Materials

AIMS Materials Science, 8(4): 622–639.
DOI: 10.3934/matersci.2021038
Received: 24 May 2021
Accepted: 22 July 2021
Published: 11 August 2021

Research article

Investigation of spider web oriented composite fabrics burst strength

Yohannes Regassa[1], Hirpa G. Lemu[2,*] and Belete Sirhabizu[1]

[1] Addis Ababa Science and Technology University, Dept. of Mechanical Engineering, Addis Ababa, Ethiopia
[2] University of Stavanger, Faculty of Science and Technology, N-4036 Stavanger, Norway

* **Correspondence:** Email: Hirpa.g.lemu@uis.no.

Abstract: Burst strength is a significant property that determines all other properties of structures to perform under induced internal pressure. In this study, the burst strength of a spider web-formed fabric structure is experimentally investigated. The spider web form orientation is prepared using Embroidery machine. A spider web develops a self-stressing nature, which offers its excellent inelasticity and provides a mechanism for competent and economical means to harmonize the local and global induced stresses in their structure. The obtained results are compared with published works on different effects of fiber architectures. The burst test result on spider web form indicated a spider web form's potential candidacy to utilize it as a future fiber orientation technique to form an enhanced composite reinforcement. However, fiber orientation influences the fiber-reinforced composite's mechanical properties. Fiber orientation via spider web form has not yet been used as a reinforcing engineering composite product. Hence, conducting rigors experimental work on spider web form reinforced composite structures can be taken as a significant step to fill the research gap.

Keywords: burst test; composite materials; composite fibers; fabric; nature-inspired design; spider web

---

1. Introduction

Research on spider webs has attracted attention due to the amazing architecture with a unique combination of geometry and mechanics [1–4]. One of the main characteristics of the web is that it can withstand the high stress required to absorb the tremendous kinetic energy of the flying prey [5]. Beyond this, the spider web's pattern can avert the insect fleeing from the oscillatory webs by reducing the absorbed energy [6]. The primary constituent of spider webs is spiral silk threads, radial silk threads, and the junction between different individual yarns in a net [7]. The radial threads are composed of dragline silk, whereas the spiral strings are constructed from viscid silk [6,8]. The web anchorages have a significant role in capturing the prey and the efficient use of the silk materials [9,10]. There is a focus on the natural arrangement for innovative technological development; the spider web has attracted a considerable attention of structural designers due to its fantastic character. Many studies are undergoing to characterize the mechanical behaviour of spider web structure. Among the mechanical characterization of spider silk, the traditional static tensile stress-strain characterization and strain rate dependency were performed [4,9,11]. The web's structural integrity is maintained due to differences in spiral and radial threads. The radial thread, which is significantly more robust and stiffer, contributes to the web's structural performance, while the spiral yarns contribute to non-structural play like capturing the prey [5]. The combined behaviour of spiral and radial yarns attracts the nature-inspired design community to consider spider web patterns for further study to respond to the candidacy of spider web structure as a fiber orientation for reinforcing composite products.

Composite materials turn out to be among the most efficient selections in the design of mechanical structures because they offer high strength/stiffness to weight ratio. On the other hand, composite materials are known to be vulnerable to out-of-plane impact loads, which may lead to structural damage that are hidden for the naked eye and can significantly decrease the structure's load-bearing capacity [12]. The combined effects of the composites failure process, which might involve fiber breakage, fiber-matrix de bonding, matrix cracking, or delamination, results in complexities in being able to predict the damage growth. Among available methods used to predict failure behaviour of composite materials, use of numerical simulations is known to provide a cost-efficient solution within relatively short processing time [13].

Tailoring material properties of composites favors the emerging needs to replace the strong metallic alloys in many applications like aerospace applications, automobile components, marine and sports goods. One method for implementing property enhancements to the composite structure is tailoring the fiber orientation through innovative approaches that are, in many cases, inspired by nature, which is a fundamental source of optimized design solution. One of the techniques to develop nature inspired products is to mimic the shape and function of those animals, insects, or birds to be copied for further engineering revolution. For instance, spider web pattern and silk fibers co-evolved about 400 million years ago, primarily as a protein cover to protect the eggs and youngs of animals [14]. The evolution of webs had different functions such as acting as wallpaper for the animal's tunnel and modifying the hole into a simple trap, though webs are not yet practiced well to adopt for structure design purpose. Mimicking of the spider's pattern and silk production requires copying its exact silk extrusion and spinning system, i.e., manufacturing method of the silks "the way the spider is doing". Among the available tools used to provide geometrical information from miniature like spider for its silk diameter, surface property and alignment can be quantified by CT-Scan, Polarizing and atomic force microscopy. The polarizing microscopy, for instance, informs about the internal chemical order of spider silk structures, and application of such tools can accelerate the undergoing research for decoding the secrets behind spider netting [15]. Though spiders have many variations, ranging from habitat to size to preferred meal, all of their species have common goals including getting a good meal and avoiding being crushed. For the last decades, silk fibers are fascinating phenomenon for people to decode the mystery behind it. For instance, groups of weaves referred to as cellular weaves are produced by placing weft and warp yarn float end to form cellular structures. Those weaves that are derived from sateen weaves are also referred to as sponge weaves referring to their soft characteristics [15].

The last century experienced new developments of materials with rapidly growing requirements, for instance in structural building of automobiles and energy storages like pressure vessel and hydrogen container that are changing the direction of materials studies rapidly. The demand for robust material performance shifted from existing materials, where different new materials are developed to meet the combined modern time requirements by creating superior designs with improved performance at micro size than their macro structures [16]. The application of composite materials in the aerospace, as well as in the whole transportation field is pushing the research community to find the best solution to allow the structure to tolerate the presence of damages. Such need led to the birth of new composite materials that are inertly damage tolerant and then, less damage prone than traditional ones [17].

Yet, many research works have been carried out for searching advanced manufacturing techniques for robust design of materials and towards developing reliable and repeatable manufacturing processes [18–20]. Thus, conventional fabrication technologies with excessive waste materials are aimed to be replaced by advanced and fast production techniques like fused deposition modeling (FDM) as a 3D printing process to be used for fast production of items used in aerospace, automotive and medical sectors [21].

With the development of new materials and new applications, there are different methods of characterizing the materials emerged. Burst strength of fabrics is a key material characterization technique used to determines the performance of knitted fabrics, where the strength is essential while selecting a proper material for fabric design of the intended application. The mechanical properties of knitted fabrics are one of the fundamental parameters for such innovation. Among these properties, the bursting strength is the critical parameter. A perpendicular exerting force is used to measure the burst strength fabric via breaking. Different studies show that bursting properties of knitted fabrics can be influenced by the knit structure [22]. Recent advances in composites create paramount opportunities for the development of improved materials from renewable resources which in turn offer significant contribution to global sustainability. Accordingly, engineers and material scientists strive to minimize the waste disposal problems associated with traditional fibers derived from petroleum-based polymers. In this regard, green composites from natural fibers and biodegradable polymers gained an increased attention in several industrial sectors such as the automotive and the construction sectors. Over the last decades, there has been a rising interest towards natural fiber reinforced composites of jute, banana, sugarcane bagasse, coir and sisal fibers. Since jute fibers have a high content of cellulose (61–72%), hemicellulose (14–20.4%), lignin (12–13%) and pectin (0.2%), they are becoming more favorable natural fibers to be considered as a full-scale substituent of synthetic fiber [23,24].

While implementing the burst testing method, the plunger motion is the source of energy to exert load to examine the ultimate bursting strength of the new specimen pattern that is under investigation and is expected to comply with pre-defined requirements [25]. In addition to the loading type, studies show that fabric structures have a significant effect on the bursting strength of the fabrics [22]. As reported in [26], bursting strength reveals that knitting is one of the important parameters in production of fabrics. In the honeycomb patterns that have zigzag designs, for instance, the material is relatively tight and hence the bursting strength values of such patterns are high. Still, in honeycomb mesh, the loops do collapse longitudinally leading to increased width of material when the length of the fabric decreases. As a result, the fabric of these patterns does not pick up as the other zigzag structured fabrics do.

The research work reported in this article aims to investigate the effect of spider web orientation on the bursting strength of plain poplin woven fabric produced by horizontal warp and vertical weft yarns.

2. State of fabric structure

Countless experimental studies were conducted to investigate the impact of fiber orientation on fiber structure of randomly oriented mat, unidirectional with 0/90° orientation, and woven fabrics. The study reported in [27] investigated the mechanical behaviour of straight knitted and twill weaved fibers and revealed that a twill woven fiber ensures excellent mechanical properties compared to the woven mat. Woven mat fiber affords a proper equilibrium in mechanical properties, and it is the favorite form of standard fiber mat for an engineered composite.

The locknut designs of fabrics have greater bursting strength than biaxial cross miss designs [26]. It means that all knit course insertion in cross-miss structures increase the fabrics' bursting strength, which is an important property of its performance. The consideration of the material's burst strength is essential when selecting fabrics that are proper for the intended garment. A systematic method is needed to find the correlation between different fabric strength properties and the parameters of yarn and the fabric build up. However, it is necessary to study the effect of twist, count, and cover factor on the fabric's strength behaviour, which is an influential parameter for designing fabric geometry. It is also mandatory to conduct an experimental validation of the designed pattern. Depending the customer requirements, the industry owners or designers use practical methods, and they perform different mechanical characterizations to realize the user requirements. Depending upon the test result for the designed geometry, the enhancement methods can be achieved by re-designing techniques that have developed to provide hint on the poorly performing existing design.

The burst strength of fabric structure is measured by examining the coherence of the fabric, i.e. the resistance to tear under external load. The characteristics of bursting strength is affected by diverse factors, such as the fiber type, regularity in diameter, knitted design, etc. A variety of materials are available for reinforcement and lining. The basic required properties of a lining fabric are less weight and pliable (i.e. bendable without breaking), smooth and soft to touch that provide comfort [28]. The character of the material highly depends on its fundamental constructing unit fiber properties. The essential properties of fabrics are the building units such as the fiber type, fabric construction, thickness or mass of the material, and the involved chemical treatments. Fabrics that are drawn down at an angle of 120-160° angle create a high take up of the tension, which is suitable for the available fabric structures such as laces and nets [29].

The warp-knitted fabrics are flexible, too; they can be inelastic or elastic, while their mechanical characteristics are like structures of woven fabrics. The best description of warp knitted fabrics combines the technological, production, and commercial benefits of the woven and weft knitted fabrics. Warp knitted fabrics can be produced continuously, with an open or closed structure, while flat, tubular, or three-dimensional geometrical form is the field's standard practice. The fact that warp knitting techniques are flexible makes them attractive for applications as sportswear lining fabrics [18].

Currently, military personnel and law enforcement officers use different body armour vests with rigid ceramics plates. They depend upon the threat level; this composite-made body armour with their building unit of woven fiber-made material protects various parts of the human body against any form of attack. Even though ceramic-based armours with heavy inserts are essential to protect against armour-piercing, it also results in excessive weights in the armour system, which will affect the mobility of a soldier in the field. As a result, soft body armour vests, which are made of high strength/modulus fiber-based woven fabrics, are widely used by law enforcement officers [19].

Abtew et al. [20] reviewed impact responses of textiles and fiber-reinforced composites and discussed the requirements of protection against ballistic projectile or combined threat type. The production process of such reinforced composites can involve soft vests made of 3D orthogonal woven, 3D angle interlock woven, and 3D fully/partly interlaced woven as well as knitted or multi-axis 3D woven. The practice of using a hybrid 2D/3D fabric-based vest of armour structures made by using single-layer and multi-layered nonwoven and braided structures is increasing the need for less weight bulletproof. 3D woven fabrics (mostly 3D warp interlock) are widely utilized as a fibrous reinforcement of composite materials many applications intended to replace laminated designs. Trends indicate that laminar slices give no longer advantage in terms of economic, practical and technical aspects than other mounts. The 3D woven fabric also shows excellent performance in ballistic protection with high flexibility and lightweight over the 2D woven structures. However, there is lack common understanding in the research community and weaving technologists due to its intricate design. Considering such problems, some researchers [20,30,31] have studied detailed descriptions, components, and general design specifications of 3D warp interlock fabrics for better clarification and understanding, unlike other woven structures. However, 3D warp interlock fabrics have also been facing some inherent drawbacks in their manufacturing and geometrical design methods like yarn's damage during the weaving of 3D warp interlock fabric due to abrasion resulted from yarn-to-yarn friction and friction by contact with other loom metallic parts, as well as 3D warp interlock fabrics have a lower value of fiber volume fraction than laminated 2D fabrics or unidirectional plies [32]. There are different types of 2D and 3D woven fabric structures available in the forms shown in Figure 1 [20] and used for diverse industrial application purposes.

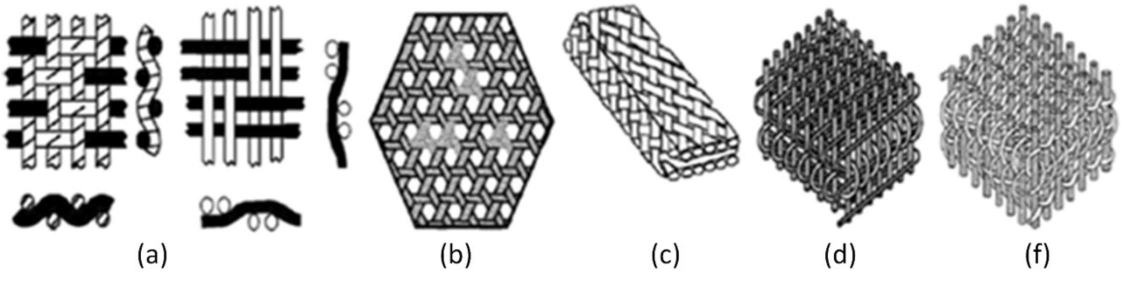


Figure 1. Possible forms of yarn orientations for 2D and 3D fabrics structure. (a) Biaxial plain woven, (b) triaxial woven, (c) 3D braid, (d) 3D orthogonal woven and (e) 3D triaxial woven.

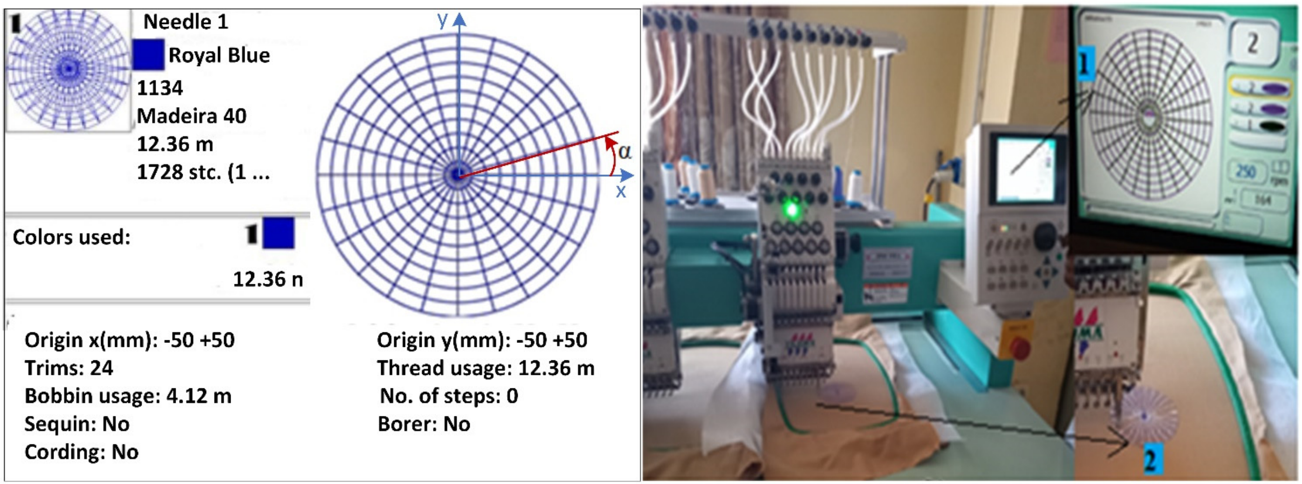
Nowadays, along with high-strength polymer fabrics, the fiber-reinforced laminated composites (FRPC's) have also been widely used as primary structural materials in different industrial applications such as aerospace, defence and transportation. This is due to their superior engineering properties such as high strength and stiffness, excellent flexibility and low relative density. Moreover, apart from traditional fibers like nylon fibers, high-performance fibers such as glass, carbon, aramid, etc., have also been exploited and applied in fiber-reinforced laminated composites, including soft, flexible fiber mats for body armour or as reinforcements of rigid polymer matrix composites (PMCs) for lightweight vehicle armours. The laminated composites are mostly composed of layered sheets of different materials. Such lamination gives the constituent layers the best aspects for combining the directional dependence of a material's strength and stiffness. Unlike randomly distributed short fiber-reinforced composites, unidirectional fibers have different fiber orientations in different layers and they have aligned distribution in the same layer. These laminated composites have commonly known to have continuous fibers because the fibers large aspect ratio [33,34].

3. Research methods

3.1. Designing the spider web model

The spider web orientation in this research is designed and modelled by Tajima DG/ML commercial licensed software at the Ethiopian textile industry development institute's embroidery laboratory. In order to investigate the suitability of spider web based pattern or orientation in design of applications exposed to bursting loads such as pressure vessels, experimental test on the burst strength was done according to the ASTM D3786 [35]. The natural spider web was constructed from radials and spirals as sticky and non-sticky structures to trap external flies. Due to angle orientation, the spider web's radials were the pioneering elements for the spider web's unique properties [36]. In line with the objective of the study and the recommendations of ASTM standard [35], the spider model was designed with a diameter of 100 mm, where the used gripper of the test machine has a diameter of about 80 mm, and each spiral varied by 10 mm outward from the centre. The 24 radials of the spider web geometry radiated at 15° from the positive x-axis. During burst testing, the effective diameter of 30 mm was used for both tested specimens (i.e. spider web form fabric and plain woven fabric). Certain embroidery machine brands such as Brother or Bernina require different embroidery design file formats (such as PES or ART) [37]. In this case, however, the designed spider web model was loaded to the Tajima embroidery machine in a DST file format, which is a compatible format for the machine. The embroidery machine's function panel allows adjustment of the working machine parameters like the apparatus's speed, yarn head selection, and weaving method through a qualified expert's support.

Figure 2 illustrates the spider web form geometry, which was developed by the Tajima embroidery machine (model: TFMX-II904) for prototyping the spider web form on plain-woven fabric (PWF), whose specifications [38], together with the spider web pattern reinforced woven fabric (SWRWF), is given in Table 1. While Figure 2a depicts the key machine set-up parameters under modelling of the spider web on the machine, Figure 2b shows loading of the model involving generating a model prototype on machine screen (marked 1) and loading on the embroidery machine (marked 2).



Needle 1
Royal Blue
1134
Madeira 40
12.36 m
1728 stc. (1 ...
Colors used: 1
12.36 n

Origin x(mm): -50 +50
Trims: 24
Bobbin usage: 4.12 m
Sequin: No
Cording: No

Origin y(mm): -50 +50
Thread usage: 12.36 m
No. of steps: 0
Borer: No

(a) (b)

Figure 2. Pictorial illustration of the research methodology: (a) Design and modeling of spider web on Tajima DG/ML software and (b) loading the spider web design model.

Table 1. Specifications of plain-woven fabric and spider web pattern reinforced woven fabric.

Pattern type	Warp/100 mm (vertical aligned fiber)	Weft/100 mm (horizontal aligned fiber)	Thickness (mm)	Density (gm^{-2})
PWF	51	51	0.44	199.9
SWRWF	51 plus 24 radials and 10 spirals via spider web form	51 plus 24 radials and 10 spirals via spider web form	0.56	229.6

3.2. Burst testing method

The used testing procedure involved the following steps outlined in [39] and recommended by ASTM D3786 [35] standard:

- Preparing the specimen for test and placing it between two flat circular fixtures, and
- Fixing the test samples achieved by manually operated geared handle equipped in the machine.

When all necessary sample procedures for production are done, the model is subjected to the motorized piston pressure. Figure 3 depicts the mechanism conducting the burst test. As the oil pressure rises via a rubber diaphragm, the test specimen expands simultaneously in all directions because it is under a uniform pressure load. Gradually, the fabric begins to tear after slowly crossing the holding capacity of the specimen, and finally, then it raptures. The displayed pressure limit on the machine’s reading panel is the burst strength of the test specimen. Usually, fabrics fail when subjected to bursting conditions rather than when exposed to a tensile force. This type of stress on plain fabrics results in elbow formation rather than tearing [40].

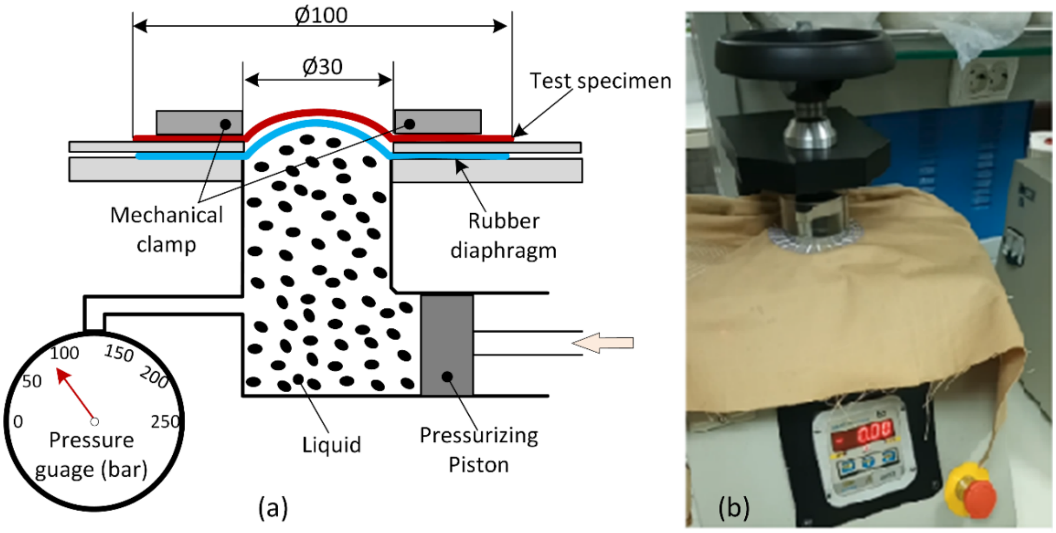


Figure 3. (a) Illustrative view of burst testing mechanism and (b) burst testing machine set-up.

The burst test, illustrated in Figure 3, is a destructive mechanical test type that destroys the specimen via hydraulic pressure until the sample ruptures, which is used as a measure of its ability to resist the pressure. The test involves an intensive experimental method used to measure the strength of textile fabrics by imparting uniformly distributed stress or pressure on the material at the same time. As illustrated, the bursting strength was measured by the force required to burst a ring clamped sample by an internal pressure exerted through sealed rubber. Tests were conducted on the burst testing machine with a 5000 kgf load cell and 100 mL/min pressure rate [35] of piston head speed. The machine operates with glycol fluid and has a measuring range of 0 to 50 bar (0 to 5 MPa) that reads at a subdivision of 0.01 bar. The sealed rubber ring diameter is 30 mm. Five specimens were tested from each sample of plain woven and spider web formed woven fabric.

4. Discussion of results

Nowadays, many applications require fibers with high-yielding properties. Different orientations can achieve their requirements in nonwoven or woven fabrics as reinforcements for polymer composites to tailor the mechanical properties [41]. The loading and application requirements of composite structures require an innovative fiber design and rigorous characterization for the designed orientation's final decision to apply for further application. As depicted in Figure 4, a multi-directional tensile test was implemented to conduct the burst test and to identify the plain-woven fabric's failure characteristics. In the experimental study, two scenarios were considered, (1) plain poplin woven fabric and (2) embroidery made spider web structures. For both scenarios, measurement of the burst strength and tear size as response of the burst test were conducted and the bursting and tearing response as a function of fiber orientation were examined, which are discussed in the following sections.

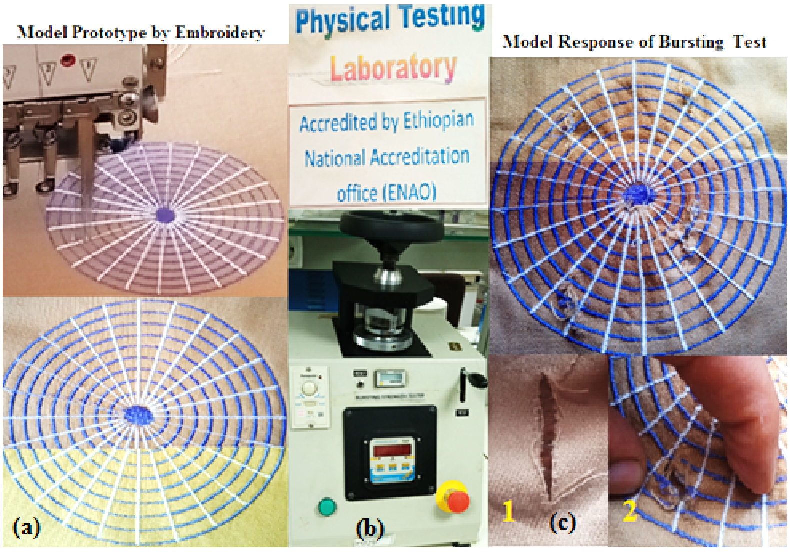


Figure 4. (a) Sample production by embroidery, (b) image of the burst testing machine, and (c) bursting result for (1) plain woven and (2) spider formed fabric.

4.1. Measuring the bursting strength of spider web pattern on woven fabric

Though the tear or crack propagation in plain woven fabric shown in Figure 4c, case 1, seems orthogonal, the actual tear is radiated in warp direction due to weakness of weft. Warp and weft are the two basic components used in bi-directional weaving to turn the thread or yarn into fabric. The lengthwise or longitudinal warp yarns are held stationary in tension on a frame and get tight strength while the transverse weft is drawn by inserting over-and-under (Figure 5a) the warp that leads to a weaker orientation than the warp. Bursting strength test deals with examining the strength of the fabric constituent while a multi-directional force is applied on it, which generates stresses both in warp and weft direction at the same time and the applied load is conserved in the form of tear. Bursting strength is defined as the difference between the pressure (P) required to rupture a specimen and the pressure (P’) required to inflate a rubber diaphragm of the testing machine (illustrated in Figure 3) can be calculated by using Eq 1 [38].

$$\text{Bursting strength} = P - P' \tag{1}$$

where, both P and P’ are in kg/cm^2 (bar).

When the yarn in the fabric has high breaking strength and large elongation, it’s bursting strength increases. The resistance to bursting of the knitted fabrics depends on the constituent units and different factors [22]. Figure 5b depicts the failure phenomena of the tested woven fabric that shows the need of weft strength improvement.

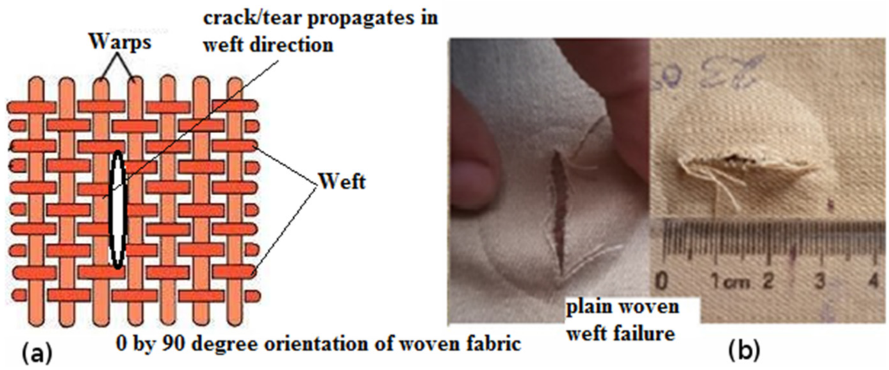
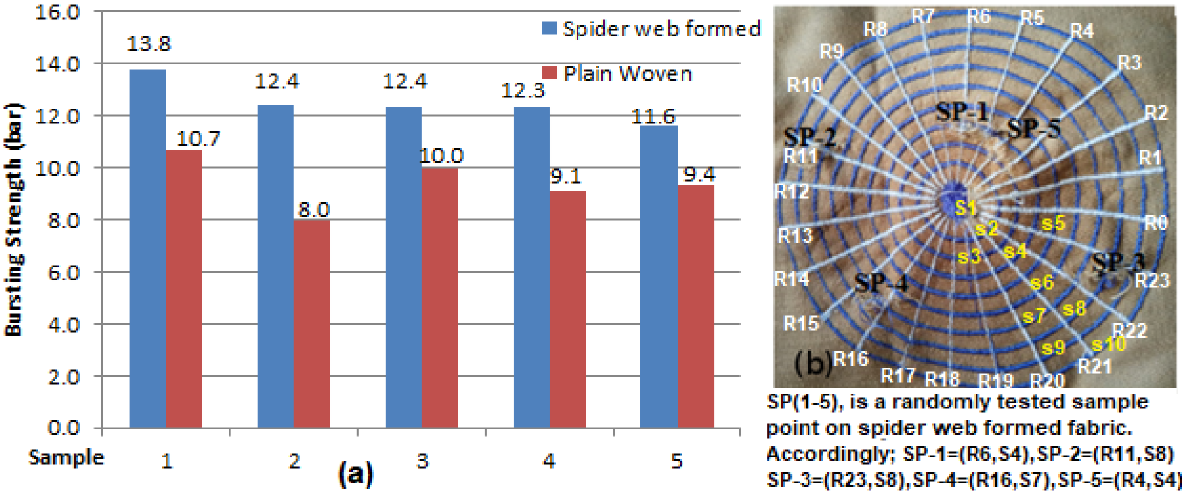


Figure 5. (a) Illustration of tear at micro level of warp and weft and (b) mechanical tear test of plain woven.

Figure 6 shows the bursting result of a comparative experimental study for the burst strength of five samples. The results on Figure 6a show that there is a general improvement of the burst strength when spider web formed design is compared with the plain fabric and this is because of the used orientation. The maximum burst strength is recorded at the SP-1, which is located at the radial junction point of spider web. The reason why SP-1 responds strongly to burst strength can be due to the combination of the behaviour of spiral and radial arrangements. The test point SP-5, which falls between radial and spiral open space behaves is weaker than the other spiral and radial test points due to lack of reinforcement. The statistical values of the obtained burst strength of each sample are given in Table 2.



SP(1-5), is a randomly tested sample point on spider web formed fabric. Accordingly; SP-1=(R6,S4),SP-2=(R11,S8) SP-3=(R23,S8),SP-4=(R16,S7),SP-5=(R4,S4)

Figure 6. (a) Graphical comparative values of burst strength of samples, (b) spider web formed test point locations.

Table 2. Burst strength performance of samples (SP1–SP5).

Samples	1	2	3	4	5	Descriptive statistics of burst strength test				
						Mean (mm)	Standard error	Standard deviation (mm)	Sample variance	Skewness
Plain woven fabric strength (bar)	10.67	8	10	9.13	9.36	9.43	0.45	1.00	1.00	−0.37
Embroidery made spider web-based plain fabric strength (bar)	13.79	12.39	11.6	12.33	12.37	12.50	0.36	0.80	0.63	1.19
Variation between PWF and EMSWF	29%	55%	16%	35%	32%	-	-	-	-	-

The bursting test was conducted on two categories of five samples; plain woven and embroidery made spider web on plain woven that was bi-directionally webbed. The obtained results for randomly selected test points of each five tests have been tabulated in Table 2 and the statistical data is discussed below.

The obtained standard error indicates that the standard deviation of the recorded test samples deviated by 0.45 mm from the sample mean, while the embroidery made spider web deviated with standard error of 0.36 from true mean implying that the plain woven provides more dispersed results and it is susceptible for poor quality. A low standard deviation of 0.8 mm for embroidery made spider web indicates that the recorded result is consistent and tend to be near to the mean of the set, while a high standard deviation of 1.00 mm for plain woven depicts that the values are spread out over a wider range.

For statistical data, skewness is a measure of the irregularity to the spreading of a real-valued arbitrary variable around its mean and if skewness falls between −0.5 and 0.5, the distribution of data can be assumed as symmetrical to the mean. Accordingly, the data tabulated in Table 2 scored −0.37 for the skewness and the randomly test result assumed as a proportional move to its mean. The possible reason for non-skewness of burst test result on plain woven is its symmetrical nature of the poplin fabric.

The statistical data indicates also that the weaving orientation characteristics are the most effective parameters to the bursting strength of a given fabric. Therefore, the radials and spirals combination of spider web orientation can be used to characterize the fabric design with respect to burst resistance and as an ideal crack arrestor. In summary, the study demonstrates the effect of the spider web to enhance the burst strength and the design possesses higher strength than the plain-woven fabric. This can be another evidence for nature-inspired innovation that serves as source of optimized fiber pattern to design and manufacture industrial woven fiber for fiber-reinforced composite.

4.2. Bursting response examination of tear size

Various parameters influence the textile material burst response. Among the key parameters, textile material properties such as fabric architecture, weave construction, weave and yarn density, fabric thickness, fabric crimp, and fabric types are significant ones [22]. However, the gram per square meter (GSM) and specific strength of the fabric are basic parameters used to measure the tear strength, where higher GSM yields improved structural integrity of the fabric against tearing. Since the specific strength of the fabric is directly related to the tearing strength of the fabric, higher yarn strength leads to less tear size, and the increase in GSM can increase the tear strength [22]. The results of this research indicate increased tear strength without increasing the GSM of spider web reinforced woven fabric. Thus, the tear test on spider web formed fabric shows a promising technique for enhancing fabric tear strength. The examination report of tear strength performed on five samples of plain woven and spider web formed woven fabrics are shown in Figures 7–9.

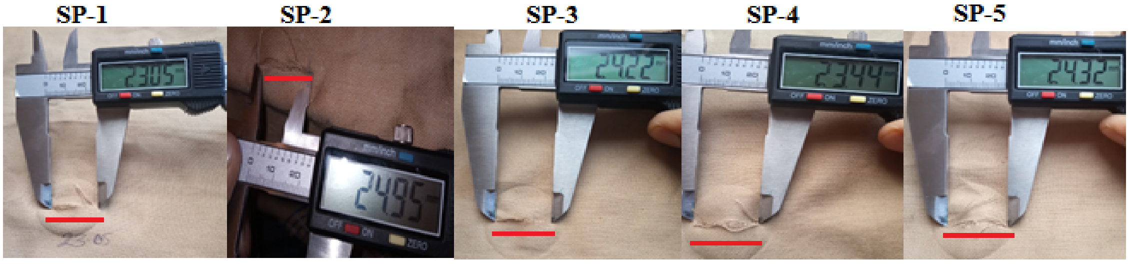


Figure 7. Tear size measurement of plain-woven fabrics.

Figure 8. Tear size examination of spider web formed plain fabric.

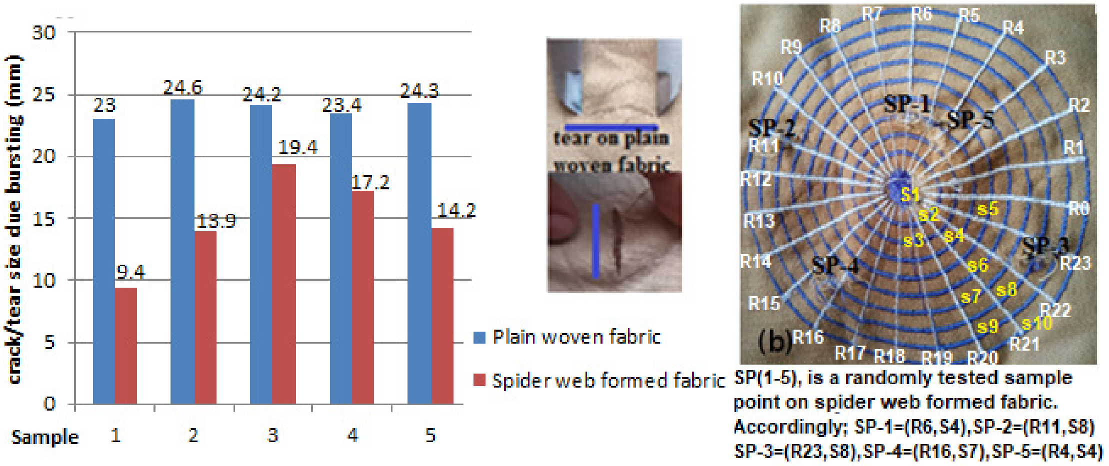


Figure 9. Tear size comparison of plain-woven and spider web formed fabric.

Burst test is designed for the fabric to bear weight or force for the designed purposes. It is one of the important mechanical characteristics of fabrics. Figures 7 and 8 as well as values tabulated in

Table 2 reveal that, in general, bursting strength of normal bi-directional fabric in terms of the tear size response is less than that of spider web reinforced fabric. The trend of the plot of the tear size of the plain-woven fabric for all samples is almost constant, while variations are observed for the spider web formed samples. This is due to the random selection of the test point and some of the sample points get a form of reinforcement from the radial oriented fibers.

The tearing strength of the samples (as can be observed in Figure 9) confirms the weakness and strength of the plain woven and embroidery made samples to the applied pressure for burst strength respectively. The fabric with spider web formed has a higher strength value than plain woven fabrics of the non-spider web. The results show a piece of evidence for an increase in burst strength and a decrease in tear size on tested samples.

From Figure 6 and Table 2, it is possible to observe that Sample 1 shows the highest recorded bursting strength values (13.7 bar) which is equivalent to 1.38 MPa, while in the case of Sample 3, the bursting strength value (11.6 bar) is the lowest. The spider web construction with radials and spirals contributes varied strength to the fabrics. Radials of the spider web provide higher burst strength than the spirals-oriented fiber of a spider web. One of the significant observations of this study is that the spider net with closely compacted orientation results in higher bursting strength compared with plain fabrics of the same materials.

The burst strength test report of each point response on the specimen is shown on Figure 10 and compared with the published results reported in Figure 3 of article [22]. Comparatively, the obtained result shows that there is a significant improvement by the spider web formed woven fabric. The study reported in article [22] discusses the effect of fabric structure on burst strength using identical method with the study reported in this article. By using similar method, the above-mentioned article reported results of a study on a fabric structure that has undergone a burst test to demonstrate experimental works on five knit patterns. Due to this similarity on the approach used, the work reported in [22] is used as a reference to proof the design and test procedure. The work reported in Figure 3 of article [22] indicates that the quasi-Sand fly mesh has the highest bursting strength of 849 N, and the quasi-Marqussite mesh has the lowest bursting strength of 347 N. As depicted in Figure 10, the embroidery made spider web structure indicates that the highest bursting strength is 1178 N, while the lowest bursting strength is 992 N. This clearly indicates that the embroidery made spider web structure excels the existing fabric arrangement’s (bi-directional-0/90°) art. The obtained results can provide a full insight result to be explored in further studies in the field to quantify such fiber arrangements as a potential fiber orientation type for lining and reinforcing the composite structure.

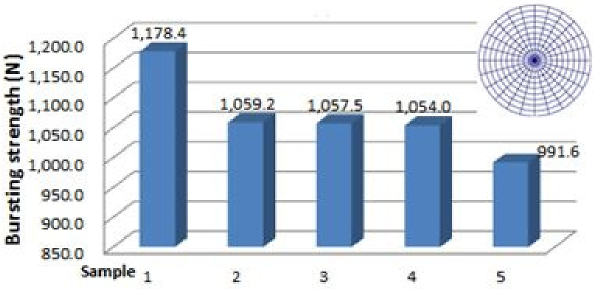


Figure 10. Plot of burst strength of a spider web form woven fabric structure.

4.3. Tearing resistance response of spider web formed woven fabric

The experimental results of the study conducted on the tearing resistance response of the spider web formed woven fabric are shown in Figure 11. To get some form of validation, the tear size results are compared with research findings of different fabric structures reported in article [22]. The plots given by Figure 4 in [22] show that the maximum burst displacement or tear size is 2.5 cm for a sandfly structure while the lowest tear size of 2.1 cm was reported for Quasi-Marqussit structure. The plots in Figure 11 of this study, on the other hand, show that the maximum tear size is 1.9 cm for sample 3 and the smallest tear size is 0.9 cm for sample 1 (SP-1). This implies that the warp and weft wise tear strength of spider web formed on plain fabric is much greater than research findings of different fabric structure reported in other studies. Hence, the spider web formed fabric provides more stability along the warp and weft direction of the plain-woven fabric because there is less tear size on the structure than the findings reported for those fabric types. Though our sample points are randomly selected because the burst load is assumed to be uniformly distributed, the largest tear size in the spider web structure test is smaller than the smallest tear size in the compared article.

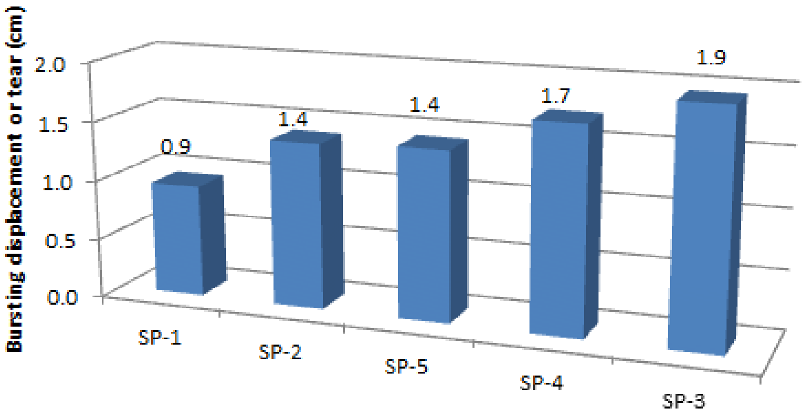


Figure 11. Plot of bursting tear of a spider web formed structure.

5. Conclusions

In this study, spider web form orientation on plain-woven fabrics has been prototyped successfully using the embroidery machine. The manufacturing of such direction-orientation can answer the most straightforward method of production of spider web orientation. Using Tajima DG/ML, the spider web mimicked fiber orientation model has been developed and installed on the embroidery machine. Soon after the sample preparation was made ready, samples bursting test was conducted on the models in order to investigate the effect of spider web form orientation on the fabric structure to characterize tearing strength extracted from bursting phenomenon and to make conclusion between bursting and tearing properties of the fabrics generated by measuring the tear size of each sample. Thus, the hypothesis of a relation between fabric structure and bursting properties and the tearing characteristics confirmed the potential method of crack arresting for the local or global fiber-based composite structure's failure.

The results obtained from the burst strength test can be summarized as follows:

- An embroidery machine can be a potential manufacturing method to produce complex fiber orientation that enhances the research on optimizing fiber orientation either by nature mimicry or any designer's choice of patterns or orientations to be made for further study.

- The entire examined spider web-based fabric samples exhibited super mechanical bursting strength compared to the poplin fabric structure. A spider web form on the fabric structure demonstrated that among the five embroidery made samples for test, the sample SP-1 on the design's radials location of test point has the highest bursting strength (1.37 MPa or 13.7 bar) while joint part of radials with spirals has the least bursting strength.
- The spider web that formed on the plain fabric is observed to be more robust than the non-spider web formed on the plain fabric. Thus, the spider web leads enhancement of plain fabrics. The non-spider web-formed fabric was susceptible to tear, and the maximum observed tear is 25.7 mm and the minimum is 21.2 mm.
- The spider web-formed fabric structure exhibited strong tear resistance. The digital measured tear response shows a maximum of 19.4 mm, and a minimum of 9.4 mm tear size, which reveals that the embroidery made spider web orientation provides additional strength to the plain-woven fabrics that tested by burst tester machine. The relation between burst strength and tearing size leads to a conclusion as inversely proportional to each other. The higher the burst strength, the higher the tear resistance.
- Nature provides a sustainable and optimized pattern or arrangement to be adapted for engineering design. Accordingly, the effects of spider web-based design of fabric structure on bursting strength were studied and comparison is done with published works. Article [22], in particular, was selected because it reports experimental study using similar fabric structure and similar procedure. Thus, the comparison is intended to serve as a proof of the fabric structure and the test procedure. In this study, the bursting characteristics and tear size of spider web pattern as reinforcement provide an excellent bursting characteristic and tear size. While plain woven fabrics exceed the results reported in [22], the fiber arrangement in spider web design provided a higher bursting strength and lesser tear size.

Generally, regarding the physical and mechanical characteristics, the spider web fiber orientation is observed to be a potential future candidate for fiber arrangement to form a fabric structure in textile for harden or strong woven fabric formation [42], as well as for a method of crack retrofitting in the construction sector, crash energy absorption mechanism in the automotive industry, and as a reinforcement method for pressure vessel construction.

Author contributions

Conceptualization, Y.R. and B.S.; methodology, Y.R. and H.G.L.; software, Y.R.; validation, Y.R., B.S. and H.G.L.; formal analysis, Y.R.; investigation, Y.R.; resources, B.S. and H.G.L.; data curation, H.G.L.; writing—original draft preparation, Y.R.; writing—review and editing, B.S. and H.G.L.; visualization, Y.R.; supervision, B.S. and H.G.L.; project administration, B.S.; funding acquisition, B.S.

Acknowledgments

The authors would like to acknowledge the Ethiopian Textile Industry Development Institute for allowing use of their facility and expert support during the experimental tests. The supports provided by Mustefa Mohammed on Tajima DG/ML software modelling, Getahun G/Eyesuse for sample production by Embroidery machine operation and Simegnewu Mersha for the operation on burst testing machine are highly appreciated.

Conflict of interest

The authors declare no conflict of interest.

References

1. Sanders ED, Ramos AS, Paulino GH (2020) Topology optimization of tension-only cable nets under finite deformations. *Struct Multidiscip O* 62: 559–579.
2. Xu B, Yang Y, Zhang B, et al. (2020) Bionic design and experimental study for the space flexible webs capture system. *IEEE Access* 8: 45411–45420.
3. Qin Z, Compton BG, Lewis JA, et al. (2015) Structural optimization of 3D-printed synthetic spider webs for high strength. *Nat Commun* 6: 1–7.
4. Harmer AMT, Blackledge TA, Madin JS, et al. (2011) High-performance spider webs: integrating biomechanics, ecology and behaviour. *J R Soc Interface* 8: 457–471.
5. Das R, Kumar A, Patel A, et al. (2017) Biomechanical characterization of spider webs. *J Mech Behav Biomed Mater* 67: 101–109.
6. Tietsch V, Alencastre J, Witte H, et al. (2016) Exploring the shock response of spider webs. *J Mech Behav Biomed Mater* 56: 1–5.
7. Qin Z, Buehler MJ (2013) Spider silk: Webs measure up. *Nat Mater* 12: 185–187.
8. Pugno NM, Cranford SW, Buehler MJ (2013) Synergetic material and structure optimization yields robust spider web anchorages. *Small* 9: 2747–2756.
9. Hudspeth M, Nie X, Chen W, et al. (2012) Effect of loading rate on mechanical properties and fracture morphology of spider silk. *Biomacromolecules* 13: 2240–2246.
10. Aoyanagi Y, Okumura K (2010) Simple model for the mechanics of spider webs. *Phys Rev Lett* 104: 8–12
11. Ko FK, Jovicic J (2004) Modeling of mechanical properties and structural design of spider web. *Biomacromolecules* 5: 780–785.
12. Li M, Wang P, Boussu F, et al. (2020) A review on the mechanical performance of three-dimensional warp interlock woven fabrics as reinforcement in composites. *J Ind Text* 2020: 1–50.
13. Gonzalez-Jimenez A, Manes A, Beligni A, et al. (2019) Modelling and experimental testing of thick CFRP composites subjected to low velocity impacts. *Procedia Struct Integr* 24: 101–109.
14. Nguyen D, Abdullah, MSB, Khawarizmi R, et al. (2020) The effect of fiber orientation on tool wear in edge-trimming of carbon fiber reinforced plastics (CFRP) laminates. *Wear* 450–451.
15. Eisoldt L, Smith A, Scheibel T (2011) Decoding the secrets of spider silk. *Mater Today*14: 80–86.
16. Jeevanandam J, Barhoum A, Chan YS, et al. (2018) Review on nanoparticles and nanostructured materials: History, sources, toxicity and regulations. *Beilstein J Nanotechnol* 9: 1050–1074.
17. De Luca A, Caputo F (2017) A review on analytical failure criteria for composite materials. *AIMS Mater Sci* 4: 1165–1185.

18. Ramesh M, Palanikumar K, Reddy KH (2016) Influence of fiber orientation and fiber content on properties of sisal–jute–glass fiber-reinforced polyester composites. *J Appl Polym Sci* 133: 42968.
19. Ghazlan A, Ngo T, Tan P, et al. (2021) Inspiration from nature's body armours—A review of biological and bioinspired composites. *Compos Part B-Eng* 205: 108513.
20. Abtew MA, Boussu F, Bruniaux P, et al. (2019) Ballistic impact mechanisms—A review on textiles and fibre-reinforced composites impact responses. *Compos Struct* 223: 110966.
21. Rafiee M, Abidnejad R, Ranta A, et al. (2021) Exploring the possibilities of FDM filaments comprising natural fiber-reinforced bio-composites for additive manufacturing. *AIMS Mater Sci* 8: 524–537.
22. Dahesh MB, Asayesh A, Jeddi AAA (2020) The effect of fabric structure on the bursting characteristics of warp-knitted surgical mesh. *J Text Inst* 111: 1346–1353.
23. Tripathi P, Gupta VK, Dixit A, et al. (2018) Development and characterization of low cost jute, bagasse and glass fiber reinforced advanced hybrid epoxy composites. *AIMS Mater Sci* 5: 320–337.
24. Mulenga TK, Ude AU, Vivekanandhan C (2020) Concise review on the mechanical characteristics of hybrid natural fibers with filler content. *AIMS Mater Sci* 7: 650–664.
25. Bolarinwa EO, Olatunbosun OA (2004) Finite element simulation of the tyre burst test. *P I Mech Eng D-J Aut* 218: 1251–1258.
26. Sitotaw DB (2017) An investigation on the dependency of bursting strength of knitted fabrics on knit structures. *Ind Eng Manag* 6: 1000221.
27. Greb C, Lenz C, Lengersdorf M, et al. (2018) Fabrics for reinforcement of engineering composites, In: Miao M, *Engineering of High-Performance Textiles*, 1 Ed., Cambridge: Woodhead publishing, 489–512.
28. Pant S, Jain R (2014) Comfort and mechanical properties of cotton and cotton blended knitted khadi fabrics. *Stud Home Comm Sci* 8: 69–74.
29. Lou CW, Lu PC, Hu JJ, et al. (2016) Effects of yarn types and fabric types on the compliance and bursting strength of vascular grafts. *J Mech Behav Biomed Mater* 59: 474–483.
30. Chen X, Yang D (2010) Use of 3D angle-interlock woven fabric for seamless female body armor: Part 1: Ballistic evaluation. *Text Res J* 80: 1581–1588.
31. Park JL, Chi YS, Kang TJ (2013) Ballistic performance of hybrid panels composed of unidirectional/woven fabrics. *Text Res J* 83: 471–486.
32. Boussu F, Cristian I, Nauman S (2015) General definition of 3D warp interlock fabric architecture. *Compos Part B-Eng* 81: 171–188.
33. Nikbakt S, Kamarian S, Shakeri, M (2018) A review on optimization of composite structures Part I : Laminated composites. *Compos Struct* 195: 158–185.
34. Rabbi MF, Chalivendra V, Kim Y (2018) Dynamic constitutive response of novel auxetic Kevlar®/epoxy composites. *Compos Struct* 195: 1–13.
35. ASTM D3786/D3786M-18, Standard Test Method for Bursting Strength of Textile Fabrics—Diaphragm Bursting Strength Tester Method. ASTM International, 2018. Available from: https://www.astm.org/Standards/D3786.htm.
36. Regassa Y, Lemu HG, Sirabizuh B, et al. (2021) Studies on the geometrical design of spider webs for reinforced composite structures. *J Compos Sci* 5: 57.

37. Taylor A (2009) Digital embroidery techniques for smart clothing, In: McCann J, Bryson D, *Smart Clothes and Wearable Technology*, Cambridge: Woodhead publishing, 279–299.
38. Zhou H, Xiao X, Qian K, et al. (2020) Numerical simulation and experimental study of the bursting performance of triaxial woven fabric and its reinforced rubber composites. *Text Res J* 90: 561–571.
39. Özdemir H, Mert E (2013) The effects of fabric structural parameters on the tensile, bursting, and impact strengths of cellular woven fabrics. *J Text Inst* 104: 330–338.
40. Elmogahzy Y (2019) Structure and mechanics of yarns, In: Schwartz P, *Structure and Mechanics of Textile Fibre Assemblies*, 2 Eds., Cambridge: Woodhead publishing, 1–25.
41. Sanal I, Zihnioglu NÖ (2013) To what extent does the fiber orientation affect mechanical performance? *Constr Build Mater* 44: 671–681.
42. Chen X, Yang D (2010) Use of 3D angle-interlock woven fabric for seamless female body armor: Part 1: Ballistic evaluation. *Text Res J* 80: 1581–1588.