Weave Structure and Fabric Properties

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Fabric structures are created by interlacing yarns or intermeshing loops to create two-dimensional (2D) flexible materials. The most prevalent structure is woven fabrics, which are made up of two sets of perpendicular yarns that are crossed and interwoven to form a coherent and stable structure.

Keywords: woven fabric ; weave structure ; fabric properties

1. Introduction

There are seven main parameters that are used to evaluate the woven fabric, including the warp and weft count, the warp and weft raw materials, the warp and weft setting, and the type of weave. These parameters have a significant influence on the structure of the woven fabric. The evaluation of weave and fabric properties, such as air permeability, strength, elongation, etc., was studied by various authors [1][2][3][4]. According to previous studies, fabric properties are influenced by the structure of the woven fabric. Numerous studies have been conducted on the influence of weave structure on various properties and qualities of woven fabric [4][5]. It is widely known that majority of the mechanical properties of the woven fabric are influenced by the structure of the weave, which could be described by the Fabric Firmness Factor (φ), a measure that considers both the weave and the setting [5]. Similarly, air permeability is one of the most essential qualities of clothing in terms of the comfort it provides. Air permeability is an inherent attribute of fabrics that is determined by their structure and is directly proportional to the density of the weft and warp in a woven fabric. Experiments reveal that the fabric firmness factor can be used to evaluate the fabric structure throughout the weaving process, as well as some fabric properties. The results of the research reveal that the fabric firmness factor can be used to compare woven fabrics with different structural parameters [6].

Fabric structures are created by interlacing yarns or intermeshing loops to create two-dimensional (2D) flexible materials [7]. The most prevalent structure is woven fabrics, which are made up of two sets of perpendicular yarns that are crossed and interwoven to form a coherent and stable structure [8]. The ability of a fabric to provide the properties required for an end use determines its engineering potential [7][9]. Fundamental structural elements of woven fabrics consist of several terms used as: yarn count, thread density, areal density, weave repeat, weave factor, float, crimp, fabric specific volume, fabric packing factor, etc. [8][10]. Many of the structural features listed here are particularly useful in characterizing various crucial fabric properties, such as air permeability, moisture vapor permeability, protection (e.g., UV protection), transparency, etc. [8][10].

The authors have investigated the impact of spinning processes (ring spun (combed, carded) and open-end (OE)), and weave design (plain, twill, and satin) on the mechanical and surface properties of fabrics. The authors reported that the increased interlacing of the yarn causes greater crimp in the load carrying, resulting in poorer breaking strength. Fabrics woven with combed ring spun yarns exhibited higher tensile strength and elongation than those woven with carded ring yarns or OE yarns. Plain weave design also shows lower strength and elongation compared to twill and satin weave. Due to rubbing exposure of the float length with the abradant in twill and satin weave, the effects are contrary in the warp-wise and weft-wise directions. In plain weave, however, the interlacing is identical in both the warp and weft directions, so it has no effect [11].

Even though a few isolated research has been conducted in the past to link the weave structure to the mechanical characteristics of woven fabrics, they were lacking in detail and did not offer relevant insights. Researchers' comprehension of fabric structure has increased with the addition of factors like the Floating Yarn Factor (FYF) and the Crossing over Firmness Factor (CFF), as suggested by Matsudaira [12]. The Fabric Firmness Factor (FFF), proposed by Milasius [5], is a parameter that considers both weave and sett. However, fabric sett is not taken into account by Matsudaira’s specifications that is also identified by Milasius. Such drawbacks were also admitted by Matsudaira and agreed for further studies on this. Milasius took the main parameters of fabric structure into account when he proposed integrated factors of fabric structure. The weave factor has been shown to alter a number of fabric properties, including weaveability [13], beat up force [14], fabric breaking force, elongation at break [15], fabric breakage, and the relationship [16] between the raw material [17] used and the fabric structure factor [6].

V. Sankaran and V. Subramaniam investigated the effect of weave structures on the mechanical properties of fabrics [18]. The authors also agreed, based on their findings, that Milasius' method of expressing fabric structure is preferable and possible to quantify the fabric properties. The study claimed a positive correlation between CFF and bending and shear properties; similar for FYF and mechanical properties. Shear rigidity decreases if the float length increases, and conversely, for CFF. The study further claimed that the bending and shear parameters can only be predicted with the weave structures [18].

2. Weave Structure and Properties of Woven Fabric

2.1. Physical and Mechanical Properties

2.1.1. Physical and Mechanical Properties of Woven Fabric

Tensile, bending, shear, buckling, and compression are just a few of the mechanical properties that influence fabric performance in a variety of applications [19]. The mechanical properties of the fabric are greatly influenced by the fiber or yarn components. Fiber morphology, such as orientations, crystallinity, and amorphous regions, is a critical component in determining fiber properties, including strength, extensibility, stiffness, and so on. Similarly, twist, fiber length, and fiber orientation all have an impact on yarn properties, which, in turn, has an impact on fabric performance. The relative value of any of these properties is determined solely by the application's demand. When a fabric is used in a tensile structure, for example, strength is necessary, while moisture or liquid transmission is crucial for a fabric used in sports clothing [20].

As woven fabrics are easily bent and stretched, as well as heterogeneous, even at low stress and room temperature, they are highly anisotropic, non-linear, and plastic; they differ significantly from typical engineering materials. They have distinct qualities, such as the ability to accommodate movement and the ability to weave intricate patterns that meet the wearer's aesthetic criteria. The previous study of woven fabric mechanics goes back to early studies published in the German aerodynamic literature by Haas in 1912, at a period when the construction of airships sparked worldwide attention [21][22].

Previous researchers investigated the shear behavior of plain, basket, and satin cotton polyester blended fabrics. They discovered that the length of the yarn float and the twist of the yarn had a substantial impact on the shear behavior. Most of the mechanical properties of the woven fabric are influenced by the structure of the weave, as is widely known [23]. Wang et al. developed equations to predict the shear rigidity of short-float worsted fabrics based on simple fabric structural data [24]. Recently, Alam et al. developed a mathematical model to predict the shear rigidity of woven fabrics [25]. The study determined the highest shear rigidity in plain woven fabric after 2/1 twill woven fabrics. The authors reported almost the same shear rigidity on other weaves as 3/1 twill, 2/2 twill, 2/2 matt, and 5-end satin.

V. Sankaran and V. Subramaniam [18] demonstrated the impact of weave structures on low-stress mechanical properties using the crossing over firmness factor (CFF), floating yarn factor, fabric firmness factor (FFF), and their correlation. Among the two fabric groups used in their study, an excellent correlation was found between shear, crease recovery, tensile, and air permeability; however, a poor correlation was recorded between hand value and parameters. In addition, an excellent correlation between CFF and FFF is also established. Furthermore, the highest FFF was reported with a pick density of 173.2 compared to 126. Therefore, it was concluded that the method of Milašius' [5] was recommended to quantify the properties of the fabric [18].

Material buckling is an important issue in current textile applications. Due to developments in new materials and changes in their behavior under buckling stresses, the examination of buckling of diverse materials has been ongoing since 1757, when the Leonhard–Euler solution was proposed. In a variety of uses, the buckling of a fabric dictates its behavior under load. It has been discovered that a fabric's drape is determined by the forces operating on its ability to buckle the fabric in its plane [26][27].

The buckling properties of a woven fabric also influence the quality and stitching of the garment, which is becoming increasingly essential as robotized sewing operations become more common [28]. The authors of an earlier study focused on a quantitative comparison of the buckling of existing and new flexible textile materials, regardless of their composition, using an empirical technique. The study also demonstrated the correlation of the buckling coefficient with Young's modulus of the fabric, the flexural rigidity of the fabric, and the design of the fabric weave. The methods in the study included segments of the fabric buckling test, fabric modulus of elasticity, fabric bending rigidity on various weave structures, materials, and fabric specifications. The buckling characteristics of the woven fabric with and without holes were also investigated. The author also indicates that the angle of the twill line to the direction of the buckling force has a major impact on the structure of the twill. It has been established that fabric bending rigidity, fabric design, and hole volume to sample volume ratio are three key types of deformation in buckling of fabric with holes. According to the findings, the interlacement of warp and weft yarns is represented by the twill line. The fabric will stiffen in that direction due to the presence of the twill line. As a result, when the angle of the twill coincides with the direction of the buckling force, the buckling force of the fabric is highest and, when it is perpendicular to it, the buckling force of the fabric is smallest [27]. Unfortunately, the authors did not analyze the direct influence of some kind of weave factor on the present properties, although the influence of weave is evident.

2.1.2. Role of Weaves in Fabric Engineering

Fabric engineering plays an important role in all fabric design, but it is especially important in industrial fabric design, and it has to be concerned with every area of the fabric structure. The weave does not affect all fabric properties equally. The strength of the yarn determines the tensile strength in either the warp or weft direction in the fabrics, while the weave contributes only a small role. The weave has a large influence on other properties, such as tearing strength and bending length (stiffness). Taylor [29] and others have looked at the effect of weave on fabric properties, but almost all of the published research has focused on a small number of traditional weaves as plain, 2/2 and 3/1 twill, 5-shaft satin, etc. The study by another researcher also examined, through experimental findings, that weave has a very significant effect on both tearing strength and stiffness in fabrics woven according to a specific design [30].

The sett and construction of the woven fabrics are known to influence their tensile performance. Fabric structure, particularly the interlacement pattern and its distribution, are essential factors in woven fabrics, and a tool that can forecast changes in attributes as a result of a change in design should be valuable in woven fabric engineering. Peirce established geometric correlations between yarn spacing, yarn diameter, modular length, and weave angle as a way of understanding the behavior of a woven fabric in various forms of deformation [3]. According to the authors, the amounts of loads carried by interlacing yarns, their spacing and interlacement pattern, the crimp of the constituent yarns and their interchange throughout the tensile deformation process are the elements that influence the tensile properties of fabrics [31].

Other authors determined the relationship between fabric structure and weavability, taking into account weave factors, integrated fabric structure factors, and maximum weft setting. The findings showed that Brierley's group factors better reflect fabric weavability than Peirce's group factors and are a more precise and practical indicator for various fabric weaves [13].

2.1.3. Fabric Structural Factor and Tensile Properties of Fabric

The mechanical properties and strength of the woven fabric are influenced by various factors such as the strength of the yarn, the setting of the fabric, and the function of the coefficient of strength of the yarn. It has been proven that when the strength of the yarn increases, so does the strength of the fabric [32]. The strength of the tear and the rigidity of the bending were also evaluated by earlier researchers [24][33].

The interrelationships between fabric structure and its strength were analyzed in a paper [34]. It is evident from the findings that there is no relationship between the breaking force and the weave factor of the woven fabric. Although the elongation at the break depends on the weave of the woven fabric, the elongation at the break increases as the rigidity (φ) of the woven fabric increases. This may be due to the higher crimp in yarn generated from the rigid weave structure of the fabric and that eventually resulted in a higher elongation. The author further illustrated that the loss of breaking force caused by increasing the weft setting and at the same time the elongation at break escalated [34]. Further studies focus on investigating the physical properties of plain and diced fabrics by means of bursting strength, breaking strength, elongation at break, and impact strength. Diced woven fabrics were reported to have higher bursting and impact strengths than plain woven fabrics, but plain-woven fabrics had higher breaking strengths in both the warp and weft directions. Furthermore, the physical properties of the diced woven fabrics improved as the yarn densities increased [35].

Nikolic et al. have studied the tensile properties of woven fabric [32]. The authors suggested looking at the strength of woven fabrics as a function of thread strength, fabric density, and thread strength coefficient. It was discovered that as the strength of the thread grows, so does the strength of the woven fabric. The authors claimed that plain weave is the strongest among the twill and satin weaves used during their research, however, the tearing strength was lower as reported [36]. The study also reported higher stiffness, abrasion, and pilling resistance in plain weave than the other two weaves. Another study emphasizes the influence of the structure of the woven fabric (weave factor P_1) on its breaking force and elongation at the break. It was revealed that the fabric weave factor and the breaking strength of the woven fabrics are not related. Consequently, if the rigidity of the weave decreases, the elongation at break also decreases as the coefficient of weave increases [15].

A recent study also investigated the influence of weave design on the tensile properties of woven fabrics using polyester-cotton (50:50) plain, twill, and satin weave designed fabrics. These fabrics were made of various types of yarn, such as combed, carded, and OE (open end) in the weft, while warp parameters were kept constant with compact cotton ring spun yarn for all weave designs [11]. The study determined the higher tensile strength and elongation in the weft direction using combed yarn compared to other fabrics. However, for all weave-designed fabrics with OE yarns, this resulted in lower tensile strength and elongation than for ring-spun fabrics.

Furthermore, a lower tensile strength was reported in plain woven fabrics than in twill and satin weaves [37]. This may be due to a greater effect of contact friction, crimp, and binding on plain weave than on twill and satin weaves. These parameters create additional bending and weak points on tensile loads, and hence the plain weave structure results in lower tensile strength than the other two weaves [38]. However, the same study reported a higher elongation in plain weave than in satin and twill weaves. This could be due to the higher interlacement and the crimps that exist in the plain weave structure [38].

2.1.4. Weave Parameters and Tear Strength

R. Milašius et al. determined the weave parameters proposed by earlier researchers and their influence on the tear strength of woven fabrics. For the study, weave parameters, such as Brierley's factor F^m [39], Milašius' factor P [4][40], and P' [41], were used; however, the authors further modified the parameter P as P_{weft} for their work. In their study, two fabric groups were investigated, the rib-based group and the twill-based group. The study illustrated the influence of weave parameters on tear strength. The coefficient of determination (R^2) was found to be high and indicates the precision of the prediction of the strength of the tear. According to the modified parameter P'_{weft}, the determination coefficient obtained was higher than P'. The authors confirmed the correlation of Brierley's parameter F^m, as well as parameter P' and the prediction of tear strength; however, for the rib-based weave group, it is recommended to calculate parameter P' by altering the influence of the parameters P_1 and P_2 [42].

Vimal et al. investigated the effect of weave factor and weave parameters on cotton woven fabrics. Based on weave factors such as the crossing of firmness factor (CFF), floating yarn factor (FYF), fabric firmness factor (FFF) and weave factor (P_1), the tear strength of 11 cotton woven fabrics is investigated [43]. The methods applied by the authors included the determination of the weave factor calculated by the previous method [41], fabric processing, porosity measurement, thickness and areal density measurement, and tear strength measurement. The author reported a significant correlation of weave factor (P_1) [5] and weave parameters (CFF, FYF, FFF) with fabric tear strength in both the warp and weft directions of the fabric. The author further reported that the number of floats (FYF) [44] in the fabric is positively correlated with the weave factor (P_1) and in addition the weave factor (P_1) has also positively correlated with tear strength in both warp and weft directions. In contrast, while FFF increases, the tear strength drops [43].

Researchers investigated the tear damage of two plain and two twill-woven fabrics by experiments and the finite element analysis method. The authors reported significantly higher tearing strength of 1/2 twill than that of plain-woven fabric. The technical reason for this difference is due to the longer floats of 1/2 twill-woven fabric, which create lower friction resistance for weft yarns to be pulled from warp yarns. Similarly, compared to weft yarns, a high warp density comprises more interlacing points, resulting in stronger friction resistance. On the contrary, weft density has little effect on the tearing strength of woven fabrics [45].

A comparative study of tear strength methods was conducted by B. Witkowska and I. Frydrych. The study focused on the problems of tear strength, measurement methods, and the correlation between the findings of different tear test methods, such as static and dynamic tearing applied to protective textiles. A set of five fabrics was investigated by applying six methods and comparing the results of the tensile and tear tests. According to the findings reported by the authors, no correlation was found between the measurements [33].

The influence of woven fabric on the strength of the tear in the warp and weft directions was analyzed in the previous study. The longer the yarn floats in the weave design, the greater the tearing force, according to the study. This is possibly due to the applied force, the threads are free to move and will be close to each other, resulting in an increase in the number of threads sharing the load in the direction of tear, resulting in a higher tearing resistance. Alternatively, the tighter the structure, the less freedom to slide the yarn and the less resistance to tear the yarn [46].

The mobility of the yarns within the fabric structure also determines the tear strength of the fabric. Due to loss of movement, the plain fabric had poor tearing strength. The fabric's tearing strength is influenced by the weave pattern, which controls the number of yarn crossing spots. This has a direct impact on the fabric's ability to bend and on the quantity of yarns that break apart. As reported by the authors, due to the variation in construction, rib fabrics have stronger tear resistance than plain weave fabrics because two yarns work together to resist tear [47].

2.2. Comfort Related Properties

2.2.1. Weave Structure and Thermal Properties

Thermal comfort, which is defined as a sense of contentment with the thermal conditions of the environment, is closely related to physiological comfort [48][49][50]. Thermal insulation is directly influenced by the type and structure of the fabrics. The thermal resistance of the fabrics, the resistance to water-vapor, and the permeability of the air are all important comfort attributes [51][52][53][54].

Clothing that provides thermal insulation is critical because it acts as a barrier between humans and their surroundings. The effect of clothing on a person's comfort is a complicated phenomenon influenced by the material and structure of the garment [51]. During heat convection, the authors studied the air permeability and thermal resistance of the textile. The heat resistance of the textiles was evaluated using a newly created instrument. It has been demonstrated that as the pore size and the ratio of the pore area to the total fabric area increases, air permeability increases, while thermal resistance decreases.

Several research studies on thermal resistance were conducted and thus published [55][56][57][58][59][60][61]. It has been reported that the porosity and thickness of the fabrics influence the thermal resistance. Thermal conductivity and thermal resistance have a positive relationship with porosity. If the porosity of a fabric is higher, it can allow more air to enter the environment. The thermal resistance of the fabric is likely to be reduced as a result of this [62].

The porous nature of the samples has a predominance of low enclosed air conductivities, and fabric conductivity is essentially consistent for fabrics of various thicknesses. Therefore, the heat insulation is proportional to the thickness of the fabric. Zhu et al. [63] pointed out that both porosity and thickness affect heat resistance. Although porosity and thickness were shown to be highly associated with thermal conductivity, no association was found between weave parameters and thermal conductivity. Studies reported that plain fabric had the lowest thermal resistance, whereas 8-thread Brighten honeycomb fabric had the highest thermal conductivity and had been collectively influenced by weave structures. This is due to the lower porosity and thickness of the plain fabric compared to other weaves [62]. This contradicts Matusiak and Sikorski's findings [64].

Other researchers also claimed higher thermal conductivity and thermal absorptivity and lower thermal resistance of plain fabrics than twill 3/1 S, twill 2/2S, rep 2/2 (2), rep 1/1 (0,1,0) and hopsack 2/2 (0,2,0) weaves with identical warp and weft thread specifications. The thermal properties of woven fabrics are greatly influenced by the weave and the linear density of the weft yarn, according to statistical investigation [64]. Similar findings on plain fabrics were also reported in a recent study [65]. The study claimed that the plain-woven fabric showed the highest thermal conductivity and the lowest thermal resistance, whereas the hopsack 2/2 (4) woven fabric resulted exactly in reverse as the lowest thermal conductivity and the highest thermal resistance.

2.3. Special Application Properties

2.3.1. Weave Structure and Ballistic Effects

Body armor [66], fan blade containment systems [67], and orbital debris protection [68] use high-performance ballistic textiles [69][70]. Aramids (such as Kevlar) [71] and ultrahigh molecular weight polyethylene (UHMWPE, such as Spectra) [72] are the most effective material types in terms of protection per unit mass. Several authors [73][74][75][76][77] have emphasized the relevance of fabric geometry and several studies give test results to support their claims. The effects of 1.1 g fragments replicating bullets on targets was reported by Figucia [77]. The V_{50} of the satin weave cloth was 4% higher than that of the plain weave and 11% higher than that of the basket weave. As a result, the satin weave appears to function better. Chu and Chen's study [78] discusses the impact tests on a set of six Kevlar 29 fabrics, comprising one plain, one harness satin, two twill, and two basket weaves. Furthermore, it should be noted that the authors found that a 2 × 2 basket weave worked well in their tests, with around 8.4 yarns that span the diameter of the projectile due to the combination of the diameter of the projectile and the count of yarns [79].

Another study investigated the ballistic performance of four types of weaves, plain, twill, basket, and HS4 (harness satin 4 weave). According to the reported findings, the harness satin weave and plain weave materials have the best ballistic performance, while the basket weave fabrics have the poorest and the twill weaves fall somewhere in the middle. Moreover, the best performance was achieved in a harness satin weave fabric consisting of Spectra 900 [80].

Three different woven structures (plain, twill, and satin) with identical yarn and fabric settings were used to investigate the impact of the weave structure and the variation in their associated energy absorption mechanisms for ballistic impact. According to the findings, plain weave provided the best resistance to bullet projectile among the three fabric structures [81].

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