Article:

Sanad, RA and Cassidy, T (2016) Fabric Objective Measurement and Drape. Textile Progress, 47 (4). pp. 317-406. ISSN 0040-5167

https://doi.org/10.1080/00405167.2015.1117243

Contents

Fabric Objective and Drape Measurement ... 1
Abstract ... 1
Keywords ... 1
1 Introduction ... 2
1.1 Fabric Objective Measurement ... 2
1.1.1 Fabric construction ... 3
1.1.2 Weight ... 4
1.1.3 Cover factor ... 5
1.2 Mechanical properties ... 5
1.2.1 Compression ... 5
1.2.1.1 Thickness ... 5
1.2.1.2 Hardness ... 6
1.2.1.3 Compression modulus ... 6
1.2.1.4 Density ... 6
1.2.2 Tensile ... 6
1.2.3 Shear ... 7
1.2.4 Rigidity ... 7
1.2.4.1 Measurement of deformation ... 7
1.2.4.1.1 The cantilever test ... 7
1.2.4.1.1.1 Shirley stiffness tester ... 9
1.2.4.1.1.2 FAST 2 (bending meter) ... 10
1.2.4.1.1.3 Russell test ... 10
1.2.4.1.2 Hanging loop tests ... 11
1.2.4.1.3 Bending loop test ... 12
1.2.4.1.4 Cassidy *et al.* Bending box ... 13
1.2.4.1.5 Cassidy Instron test for bending ... 13
1.2.4.1.6 Planoflex ... 13
1.2.4.1.7 Ordinary beam test ... 14
1.2.4.1.8 Hanging strip ... 14
1.2.4.2 Measurement of deforming force ... 14
1.2.4.2.1 Gurley stiffness tester ... 14
1.2.4.2.2 Schiefer Flexometer ... 15
1.2.4.2.3 Munzinger Impact test ... 16
1.2.4.2.4 Searle pendulum test ... 16

1.2.4.2.5 Twisting rigidity 16

1.2.4.3 Relationship between methods of measuring fabric stiffness 16

1.2.5 Bending modulus 20

1.2.6 Friction 20

1.2.7 Buckling 21

1.2.8 Torsion 2122

1.3 FOM systems 22

1.3.1 Kawabata evaluation system of fabrics (KES-F) 22

1.3.1.1 Shear test (KES-FB-1) 23

1.3.1.2 Tensile test (KES-FB-1) 24

1.3.1.3 Bending test (KES-FB2) 25

1.3.1.4 Compression test (KES-FB-3) 27

1.3.1.5 Surface Friction and Roughness tests (KES-FB-4) 28

1.3.2 Fabric assurance by simple testing (FAST) 31

1.3.2.1 FAST 1: Compression meter 31

1.3.2.2 FAST 2: Bending meter 31

1.3.2.3 FAST 3: Extension meter 32

1.3.2.4 FAST 4: Dimensional stability test 32

1.4 Fabric Subjective evaluation 32

1.4.1 Training of assessors 33

1.4.2 Number of assessors 33

1.4.3 Assessment procedure 33

1.4.4 Assessment scale and rating technique 33

1.5 Summary of Fabric Objective Measurement 34

2 Evaluation of Fabric Drape 36

2.1 Objective Evaluation of Fabric Drape 37

2.1.1 The Development of Drapemeters 37

2.1.2 Static drape testers 3738

2.1.3 Integrated drapemeters 43

2.1.4 Image analysis 44

2.1.5 Photovoltaic drapemeters 45

2.2 Dynamic drapemeter 46

2.3 Alternative Drapemeter Designs 50

2.4 Drape coefficients (DC) 54

2.5 Static drape profile/image analysis 55
2.6 Fourier analysis 60
2.7 Standard Drape Values 61
2.7.1 Measurement of number of nodes objectively 61
2.7.2 Dynamic drape parameters 62
2.7.3 Garment drape parameters 63
2.7.4 Summary of Fabric Drape Measurement Methods 64
3 Factors Affecting Fabric Drape 67
3.1 Fabric Composition and Structures 67
3.2 Fabric Mechanical Properties 70
3.3 Fabric Finishing 73
3.4 Effect of test procedure on stability of drape values 7576
3.4.1 Supporting-disc size 77
3.4.2 Test Duration 77
4 Garment Drape 80
4.1 Fabric Drape versus Garment Drape 80
4.2 Grain Alignment 81
4.3 Interfacings 82
4.4 Seams 83
4.4.1 Seam Addition 83
4.4.2 Seam Allowance (SA) 84
4.4.3 5.4.3 Drape Coefficient 84
4.4.4 5.4.4 Drape Profile (DP) 85
4.4.5 Seam Position 85
4.4.6 Seam Direction 85
4.4.7 Seam Number (SN) 86
4.4.8 Seam Type 8788
4.5 Girth Ease Allowance 88
4.6 Deformation in Garment Drape 8889
4.6.1 Effects of Fabric Distortion on Garment Drape 8889
4.6.2 Effects of Fabric Skew on Garment Drape 89
4.6.3 Effects of Asymmetrical Body Features 89
4.6.4 Effects of Pattern Layout and Production Markers 90
4.6.5 Effects of Sewing Operations 90
4.6.6 Effects of Unbalanced Seams 90

5 Subjective Assessment of Drape 91
6 Prediction of Drape Coefficient 95
7 Drape Simulation 100
8 Priorities for Future Research 102
9 References 103

Fabric Objective and Drape Measurement

Reham Abdelbaset Sanad[1] and Tom Cassidy[2]

[1] Department of textiles dyeing, finishing and printing, Faculty of Applied Arts, Damietta University, Egypt.

[2]School of Design, University of Leeds, UK.

Commented [R1]: Good detailed account of terms tests and processes, however this would benefit from more critical reflection on these, their merits and disadvantages.

Abstract

This Textile Progress is a review of the generally accepted origin of fabric objective measurement research through its development and current use in research and industry. It then goes on to look in greater detail at the use of FOM methods for the measurement and prediction of fabric drape. This has become increasingly important in recent times due to the push from the fashion industry for accurate 3D simulation and animation of apparel in its various forms. This would allow fashion designers to visually prototype their garment creations without the tedious and time consuming real garment prototyping stages which are required at this time. The demand for accurate 3D simulation and animation is occurring in the face of the ever increasing variety of fabric types which means that the drape measurement methods must be more sensitive and more widely applicable. The authors, having carried out this review and in the light of their own research, offer the view that the measurement of fabric objective measurement and drape is unlikely to provide the accuracy and wide applicability required. Fabric is not draped or supported horizontally in a garment.

Keywords

Fabric Drape, Garment Drape, Drapeability, Drapemeter, Appearance, Objective assessment, Subjective assessment, Quantitative analysis, Dynamic drape, Static drape, Drape prediction, Virtual 3-D drape simulation

1 Introduction

1.1 Fabric Objective Measurement

FOM is defined as "The evaluation of fabric handle, quality, and related fabric-performance attributes, in terms of objectively measurable properties" [1]. FOM systems are a set of instruments used to measure a combination of fabric surface and mechanical properties. The measurements provide a means of comparing fabrics in terms of their handle, performance and behaviour.

Commented [R2]: Direct reference for this definition? Is it combined from multiple sources?

Commented [R3]: Possibly add why FOM here: i.e. These measurements provide the means to compare fabrics to determine performance and behaviour.

FOM systems are essential for the reproduction of already existing or pre-identified fabrics and/or selecting the most suitable which is becoming more difficult because of the wide variety of fabrics available. Ever increasing product development activities across the textile and fashion industries means that we are faced with new and finer fibres. New types and varying linear densities of yarns, New fabric structures and new coloration and finishing techniques all of which (and many other factors) effect fabric mechanical properties. Based on this, fabric objective measurement is used to: help engineer fabric properties for desirable performance and quality, develop new finishes and finishing machinery and control the produced fabric to meet specific mechanical properties (from raw material to garment).

Commented [R4]: Is this about new processes, new fibres, mixed fibres? Further clarity here would be useful.

A globalised and reliable objective system of measurement should, for fabric properties, fulfil some financial and technical specifications. Its purchase price, setting, and maintenance expenses should meet the budget of as many manufacturers as possible. It should be safe and reliable electrically and mechanically, easy to run and use. The most important criterion for an FOM is its accuracy and reproducibility [1, 2].

Commented [R5]: Insert: for fabric properties

Apparel appearance including handle, drape, lustre, smoothness, roughness and stiffness have been measured subjectively using a panel of judges as reported in many of the references cited in this review. However, research studies claimed that these characteristics are related to fabric physical, mechanical and surface properties. These properties are able to be measured objectively using instruments. Whilst it is realised that it is important that there is good correlation between subjective and objective measurements the important difference between the methods is that the latter are more accurate, reproducible and lend their resultant values to higher levels of statistical analysis.

Commented [R6]: Does this relate to publications, should references be given or some further context provided?

Commented [R7]: It may be worth indicating here how relatable subjective and objective evaluations are and if any studies have been done to qualify this.

Different instruments are available for measuring these properties. The aim of textile researchers is to correlate these objectively measured properties such as bending and compression properties to subjectively assessed properties such as drape which is of growing importance and interest as researchers try to improve the accuracy of CAD simulation of garments and fabrics.

Commented [R8]: Why? Just needs a sentence to clarify.

1.1.1 Fabric construction

Woven and knitted fabric structures are conventionally used in apparel manufacture. Both of them have different structures and varied methods of production.

In the **Woven Fabric** category, plain, twill and satin weaves are the basic types of fabric construction.

1. The plain (or tabby) weave, is the simplest type of weaving. The fabrics produced have a smooth surface. Relative to fabrics with longer yarn float lengths, they exhibit lower tensile strength due to high yarn crimp in each interlacing; more wrinkle ability than other types and the lowest absorbency behaviour. The plain weave structure can be modified to make different types of weave such as ribbed, basket weave, or seersucker fabric [3].
2. In twill weaves, the most distinctive appearance is the diagonals on the surface, which looks like a series of steps. Twill fabrics can be woven closely because of the low number of entangled yarns. They have high tensile strength and abrasion resistance. Compared with plain weaves, they are softer, more flexible, give better drape behaviour, better wrinkle recovery, high resistance to stains and easy stain repellence. There is a texture dominant on the surface. The appearance of both twill fabric sides are similar due to the reverse of twill lines at the back[3].
3. Satin weave uses low twisted filament yarns. It is used in making dresses, linen, lingerie and draperies. This structure allows either the warp or weft yarns to pass over four or more of the other (sometimes 12). Satin fabrics have smooth appearance due to the long floats. The few entangled filament yarns with high thread counts allow them to be interlaced compactly, which causes the lustre or glossy appearance. Due to the threads long pass, they are capable of shredding and wearing easily by abrasion. Selecting high thread counts with appropriate fibres improves the endurance. Satin weave with high thread counts has good resistance to wind. Satin weave with a low thread count is more flexible and resistant to wrinkling but may have yarn slippage. Soil spreads easily due to its smooth surface. It is used as apparel lining due its easy sliding over other surfaces and because of its softness[3].

Knitted fabrics are formed by the implementation of manual or mechanical applications through the process of producing loops by one or more yarns with one needle or more. Fibre type, yarn properties, the method of production, needle specifications and the stitch size, formation and pattern affect the visual and mechanical properties of knitted fabrics [3, 4].

The gauge is one of the most important parameters in knitted fabric production. It is the number of needles per inch, which affects the number of stitches per inch square. It determines the fineness or density of the fabric, and the closeness and compactness of stitches.

Commented [R9]: Images would help here, examples of the knitted structures or reference to suitable example images in existing literature.

Commented [R10]: Use of bulleted or numbered lists, will help make these distinctions more explicit

Commented [R11]: All of which will impact on the fabrics properties, it may be worth reinforcing this.

There are two main fabric types weft knit and warp knit.

In weft knit, the loops are interlocked in the weft or crosswise direction. Each course is built on top of the other. The adjacent needles draw a yarn from the creel attached to the machine. They are operating independently to one another. All stitches per course are produced by one yarn. There are three categories in weft knit: Jersey, rib and purl. Double, interlock stitch and plain/single/jersey knit are variations of weft knit structures.

1. **Plain/single/Jersey knit** has a distinctive face and back. It is formed by interlocking stitches in the same direction on the face and a series of semicircular loops on the back. It stretches both length- and cross- wise directions out of shape. It has poor dimensional stability and curls at the selvedges. **Purl knit** is a double-faced fabric. It is formed from alternate rows of knit and purl stitches. They interlock as semicircular loops, in the crosswise direction. It has a bulky behaviour, stretches in both length and cross wise direction and does not curl at raw or cut edges. **Rib Knit** is a double-faced fabric with vertical ribs on both sides. It is produced from alternate plain and purl stitches, which interlock in opposite directions in the lengthwise direction. It stretches a little in the lengthwise direction, but has high extension and elasticity in the crosswise direction and does not curl at raw or cut edges [3, 4].
2. **Double knit** is a variation of the rib knit. Both sides have fine ribs in the lengthwise direction. The face and back has the same appearance. These types of fabrics are strong and durable. They are heavier and have more body than single jersey. They do not stretch or curl at cut edges. They have good stability and shape retention. **Interlock stitch knit** is characterised by fine ribs in the lengthwise direction on the face and back. It looks as if two separate 1×1 rib fabrics are interlocked in one fabric. **Weft knit variations** may be produced in jersey, purl or rib knit or by combining any or all of them [3, 4].

In warp knit, the loops are interlocked in the lengthwise direction. Parallel yarns are used to produce one stitch per course and every yarn makes one stitch per course. All stitches are produced in each course simultaneously by the movement of the needles (up) at the same time.

Milanese knit, Raschel knit, kettenraschel knit, tricot knit and weft insertion warp knit are different types of warp knitted structure [3, 4].

1.1.2 Weight

Fabric weight can be measured for unit area or length (running metre). In the first method, the weight of known area is measured. This method is easier for fabric description as the second needs explicit explanation because the weight of fabric length will be affected by its width as produced on the fabric formation machine. Fabric sampling, cutting, accuracy of weighing and conditioning must be considered. Error of area measurement and cutting should not exceed ±1% [5, 6].

Commented [R12]: Is this governed by a standard? Can these be mentioned here?

1.1.3 Cover factor

This is the extent to which an area of a fabric is covered by the yarns used. This could be measured in the warp and/or weft directions. High cover factor values produce stiff and low drape fabrics. However, yarn count, twist factor, fibre and other properties should also be considered [5].

1.2 Mechanical properties

1.2.1 Compression

1.2.1.1 Thickness

Fabric thickness is one of the most important factors affecting its warmth, heaviness and stiffness properties. Basically, fabric thickness is the distance between two plane parallel plates (presser foot and anvil) when they encompass the material tested which is subjected to a known pressure. In this test, the shape and size of both presser foot and anvil, applied pressure and velocity of presser foot are to be considered. The ratio of circular (usually) presser foot diameter to fabric thickness should not be less than 5:1. The circular anvil's diameter should be greater than the presser foot by at least 5 cm [7].

Using low pressure such as lower than 0.25 lb/in^2 in testing thickness produces values similar to human eye evaluation because of the minor compression at this level of pressure. Moreover, the presser foot should be lowered with slow velocity and carefully to ensure that readings are taken accurately at the various stages of compression. A clock-type gauge is used to read out the thickness measured on a tester, unless a digital tester is employed. This method of measurement is called a "Contact method" [5].

During pressure application, three stages for resistance to compression take place. First, the individual fibres protruding from the fabric surface are compressed, followed by inter-yarn and/or inter-fibre friction, then lateral compression of the fibres themselves. The second stage is more responsible for fabric handle. Soft fabrics have a faster transition between stages one and three.

A visual or non-contact method could be used as an alternative measurement of thickness. This method does not use physical contact with the fabric surface. In this method, optical instruments use different principles such as infra-red light or laser beam. A sample measured blocks a portion of the light projected. The intensity of this beam is used to measure fabric thickness. As most fabrics have loose fibres protruding above the surface, one of the major risks in this method is the determination of the surface start accurately which is operator dependant [7].

Commented [R13]: Why? It is important that the nature of these factors is made explicit and that their impact can be understood.

Commented [R14]: And their determination?

Commented [R15]: Some initial or preceding discussion of the relative merits and flaws of each method may be useful context here.

Commented [R16]: Why? To avoid compressing the fabric?

Commented [R17]: Is the interpretation of this is that fabrics with a soft feel transition faster between stages, or does it mean that fast transition leads to fabrics having a soft handle? It might be useful to make this explicit.

Commented [R18]: How would this work?

1.2.1.2 Hardness

This is a measurement of fabric resistance to compression. It is presented by the relation between thickness and pressure. This is calculated as the ratio of difference between two thicknesses measured at two different loads to the difference between loads (pressures) applied to the sample measured [8].

1.2.1.3 Compression modulus

Another measure of fabric compactness is the “Compression modulus”. This is calculated as the ratio of stress (difference in pressure) to strain (difference in thickness divided by the original thickness) which produces Young’s modulus. In other words, it is calculated from the “Hardness” multiplied by the thickness. It shows the degree of hard fabric surface irregularities [8].

1.2.1.4 Density

This is a third measure of fabric compactness. It is calculated as the area weight of fabric divided by the thickness. This is affected by gaps between yarns.

1.2.2 Tensile

Basically, a tensile test measures the fabric strength which is often considered as the main criterion of its quality. It is affected by different fabric features such as its construction and finish. Generally, conventional textiles have higher tensile strength than nonwovens (except in the case of parallel-laid nonwoven structures). Apparel fabrics need good strength properties to withstand stresses applied in use [2].

A tensile test involves the application of a load to a specimen (under constant rate of loading or extension) in its axial direction causing tension. This is expressed by gravitational units of force such as grams. The load used is pre-set according to the test condition and purpose. It could be conducted to measure fabric breaking length or breaking extension. The stress is the force applied to a material. The elongation is the increase in the sample length compared to its original length (they are proportional to each other). In other words it is the strain or percentage of extension. The elongation at the maximum load is an important tensile parameter as this reveals how far a fabric can be stretched [5].

A load-elongation curve can be partitioned into three significant stages for mechanisms taking place. These start with inter-fibre friction, also called the initial de-crimping region (producing initial high modulus), followed by de-crimping (relatively low modulus is obtained), then the yarn extension region [9].

The term “extensibility” was proposed for measuring fabric resistance to extension which affects the subjective judgment of handle. The initial slope of a tensile stress-strain curve obtained from testing a sample is used to compare handle and bending properties. The extensibility is expressed by the ratio of tensile stress to strain (Young's modulus) [8].

Commented [R19]: Some further clarity would be beneficial here. Does this approach use benchmark fabrics and gauge the sample against them or is it all carried out only with the sample?

Commented [R20]: Due to the structure reacting to the application of mechanical forces?

Commented [R21]: Should this be that fabrics with good strength usually withstand stresses in use better than lower strength fabrics, or something similar. What is ‘good’. Does it include the kind of pulling/tugging that takes place on a garment, eg during putting on a sweater, plus what kind of stresses occur during use….where and how? During care treatments?

Commented [R22]: Why? Explicit definition here will help the reader understand its importance. Examples of when the parameter becomes important will be helpful

Commented [R23]: These specialist terms would benefit from being defined.

1.2.3 Shear

In this test, a sample is subjected to a pair of equal and opposite stresses acting parallel to one side of the sample and its area remains constant. Shear is the rotation of the warp and weft yarns from their original position (changing of the angle between the vertical and horizontal yarns). The forces acting on a fabric are extension forces in one diagonal direction and compression in the other diagonal direction. If the fabric has no resistance to the rotation of the yarns, there will not be a resistance to elongation. Shear deformation of fabric determines its behaviour when it is subjected to complex deformation in use. This property may affect fabric appearance positively or negatively [9].

A shear stress-strain curve is plotted as a result of this test from which shear parameters are measured including initial shear modulus, shear modulus and shear hysteresis. The “shear modulus” is the ratio of shear stress to shear strain. The recovery percentage after stress release is an effective influence on fabric behaviour. The shear stiffness (rigidity) is the force required for shear deformation.

Fabrics’ looseness degree (level) would affect their cutting and sewing. Very loose fabric which has low shear rigidity might cause pattern distortion during cutting, while very rigid fabrics with high shear rigidity would be difficult to form into a three dimensional shape without unwanted buckling as well as making it difficult to match patterns on the fabric[10]. This property signifies fabric from thin sheet material such as paper. Cusick *et al.* tested the physical properties of some commercial nonwovens and determined higher shear moduli than woven fabrics [11].

1.2.4 Rigidity

Fabric rigidity is it’s ability to bend or flex under an applied force. It could be given by exerting bending or twisting forces on the tested specimen to obtain flexural rigidity or torsional rigidity respectively. Measurement methods of this property could be classified into two main categories in which either the deformation or the deforming force is measured.

1.2.4.1 Measurement of deformation

1.2.4.1.1 The cantilever test

In 1930, Peirce described an instrument called a “Flexometer” developed by the “British Cotton Industry Research Institution” to measure fabric stiffness (see Figure 1.1~~Figure 1.1~~). The instrument was based on the cantilever principle and is used to overhanging length and angle of deflection of a tested rectangular specimen. The bending length c (the length of the fabric that bends under its own weight to a definite extent) was calculated using Equation 1.1~~1.1~~.

$$c = l.f_1(\theta) \qquad 1.1$$

where:

l is the overhanging length of the tested material

$$f_1(\theta) = \sqrt[3]{\left(\frac{\cos 0.5\theta}{8 \tan \theta}\right)}$$

θ is the angle of deflection.

Fabric flexural rigidity is the external bending force required per unit fabric width to cause alteration to its curvature. This is calculated by multiplying the fabric weight by c^3.

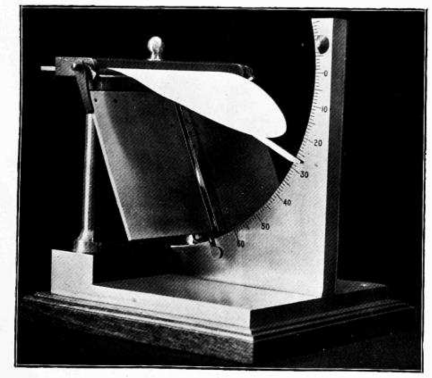


Figure 1.1Flexometer (reproduced from [8])

Peirce [8] mentioned that the difference between the face and back bending length, due to slight curl and/or twist which would take place in some fabrics due to their weave structure or the finishing strain, would be eliminated by averaging their bending length values. He stated that the bending length should be measured in both warp and weft directions but it is not important to measure it in the bias direction. The stiffness of the fabric is governed by the warp and weft directions' stiffness.

Commented [R24]: Reference?

Peirce tested a range of fabrics (around 50) with different stiffness behaviour. He reported that the measured mean bending length using the Flexometer (in standard conditions) ranged between 1.81 cm (for soft fabrics) and 6.35 cm (for stiff ones). This range increased to be between 1.6 to 8.5 cm by adjusting the overhang length and angle of deflection.

It is assumed that the tested sample is flat when unstressed and bends under its own weight to produce the angle of deflection. Although, some samples tend to curl or twist and others make 90° angle of deflection with the horizontal plane which causes difficulties in measuring the bending length using the original Flexometer. Therefore, some adaptations have been developed to the Flexometer and the measured samples to overcome their unsuitability to the original apparatus, for example a weight could be added to very stiff fabric, this test was called “weighted rectangle”, a large circular or square sample could be used to measure flimsy fabrics. The selection of the applied procedure is dependent on the level of fabric stiffness. Each method has its corresponding applied formula for calculating the bending length.

There are bending meters available based on the cantilever principle such as the Shirley stiffness tester and FAST 2 bending meter. However they have different methods for obtaining the bending length value. In these tests, a rectangular specimen is mounted on a horizontal platform in its length direction. This position of the sample enables it to overhang and bend under its own weight. The operator moves it forward until its tip reaches a plane which passes an angle of 41.5° from the horizontal plane. At this angle, the bending length is half the overhanging length (see Figure

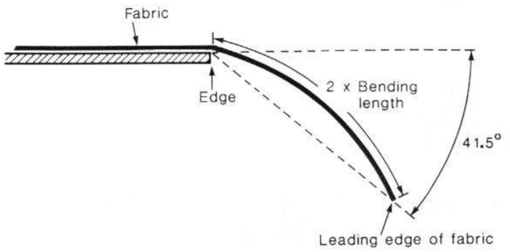


Figure 1.2 Schematic representation of the measurement of the bending length based on the cantilever principle(reproduced from **[10]**)

1.2.4.1.1.1 Shirley stiffness tester

Using this apparatus, the operator can calculate the bending length and flexural rigidity from the overhanging length of fabric. The bending length is the overhanging length divided by two; flexural rigidity is obtained from the bending length and the fabric mass.

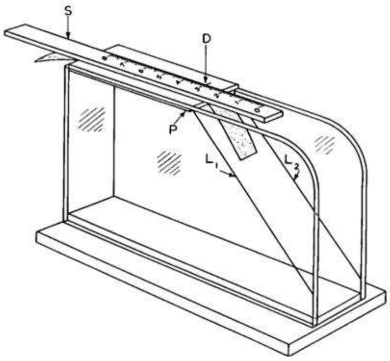


Figure 1.3 Shirley stiffness tester (reproduced from [12])

1.2.4.1.1.2 FAST 2 (bending meter)

The FAST 2 meter's principle for measuring bending length is the same as the previous manual-bending tester (Shirley) (Figure 1.4~~Figure 1.4~~). However, the shown on the display monitor directly.

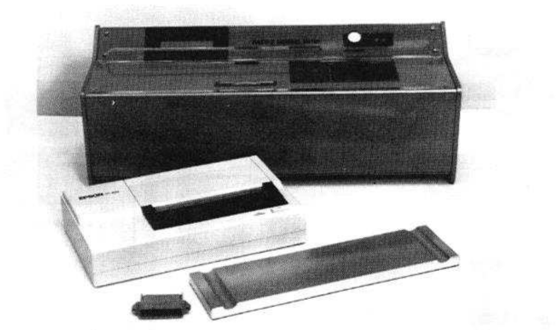


Figure 1.4 FAST 2 - bending meter (reproduced from [10]**)**

1.2.4.1.1.3 Russell test

Russell[13] developed an alternative method of measuring the fabric cantilever bending length. This method was adapted for testing slippery and easily-deformed fabrics as they would be cockled when measured using Shirley or FAST testers due to sliding a support body over the fabric. A Comb Sorter apparatus used for the measurement of fibre length distribution was adjusted for laying the strip tested on its faller bar (A) in Figure 1.5~~Figure 1.5~~. To measure the fabric bending length, the faller lowered until its tip intersects with a plane making 41.5° with the horizontal plane and the overhanging length is read from the scale F.

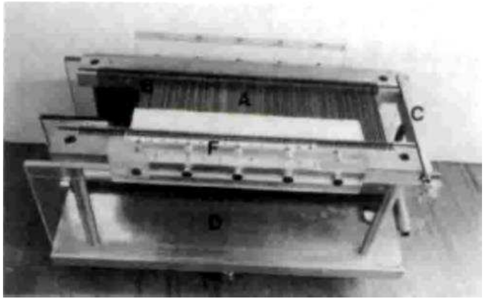


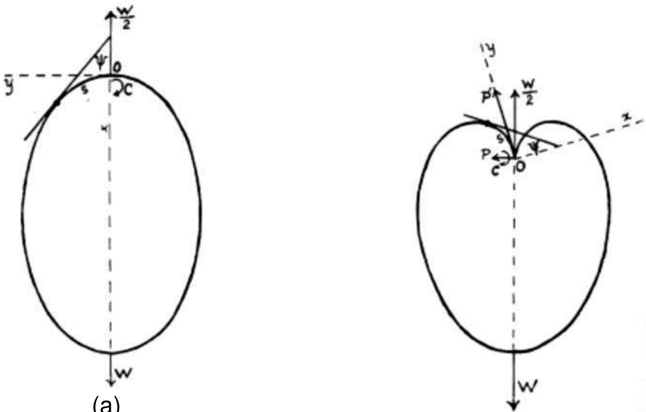
Figure 1.5 Russell test for measuring fabric bending length (reproduced from **[13]**)

1.2.4.1.2 Hanging loop tests

These tests are from the series of alternative tests developed by Peirce in 1930 for measuring fabrics unable to be tested using the standard Flexometer. The specimen is distorted into one of three loop shapes (ring, pear or heart loop) supported at one point and hung vertically. These tests were developed to increase fabric resistance to bending when it is exposed to greater bending force than that of the cantilever method which makes it measurable.

In these tests, both ends of the strip are held together using a clip to form a loop, and then allowed to hang under the grip to produce angles 180°, 360° and 540° (see Figure 1.6~~Figure 1.6~~). These three loops are pear, ring and heart respectively. The hanging heart loop test was developed for testing very limp and soft fabric bending lengths which bend to a right angle on the Flexometer. This method reduces fabric curl in the test and lets the tested strip bend freely under its own weight. Therefore, it was intended to increase the amount of bending to make the resistance to bending measurable [8].

Formatted: Font: (Default) Arial



(a)
(a)
(b)

Figure 1.6 Examples of loop test form (a) Ring loop, (b)Heart loop(reproduced from **[8]**)

Peirce determined the standard sample dimensions used on the Flexometer to be (6 inch length × 1 inch width). Regarding the heart loop test, he stated that it would be carried out using a strip of 10 cm or less. Later in the paper he mentioned that a fixed length of strip 15 cm would be suitable to test soft fabrics (using a table from which the bending length would be obtained directly from the loop height which is less laborious).

Winn and Schwarz studied the effect of the heart loop test strip length (the circumference of the loop) on the obtained bending length value. They found that there is a critical length for the strip. An increase in this length will change the bending length; however any decrease will not have an impact. The bending length remained constant for specimen lengths between 12.5 and 37.5 cm. It was noted that stiffer fabrics would require longer samples than less stiff fabrics. In this range the operator could select her/his sample length to carry out accurate experiments [14]. Afterwards, the hanging heart loop test was carried out by Abbott using a strip of 20 cm [15].

Winn and Schwarz reported that the formula of the heart loop test is simple compared to the pear loop. They reported from previous studies that the heart loop test is preferred for very limp fabrics than stiff fabrics and vice versa (the pear loop for stiff fabrics). The heart loop test showed the best range of measurement for all types of materials compared with other tests (Gurley stiffness tester, Schiefer Flexometer and Drapeometer measurements) [14].

1.2.4.1.3 Bending loop test

In 1966 Stuart and Baird [16] developed a measurement method for fabric bending length using a loop of a material. In this test, a strip is laid on a flat and non-adhesive surface and one end is bent to meet the other one to form a bent loop shape (see Figure 1.7~~Figure 1.7~~). The sample length was 5 times its width. It was suggested to method with soft fabrics as they were measured more accurately using the loop tests than the cantilever. This is the simplest style of a fabric loop test as it is very quick and easy to be carried out [16, 17].

The height of the loop is substituted in a formula to obtain the bending length of a strip (see Equation 1.2 **Error! Reference source not found.**):

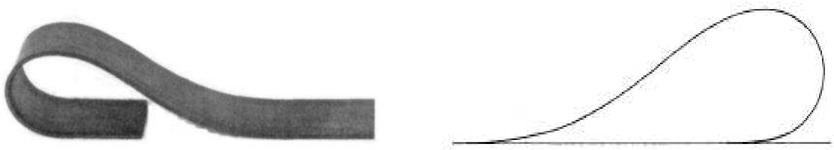
$$BL(loop)cm = 1.1 * Lh(cm) \quad \textbf{1.3}$$

where: Lh is the loop height which is the distance between the highest and lowest portions of the loop on the vertical axis (see Equation 1.4).

$$Lh(cm) = height\ of\ the\ loop\ above\ the\ the\ flat\ surface(cm) - Thickness(cm) \quad \textbf{1.5}$$

Commented [R25]: It may be good to indicate the year and then follow this with the numeric reference so the reader has a context in terms of who and when. It's good in any case to keep the numeric reference close to the authors' names.

Formatted: Font: (Default) Arial



(a) (b)

Figure 1.7 Bending loop (a) A loop of neoprene, (b) loop shape as plotted by a computer (reproduced from **[17]**)

1.2.4.1.4 Cassidy *et al.* Bending box

Cassidy et al. developed a tester called a "Bending box " which would better meet the requirements of objective measurement related to knitted fabric performance in handling during production, as the previous used methods lack the reproducibility for those knitted fabrics which tend to curl or twist and/or there are difficulties in application of the results to the performance of fabric in garment assembly. Moreover the tester was easy to use and inexpensive.

This tester used the same principle as Stuart and Baird (1966) but the use of the box obviated operator handling errors. Three initial experimental trials were carried out in order to investigate the degree of this method's reliability. The meter proved a more dependable measurement of knitted fabric bending length than the Shirley tester in terms of reproducibility. The comparison between the results of KES-F bending tester and the method results showed similar identification for fabric stiffness [18].

1.2.4.1.5 Cassidy Instron test for bending

Cassidy, C. developed a system for measuring fabric bending length. This method was developed due to the limitations in every individual common method used i.e. cantilever and loop tests. She worked on combining the advantages of both styles. A tensile tester (Instron 4302) was used in a compression mode to produce a dynamic loop. The tested sample was allowed to generate the first fold and the distance between it and the second loop was measured using the manual cursor settings. The bending length was calculated from the load displacement graph which was obtained by the PC attached to the tester [19].

1.2.4.1.6 Planoflex

Dreby (cited in Abbott 1951)developed an instrument to measure the required angle for producing a wrinkle in a tested sample. In this test, the specimen measured is mounted on a frame which allows lateral displacement of one end of the fabric to take place. The angle measured is a stiffness parameter. The values of both sides are averaged [15].

Commented [U26]: It is cited in Abbott 1951

1.2.4.1.7 Ordinary beam test

An inverted self-supported U-shaped specimen was originally laid horizontally against a smooth coordinated platform and was proposed by Hall to compare fabric stiffness [20].

1.2.4.1.8 Hanging strip

A sample is supported vertically using a clamp which is connected to a graduated disk. The sample is allowed to make a standard angle of 22.5 degrees with the horizontal plane and the displacement is read from the disk [20].

1.2.4.2 Measurement of deforming force

This is a measure of the resistance offered by the sample to bending or to twisting. According to Schwarz, in bending tests it is important to consider the weight and whether to correct for or eliminate it. This is to determine that the deformation took place only due to its weight or to apply a definite force and measure both of them. There were several methods proposed for measuring the deforming force subjected to a sample tested [20].

~~1.2.4.3.0~~1.2.4.2.1 Gurley stiffness tester

This instrument supports a tested sample vertically at its upper end by means of a rotating arm (see Figure 1.8~~Figure 1.8~~). The force required to bend and slip the lower end over a vane is measured. A weighted pendulum-type vane is used to measure the strip deflection. The stiffness is calculated by multiplying the read value by a factor. Variables such as sample size, thickness and the vane's weight would affect the results. Besides, the tester was not found to be of high precision for soft fabrics which had values at the minimum range of the instrument. Thicker and heavier materials show relatively stiffer results in the Gurley stiffness tester than by the hanging heart loop. However similar results were produced from both methods whensamples of the same weight and thickness were employed[21].

Saxl (cited in Schwartz 1939) described an instrument with a similar principle. However, the strip was supported horizontally on a platform and would be bend to take a U shape [20].

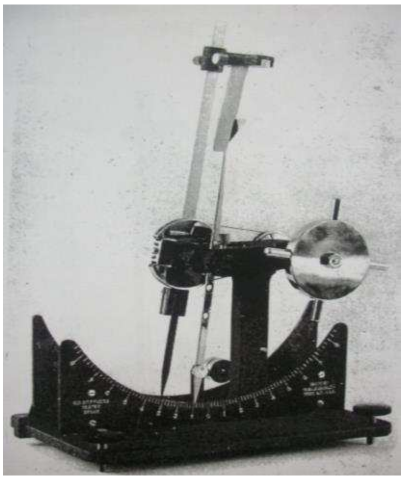


Figure 1.8 Gurley stiffness tester(reproduced from **[21]**)

1.2.4.3.11.2.4.2.2 Schiefer Flexometer

This instrument measures the force required to bend (fold) a pair of standard samples mounted on two plates placed opposite to each other vertically by means of a spring to a definite angle θ (see Figure 1.9Figure 1.9). A pair of samples are used for increase the torque exerted from the sample on the plates during folding (due to their resistance to folding and bending). The angle of deflection (folding) between the two plates is dependent on and calculated from the sample thickness (using an equation provided).

The force required for folding the specimens through a definite angle between the plates, the recovered force when they are allowed to unfold, and the force lost (difference between folding and unfolding forces) are measured to obtain three stiffness parameters including flexural force, resilience (expressed as percentage of the folding force) and hysteresis respectively.

This instrument provided results similar to those of the hanging heart loop and Gurley stiffness tester. Although, hard finishedfabrics gave stiffer results in the Schiefer flexometer, close agreement was lacking because the compactness of the sample is more important in the Schiefer flexometer which bends the sample to a much smaller angle (but you said previously that the Gurley tester gave higher values than the heart loop?)[21] .

Commented [U27]: Please see literature added.

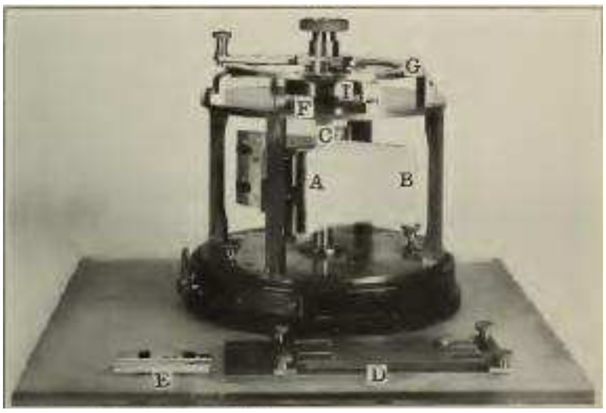


Figure 1.9 Schiefer Flexometer(reproduced from **[22]**)

~~1.2.4.3.2~~1.2.4.2.3 Munzinger Impact test

Commented [R28]: Should these be in a table or a bulleted list, rather than 5 steps in to the numbered list?

Munzinger used a type of ballistic pendulum instrument to measure fabric stiffness. The sample tested is supported vertically in a swinging pendulum path and allowed to bend with it. The difference between the distance passed by the pendulum with and without a mounted strip beyond its lowest point was calculated and determined as a measurement of stiffness. This energy difference was absorbed by the strip [20].

~~1.2.4.3.3~~1.2.4.2.4 Searle pendulum test

This test was proposed for measuring fabric stiffness. In this test, two torsion pendulums (rotating in opposite directions) were arranged to hold both ends of a tested strip in a vertical position. The force required to bend the held strip was then measured. The flexural rigidity was calculated from the period of oscillation when the pendulums were allowed to rotate while the strip is mounted [20].

~~1.2.4.3.4~~1.2.4.2.5 Twisting rigidity

Mori and Lloyd designed an apparatus to measure simultaneously, the torque and the in-plane load caused by twisting a fabric supported vertically between upper and lower jaws. The raw data were presented as torque (twisting moment), twist and in-plane load twist hysteresis curve. The twisting rigidity could be measured from the initial slope of this curve [23].

1.2.4.3 Relationship between methods of measuring fabric stiffness

Peirce carried out a comparison between 7 different methods developed by him in 1930. He stated that this comparison was limited by fabric variability, changes in test conditions, effects of handling the fabric during the test, observational error and no one fabric being applicable for all methods. However, tests were carried out for investigating the validity of the formulae used, it was recommended by him to apply one method in the aim of doing direct/close comparisons between fabrics [8].

Schwarz *et al.* published a series of papers concerned with “Technical evaluation of textile finishing treatments”. These studies focused on different methods of measuring fabric stiffness, as the need for an objective method which could be carried out in the laboratory and was highly correlated with the subjective assessment of fabric handle was of great interest from both manufacturers and consumers at that time. They looked for a sensitive method for measuring fabric stiffness to differentiate between differences in finishes [24].

Firstly, they used the Spearman rating system as they thought it would be a reliable statistical tool to study the correlation between four different methods for measuring fabric rigidity. They did not expect complete agreement between different systems. This incomplete agreement was especially expected among low sensitivity instruments for fabric rigidity and would be expected for other reasons such as the inherent variability of textile materials and because of difference in test processes and procedures, and other differences and complexities.A Spearman rating of 88% between bending length and bending modulus was found. On the other hand some correlations were found ranging between 30% and 60%. They reported that high Spearman ratings were not expected for measurements related to each other only by physical tests and not related by mathematical computation[14].

Commented [U29]: rewritten

[14]. (please check over this para to see if you think it is accurate)

Later, they used the Kendall rank correlation coefficient instead of Spearman rating systems as they thought it had higher efficiency in studying such correlations. Despite their opinions, they found similar correlation between methods. In that study and the previous one they ranked the values of fabric stiffness obtained from the grand average (which is the mean of face and back in each direction) [25]. In a subsequent study, they did not compare the methods with each other as they did before, but they used the heart loop test as the basis of comparison as it would produce values with weight or without weight correction and it does use an external force to bend the fabric.

Analysis of variance was introduced as a statistical method to investigate the variation in finishing different types of fabric using different treatments and the t-test was proposed to determine the test methods’ sensitivity to differentiate between fabrics’ stiffness [25].

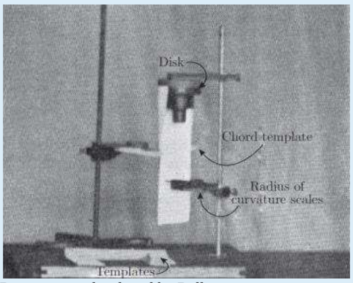
In further work, they suggested a comparison between different methods for measuring fabric stiffness. Using a correction factor based on fabric weight and thickness of the tested fabrics was recommended, as different methods would be based on different principles (for example some would bend the fabric under its weight and others not). Therefore there is a need to take these variations of tests into account [21].

Abbott in 1951 [15] compared five different methods of measuring fabric stiffness with the subjective assessment of stiffness which was considered by him as the standard

Commented [rm30]: Numeric reference required here method. The geometric mean of the lengthwise and crosswise directions was used as the representative value for each fabric bending length.

The compared parameters were the cantilever BL, heart loop BL and BR and the values of the Schiefer Flexometer, Planoflex and Drapeometer(should this be drapemeter? It is Drapeometer). All of them ranked the fabrics in approximately the same order. The Kendall coefficient was applied to measure each method's correlation with the subjective assessments. All these methods except the Drapeometer(as above?)showed significance correlations with the subjective rating of fabric stiffness, which means that they are reliable in measuring fabric stiffness and there is a strong relation between them and the subjective assessment. However, the Pierce cantilever flexural rigidity had the highest rank correlation with the subjective assessment.

Commented [U31]: Drapeometer



Drapeometer developed by Bellinson

A study followed this investigation to compare Tinius Olsen's stiffness tester (measures the the applied load for bending a sample to 60°) with the Pierce stiffness tester - the measurements were carried out in the warpwise direction to eliminate as many variables as possible, in terms of:

- Similarity or relationship using the correlation coefficient and the best line fit (trend line) equation showing the quantitative relation between the two methods. There was found high correlation between them r=0.93.

- Precision or reproducibility employing the average standard deviation SDEV and coefficient of variation CV (relative precision) of tested fabrics using each method. A small relative spread is expected from a precise instrument. However, Tinius Olsen's SDEV average was 3 times that of Pierce's, although their CV's were the same, which means that there was little difference between them with respect to the relative precision of the readings about the average.

- Sensitivity or relative ability to discriminate among fabrics of varying degrees of stiffness was carried out using the SDEV and CV of each method average to show how much variation exists from the method average. A sensitive method shows high SDEV and CV and means that different degrees of stiffness are registered by a spread in the values greater than that attributable due to experimental error. It was found that the relative spread (i.e. CV) of stiffness values measured on both machines is about the same. This means that both machines have similar sensitivity for measuring stiffness.

- Discrimination level (Sensitivity index SE) shows the ability of a method to discriminate between fabrics with different stiffness. $\mathrm{SE} = \sigma_a^2/\bar{\sigma}_w^2$:where σ_a is the average SDEV of a method, $\bar{\sigma}_w^2$ the overall average standard deviation (the reproducibility among the specimen stiffness values for a fabric). This SE was not statistically different between the two methods. This means that both machines were able to discriminate fabrics with different stiffness attributes.

- Dependability of the test method. It includes the two major sources of variability- inherent operator variability and differences between operator.

a. Inherent reproducibility is the influence of an operator differences on the results. In other words, this is the ability of an operator (precision) to reproduce his own results. One operator maximum deviation from average stiffness measured on the same machine was found of 10% on TiniusOlsen and 14% on Peirce tester.

b. Overall reproducibility is the operator average from the overall fabric average. It was found that-when using either Tinius Olsenor Peirce testers- an operators average should not exceed 15% deviation from the overall average stiffness value.

Commented [rm32]: Bullets or a's and b's

- Ease of operation and speed of obtaining results: if the measurements obtained by both machines are equally reliable, reproducible, and discriminating, then these two factors should be used to judge between two instruments.The Peirce tester was found a simpler machine and easier to operate than Tinius Olsen.

- The fabric range able to be tested on the apparatus. The Peirce tester compared to TiniusOlsen testers was found limited with regard to the fabric range able to be measured as it could not measure the wide range of stiffnessesof military fabrics used.

- Mechanical failure or misfunction: If the machine must be checked before each sample is tested; and repairs frequency should be taken into consideration. The Peirce tester was found simpler thanthe Tinius Olsen tester as the latterwasfound susceptible to mechanical failure or misfunction.

- The time necessary to place the sample on the apparatus, test it, and remove it from the instrument. The Peirce tester was approximately 6 times faster than the Tinius Olsen instrument[26].(you do not give the results for all these bullet points?)

Stuart and Baird introduced their loop test to measure the bending length as an alternative method for the Pierce cantilever. Theoretical comparison suggested that their loop test produces higher values than the Cantilever does which is against the experimental results except for the soft fabrics. This difference between the two methods was more obvious in soft felts than in woven fabrics because of the lower deviation of the latter (woven fabrics).

Comparison between the two methods was carried out in terms of significance, difference and variability. There was no significant difference at the 5% probability level which means that they produced similar results. The variance of the Shirley was less than the Stuart and Baird loop.

Kalyanaraman and Sivaramakrishnan in 1984 studied the efficiency and validity of their electronic instrument based on the cantilever principle for measuring fabric stiffness. This study was based on comparing the new device results with results obtained from the Shirley stiffness tester.The F ratio was used as a statistical tool for comparison in terms of determining the significance level of each method and was applied on a group of fabrics [27]. It was found that the new instrument applied the principle reliably but it was not more accurate than the Shirley tester. They stated that their device had some merits over the manual Shirley stiffness tester for quick and easy measurements and there was a lower dependence on the operator efficiency.

Zhou and Ghosh compared 4 methods of measuring fabric bending length, namely: Pierce cantilever, heart loop, loop test 3 and 4 (as they were developed and called by them). They presumed that the results (different fabric stiffness values obtained from different methods) would not be identical as the measured parameters (BL or BR) depend on the test conditions and because of the nonlinear behaviour of the tested woven fabrics. There was a critical value for their developed loops 3 and 4 beyond which the bending length values will not be affected. The cantilever BR showed higher values than KES BR. However, the BR from the heart loop, loops 3 and 4 were similar except for stiff fabrics. The difference between cantilever and loop tests increased with increased fabric stiffness [28].

1.2.5 Bending modulus

This is the intrinsic stiffness of a fabric, as it is independent of the direction measured and is related to its thickness. In other words, it is an abstraction for fabric stiffness. It is called “Paperiness” and is a measure of fabric compactness and measures the degree of adhesion between fibres and yarns. The bending modulus is calculated from flexural rigidity and thickness (see 1~~Equation 1.4~~) [8].

$$Bending\ modulus = \frac{12 \times\ Flexural\ Rigidity}{Thickness^{\ 3}} \qquad \textbf{11.4}$$

1.2.6 Friction

Fabric resistance to motion is defined as its friction. Measurement of the coefficient of friction is based on pulling a mass block, across tested sample of fabric. This block is connected to a load cell which records the force needed to start and keep moving the block producing static and dynamic friction coefficients respectively [7].

The coefficient of friction is the ratio of the force required to move the block to it’s weight. The frictional force could be plotted against the displacement. The selection of the block material is important as the coefficient of friction is affected by both the materials of the block and the fabric. In measuring the static coefficient of friction “stiction”, a block is placed on a fabric mounted on a plane. The plane is adjusted until the block starts to slide. The coefficient of friction is tanθ, where θ is the inclination angle of the plane. If an impetus is given to the block and the angle at which motion just continues is determined, the coefficient of dynamic friction could be measured [7].

This was also used by Cassidy in her thesis [19]. She used the load displacement graph produced on an Instron tester in a friction test to measure Coefficients of Static and Dynamic friction and Roughness Factor. In this test the sled and platform attached

Commented [R33]: Can this described in more detail?

Formatted: Font color: Auto, Check spelling and grammar

Commented [R34]: Reference?

to the instrument were used to carry out the test. The standard sled was a sheet metal plate covered with foam. The platform was made of polished metal and had a locating pin on the underside of one end which fitted into the bottom clamp housing directly under the cross-head of the Instron tensile tester and secured with a metal pin. There was a small metal pulley fixed to the platform which had negligible friction. She developed the sled to involve the minimal handling of the fabric samples. The highest peak of the frictional trace at the beginning of the movement was taken as the coefficient of static friction, and the mean between the peaks and troughs during motion was taken as the coefficient of kinetic or dynamic friction. The roughness parameter was also calculated by taking the difference between the troughs and peaks during the movement of the sled.

1.2.7 Buckling

Fabric buckling (such as bending of a sleeve or a trouser leg) takes place when apparel is in use. Plate buckling is the simplest method for testing this property. It gives a good indication of the fabric's likely behaviour but does not closely replicate the many other factors which will influence buckling in a garment being worn such as stitch and seam type, body shapes and other garment design features. This method was proposed for measuring fabric bending rigidity and frictional resistance to bending.

Commented [R35]: Why?

Grosberg showed that different cases of applied loads on a sample could be considered in which both tips are free, one tip is supported or both tips are supported. In the case of both sample tips being clamped the critical load is the ratio of bending rigidity to gauge length. Moreover, the return curve after buckling which presents cloth recovery from buckling could be considered [9].

In this test, a load-compression curve is plotted. A comparison between elastic material and cloth buckling showed that they have significantly different behaviour. In cloth buckling the load decreases with compression (in loading) and when the load is released the curve does not retrace the loading curve but showed marked hysteresis [9].

The relation between bending moment and the inverse of radius of curvature was first proposed by Eeg-Olofsson in 1959 [9]. This plot was developed and used later by Kawabata in the pure bending test using KES-FB2.

1.2.8 Torsion

In 2012 Mohamad et al. reported work carried out on equipment developed by H. Dawson & Sons Ltd and WIRA Instrumentation for the measurement of torsion data of various flexible fibre assemblies whilst they are being twisted. This system proved particularly successful in the measurement of knitted fabric stiffness. Unlike measurements based on bending rigidity, the assessment of knitted fabric stiffness based on torsional rigidity was in very good agreement with the tightness levels of the measured fabrics. It might have been expected that the suppliers and retailers of knitted fabric garments would have welcomed these results and the new measurement equipment. This was, however, not the case [29].

Commented [R36]: More specific details are required here…. was it not adopted, or was there disagreement? It needs to be clear what the context of this is.

1.3 FOM systems

Peirce in 1930 launched what is called the "Objective measurement" of fabric properties by publishing his paper "The handle of cloth as a measurable quantity". However over the years, there has been gradual and continuous development of testing methods and national and international standards, which aim at reaching the optimum and most efficient measurements. This is to improve the applications included in all steps of production process of fabric and satisfy the needs of both manufacturers and consumers. Consequently, there is continual competition between organisations to improve FOM applications in textile industry quality control. There have been many objective methods developed for different purposes. They are used universally in physical testing and quality control in the clothing industry. These methods rely on national or international standards such as British Standards (BS) (www.bsigroup.com/), American Society for Testing and Materials (ASTM) (www.astm.org/), and the International Organization for Standardization (ISO) (www.iso.org/iso). The Kawabata evaluation system of fabrics (KES-F) and The Fabric assurance by simple testing (FAST) are the best-known methods for objective measurements available commercially [1].

Commented [R37]: It may be suitable to start with discussion of the standards, give some examples of them and then explain their importance, application and development.

1.3.1 Kawabata evaluation system of fabrics (KES-F)

Commented [R38]: Some further context in discussion would be useful, are the tests heavily used? are they critiqued anywhere? what are the advantages/disadvantages?

Due to high cost, sensitivity, complexity and high maintenance prices, KES-F is more suited to research applications. In 1972, Sueo Kawabata introduced the Kawabata evaluation system of fabrics (KES-F) by participation with the Textile machinery Society of Japan[7]. The main purpose of this system was to carry out identification and evaluation of fabric mechanical properties. Due to his work and experience in the field of fabric mechanical properties and the evaluation of fabric handle and attributes, he found an essential need to introduce a system to measure accurately a group of sixteen fabric qualities. These could be plotted on charts provided with these instruments. This system went through different developments to have a computerised and automated version with software to collect and analyse the output data. The tests are carried out using a sample of standard dimensions. The system produces stress(force)-strain plots resulting from the applied force in one direction and then it is released to apply it in the opposite direction. The plots show the hysteresis behaviour of a sample tested resulting from the energy loss during deformation.

The system consists of four instruments to measure the following properties:

- KES-FB1 measures Tensile and shear strength
- KES-FB2 tests fabric Pure bending
- KES-FB3 measures Compression properties
- KES-FB4 measures Surface friction and roughness

1.3.1.1 Shear test (KES-FB-1)

In this test, a sample of dimensions 5 × 20 cm is subjected to a constant tension of 10 gf/cm to maximum shear angle 8 degrees in its long direction and then the shearing motion is reversed to the opposite direction (see Figure 1.10Figure 1.10). The relation shear force - strain is detected during the test and plotted (see Figure recommended to carry out this test before the tensile test because the tensile deformation is greater than shear deformation.

The following shear parameters are measured:

- **Shear stiffness (G)** (gf/cm.degree) is the slope of shear force-angle (strain) curve measured between 0.5º and 2.5º. Low values indicate less resistance to the shearing motion; corresponds with better drape.
- **Shear Hysteresis at shear angle 0.5º (2HG)** (gf/cm) is the width of the hysteresis loop at ø = 0.5º.
- **Shear Hysteresis at shear angle 5º (2HG5)** (gf/cm) is the width of the hysteresis loop at ø = 5º.

The average of these values for positive and negative curves in warp and weft directions are calculated.

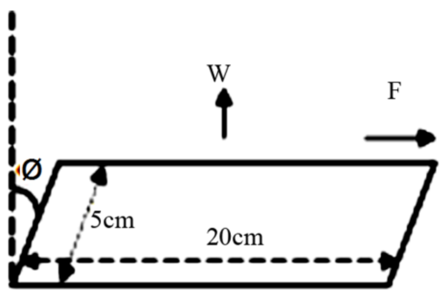


Figure 1.10 Shear test using KES-FB-1 **[30]**

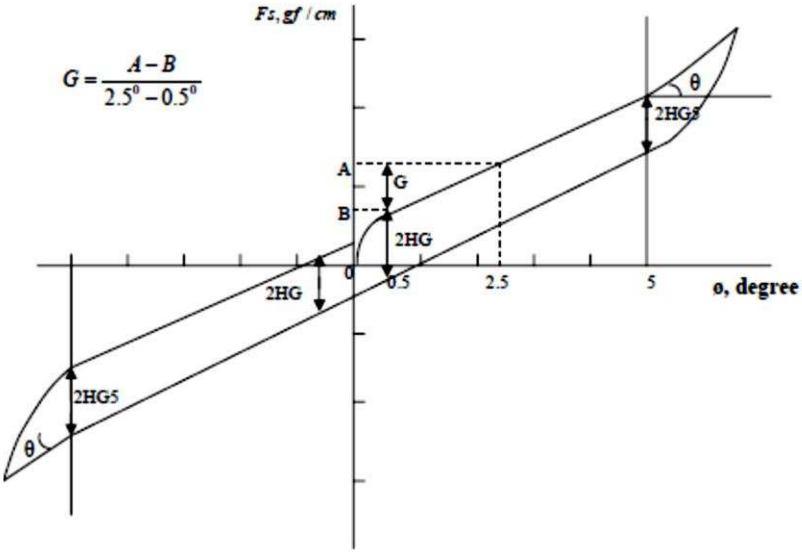


Figure 1.11 An example of Shear force-angle resulting curve, where *Fs* is the shearing force and ø is the measured angle (reproduced from**[31]**)

1.3.1.2 Tensile test (KES-FB-1)

A sample tested is subjected to a constant tensile force in one direction to reach the maximum tensile force 500 gf/cm (see Figure 1.12~~Figure 1.12~~), the force is then recover to the origin position to obtain a pair of curves (a and b respectively in Figure 1.13~~Figure 1.13~~) which represent the tensile force (F) and strain (ε).

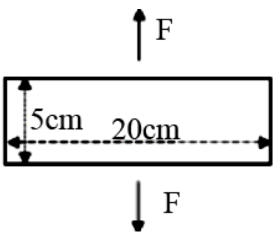


Figure 1.12 Tensile test using KES-FB-1 **[30]**

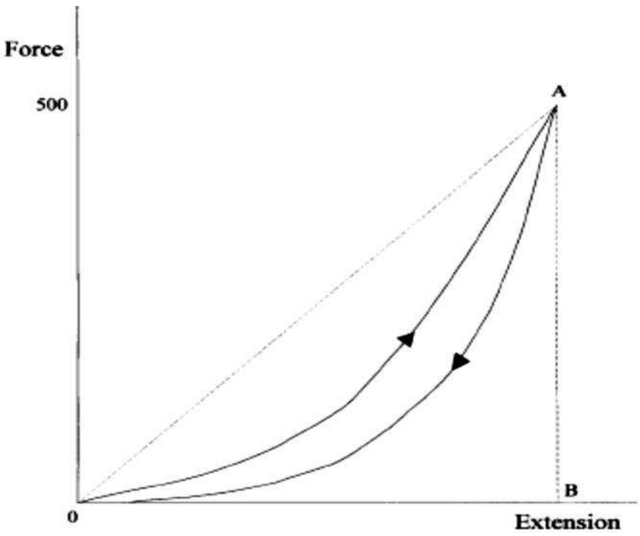


Figure 1.13A Typical Force-Extension Tensile Curve of a Fabric (KES-F1) (reproduced from **[7]**)

From this plot, different parameters can be measured:

- **Tensile energy WT** (gf.cm/cm[2])(the work done while stretching the fabric until maximum force) is the area under the increasing load -strain curve.
- **Linearity of load-extension curve** (see Figure 1.13~~Figure 1.13~~)

$$\mathbf{LT} = \frac{\mathrm{WT}}{\text{Area of triangle 0AB}} \qquad \mathbf{1.5}$$

- **Tensile Resilience**(Equation 1.6 **Error! Reference source not found.**)

$$\mathbf{RT}\,(\%) = \frac{\text{Area under load decreasing curve}}{\mathrm{WT}} \times 100\% \qquad 1.6$$

This measures the recovery from stretch when the applied force is removed. High values indicate good recovery from having been stretched.

- **Tensile strain or elongation EMT** (%) is the tensile Strain at the point A on the curve.

1.3.1.3 Bending test (KES-FB2)

In this test, pure bending force is applied to the sample with a constant rate of curvature (K) 5 mm/sec in a range of curvatures −2.5 ≤K ≤ 2.5 cm^{-1} (forward and backward). Two chucks hold a sample, one is fixed and the other is movable to bend the sample (see Figure 1.14~~Figure 1.14~~). The bending moment-bending curvature relationship is plotted (see Figure 1.15~~Figure 1.15~~).

Formatted: Font: (Default) Arial

Formatted: Font: (Default) Arial

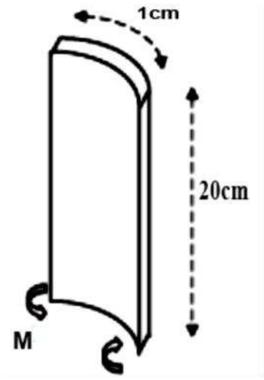


Figure 1.14 Pure bending test **[30]**

The following parameters are measured:

- **Bending stiffness B** (gf.cm^2/cm) is the slope of the bending moment – curvature curve between K = 0.5 cm^{-1} and K = 1.5 cm^{-1}. Higher B values indicate greater stiffness/resistance to bending motions.

- **Hysteresis of bending moment 2HB** (gf.cm/cm) is the width of the hysteresis curve at K = 0.5 cm^{-1}

The average of two measurements for sample face inside and outside is calculated.

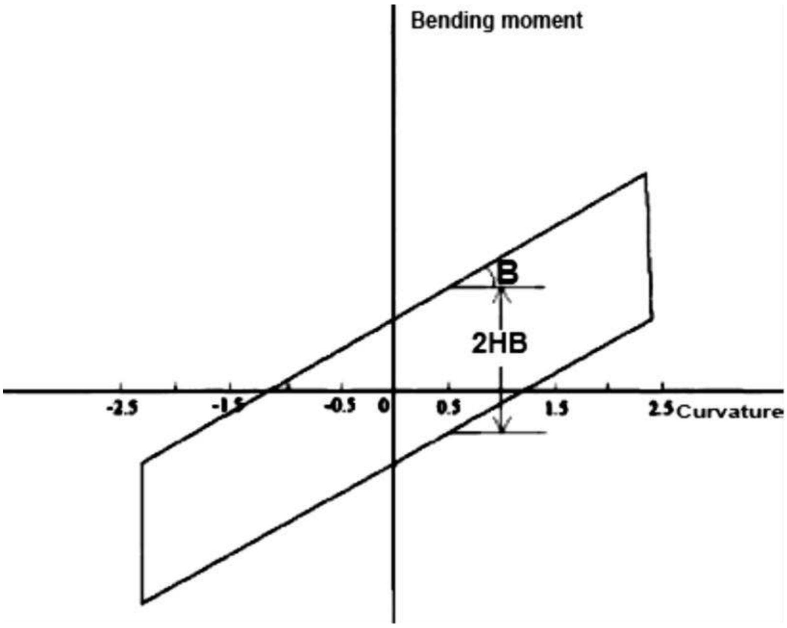


Figure 1.15 Bending moment-curvature plot from pure bending test **[7]**

1.3.1.4 Compression test (KES-FB-3)

A sample tested is placed on a plate and the plunger moves downwards with constant rate of force 1mm/50sec until it reaches the pre-set upper limit of the compression force 50 gf/cm^2, it then moves upwards to recover the compression (see Figure The stress(pressure) / strain(thickness) curve is plotted (see Figure 1.17~~Figure 1.17~~).

The following properties can be calculated as LT, WT and RC calculated in the tensile test:

- **Linearity of compression thickness curve LC**
- **Compressional energy WC (g f .cm/cm^2)**
- **Compressional resilience RC (%):** Higher value indicates a greater recovery from being compressed.

The **Thickness** (millimetres) measured at 0.5 gf/cm^2.

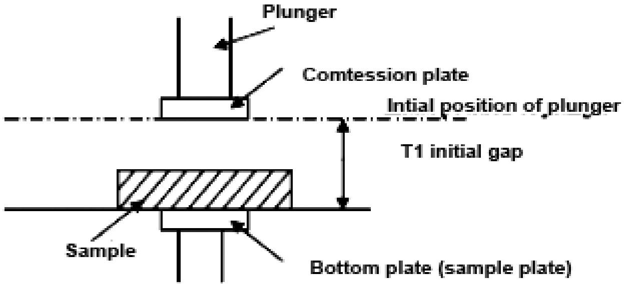


Figure 1.16 Compression test **[31]**

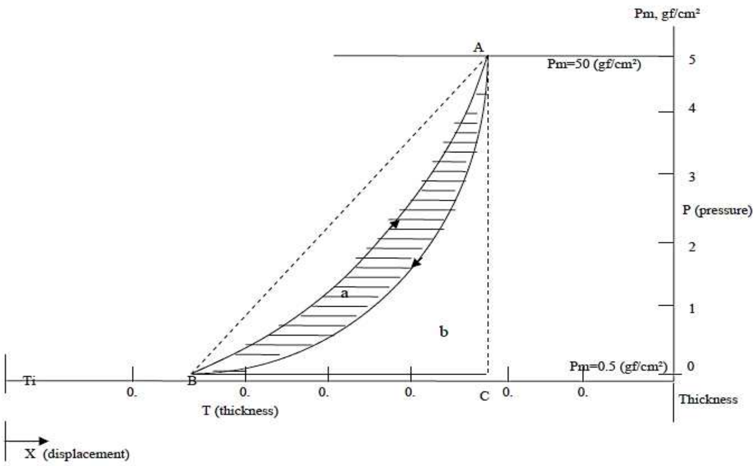


Figure 1.17 Pressure-Thickness curve resultant from compression test **[31]**

1.3.1.5 Surface Friction and Roughness tests (KES-FB-4)

In these tests, a sample is placed horizontally on a plate. One of the sample's ends is fixed to a winding drum and the other end is connected to a tension device. The rotation of the drum moves the fabric at a constant speed 1 mm/sec.

For surface roughness (SMD) measurement, a contactor (of 0.5 mm diameter) designed to simulate the human finger is placed on top of the sample and makes a contact force of 10 gf (Figure 1.18~~Figure 1.18~~) with the fabric. The displacement of the is recorded while the fabric moves as an indicator of thickness variation to plot the height-distance curve. The SMD is the mean deviation of surface roughness and is measured automatically (Figure 1.20~~Figure 1.20~~).

To measure the surface friction, a series of ten contactors similar to the previous one is used with 50 gf contact force to record the force required to pull the fabric past the contactors (Figure 1.19~~Figure 1.19~~). A distance curve is plotted, from which the Mean coefficient of friction (MIU) and Mean deviation of coefficient of friction (MMD) are calculated (Figure 1.21Figure 1.21).

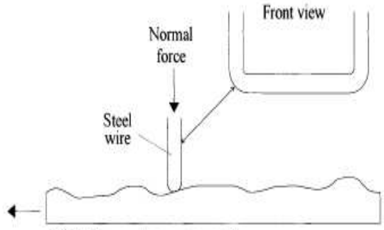


Figure 1.18 Surface roughness measurement (reproduced from **[7]**)

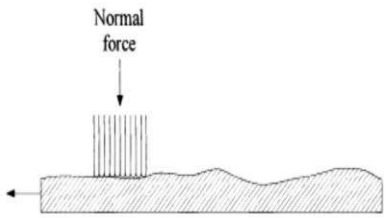


Figure 1.19 Surface friction measurement (reproduced from **[7]**)

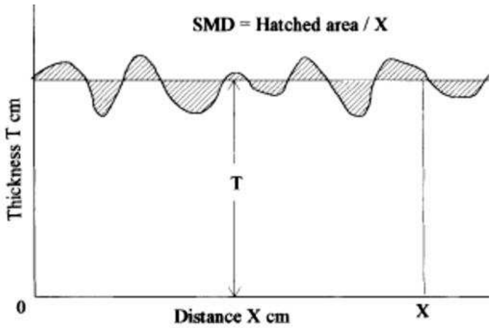


Figure 1.20 Surface thickness variation (reproduced from **[7]**)

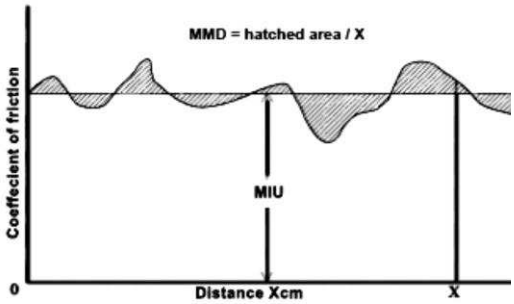


Figure 1.21 Surface friction variation **[7]**

- **Mean value Frictional coefficient** (Equation **Error! Reference source not found.**1.7)

$$MIU = \frac{1}{L_{max}} \int_{0}^{Lmax} \mu \; dL \quad (1.7)$$

where:

$Lmax$ = the sweep length,

$\mu = \frac{Frictional\ force}{\text{The force applied by the contractor pressing on the fabric sample}}$,

L= distance on fabric surface.

$\boldsymbol{MIU}$ ranges from 0 to 1 with higher values corresponding to greater friction or resistance and drag.

- **Mean deviation of the coefficient of friction** (Equation1.8)

$$\boldsymbol{MMD} = \frac{1}{L_{max}} \int_0^{Lmax} |\mu - \bar{\mu}|\ dL \qquad \mathbf{1.8}$$

- **Surface roughness** (Equation **Error! Reference source not found.**~~1.9~~)

$$\boldsymbol{SMD} = \frac{1}{L_{max}} \int_0^{Lmax} |Z - \bar{Z}|\ dL \qquad \mathbf{1.9}$$

where:

Z is the vertical displacement of the contactor. High values correspond to a geometrically rough surface.

The sixteen parameters measured can be normalised and plotted on the control chart developed (see Table 1.1~~Table 2.1~~) [7].

Table 1.1 Summary of properties measured using KES-F

Test	Property	Description	Units
Shear	***G*** 2HG 2HG5	Shear stiffness Hysteresis of shear stress at 0.5 degree Hysteresis of shear stress at 5 degree	gf/cm.degree gf/cm gf/cm
Tensile	LT WT RT EMT	Linearity of stress-strain curve Tensile energy Tensile resilience Tensile strain or elongation	None $gf.cm/cm^2$ % %
Bending	B 2HB 2HB 1.5	Bending stiffness Bending hysteresis Bending hysteresis at k value 1.5	$gf.cm^2/cm$ gf.cm/cm gf.cm/cm
Surface	MIU MMD SMD	Coefficient of friction Mean deviation of MIU Surface roughness	None None micron

Compression	LC WC RC	Linearity of stress-thickness curve Compression energy Compression resilience	None gf.cm/cm^2 %

1.3.2 Fabric assurance by simple testing (FAST)

Compared with KES-F, FAST is simpler, quicker to use and more suitable in the industrial area. The FAST system was developed by the Commonwealth Scientific and Industrial Research Organisation (CISRO) in Australia to measure the wool and wool blend fabric attributes and their impact on garment performance, handle and appearance. In other words, the generated data provides a language with which garment makers and fabric producers can communicate about cloth and garment properties and performance.

Commented [R39]: Because? It would be useful to substantiate this here.

There is a special control chart provided to allocate and display the measurement output data. The normal shape of the connecting line between these data is snake-like. In the charts, there are shaded areas showing the limits of values' acceptance and rejection (where failure in cutting, laying-up, and garment construction and the sewing process is highly expected) [1]. The system consists of three instruments and four tests. There is a template provided with the FAST system of 3 samples of 5 cm (width) by13 cm (length).

1.3.2.1 FAST 1: Compression meter

This is used to measure the thickness at two loads 2 and 100 gf/cm^2. The surface thickness is defined as the difference between the thickness at the two loads. The surface thickness could be a measure of fabric compressibility. The higher the surface thickness is, the higher the compressible the fabric is. This determines the stability of a fabric in the manufacturing processes.

1.3.2.2 FAST 2: Bending meter

This is the instrument used to measure the bending length. This instrument is based on the cantilever principle. In this apparatus, a light beam at an angle of 41.5° is used instead of the two engraved black lines on the transparent sides on the Shirley stiffness tester and the mirror. This instrument is electronic and can measure the bending length and display it on the panel directly.

The following parameters are measured:

Bending length BL **(mm)** is read directly from the device display.

Bending rigidity BR **(μNm)** The FAST system determines the bending rigidity from the measured cantilever bending length of the fabric using the principle described in BS: 3356 (1961), and the fabric area density [10](see Equation 1.10).

$$BR = W\ x\ BL^3 x\ 9.81\ x\ 10^{-6} \quad \mathbf{1.10}$$

where: W= Fabric area density in g/m²

~~1.3.3.0~~1.3.2.3 FAST 3: Extension meter

Fabric extensibility is measured at three loads: 5, 20 and l00 gf/cm to obtain $E5$, $E20$ and $E100$ respectively. A sample is tested in its long direction. The extensibility in the bias direction is used to calculate the fabric shear rigidity.

Commented [R40]: Good clear description of FAST tests in this section

Shear rigidity($\mathbf{G}$) (seeEquation 1.11) [10]

$$\mathbf{G}\ (\mathbf{N/m}) = \frac{123}{EB5} \quad 1.11$$

where: $EB5$ is the extension in the bias direction at 5 gf/cm.

Additional properties:

Formability (F**) (mm²):** This is a measure of the extent to which a fabric is compressed in its own plane before it will buckle (see Equation 1.12 **Error! Reference source not found.**)[1].

$$F = \frac{(E20 - E5)\ \times BR}{14.7} \quad 1.12$$

~~1.3.3.1~~1.3.2.4 FAST 4: Dimensional stability test

This does not require a special apparatus. It measures the dimensional stability of the fabric. The method involves measurements of the fabric before and after a wet relaxation process. It can be completed in less than two hours and does not require a conditioned atmosphere. This test shows whether there will be any shrinkage or increase in the length of the fabric in either the weft/course or warp/wale direction.

Commented [R41]: What does it show?

1.4 Fabric Subjective evaluation

Measurement of fabric mechanical properties are carried out subjectively. Subjective evaluation is based on the identification and assessment of fabric properties by people (subjects).

Clothing appearance is one of the most important aspects of clothing quality control. In the apparel industry, the assessment/evaluation of clothing appearance is vital for product development and quality assurance. However, the subjective assessment is completely assessor dependent, though it is still the main applied method of evaluation rather than objective measurement systems because appearance is an aesthetic judgement not easily assessed objectively. The visual assessment should be carried out on the materials (components) of the cloth and on the overall appearance [32].

The major cloth characteristics (which are usually assessed) are the fabric surface smoothness, including the fabric wrinkle recovery, pilling propensity, smoothness after repeated laundering, seam appearance, crease retention and appearance retention of finished garments. Different methods and standards are available for assessing these characteristics subjectively.

Reliability of subjective assessment output (results) is affected by several factors. Some of them are related to the assessors themselves (as an example: personality, state of mind or health) and others are due to factors which are outside of the assessor's control (eg: the inappropriate evaluation scaling or grading). The quality of the assessors, the assessment scaling and finally the results analysis should be done carefully to ensure as accurate an assessment as possible [32].

1.4.1 Training of assessors

Training of assessors is important to cope with probable individual internal assessment scales while rating sample/s tested. This should enhance the chances of a subject to be a reassessor. Besides, employing subjects with good experience can produce consistent results.

1.4.2 Number of assessors

It is recommended by the AATCC standards that three independent assessors are required in the subjective assessment. But generally, improving the results reliability could be made by increasing the number of assessors which gives the analyser an opportunity to cancel any individual difference or by calculating the 95% confidence interval of the average rating. A statistically significant sample is commonly recognised as 30 or more though some companies use sample assessor numbers of 40.

Commented [R42]: Is there an ideal number, how many are usually used?

1.4.3 Assessment procedure

Blind tests are recommended for tests dependent on tactile sensation in order to avoid biased or intentionally impaired/sabotaged assessment. But, this is impossible in the assessment of garment appearance which depends on visual assessment. So, an unspecified/undetermined evaluation purpose is desirable to avoid affecting the subject response for observation which would produce bias assessment.

1.4.4 Assessment scale and rating technique

The subjective assessment scale or grading rates should be accurately established. The uniformity of intervals between grades should be born in mind during grading. It is preferable to check these using objective measurement methods.

There are different rating techniques in the subjective evaluation for instance:

- Yes/No evaluation (the simplest)
- Rank ordering (In this technique, each assessor is asked to rank (order) the tested samples from best to worse, and points are used to express the grades).

- Paired - comparison By this system, a pair of samples are compared in every assessment. The better sample of both of them is given a value of “1” and the other “0”. At the end of the test (evaluation), the samples are ranked according to the total sum of each specimen value [33].

1.5 Summary of Fabric Objective Measurement

Since the seminal work of Pierce in 1930, many researchers have worked to try to improve the objective measurement of fabrics. They have developed many different types of testing instruments and all have claimed various degrees of success in the measurement of various properties for different types of fabrics and for different fabric uses: formability, drape and handle. The most sophisticated and deeply researched of the FOM systems is KES-F. However, though some South-East Asian countries, such as S. Korea and of course Japan, appear to continue to use this system, KES-F seems to have lost popularity in the west and particularly in the UK. This is probably due to high capital cost, high maintenance cost and its operation being too complicated and time consuming. The FAST system however has maintained its popularity and so too has the Shirley bending test and the Drapemeter.

2 Evaluation of Fabric Drape

Commented [U43]: Numbering is corrected

According to British Standards, fabric drape is defined as the ability of a fabric (a circular specimen of known size) to deform when suspended under its own weight in specified conditions [34-36]. It was defined by Chu *et al.* as "the property of textile materials which allows a fabric to orient itself into graceful folds or pleats when acted upon by force of gravity" [37], differentiating fabric drape from that of other materials such as paper which could have a similar bending length.

Fabric drape, along with lustre, colour, texture and pattern, is one of the important characteristics that define fabric and garment appearance. It is a significant property as it not only affects fabric and garment appearance but also contributes to apparel fabric comfort along with other properties such as handle and performance factors [38]. Fabric drapeability is dependent on variables such as fabric properties, object shape over which it is draped/hung and environmental conditions [30].

Drape is a quality which describes an important visual aspect of fabric properties typically evaluated by subjective assessment by the textile and apparel workers involved in fabric design and manufacture. Researchers have worked on interpreting drape by quantitative methods because of the limitations of individuals' assessments from lack of reproducibility to inconsistent agreement between assessors, etc. The significance and importance of analysing, understanding and measuring drape quantitatively is becoming increasingly realised by researchers and workers in the textile industry. To measure this quality, it is important to find a reliable, efficient and accurate method to reflect real fabric drape characteristics properly. Understanding drape using measured parameters can help to evaluate and ensure the appearance of the final clothes in real life, as well as improving computer simulation of fabrics. Quantifying this property determines to which extent and how a fabric is suitable to be made into a garment.

The importance of fabric and garment drape hasencouraged textile, apparel, and cloth modelling researchers to study various aspects of drape. Different studies have been carried out in different areas such as: studying factors affecting drape, development of drapemeters (to make the measurement process: easy, accurate, less dependent on operator skills and to find a satisfactory presentation for drape) and proposing alternative fabric drape parameters (which was sometimes a result of drapemeter development). Deriving equations to predict static and dynamic drape coefficients (the conventional drape parameters) and number of nodes theoretically using fabric mechanical properties was one of the fields of fabric drape investigations to make drape prediction and assessment easier and quickerthan experimental methods. This approach was extended to be applied in virtual 3-D drape simulation. New techniques such as image analysis methods have been used in this area to carry out accurate and comprehensive studies. Moreover, dynamic drape behaviour (which is different from conventional static drape)using a swinging motion similar to human body motion has been developed and studied. Different sewing parameters' effect on garment

Commented [R44]: It would be advisable to provide reference here to give context to the discussion.

Commented [R45]: Reference

drape were considered in different investigations as apparel products must include seams and few tests take account of the effects of seams on behaviour.

2. Evaluation of Fabric Drape

Generally, there are two approaches to evaluate fabric drape, objectively by measuring either fabric physical and mechanical properties related to drape namely shear, bending, and weight or drape values on a drapemeter, and subjectively to relate it with the end-use product [39, 40].

2.1 Objective Evaluation of Fabric Drape

Measurement of fabric drape started with Peirce in 1930 when he published his seminal paper "The handle of cloth as a measurable quantity". In this paper he developed objective tests for measuring fabric bending length which he proposed as a measure of fabric draping quality [8].

2.1.1 The Development of Drapemeters

Bellinson set up a drape tester called a " Drape-o-meter" at the M. I. T. Textile Research Laboratory. A fabric specimen was attached to the edge of a circular disc horizontally supported on a column. The drape length was the length of a sample measured from the top of the material to a point such that the length of the chord (distance between two ends of thesample) had reached a given constant value. The higher the drape length, the higher was thedrapeability ofthe fabric. The radius of curvature of the sample and its variation along the sample test length was also used to compare fabrics' drapeabilities. It had a negative relation with fabric drapeability [20, 24].

Commented [R46]: A diagram (Figure 1) would be good here.

Commented [U47]: Figure 1 is added

Thedrape-o-meter was designed to measuredrape rather than stiffness, but themeasured sample wassubjected to simple bending under zerogravitational force. Therefore,fabric drape was not clearly determined by those tests based on two-dimensional (mono planar bending) distortion of samples tested, as they measure bending properties rather than drape. A piece of paper and fabric could have similar bending properties while differing in their drape behaviour. These tests were not correlated with the subjective evaluation of drape. Consequently, a three-dimensional (multi-planar bending) distortion apparatus was introduced by the Fabric Research Laboratories in Massachusetts. This tester measured drape quantitatively in a way which showed its significant anisotropic properties. It was based on a principle similar to the one of showing and displaying yard goods in window shops at that time by draping them over a circular pedestal[37].

2.1.2 Static drape testers

In 1950, the original Fabric Research Laboratory's drapemeter was developed. In this optical apparatus, the sample tested was sandwiched between two circular plates mounted on a movable (up and down-wards) pedestal and was not allowed totouch the apparatus base. The optical system of this apparatus was used to cast the image of the sample draped on the ground glass - placed above the circular plates - which was traced by the operator (see Figure 2.1Figure 2.1).

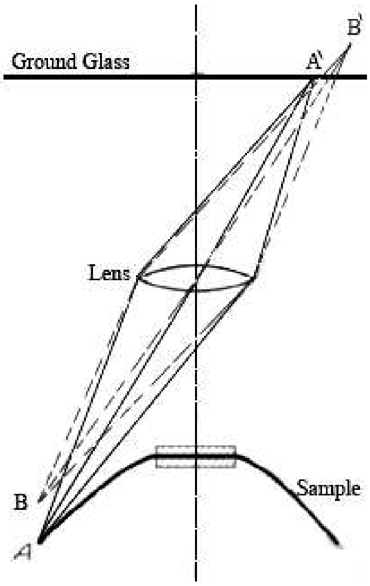


Figure 2.1 Schematic diagram of F.R.L. optical drapemeter [37]

First the "Drape coefficient",F, was developed, as a parameter to analyse the drape test data/image. It was defined as the fraction of the area of the annular ring between the flat fabric edge and the supporting disc edge covered by the projection of the draped sample (see Figure 2.2 and Equation **Error! Reference source not**)[37]. I note the editor says this reference was not found

Commented [U48]: Reference number is added

$$F = \frac{\text{Area of the draped sample on the annular ring}}{\text{Area of the annular ring (between the two circles)}} \qquad \textbf{2.1}$$

This was analogous to the circularity coefficient which was used in textile microscopy. The higher the drape coefficient was, the less drapeable the fabric was [37]. It is noteworthy that this was the drape coefficient used in most subsequent drape studies.

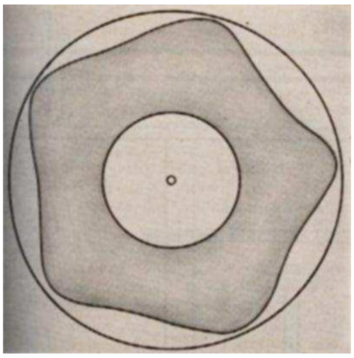


Figure 2.32 Drape diagram (the dark grey area is the shadow of the draped sample on the annular ring); reproduced from[37]

A study of the accuracy of this apparatus found that there were errors which reached 8.5% in the image diameter and 17% in the measured area for a 1 inch difference in elevation levels of the fabric edge (as fabric drape occurs with double curvature). Figure 2.1Figure 2.1 shows the possibility of having different projections for points with distance from the central vertical axis of the supporting disc with different elevation levels. This was one of the significant disadvantages of using this apparatus for measuring drape coefficient. The principle of the F. R. L. drapemeter of draping the sample tested on a circular disc was the basis of all/most of the further developed drapemeters. Improvements were carried out only to obtain more meaningful and accurate data easily.

This F.R.L. drapemeter is the first 3D drapemeter developed to simulate fabric draping over a circular pedestal and to differentiate between 2D planar material (such as paper) and 3D structural material (i.e. textile fabrics). Moreover, using this apparatus, a new quantitative parameter was developed (i.e. Drape coefficient).

It was noticed that there is an error in measuring the “Drape coefficient”. This error limited the accuracydegree of this apparatus as different drape coefficients would be produced for one sample measured.This error was because of the optical system used in the apparatus.

An improved F. R. L. drapemeter was developed to cope with the error in the original drapemeter. In the improved tester, a sample (25 and 30 cm diameter samples were able to be measured) was draped on a circular disc (10 or 12.5 cm in diameter) mounted onone of two synchronised turntables and a standard circular chart was mounted on the other one. An optical system mechanically connected to a pen was used to scan the edge of the sample tested continuously and automatically in order to draw/trace the scanned edge on the chart. When one revolution was performed with the turntable carrying a sample, a complete drawn image of the draped sample was generated. As stated by Chu, Cummings and Teixeira 1950, a planimeter was used to obtain the drape coefficient, namely the ratio of the draped sample's shadow area to the flat sample's area.

In this drape meter an improved optical system was used to produce a drawn image of the measured sample. This system of measuring drape allowed the operator to keep an autographic diagram of the measured sample. Relaxation of fabric over time intervals would be studiedby drawing several diagrams on the same chart. The drape coefficient was measured using the area of the image drawn forthe draped sample.This apparatus was "null operator". This means that area was computed mechanically which increased the accuracy degree of measuring drape. This technique of measuring drape coefficient needed little time and had high accuracy compared to the original F.R.L. drapemeter.

However, the accuracy of drawn image of a measured sample was dependent on fabric translucency. Fabric does not always sufficiently alter the light beam when translucency varies across the fabric. This would decrease the reliability degreeof this apparatus. Therefore, it wasbelieved that this device neededa more sensitive optical system for use as an area measuring device.

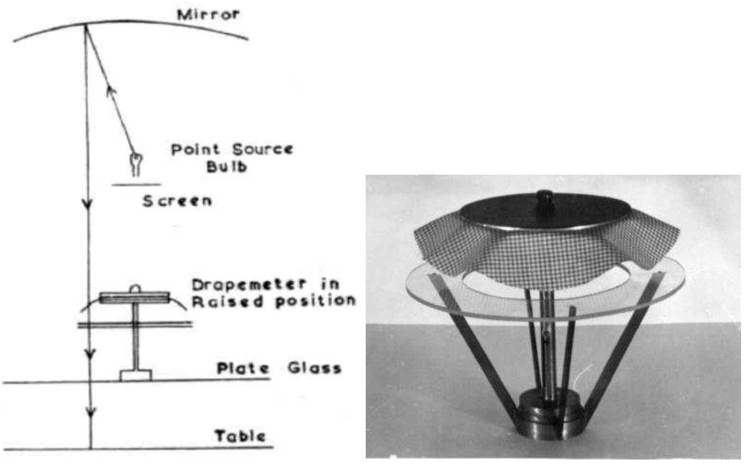
A further upgrade was carried out for the F. R. L. drapemeter by Cusick in 1962 by developing the optical system used in obtaining a draped sample projection (see Figure 2.4~~Figure 2.3~~**Error! Reference source not found.**)[41].

Field Code Changed

In this tester, the sample tested was also sandwiched between two horizontal sample discs with a diameter smaller than that of the sample. The sample was mounted on the sample disc by means of a vertical pin placed centrally on the sample disc while the annular supporting disc was at the same level of the supporting disc. To carry out a test, the two discs with the sample were raised up in order not to touch the annular disc (see Figure 2.4~~Figure 2.3~~ (b). The apparatus was placed on a glass sheet as the shadow was projected on a table underneath the apparatus by means of a light source and spherical mirror positioned above it which produced near parallel vertical light. The projected shadow was drawn on a sheet of paper placed on the table. The projection area was measured using a planimeter from which the drape coefficient (DC) was calculated as the percentage of the annular ring (between two edges of the sample disc and the flat sample) covered by the draped sample. A sample disc with 18 cm diameter and sample with 30 cm diameter were found to give the best results and were sensitive to a wide range of fabrics from limp to stiff producingDCs from 30% to 98%. Drape coefficient value errors were high at high DC values.

This instrument has an improved optical system (near parallel vertical light) to enable getting amore reliable measurement of the drape coefficient.Therefore, the method of obtaining the vertical projection of the deformed sample was improved.The sensitivity degree of measuring drape was improved due to the use of two different sizes of samples dependent on fabric stiffness. The vertical projection was drawn on paper placed on the table beneath the instrumentby the operator and a planimeter used to measure the area.

This instrument was highly operator dependent, tedious and took a lot of time to get a drawn image of draped sample. Inherent error was found due to the use of the spherical mirror.



(a) (b)

Figure 2.43 An F.R.L drapemeter improved by Cusick in 1962[41], (a) Schematic diagram(b) Photograph(reproduced from [41, 42]

Cusick in 1968 further improved the F. R. L. drapemeter in terms of obtaining more accurate drape coefficients with less tedious and less costly procedures. First, three different sample sizes (24, 30 and 36 cm diameters) were proposed as the smallest and largest samples were more sensitive for limp and stiff fabrics respectively. Second, an alternative less expensive optical system was proposed to replace the previous one. Divergent light from an ordinary light bulb with a mask of a 1 inch diameter hole placed centrally above the sample was proposed instead of the parallel light. He set equations for calculating DC values from practical and theoretical divergent light. According to the comparison between these two equations' results, he found that using the divergent light produce DC experimental values lower than the DC true/theoretical values. A graph was established and used in correction to the true values. He found highly correlated differences between DC diverging light values and each of the true (theoretical) DC values and DC parallel light values. Therefore he proposed that the correction of DC diverging light values to the theoretical true values would be reasonable. However, this correction graph did not produce DC values below 10% and this was found to be impractical.

The third proposal was to use a cut and weigh method to measure the drape coefficient rather than using a planimeter, as using a planimeter needed double checking of the measurement. The weight of a circular paper with a drawn vertically projected shadow was measured (W1) and another measurement was done after cutting along its perimeter (shadow) (W2) and the ratio W2 : W1 was calculated. This drape coefficient correlated strongly with DCs measured using a planimeter employing diverging light [43].

Three improvements were set for this instrument. The sensitivity level of measuring drape was improved due to using three different sizes of samples dependent on fabric stiffness.A cut and weight method was used to compute drape coefficient to eliminate the usage of a planimeter. Divergent light was used instead of parallel light to get accurate projection of the measured sample.

This instrument is operator dependent. However, the planimter was replaced by the cut and weight method, it was more tedious than previous version of Cusick (1962). It takes time to obtain the drape coefficient.

In 2003, Behera and Pangadiya[44]developed a drapemeter with an optical system based on the principle of Cusick's 1962 drapemeter but in a turned over position. This drapemeter was devised with a camera to capture images of tested fabrics. DC results were not significantly different from the conventionally measured DC.

Three British standards published by the British Standards Institution were found for measuring fabric drape coefficient.

1. Method for the assessment of drape of fabrics (BS 5058:1973).
2. Textiles - Test methods for nonwovens - Part 9: Determination of drape Coefficient (BS EN ISO 9073-9:1998)
3. Textiles - Test methods for nonwovens Part 9: Determination of drapability including drape coefficient (ISO9073-9:2008).

These standards were inspired by Cusick's work in 1962 and 1968. The optical system and apparatus were based on Cusick's paper of 1962[41] but in an overturned position as the shadow was cast above the sample on a paper ring placed centrally above the supporting discs (see Figure 2.5~~Figure 2.4~~ **Error! Reference source not found.**). The weigh method was inspired by Cusick 1968[41](an alternative image analysis method was used in BS : ISO9073-9:2008).

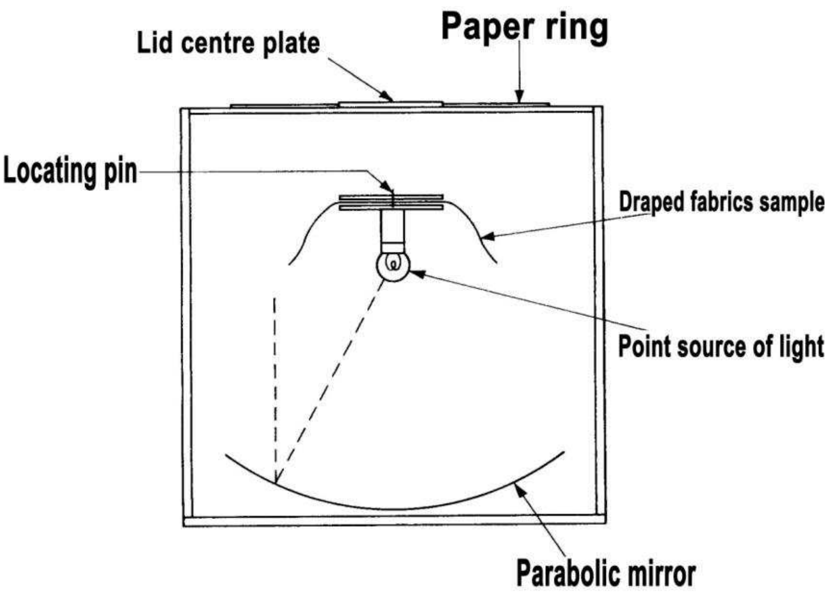


Figure 2.54 Drapemeter used in British Standards with codes: BS 5058:1973, BS EN ISO 9073-9:1998 and BS : ISO9073-9:2008

Fabric samples with corresponding paper rings with different diameters 24, 30 and 36 cm were used. Medium stiffness fabrics (DC between 30 - 85%) were measured using the medium size samples (30 cm), fabrics with stiffness higher than this range were measured using the largest sample size (36 cm) and ones with DC lower than that range were measured using the smallest sample size (24 cm) [34-36]

In the standard concerned with nonwovens drape, it was observed thatthe sample tested behaviour sometimes tended to bend rather than making folds. If this was the case, it was suggested not to carry out the test.

2.1.3 Integrated drapemeters

Limitations, inaccuracy, poor data and tedious measurement using the conventional drape testers encouraged drape researchers to adapt static traditional drapemeters to obtain more data with higher accuracy, reproducibility and ease. Therefore, several adaptations were carried out for conventional drape testers, the most important effective integrations devised forstudying drape were drapemeters integrated with camera systems to capture images for the tested samples and/or rotatable supporting discs.

2.1.4 Image analysis

Researchers investigated the use of image processing technology in studying drape. In this method a digital camera is attached to a drape tester in order to capture images of the draped samples (see Figure 2.6~~Figure 2.5~~). By means of computer software such asdrape shape parameters and otherinformation including drape wave amplitude, wavelength and number of nodes were produced from these images. There are definiteadvantages forstudying fabric drapeability using an image analysis method as it is rapid and easy to carry out multiple measurements. Moreover, it enabled researchers to carry out studies such as fabric drape dependence on time from minutes to hours and investigating drape value instability and repeatability. Studying the relation between the rotation speed of the fabric tested and its drapeability was also facilitated [45-51].

Commented [U49]: Advantages of using image analysis systems

Farajikhah *et al.* studied virtual reconstruction of draped fabric using shadow moiré topography employing front lighting and a linear grating. A captured image's centre and points located in the fringes were determined. The intensity and height of all pixels in the fringes were determined and plotted against the radius of the fabric edges. Using the radius (x), intensity(y) and height (Z) values calculated by given equations, 3D profiles of draped fabrics were generated [52].

An image analysis technique was used in the British Standard: Textiles - Test methods for nonwovens, Part 9: Determination of drapeability including drape coefficient with code number BS EN ISO 9073-9:2008 [34].

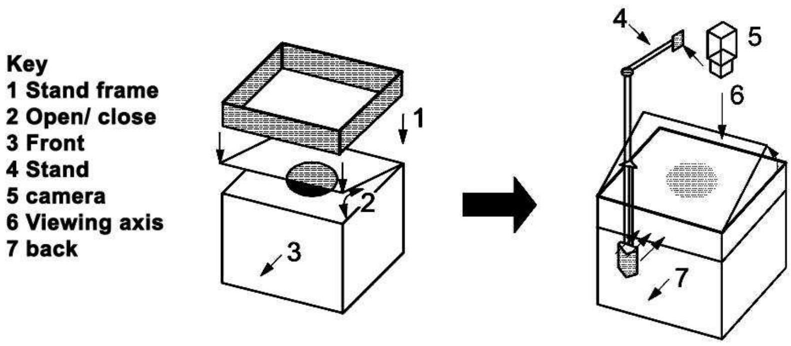


Figure 2.6~~5~~ Tools used in studying fabric drape by image processing technology proposed by BS EN ISO 9073-9:2008

There were two methods of fabric drape image acquisition; namely projection capture and direct acquisition. Tsai *et al.* argued against the accuracy of the first method because the draped fabric shadow was projected on a sheet above it as a single grey scale image, the projected light was not truly parallel which made the edge's points blurry; consequently the obtained contour was not highly accurate. Therefore they proposed an alternative method to enhance the image using the second method (directly acquired images). A backlight was placed underneath thefabric tested to enhance the contrast between the fabric and the background. The captured images were digitised and passed through a number of stages to calculate the drape coefficient. An image segmentation technique was used, the grey scale gradients in the image were calculated which was used to calculate the threshold value (if a pixel's gradient was higher than the defined threshold, it was defined as an edge point). This method exhibited higher speed in finding the image contour and better efficiency in obtaining images with better greyscale contrast which subsequently enhanced the application of image segmentation including calculations of gradient and threshold [50].

2.1.5 Photovoltaic drapemeters

In 1988 Collier and his colleagues developed a photovoltaic drapemeter. A drape coefficient was measured by means of a voltmeter. This drapemeter was a box with the bottom surface made of photovoltaic cells, 2 supporting alternative plates (3 and 5 inch diameters) were centrally placed on a column inside the box and a lid with a light source and a voltmeter [53]. The light source became horizontal and directly above the sample tested when the lid was closed to carry out a measurement and the draped sample blocked the light emitted by this source. The voltmeter attached to this drapemeter determined the amount of unblocked/sensed light by a sample by means of the photovoltaic cells.

Adapting the conventional drape testers with photovoltaic cells allowed measurement of the drape coefficient directly from the machine without any calculations. This instrument's output values (DC) ranged between 0 and 100%. The higher the DC value was, the more drapeable the fabric tested was, as more light was absorbed by the sensitive cells [54].

The tester was calibrated when the fabric tested was changed in order to obviate the effect of fabric opacity on the measurement. The voltmeter was adjusted to 0% when a single layer of the tested sample completely covered the base and 100% when the cells at the bottom were exposed to the light directly without fabric barrier. They used the mean values of two specimens from each fabric with the face up and down. The increased blockage of light due to folded layers of a tested fabric was not considered as a measurement method's limitation, as high fabric drapeability was correlated positively with a high number of folded layers which increased the obstruction of light.

The fabric opacity effect on drape values was tested using a type of fabric in two colours (black and white). As it was important to be sure that the opacity of a tested fabric did not affect the amount of light absorbed by the photocells. A sample tested with any degree of opacity should have blocked the light completely and its drape values differ only due to its shadow area. They found that these two samples were not significantly different with respect to the drape values which indicated good accuracy of this digital photo drapemeter [54].

The advantage of this apparatus was that direct measurement of drape coefficient could be carried out. However, sensitivity and lifespan of the photocells employed waslimited.

2.2 Dynamic drapemeter

Drape researchers were concerned with obtaining drape values which correlated with real fabric drape and movement which encouraged them to start investigating dynamic drape rather than static drape in order to include the body motion aspect in their studies.

Ranganathan *et al.* used a dynamic apparatus to measure fabric drape behaviour in a style simulating the subjective assessment of average customers. Customers are used to assessing fabric drape by observing fabric draped vertically downwards and generating folds. The main aim of establishing this device was to tackle the big sample dimensions of conventional methods used to evaluate the drape behaviour, adopt an economical and efficient test for drape and to generate a test similar to the subjective assessment method which was the main reference assessment method since drape is considered as a quality rather than a quantity.

They were inspired by the shape and dimensions of the sample from bending behaviour and shape of the real folds constructing fabric drape (see Figure Figure 2.7). Half of the sample shape was drawn by marking two vertical parallel straight lines (one of them was at the hidden part of the fold) and connecting them by a curve to make a tapered(nose) shape; this was doubled (folded) to obtain a sample. A needle was attached to the tested sample at the middle bottom of the taper. This needle was used to increase the effect of the fabric bending under its own weight and as an indicator of its response to the test. The sample was clamped in the apparatus and an arm was used to rotate the sample (needle) from 0° (original position) to 45° degrees twice at 5° intervals. The movement of both the arm and the response of the needle (sample) were recorded by means of a protractor to obtain a hysteresis diagram. The maximum value at 45° and the area of the hysteresis loop were used as parameters of drape behaviour. So, this objective method simulated subjective evaluation of drape, measured drape dynamically rather than statically as is the case in the conventional drape test and plotted the results in a simpler way than bending test plots. The handle displacement was plotted against the needle reading rather than plotting the curvature against the couple in bending tests [55].

The measurement process wasinspired by subjective assessment of drape employing folds consisting draped fabric. The collected data and subsequent results would be more related to bending properties rather than 3D deformation produced for textile fabrics. This apparatus would not be reliable for differentiating between paper and fabric. Besides, this apparatus was operator dependent in carrying out the sample preparation, measurement process and obtaining the results.

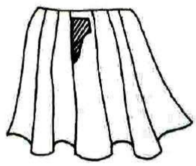
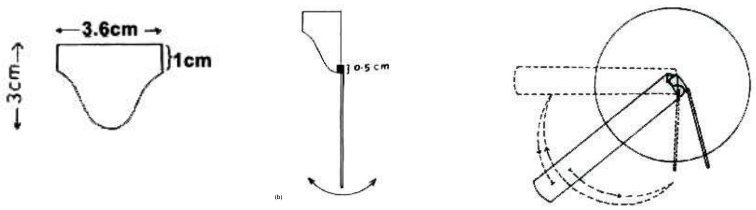


Figure 2.8~~6~~Contour of a specimen on a vertically draped fabric **[55]**.



(a) (b) (c)

Figure 2.9~~7~~(a) sample dimensions, (b) Needle suspended on the specimen, (c)The sample mounted on the apparatus(reproduced from[55]).

Dynamic drape behaviour was studied later using a system consisting of a drapemeter with a circular rotatable supporting disc and image processing devices (CCD camera and PC). The camera used should be able to capture images for the tested sample at very short intervals (perhaps) at every 1/30th second. The range of the revolution speed changed according to the investigation.

Stylios and Zhu indicated the importance of measuring dynamic drape of fabrics, as they found that fabrics had similar static drape behaviour, while they differ in dynamic drape behaviour. The dynamic drape presented the real fabric performance and would help textile, clothing and design workers in quantifying the realistic drape behaviour of fabric. In the Research Centre of Excellence (University of Bradford) a true (static and dynamic measurement system) 3D drapemeter called The Marilyn Monroe meter (M^3) was developed to work on the modelling of the dynamic drape of garments. This device consisted of a CCD Camera, a monitor to display the image, a cabinet with a suitable light system, a computer to process the captured images and a drapemeter with a rotatable supporting disc (43 r/min and 86 r/min) to investigate the static and dynamic drape of the tested fabric.

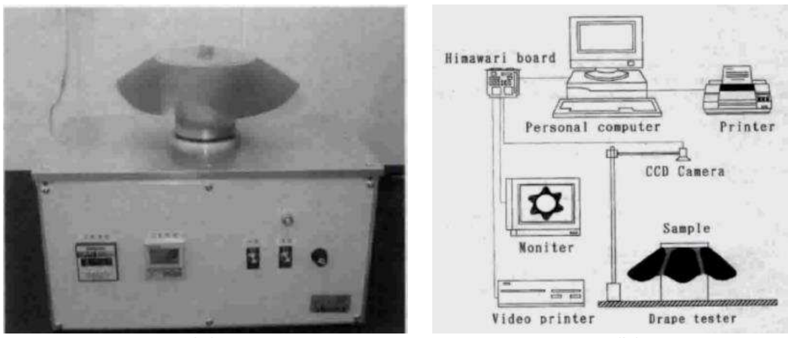
They proposed an efficient parameter correlated with subjective assessment of fabric drape called a feature vector V expressed as $(\bar{p}_{max}, \bar{p}_{min}, S)$, where $\bar{p}_{max}$ was the average of the maximum fold length (peak),$\bar{p}_{min}$is the average of the minimum fold length (trough) and parameter S was an indication of how balanced or even the folds/nodes were (see Equation2.2).

$$S = \sum_{i=1}^{n} \frac{\left(p_{max(i)} \times \bar{p}_{max}\right)^2}{\bar{p}^2{}_{max}} \qquad \textbf{2.2}$$

where: $p_{max(i)}$was the maximum length of the i th fold/node, and $\bar{p}_{max}$ was the average of the maximum length of the folds that make up the drape projection. S was equal to 0 when the folds were even and S was equal to 1 if the variation in the fold length was in the order of a fold length itself(is this correct?). Two more parameters α_{max} and α_{min} were proposed, these were the slopes of lines connecting overhang points on the circular disc and the free ends at maximum and minimum node length respectively. They classified the measured fabrics subjectively into 4 classes used in the clothing industry according to the feature vector results [56].

Commented [U50]: Reference is checked and it was found correct. The word "itself" is added.

Matsudaira and his colleagues proposed studying the dynamic drape behaviour as an alternative approach for investigating fabric drape and published a series of papers focused on this subject. The device and system shown in Figure 2.10~~Figure 2.8~~ (a) and (b) respectively were built to carry out this series of studies. The tester consisted of a circular supporting disc with the same diameter as the Japanese industrial standard drape tester (12.7 cm) and capable of rotating with speeds ranged between 0 - 240 rpm. An image analysis system was employed to capture and analyse the images of the tested samples[57].



(a) (b)

Figure 2.10~~8~~(a) Dynamic drape tester, (b) System of measuring dynamic drape using an image analysis method (reproduced from [57])

Dynamic drape parameters with rotation speed ranging from 0 to 240 rpm with the ability to reverse the rotation direction at an arbitrary angle were developed. The first property was the revolving drape-increase coefficient (DC_r) which presented the overhanging fabric's degree of spreading with increasing rotational speed (presented by the slope of the curve of the relation between revolutions and drape coefficients between 50 - 130 rpm). High DC_r values indicated a fabric's ability to change in response to changes in rotational speed/centrifugal force . The drape coefficient at 200 rpm was selected for the dynamic drape coefficient (DC_{200}) which represented saturation of fabric spreading at rapid speed, because by this point, the change of the drape coefficient became lower than for previous incremental increases. It was observed that the drape coefficient did not reach a maximum even at the maximum revolution speed (240 rpm). It was noted by Matsudaira and Yang 2000[57]that the drape coefficient at the first stage (below 40 rpm) showed similar values to the static conventional drape coefficient DC_s.

Lin et al.[58]studied the dynamic drapeability of four natural fabrics at a wider range of revolution speeds (0 - 450)rpm for a sample disc with 18 cm diameter. Images were captured for fabrics tested at 25 rpm regular intervals. The resultant curve presented the relation between drape coefficient and revolution speed and showed four stages of dynamic drape behaviour by the tangent partition method. These were initial growth, fast growth, slow growth and the last stage was the dynamic stable drape coefficient. Plots of experimental drape coefficients showed that the order of the fabrics was dependant on the revolution speed at which the DC was measured. Their order was changed three times in the fast growth stage and returned to the initial growth order and became stable at the two periods following the fast growth (i.e. slow growth and dynamic stable regions)(is this correct?). The analysis of the results showed that a nonlinear logistic function was appropriate to present the drape coefficient curves throughout the static state and the dynamic stable region.

The Sylvie 3-D drape tester based on 3D scanning of the fabric tested was developed at the Budapest University of Technology and Economics (see Figure 2.11~~Figure 2.9~~). was developed to reconstruct a virtual image for the scanned fabric from which ordinary drape parameters were calculated. Annular supporting discs with 21, 24 and 27 cm were used to exert dynamic impact (similar to the real dynamic effect of a garment) on the fabric tested, which was already supported by a circular disc (18 cm diameter). Using this tester they studied fabric drapeability in terms of effect of composite yarns twisting direction and exerting dynamic effect on fabric tested [59].

Commented [U51]: Reference is checked. It was found correct.

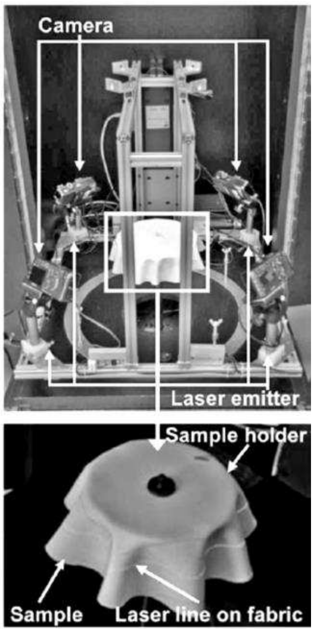
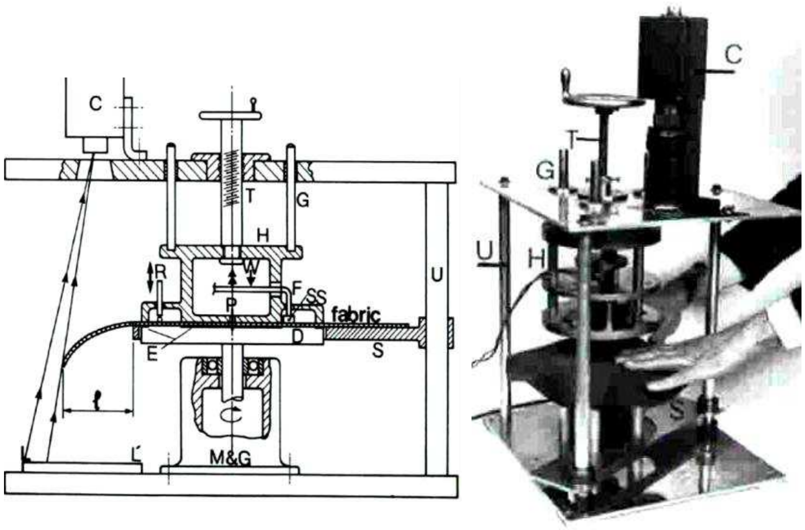


Figure 2.119 Sylvie 3D Drape tester (reproduced from [59])

The reviewed Dynamic drapemeters employed rotatable circular sample discsto simulate real configuration of draped fabric while being worn by humans. However, the high velocity rate (could reach 450 rpm) used by some of these dynamic drapemeters do not replicate normal human body motion.

2.3 Alternative Drapemeter Designs

Hearle and Amirbayat developed a multipurpose fabric tester (see Figure tester was capable of measuring different physical and mechanical fabric properties such as surface properties, drape coefficient, and bending stiffness by means of simple adjustments to its functional parts. A tested sample (24, 30 or 36 cm diameters) was located by pin P centred on a platform which included a supporting disc D with 18 cm diameter. Plate S was lowered to drape the sample freely as it was with the conventional test method disc, 600 readings at regular intervals were recorded for space/distance between the pin and the sample edge PL by camera C fixed above the rotating disc. The readings were used to obtain the projected area of the draped sample from which the drape coefficient was calculated. This device's microprocessor could analyse the resultant values statistically except the drape values (which is an overall property). The absence of the physical contact between the measured sample and the device parts during bending stiffness and drape coefficient tests maintained high measurement reproducibility. Results obtained from this tester showed strong correlation with the conventional method [60].



(a) (b)

Figure 2.12~~10~~(a) Schematic diagram and (b) photo of Hearle and Amirbayat 1988 multipurpose tester of drapeability (reproduced from [60])

According to Mizutani *et al.*, the conventional Japanese drape test (JIS L-1096 1999) included a drape apparatus based on the Fabric Research Laboratories drapemeter features. However, it was adapted to be a closed drapemeter with a 12.7 cm diameter rotatable sample disc. The measurable sample dimension was 25.4 cm in diameter. The tested sample rotated after mounting for 10 seconds at 120 rpm rotation speed to hang down under its own weight. A photoelectric tracing method was used to record the vertically projected shadow of a draped sample.

Mizutani et al. developed a drape elevator to investigate the effect of the initial state of the measured sample on its drape, in addition to the stages of drape generation (see Figure 2.13~~Figure 2.11~~). It is similar to the conventional Japanese drape tester but they replaced the rotatable sample disc with a fixed one and attached an elevator table to it, which was capable of moving downwards and upwards by means of a lever. A test started with both table and disc at the same level and then the operator lowered the table until the tested sample became completely free and hung under its own weight (6.4 cm distance down the sample disc was enough to allow any tested sample to hang down). A digital camera was set above the drapemeter to record and capture the stages of drape generation [61].

Commented [U52]: advantage

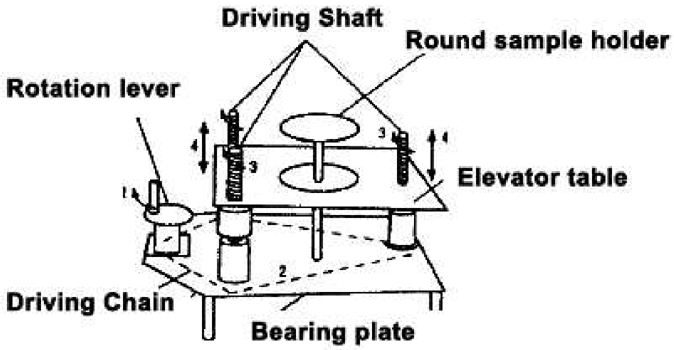
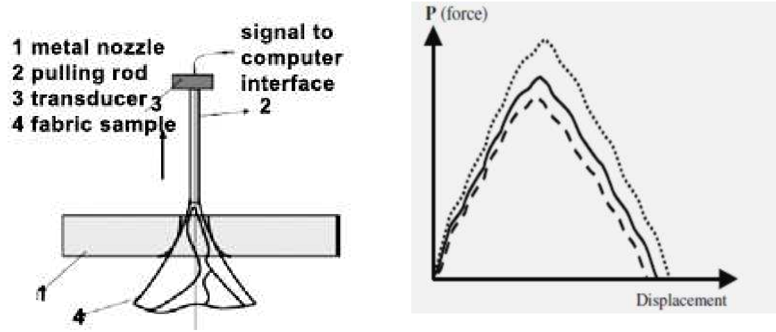


Figure 2.13~~11~~Drape elevator of Mizutani et al. **[61]**

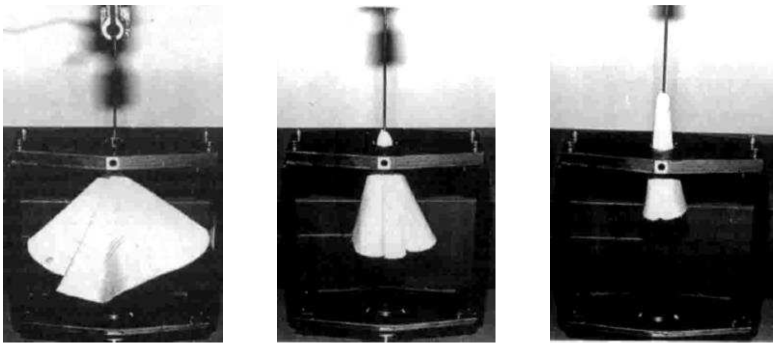
They used their drapemeter to study the stages of drape formation. They determined that there were three stages of drape formation. These were node appearance (early stage), drape growing from the nodes (next stage), stabilised drape (final stage). They proposed that correlation between the drape coefficient and drape formation (shape) during its generation would provide useful data for computer drape simulation to represent reliable virtual drape. The early stage has the most important role to determine the drape characteristics, however the final stage was responsible for the completion of this determination. The drape formation resulted from mutual relationships between the sample weight and bending properties, and the friction between the sample and the elevator table surface (in the drape elevator of Mizutani *et al.*)[61].

Textile researchers were inspired by consumers' (ladies) evaluation for scarf fabrics as they used to pull a scarf through a ring to assess its behaviour. In this test, the fabric is subjected to multi deforming stresses: tensile, shear and bending. This test produced a load- displacement extraction curve and the peak or slope at certain points were used to compare between fabrics. Researchers correlated fabric drapeability with its hand property measured by their developed fabric extraction test apparatus and programme (see Figure 2.14~~Figure 2.12~~ and Figure 2.15~~Figure 2.13~~) [62, 63].



(a) Fabric extraction technique (b)Force displacement curves for 3 different fabrics

Figure 2.14~~12~~Pan's system for measuring fabric hand [64]



(a) Handle force device on tensile tester (b) Initial portion of fabric specimen being withdrawn through the ring (c) Later portion of fabric specimen being withdrawn through the ring

Figure 2.15~~13~~Stages of extraction tests used by (reproduced from[62])

Cassidy in 2002 proposed an alternative method for measuring fabric drape using an Instron tester. In this method a circular sample is supported between two discs, one of them is movable vertically by means of the Instron cross head and the other disc holds the sample tested and is considered the raised solid platform. A load-displacement graph was used to measure the drape behaviour of measured fabric. The area under load - displacement curve of fabric measured was compared with the areas under load displacement curves calculated for theoretical perfect flexible and perfect stiff fabrics. This method had significant correlation with the traditional DC ($r = 0.83$, $p<0.01$)[19]. Drape parameters

Since, fabric drape is a quality rather than a quantity, workers in apparel design and garment-making depend on subjective assessment to evaluate it. Researchers concerned with drape have long been working on developing objective drape parameters due to errors that may arise in subjective evaluation. They aimed to find parameters which could be reliable and representative of fabric drape. These parameters were highly related to the drapemeter used and its features (parts integrated to it). Conventionally, a drape coefficient has been used to determine fabric drapeability. While integrating, devising and/or adjusting the conventional drapemetres allowed drape researchers to develop alternative parameters.

3.02.4 Drape coefficients (DC)

Generally, drape coefficient was used as the traditional fabric drape parameter. It is expressed as the ratio of a draped fabric's shadow when it is partially supported to its undeformed flat state in terms of area. This ratio was calculated using weight or area units measured by a planimeter [37], weight [43], image processing software [65] or photosensitive cells [54]. It basically ranges between 0 – 100%.

Alternative drape coefficients were developed and considered as adjusted coefficients from the original drape coefficient of Chu *et al.* 1950.

Vangheluwe and Kiekens in 1993 were the first researchers to use the number of pixels to calculate a drape coefficient using image processing software. Images were captured for fabric tested, transferred to acomputer, its dimensions were calibrated(should this be calculated?) and the shadow was traced. DC was calculated as the ratio of the area of the annular paper ring covered by a draped sample shadow to the annular paper area (both of them expressed in the number of pixels [65]. This method was used by further researchers [66].

Commented [U53]: Yes, it should be calibrated in terms of size.
If the actual diameter of the captured fabric is 30 cm, it should be of this diameter on the computer.

In 1998, Jeong argued against the accuracy of Vangheluwe and Kiekens's method, as different drape coefficients resulted for similar shapes with different directions relative to the camera. The difference increased as the shape became bigger or more uneven. He proposed an alternative approach as the captured image was digitised, thresholded and processed by the closing operation. The image analysis system detected the edges of the circular plate and shadow of the draped fabric. The drape coefficient was calculated using these boundaries (see Equation 2.31):

$$\mathrm{DC} = \frac{\text{Fabric's shadow area} - \text{support disc's area}}{\text{the area of the region outside the supporting plate} - \text{support disc's area}} \times 100 \qquad \textbf{2.41}$$

This method showed good correlation with the cut and weigh (conventional) method and high repeatability [47].

Frydrych *et al.* used the Polish standard for measuring the fabric drape coefficient (K). It was defined as the ratio of the area between two edges of the original and the draped sample's shadow to the area of its flat unsupported part (0.027 m^2). It was calculated according to Equation 3.2.

$$K = \frac{\pi r^2 - s}{\pi (r^2 - r_1^2)} \times 100 \qquad \mathbf{3.2}$$

where, S is the sample's shadow area (m^2), r_1 is the radius of the disc supporting the sample (0.035 m), r is the sample's radius (0.1 m). This ratio was considered to be more comprehensive than the conventional DC as it correlated directly with fabric drapeability (subjectively assessed?). It increased with the fabric drapeability which was the opposite of the conventional drape coefficient which decreased for highly drapeable fabric [67].

Gider developed an alternative approach for measuring drape coefficient. The drawn shadow of a draped sample was scanned using a 2D digital scanner after reducing its scale to 70% on a photocopying machine to fit on the scanner pad. After that, the image was exported to Photoshop software to calculate the drape coefficient by counting the number of pixels which occupied the area of the projected shadow and divided it by the flat specimen area expressed in number of pixels [31].

Kenkare and Plumlee modified the digital calculation of drape coefficient and applied Equation 3.3 **Error! Reference source not found.**[49].

$$DC = \frac{\text{Total shadow pixels} \div \text{pixels/cm}^2 - \text{area of supporting Disc(cm}^2\text{)}}{\text{Area of the specimen (cm}^2\text{)} - \text{area of supporting Disc (cm}^2\text{)}} \qquad \mathbf{3.3}$$

~~3.1~~2.5 Static drape profile/image analysis

Drape researchers aimed to obtain more representative drape parameters. Further analysis of the draped fabric shadow image was their approach to generate their proposed parameters.

In 1960, Chu *et al.* indicated that one of the most important aspects of understanding the drape mechanism was studying fabric drape geometry; i.e. the draped sample shadow configuration. The drape diagram (a projected two-dimensional simplification of the three-dimensional draped sample) contains three items of significance: the area, the number of nodes and the shape of the nodes. The area is the basis of the drape coefficient F and the nodes or pleats formed in a draped sample by virtue of the buckling of the material. It was observed that the number of nodes within any particular

Commented [U54]: This refers to Dc measured using either cut and weight method or digital method.
This is the DC used by most of the researchers, that is why it is called conventional.

sample correlated directly with DC for a given test condition. They induced that drape profile/geometry could be easily predicted from the drape coefficient [68].

Hu and Chung determined and compared the drape behaviour of seamed woven fabrics in terms of drape coefficient, node analysis and drape profile. The variability of the number of nodes was used as an indicator of fabric drape stability. Regularity of node arrangement, their orientation, location and highest and lowest node length were proposed as drape parameters [69].

Rodel *et al.* characterised the drape configuration by area, form and amplitude of the folds, the number of folds and their position with regard to warp and weft directions [70].

Jeong proposed "Drape distance ratio" as an alternative measure of drape. It was based on distance whereas the drape coefficient is based on area. It increased as a fabric become more flexible and was calculated using Equation 3.4.

$$R_d = \frac{r_f - r_{ad}}{r_f - r_d} \times 100 \qquad \textbf{3.4}$$

where R_d was the drape distance ratio, r_f was the radius of the undraped sample, r_{ad} was the average radius of the draped sample's profile and r_d was the radius of the supporting disk. He deduced from this study that the drape coefficient was not a sufficient parameter in establishing an objective index for drapeability as garment drape was affected by different factors which should be involved in characterising fabric drape. There were geometrical factors affecting drape such as the number of nodes and the curvature of the draped fabric. It was preferred to use the node distribution to characterise the drape profile [47].

Four virtual parameters were used by Stylios and Wan to define the drapeability of textile materials as follows: virtual drape coefficient, drape fold number, fold variation, and fold depth [71].

Robson and Long used imaging techniques to analyse fabric drape profile. Fabric drape profile was transformed from r - θ polar coordinates into x - y coordinates. The nodal configuration was characterised by automatic measurement of: number of nodes NN, mean node severity MNS (node height/node width) (similar to Chu *et al.*'s 1960 "shape factor"), the variability of node severity VNS and circularity of the drape profile. Strong correlation was found between DC and circularity CIRC and the mean node severity. Node severity was found to be strongly and inversely related to DC. The DC was not found strongly correlated with the number of nodes and variation in node severity parameters which were poorly correlated between themselves. Measurement of these three parameters (DC, NN and VNS) in combination provided an excellent description of fabric drape profile, with potential application in a number of garment design and assembly areas. A DC value essentially provides information concerning the overall degree of drape, whereas the NN and VNS values gave more detailed information concerning the nature of the drape pattern [72].

Behera and Pangadiya proposed using a combination of drape parameters namely: Drape coefficient, average, maximum and minimum radius, drape distance ratio (DDR) (see Equation 3.5), amplitude to average radius ratio(ARR)$\left[\frac{A}{\bar{r}}\right]$, number of nodes and fold depth index (FDI) (see Equation 3.6).

$$DDR = \frac{r2 - rs}{r2 - r1} \quad \textbf{3.5}$$

$$FDI = \frac{r\,max - r\,min}{r2 - r1} \quad \textbf{3.6}$$

where $r1$, $r2$, rs, $\bar{r}$, were the radii of the supporting disc, flat sample, draped sample, average of draped sample and A was the amplitude $[r\,max - r\,\min/2]$[44].

Ucar *et al.* investigated the drape behaviour of seamed knitted fabrics using image analysis in terms of drape coefficient, drape profile and node analysis [51].

Jevšnik and Geršak investigated using a finite element method for fused panel simulation. Experimental drape parameters including drape coefficient, number of folds, minimum and maximum amplitude and the distance between folds, fold distribution G_p(see Equation 3.7) were used.

$$G_p = \sum_{i=1}^{n} \frac{\left(l_{G_{max}(i)} \bar{l}_{G_{max}}\right)^2}{\bar{l}^2_{G_{max}}} \quad 3.7$$

New parameters were proposed (see Figure 2.16~~Figure 3.1~~); namely Maximum hang of fabric sample f_{max}(Equation 3.8), Minimum hang of fabric sample f_{min}(Equation 3.9) and the fold depth d_G, where $l_{G_{max}}$ was the maximum depth of the fold and$l_{G_{min}}$(Equation 3.10) was theminimum depth of the fold and p was the perimeter/length of the circular sample (60 mm) draped over the pedestal. There was similarity between virtual and experimental fabrics. Moreover, rheological parameters: Young's and shear modulus in warp and weft directions and Poisson's ratio were used [73].

$$f_{max} = \sqrt{p^2 - (l_{G_{min}})^2} \quad 3.8$$

$$f_{min} = \sqrt{p^2 - (l_{G_{max}})^2} \quad 3.9$$

$$d_G = l_{G_{max}} - l_{G_{min}} \quad 3.10$$

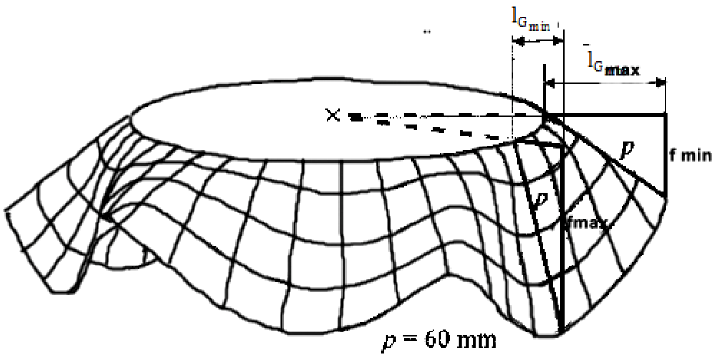


Figure 2.161Jevšnik and Geršak drape parameters **[73]**

Mizutani *et al.* proposed an alternative drape shape parameter (R) gave a value for the complexity degree of tested sample drapeability with positive correlation between them. This parameter characterised the drape behaviour of fabric clearer than the drape coefficient only. It was calculated using Equation **3.11**.

$$R = \frac{\sqrt{\overline{(r - r_0)^2}}}{r_0 - r_s} \quad 3.11$$

where:$(r - r_0)$was calculated along the whole contour of the drape projection,r, $r_0$andr_s were radial coordinates of the drape projection, the radius of a circle with an area equal to that of the drape projection, and the radius of the sample holder [61].

Kenkare and May-Plumlee used the number and dimensions of nodes as alternative parameters to drape coefficient to quantify drape [49].

Jevsnik and Zunic-Lojen proposed using the maximum amplitude of folds $I_{G_{max}}$, minimum amplitude of folds $I_{G_{min}}$ and the angle between two neighbouring peaks of the folds α_i to measure drape[74].

Ngoc and Anh measured fabric drape coefficient and drape profile using a Cusick drapemeter. To compare between measured fabrics, the displacement of the folds were measured on the original drape profile at 32different angles at regular intervals to convert them into x (angle), y (fold's displacement) coordinates [75].

Behera and Pattanayak used MATLAB software to write a programme in order to calculate a combination of parameters including: drape coefficient, drape distance ratio, amplitude to average radius ratio, number of folds and fold depth index. This measurement was based on an Indian standard [45].

The British Standard for determination of drapeabilty of nonwovens describes using image processing technology to analyse fabric drape. The contour of two-dimensional monochrome images of draped shadows were firstly transformed into polar (θ, r) coordinates and then transformed into an x, y chart. The X-axis gives the angle in degrees (θ) from 0° to 360°, from the baseline passing through the centre of the circle, and the Y-axis gives the amplitude (r) in centimetres. The shape parameters of a two-dimensional geometric drape model were defined as the number of nodes (waves or folds), the positions of nodes, wavelength and amplitude data [34].

Shyr *et al.* transferred fabric drape image to fabric drape profile using Matlab® software. The pixels making up the boundary of the silhouette of a drape profile were converted into drape profile coordinates (x_m, y_m). These coordinates were then substituted into a drape profile ratio formula, which converted the drape profile coordinates into the corresponding drape profile locations (p_m, v_m) in a clockwise direction starting at 180°. Calculation of the fabric drape profile ratio yielded a drape waveform diagram. The drape profile ratio DPR was calculated as the ratio between the distance from a small disk's edge to the margin of the draped profile and the difference between the radii of the large and the small disks using Equation **3.12** .

$$DPR = \frac{r - r_0}{r_f - r_0} \qquad 3.12$$

where r was the distance from the drape profile's edge to the origin, r_0 was the radius of the small disk (9 cm) of the drapemeter and r_f was the radius of the circular fabric profile (15 cm) [76].

Al-Gaadi et al. studied fabric drapeability using drape parameters including: drape coefficient (DC), drape unevenness (DU), number of waves/nodes, maximum amplitude, minimum amplitude and the deviation of amplitudes. Drape coefficient (DC) was calculated using Equation **3.13** **Error! Reference source not found.**.

$$\mathrm{DC} = \frac{\mathrm{A_r} - \pi \mathrm{R_1}^2}{\pi \mathrm{R_2}^2 - \pi \mathrm{R_1}^2} \times 100 \qquad 3.13$$

where $\mathrm{A_r}$ was the area of the draped fabric's projection, $\mathrm{R_1}$ was the radius of the sample disc and $\mathrm{R_2}$ was the radius of the flat fabric. The drape unevenness (DU) was calculated using Equation **3.14** .

$$DU = \frac{\sqrt{\frac{\sum_{i=1}^{n}(WL_i - \overline{WL})^2}{n-1}}}{\overline{WL}}, \quad 3.14$$

as follows: where WL_i was the central angle between two adjacent maximum amplitudes (i.e. the wave length of single waves), $\overline{WL}$ was the average central angle on one wave (i.e. average wave length, $\overline{WL} = 360/n$) and n was the number of waves. DU had a reverse/negative relation with drape profile evenness [59].

3.22.6 Fourier analysis

Fischer *et al.* developed a program to use Fourier analysis to interpret drape profile geometry. They proposed using the resultant Fourier coefficients as alternative drape values to obtain information about the drape profile in terms of wave amplitude, number of waves and the curvature of the waves [77].

Behera and Pangadiya studied the correlation between drape coefficients measured using different image analysis techniques. Pixel counting (number of pixels occupying a draped fabric shadow), boundary approximation (area of the shadow calculated using its edge's points at 10 or 1 degree(s) interval 36 or 360 points respectively). Fourier approximation and conventional methods were compared. The first two techniques showed significant differences. The pixel count method and the conventional method showed good correlation and agreement. The image processing methods showed lower variation than the conventional method. The pixel count had higher variation than boundary approximation and the Fourier series methods [44].

Sharma *et al.* in 2005 studied fabric drape using Fourier analysis software. The following drape values: Drape coefficient, number of nodes, minimum, maximum and average radius, and average amplitude were obtained from resultant Fourier coefficients [78]

Kokas-Palicska *et al.* proposed using a spectral function (x *wavelength*, y *wave amplitude*) resulting from a Fourier transform for drape projection as an easy and fast approach/method for drape comparison. This approach was tested on fabrics treated with a soft finish and showed efficiently the effect of that treatment [79].

British Standard (BS EN ISO 9073-9:2008) proposed using Fourier analysis in studying drape. Fourier transformation was conducted for the Cartesian plot which presents transformation of the original polar plot of the drape profile. An ideal wave was reconstructed using the dominant wave resulting from a Fourier transform. Fitness factors were proposed to verify the fit of the Fourier transformation and to determine the dominant wave, expressed as percentages. These were ratios of the following (Equations **3.15** and **3.16**).

$$\text{Fourier transform/original} = \frac{B_f}{B_0} \times 100 \quad 3.15$$

$$\text{Dominant/original} = \frac{B_d}{B_0} \times 100 \quad 3.16$$

where: B_0 was area of the original captured draped image, B_f was the B_0 Fourier transformed shape, B_d was the ideal shape recomposed from a determined dominant wave [34].

~~3.3~~2.7 Standard Drape Values

Measurement of a parameter or property should be carried out several times for statistical requirements. It is necessary to measure drape values several times to obtain reliable and dependable results. But how many tests (drape values) are required and what number of nodes represent the drape value?. Jeong proposed what was called the standard drape values. These were the values with the most frequent number of nodes obtained, since the variation of the drape values within the same node was not large/high. It was found that the deviation of drape values for each number of nodes was smaller than the variance of the whole measurements (entire node set), this may be due to hysteresis of fabric shear and bending. This indicated that the number of nodes affected the drape values. Fabrics with high sensitivity to the tests should be measured more times than those with lower variance. At this point the importance of the image analysis method was revealed as this investigation was so tedious when carried out by the conventional cut and weigh method [47].

~~3.3.1~~2.7.1 Measurement of number of nodes objectively

Since subjective node numbers were determined by visual judgment of a drape image, different results could be obtained by different personnel. The increased inconsistency of the subjective assessment of nodes number encouraged Shyr *et al.* to develop an objective approach for this measurement/test.

Fabric drape images were converted into drape profiles with (x, y) coordinates for all boundary points which were illustrated in a wave form to calculate the threshold node (TN) value. The objective node numbers were determined by the threshold node value resulting from Equation **3.17** (should this be equation 18?), the distance between peak and trough (P – T) > TN,a node was defined as in Equation **3.17**.

$$TN = \bar{x}_{(p-T)} - z_{(1-\alpha)} \times s_{(p-T)} \quad 3.17$$

where: TN was the threshold of the node, $\bar{x}_{(p-T)}$was the sample mean of the difference between peak and trough, $z_{(1-\alpha)}$was the (1 – α) percentile of a standard normal variable, and $s_{(p-T)}$was the sample standard deviation [76].

> **Commented [U55]:** Equation 18 is $\frac{\text{Dominant}}{\text{original}} = \frac{B_d}{B_0} \times 100$.
> This equation is 19.

3.3.22.7.2 Dynamic drape parameters

Some researchers proposed that static drape values which had been used traditionally in studying fabric drape behaviour were insufficient and did not represent the actual motion of a fabric in a garment which is produced during the natural draping of clothes. Therefore, they proposed that studying the dynamic drapeability of fabrics was more representative and could show the actual dynamic real- life performance [80].

The importance of the dynamic drape coefficients developed by Yang and Matsudaira in 1999 was evident in the investigation of different types of shingosen fabrics (distinctive Japanese polyester woven fabrics). However, there was no difference found in DC_s and the number of nodes between different fabrics tested (fabrics tested were subdivided according to fibre production, yarn processing and fabric finishing), significant differences were found between the groups when measuring DC_r and DC_{200}, as the differences became clearer in the dynamic drape parameters. The DC_r of one group (peach face type) was higher than another group (new worsted type), this relation was reversed at DC_{200}. This indicated that these parameters were important in investigating fabric drape especially fabric in garments as wearing clothes includes movement (walking) [57].

A dynamic drape coefficient with swinging motion (D_d) was proposed as it could better simulate actual body motion and was more akin to apparel appearance in use. The sample was subjected to a rotation velocity of 8.4 radian/second, the projected area of the tested sample increased to reach the maximum and then decreased to the minimum when it reached the set angle (the turn-around angle).D_d was calculated as the change of the projected area at the turn around angle (see Equation 3.18).

$$D_d = \frac{S_{Max} - S_{Min}}{\pi R_1^2 - \pi R_0^2} \times 100 \qquad 3.18$$

where:S_{Max}=maximum projected area at the turn-round angle, S_{Min}=minimum projected area at the turn-round angle, R_0wasthe radius of the circular supporting stand and R_1 was the radius of the fabric sample [81].

In 2003, Matsudaira and Yang characterised 5 groups of silk woven fabrics which were classified on the basis of yarn structure using static and dynamic drape coefficients (DC_s, DC_r, DC_d, DC_{200}) and the number of nodes. Differences between the fabrics tested became clearer by using a function of the combination of these five parameters produced by discriminate analysis [82].

Tandon and Matsudaira developed a new parameter "Index of Drape Fluidity (I)" which expressed the drape fluidity better than static and dynamic drape parameters (see Equations 3.19- 3.21). This was the ratio of the dynamic drapeability to the static drapeability as static drape coefficient was separated from the dynamic drape coefficient values. The higher the I value was, the softer fluid drape the measured fabric displayed.

$$I_r = DC_r/DC_S \qquad 3.19$$

$$I_{200} = DC_{200}/DC_S \qquad 3.20$$

$$I_d = DC_d/DC_S \qquad 3.21$$

where: I_r,I_{200}, I_d were ratios of the relative dynamic drape parameters D_r, D_{200} and D_d respectively to the static drape parameter.

As the coefficient of variation CV% was used to measure the drape coefficient's dispersion within a group of fabrics. The higher the CV% was, the higher the sensitivity to differentiate between fabrics within one group. I_r, I_{200}, I_d showed significantly higher CV% values than the relative D_r, D_{200} and D_d which indicated that these new parameters significantly distinguished between different fabrics [83].

Shyer *et al.* used a new automatic dynamic drape measuring system employing an image analysis technique to measure the static and dynamic drape coefficients of four different woven fabrics (cotton, wool, linen and silk). Their system integrated a Cusick drapemeter with a rotatable supporting sample disc, its speed reached 125 rpm. The correlation between the static (DC_0) and the dynamic drape coefficients at four different speeds (50, 75, 100 and 125 r. p. m.) were studied. The results showed that the drape coefficient increased significantly with the rotating speed. There were high correlations between static DC_0 and dynamic drape coefficients at low rotating speeds (DC_{50} and DC_{75}).There was still a good correlation between the dynamic drape coefficients at high rotating speeds (DC_{100} and DC_{125}). There was poor correlation between the dynamic drape coefficients at high and low rotating speeds. So, they used the DC_0 and DC_{100} as representatives for static and dynamic drape coefficients respectively in studying the effect of mechanical properties on drape coefficients. DC_0 of cotton and linen fabrics were higher than wool fabrics, the latter (wool) showed higher incremental rates with revolution speeds [80].

~~3.3.3~~2.7.3 Garment drape parameters

Moore *et al.* photographed and characterised the drape profiles of four-gore skirts worn by a mannequin suspended from the ceiling. The photographed pictures were digitised. The digitised data included the area of the profile of each quadrant, the distance between the apexes of adjacent nodes, the maximum distance in each quadrant between node apexes and the intersection of the axes, and the asymmetry of the right and left sides of the profile [84].

Kenkare studied the evaluation and presentation of garment drape virtually. Three drape parameters were developed: garment drape coefficient (GDC) (Equation **3.22**), number of nodes (NN) and drape distance coefficient (DDC). The amount of garment drape was defined using the first two parameters while the last represented the lobedness of garment drape. These parameters were used to compare virtual and actual garment drape (measured using a 3D scanner).

$$GDC = \left[\frac{\text{Volume of the draped garment}}{\text{Full geometrical volume of the garment form}}\right] \times 100 \qquad 3.22$$

The garment's waist line and hem line contours were projected on the bottom surface to obtain a diagram with which the ratio DDC was calculated (see Equation **3.23**).

$$DDC = \left[\frac{\sum Y_i}{n} \Big/ \frac{\sum X_i}{n} \right], \quad 3.23$$

where: Y = maximum distance of a node from the edge of the waistline contour, X = minimum distance of a node from the edge of the waistline contour, n = number of nodes [85].

3.3.42.7.4 Summary of Fabric Drape Measurement Methods

Drape is a quality which describes an important visual aspect of fabric and garment properties. Textile researchers have been working for a long time on fabric drape measurement. Generally, there were two approaches to evaluate fabric drape, objectively by measuring either fabric physical and mechanical properties related to drape namely shear, bending, and weight or drape values/attributes on a drapemeter or subjectively to relate it with the end-use product [39, 40]. However, validation of the objective measurement of fabric drape was carried out by correlating the developed method with subjective assessment as drape is basically a quality rather than a quantity. The first 3D drapemeter was introduced by the Fabric Research Laboratories in Massachusetts in 1950. Cusick in 1962, 1965 and 1968 contributed to drapemeter development and carried out significant improvements. Three British Standards concerned with drape measurement, namely, BS 5058:1973, BS EN ISO 9073-9:1998 and BS EN ISO 9073-9:2008 were based on Cusick's work. Researchers worked on adapting the original drapemeter to obtain detailed data with high accuracy, repeatability and ease. Therefore, several adaptations were carried out for conventional drape testers, the most important effective adjustments for studying drape included devising drapemeter with camera to capture images for the tested samples and/or a rotatable supporting disc (dynamic drapemeter). The basic drape parameter is Drape coefficient. It is measured as the percentage of 2D projection of draped fabric in its flat state. Alternative drape parameters were developed including: Drape distance ratio (DDR), Drape profile ratio, Fold depth index, Drape profile circularity (DPC), Node number (NN), Wave amplitude, Wavelength, Amplitude to wave length ratio, Amplitude to average radius ratio, Drape profile evenness, Fourier transform to original ratio and dominant to original ratio. In Table 2.1 drape researcher contributions to development of drapemeters and parameters are stated chronologically and are classified according to the level of achievement/ progress using the colour system of the taekwondo belt . The black is the highest level of progress and the green is the least from the.authors'assessment.

Table 3.1 Drape researchers contribution to development of drapemeters and parameters

Significant progress ← Minor progress

Developer/Researcher	Achievement	Progress
Peirce 1930	First parameter (BL) for measuring fabric drapeability	
Chu *et al.* 1950	First 3D drapemeter (F.R.L.), drape coefficient and an improved F.R.L. (scanning fabric edge using optical system)	
Chu *et al.*. 1960	Drape shape parameters (Area, NN, nodes shape)	
Cusick 1962	Further improvement for F.R.L. drapemeter	
Cusick 1968	Standard samples, cut and weigh method and improved optical system	
BS 5058:1973	Cusick proposal for measuring fabric drape was applied	
Ranganathan *et al.* 1986	Measurement of dynamic drape using small sample making a node/fold	
Collier *et al.* 1988	Photovoltaic drapemeter and a comprehensive digital DC	
Hearle and Amirbayat 1988	Multipurpose fabric tester	
Vangheluwe and Kiekens, 1993	First digital DC using number of pixels	
Moore *et al.* 1995	Garment drape parameters (four gore skirt)	
Stylios and Zhu 1997	Investigating dynamic drape using Marilyn Monroe meter and Feature vector parameter	
Jeong, 1998	Alternative digital DC and New parameter "Drape distance ratio"	
Hu and Chung 1998	Number of nodes variation (drape profile stability),Nodes arrangement, greatest and smallest nodes length and their position	
Stylios and Wan 1999	Fold Depth Index, Alternative fold variation parameter	
Fischer *et al.* 1999	Fourier coefficients as drape parameters	
Matsudaira and Yang 2000	Dynamic drapemeter and parameters	
Robson and Long 2000	Mean node severity, variability of node severity, circularity	
Frydrych *et al.* 2003	More comprehensive DC	
Behera and Pangadiya 2003	Minimum, average radius, amplitude/average radius	
S. Jevšnik and J. Geršak 2004[73]	Max and Min hang of fabric and amplitude, fold depth, wavelength	

Gider 2004	Alternative method for measuring DC	
Mizutani *et al.* 2005	Drape elevator (drape stages), complexity degree of drape profile parameter	
Kenkare and May-Plumlee 2005	Alternative digital DC	
Sharma *et al.* 2005	$\text{Alternative Amplitude} = \frac{\text{ri max} - \text{ri min}}{2}$	
Kenkare 2005	Garment drape parameters	
BS EN ISO 9073-9:2008	Most dominant wave amplitude, amplitude average and variance, Fourier analysis for measuring drape, Fourier transform/original ratio, Dominant/original ratio	
Shyr *et al.* 2009	Drape profile ratio, measurement of number of nodes objectively	
Al-Gaadi *et al.* 2011	Evenness of nodes distribution parameter	

43 Factors Affecting Fabric Drape

Textile and apparel researchers have been (for a long time) interested in identifying the different factors and their correlation with fabric drape behaviour as this is arguably the most important influence on garment appearance and comfort.

Commented [R56]: Why? It may be useful to add a sentence here to qualify its importance

4.13.1 Fabric Composition and Structures

Backer found that yarn properties and fabric structure affect fabric drape [86]. This means that fabrics with different yarn count and/or structure would produce different drape behaviours.

Werner and James compared the drapeability of different woollen fabrics made from fine and medium wool fibres. Fine woollen fabrics had higher drapeability than medium fabrics [87].

Fabric drapeability was found to have a positive relationship with yarns' float lengths while having an inverse relationship with both cover factor and yarn diameters [68]. Fibre cross-sectional morphology was found to have a good impact on fabric drape behaviour. Chu *et al.* developed a formula for the relation between three physical parameters affecting drape in terms of drape coefficient (see Equation 3.14.1).

Commented [U57]: This reference is taken out of the referencing list as well.

Commented [R58]: If this is by Werner and James, then this paragraph needs linking to the previous sentence.

Formatted: Font: Not Bold, Check spelling and grammar

Formatted: Font:

Formatted: Font: Not Bold, Check spelling and grammar

$$DC = f(EI/W) \qquad 3.1$$

where the function f can involve interactions in these parameters between the warp and filling systems, E is Young's modulus, I is the cross-sectional moment of inertia, W is the weight and EI is the bending stiffness [68].

Elder *et al.* found that the drape coefficient could be used as a fabric handle parameter/index as it (DC) was correlated strongly with bending length and flexural rigidity which were considered as handle properties [88].

From 1990 to 2010 the following research on fabric composition and structures has been carried out. According to Collier in 1991, researchers found that thickness and weight properties characterise and affect 3D materials. Collier did not find that they have an impact on fabric drape behaviour, which made him consider fabric as a 2D planar structure material rather than 3D planar [54].

Matsudaira *et al.* investigated the impact of ratio of polymer to space in the fibre cross-section on fabric mechanical properties. They found that the greater the space ratio in the fibre cross-section was, the softer, more deformable, unrecoverable and inelastic the fabric was. However, the fibre assembly structure (yarn density and count) had higher and more significant impact on fabric mechanical properties than fibre cross sectional shape [89].

Hu *et al.* found that the drape profile of woven unsewn fabrics became clearer, more stable and had better fold arrangement as the difference between warp and weft bending rigidity and fabric thickness increased. In seamless fabrics, two nodes always existed in the warp direction as it had higher BR than the weft direction [90].

Jeong and Phillips in 1998 studied the effect of fabric physical (construction) properties namely; cover factor, yarn interaction, and weave crimp and tightness (compactness) on fabric drapeability. The cover factor was found to decrease the drapeability (drape distance ratio DDR) while increasing the bending rigidity and both correlations were strong. The effect of yarn interaction on fabric drapeability was studied using two types of 3/3 (with constant cover factor) and 4/4 (with similar cover factor) twill fabrics. In the first group the fabrics had similar bending rigidity and different shear rigidity; this produced a large difference in fabric drapeability. However in the second group, the fabrics had similar shear rigidity and different bending rigidity, this produced insignificant differences in drape values. This means that differences in drape behaviour were due to changes in shear rigidity which is a result of different yarn interactions. They found positive strong correlation between the weave crimp and tightness and the bending rigidity which affected the fabric drapeability negatively. They found that increasedcover factor increases the instability of fabric drape [48].

Kim and Slaten found that the conventional drape coefficient correlated strongly with fabric handle measured by the extraction method. In this test a circular sample was passed through a nozzle mounted on a tensile tester in 4.5 mm/min to produce a load-displacement curve. The drape coefficient was responsible for 93% of variances in fabric hand evaluation which means that it was the most relevant fabric parameter to represent hand as evaluated by the extraction method [63].

Frydrych *et al.* studied the effect of the weave type and weight of fabrics on the drape coefficient measured. High drape coefficients were produced for fabrics with skew weaves and low weight. Anyinfluence of fabricthickness on the drape coefficient was not found [91].

Matsudaira and Yang determined that a yarn weave density effect was obvious in D_d, D_{200} and D_r (dynamic drape parameters) and did not significantly affect the D_s and had no impact on NN. They found that dynamic drape parameters of high density fabrics were very sensitive to changed weave density[92].

Commented [R59]: Would these developments benefit from being presented in a summary tabular format, with the year, the development and those responsible listed? This could also include a note on their significance. This would provide a clear narrative timeline for the reader.

Sidabraitė and Masteikaitė studied the effect of the anisotropic behaviour of woven fabrics on drape. High correlation was found between the polar diagrams plotted using BR values and experimental drape profiles. The relation between BR in warp and weft directions was expressed by the ratio of B_L / B_C (B_L and B_C are the bending rigidity in the lengthwise and crosswise directions respectively). This ratio illustrated the anisotropy level and shape of BR polar diagrams which were repeated by drape profiles for the same measured fabrics. Three different shapes were found for bending rigidity polar diagrams and drape profiles according to this ratio: If $B_L/B_C<1$ (BR of warp

$<BR$ weft), the profile shape was oriented horizontally. $B_L/B_C=1$ showed the least level of anisotropy in two warp and weft directions. If $B_L/B_C>1$ (BR of warp$>BR$ weft), the profile shape was oriented vertically. If the ratio B_L/B_C was similar for different fabrics, the fabrics could stillhave a different average bending rigidity [93].

Önder *et al.* studied the effect of polyester type and fineness on fabric drapeability. Two-fold conventional ringspun (average denier 2.5) and a Sirospun yarn (average denier 1.7) with 76 mm cut length were used in wool blended fabrics with different lightweight constructions. Fabrics with Sirospun yarns had lower bending rigidity and higher extensibility than the conventional ones because of their higher mobility fibres. The DC was not different significantly however the number of nodes of the fabrics made from the conventional two-fold yarn was higher than the Sirospun [94].

Commented [R60]: Spirospun or Sirospun?

Commented [u61]: Sirospun- Thank you- it is corrected.

It was found that fabric density had a positive relationship with DC and negative relation withthe number of nodes. The first relation was stronger than the second. This was considered to be due to high BR (bending rigidity) and $\boldsymbol{G}$ (shear rigidity) of high density fabrics which decreased fabric drapeability [51].

Matsudairaa *et al.* studied the effect of weave density, yarn twist and count on different polyester woven fabric drape behaviour. Weave density was found to decrease the number of nodes and increase the static drape coefficient. However the change in DC_{200} for fabrics with different weave density, yarn twist and count was insignificant. Yarn twist increased the DC_s, DC_r and DC_d but not by a similar rate in all types of fabrics tested. While, the yarn count had a contradictory effect on different fabrics [95].

Chattopadhyay studied factors affecting fabric handle and drape. These were fibre fineness, length, friction coefficient and bending rigidity, yarn count, bending rigidity and twist, in addition to fabric ends and picks/cm and weave type. Fine fibres were found to improve fabric drapeability [96].

Quirk *et al.* compared the drapeability of basket weave and broken twill fabrics with similar density and material. It was found that the basket weave had less drapeability than the broken twill as it had longer floats and fewer interlacings [97].

Ramakrishnan *et al.* showed that viscose Knitted fabrics made from micro denier fibres had better drapeability than fabrics with normal denier fibres. This was due to the lower bending rigidity of the former because of fibre fineness which resulted in a higher tightness factor [98].

Al-Gaadi *et al.* studied the effect of composite yarn twisting direction on drape behaviour of woven fabrics. They used three fabrics with identical structure parameters. The three fabrics had warp yarns twisted in z direction. However, each one had different weft yarns twisting directions (Z, S and Z+S). Fabrics with a combination with weft yarns in the Z direction were thinner, more rigid, more even node distribution and less drapeability than fabric with weft yarns twisted in S direction which were thicker and less rigid. Fabrics with Z+S twisting directions for weft fabrics were between fabrics with Z and S [59].

4.23.2 Fabric Mechanical Properties

Chu *et al.* in 1960 studied factors affecting fabric drapeability. They found a high correlation coefficient between mono and multi planar bending characteristics (cantilever bending length and drape coefficient respectively). However, bending properties are not presenting trellising and buckling properties signify fabrics from other mono planar material such as paper [68]. This shows that… .Brand investigated measurement of fabric aesthetics. Fabric drape was found one of the words defining fabric aesthetic character. There was found a relation between fabric liveliness (ability of a fabric to restore its flat/planar state after being deformed in a wavy or accordion shape) and drape. Liveliness could be evaluated subjectively using different methods which could be used to define fabric drapeability. Moreover, the word liveliness is one of the words could be used in subjective tests assessing fabric drape [99], this suggested that… .Cusick in 1965 studied fabric drape dependence on bending length and shear rigidity. The results of his study established main factors affecting drape behaviour. They reported that there was a positive relationship between DC and both BL and shear rigidity. However, the change/increase in bending length values became insignificant as the drape coefficient increased. This means that as the bending length increased, it became less effective on drape coefficient. At a certain value of bending length, fabrics with different shear rigidity values had different drape coefficient values which showed the importance of shear rigidity on DC[42].

Hollies studied visual and tactile textile qualities. Individuals were asked to select words related to fabric comfort response assessment using a survey form including 16 descriptors. Stiff and staticky words/descriptors (which sat in the drape category) were used by subjects with frequency 2.7% and 2% respectively which means that comfort and drape were not as correlated as other descriptors which were repeated with 100% frequency [100].

The drape instability (variance/deviation) was found to be strongly and positively correlated with two proposed parameters; namely residual bending curvature RB (amount of unrecovered bending strain left in a fabric after a bending recovery cycle) and residual shear angle RS (the extent to which fabric recovers from shear deformation). Fabric with low values of RB and RS were able to keep their initial state. Strong correlations were found between bending rigidity and hysteresis and between shear rigidity and hysteresis which had a good correlation with fabric drapeability [48].

Morooka and Niwa studied the effect of 16 mechanical properties on138 woven fabrics measured by KES-F on their drape coefficients. Experimental results showed that the following blocked properties affected fabric drapeability namely; bending > weight > thickness > shearing properties. Different combinations of mechanical properties were studied to find the best parameters used to predict the drape coefficient. They derived equation to calculate the drape coefficient including the group of mechanical properties most correlated with the measured drape coefficient. These parameters were: $\sqrt[3]{\frac{B}{W}}$, $\sqrt[3]{\frac{2HB}{W}}$, $\sqrt[3]{\frac{G}{W}}$, $\sqrt[3]{\frac{2HG}{W}}$, where, $B, W, 2HB, G \ and \ 2HG$ were the bending rigidity, weight/unit area, bending hysteresis, shear stiffness and shear hysteresis respectively. However the first parameter $\sqrt[3]{\frac{B}{W}}$ was the most significant [101].

Collier studied the correlation between fabric mechanical properties and drape values. Bending rigidity (Pierce method), bending modulus and hysteresis (pure bending tester) and shear resistance and hysteresis (Kawabata tensile and shear tester) were found to have great impact on fabric drapeability. All bending and shearing properties were good predictors for drape values. The most important property was shear hysteresis at 5°[54].

Amirbayat and Hearle developed an approach to describe and analyse complex (three fold) buckling of fabrics and sheet materials theoretically and experimentally. They proposed that understanding this kind of deformation was the basis of analysing more complex buckling, determining the suitability of a material (fabric) for a product involves such buckling experimentally and designing fabrics theoretically using the relation between structure and the relevant complex deformation [102]. They introduced two dimensionless parameters J_1 and J_2 which could be used to analyse the deformed shapes of fabrics. These groups were characterised either by the energies involved in producing this deformation or the material properties and dimensions (see Equations 3.2~~4.2~~ and 3.3~~4.3~~).

$$J_1 = \frac{Yl^2}{D} \qquad 3.2$$

$$J_2 = \frac{\gamma l^3}{D} \qquad 3.3$$

where: Y was the membrane modulus $= (\text{force/width} \div strain)$, l was the characteristic length defining the size of the material, D Bending stiffness and γ was the areal density (mass/area).

As fabric drape was a form of double curvature, they studied the relationship between the drape coefficient and these dimensionless parameters using four different fabrics with different sample diameters. The DC was correlated with J_1 and J_2 with correlation coefficients -0.56 and -0.89 respectively (J_2 was more correlated with the drape coefficient). They noted that other dimensionless parameters varied with sample size, therefore these correlations were not the final result, which means that the drape coefficient is not only affected by (function of) J_1 and J_2, but was affected by other parameters such as the full set of anisotropic in-plane (membrane) and out-of plane (bending) effects[103, 104].

Okur and Gihan studied the correlation between traditional drape coefficient and mechanical properties measured on a FAST system. The highest correlation was found with shear rigidity and then the bending properties and extensibility at 45°. A positive relationship was found between DC and shear and bending stiffness. Stepwise regression analysis showed that bending length in the warp and weft directions and extensibility in the bias direction at 5 gm/cm were the best predictors for DC[105].

According to Hu, Sudnik in 1972 had studied the relationship between the drape coefficient and bending length. He observed that the ranges of DC and BLvalues of fabrics used in apparel making ranged between 20-80 % for the first and 1.5-3 cm for the latter [106].

Hu and Chan studied the effect of the sixteen mechanical properties measured by aKES-F on woven fabric drape coefficient measured by a Cusick drapemeter. The following eight properties out of the sixteen had high correlation coefficients (significant at 90-95 % levels) with drape coefficient: the bending stiffness > bending hysteresis > shear hysteresis at 5^0> tensile linearity LT at 0.5^0> shear stiffness > weight >mean deviation of friction coefficient MMD. LT and MMD entered the analysis unprecedentedly and highly correlated with the drape coefficient. Compression properties were not correlated with fabric drapeability. They found that bending and shear hysteresis had higher impact on drape than stiffness as these properties included internal friction which played an important role in complex fabric deformation [107].

Kim and Slaten found that highly drapeable fabric had low bending stiffness (measured by the extraction technique). The deformation of fabric tested on both drape and extraction tests was similar. The static friction coefficient (SFC) showed lower (negative) correlation with drape than with thekinetic friction coefficient as highly drapeable fabrics had rougher and looser surfaces which required higher force for the sled to move on the fabric which produced high SFC. Drape coefficient showed correlations with hand force, weight, thickness, flexural rigidity, roughness, static coefficient, kinetic friction coefficient with r values 0.86, 0.86, 0.93, 0.82, - 0.56, -0.72, -0.7 respectively. From multiple regression analysis, BR, DC and SFC were the more effective parameters on fabric hand [63].

Frydrych *et al.* investigated the mechanical parameters affecting drape properties of wool and wool like woven fabrics. They investigated the potentialforobtaining correlations between mechanical properties measured on high stress mechanical properties testers (Instron) with drape parameters, as low stress mechanical properties testers were not always available in their country. The highest correlation was found for drape coefficient with: average bending rigidity (R^2 = 0.89), initial tensile modulus (ITM) in warp direction (R^2 = 0.68) and formability ($BR/$ ITM) in the weft direction (R^2= 0.64) [91].

Mizutani *et al.* tested the dependence of node generation on fabric mechanical properties; namely bending rigidity and recovery. Bending rigidity and recovery of different woven fabrics were measured at warp, weft and both bias directions. The bias direction had the lowest bending rigidity and recovery values, the nodes were generated in this direction [61].

Shyr et al. studied the effect of the sixteen physical properties measured by KES-F (which were grouped in six sets) on both static and dynamic drape coefficients were investigated. The results supported previous research studies' findings that the bending and shear properties had a high effect on fabric drape behaviour. Although the effective parameters were different for the tested fabrics, the bending property was found effective on all fabrics. Low effect properties were considered as complimentary properties which would complete the representation of fabric drape behaviour [80].

Behera and Pattanayak found good negative correlations between fabric drapeability and bending rigidity, shear rigidity, tensile energy (analogous to initial modulus) and compressional properties. However, positive strong correlations were found between drapeability and extensibility at low loads [45].

Tandon and Matsudaira found that bending and shear properties measured on KES-F correlated with static and dynamic drape values. Bending stiffness, ability to shear, tensile behaviour, surface friction, mass per unit area and thickness had impact on fabric drape. Stiffness to weight ratio affected fabric drapeability negatively [83].

Tokmak *et al.* studied the relationship between FAST, KES-F and Cusick drapemeter values. FAST and KES-F were strongly correlated with regard to the equivalent parameters measured on both of them. They found that the drape coefficient correlated strongly with FAST bending and shear rigidity with R^2 = 0.9 and R^2 = 0.8 respectively [108].

~~4.3~~3.3 Fabric Finishing

It was found that woven fabric relaxation treatments reduced the frictional pressure at intersection points between warp and weft yarns which consequently reduced both bending and shear rigidities and affected fabric drapeability [54].

Michie and Stevenson investigated the possibility of enhancing aesthetic properties including drapeability of chemically bonded nonwoven fabrics without affecting their tensile strength. The approach of subjecting commercial nonwovens to extension in order to allow them to relax was applied. It was found that stretching fabrics for higher than 3% decreased initial modulus, shear modulus, bending length, and drape coefficient (from 96% to 91%) and slightly decreased rupture stress. On the other hand tensile strength and elastic recovery were not highly affected. They found that this approach improved fabric drapeability but still did not reach normal textile behaviour (DC = 80% would be acceptable) as extending the study was recommended. Their study indicated the role of bending length in identifying drape behaviour more than shear resistance [109].

Matsudaira and Yang studied the effect of weight reduction ratio (WRR) on drape behaviour of shingosen fabrics. They reported that increased weight reduction ratio increased NN, D_r and D_d (stabilised at around 23% WRR) but reduced D_s and D_{200} which reached stable state at around 20% WRR. High ratios of WRR were responsible for stabilising the drape parameters [92].

Matsudaira *et al.* extended this study to investigate the effect of different finishing processes (not only the weight reduction) on drape behaviour. Shingosen fabric was finished using two different methods to make two sub groups A and B. In group A, a washer was used in the relaxation process resulting in 16% weight reduction, however in group B, a jet machine in the relaxation process resulted in23% weight reduction. D_s, D_{200},D_d and D_r were not affected by the dyeing and raising processes. The applied finishing processes (specially the relaxation) increased the number of nodes, D_d and D_r ,and decreased D_s and D_{200}. However, the washer relaxation effect was stronger than the jet machine relaxation. The effect of high weight reduction ratio was observed with the decrease of D_{200} and increase of D_r. However, there were differences between samples A and B with respect to drape parameters, parameters at the final output (end of finishing stages) were similar [110].

Frydrych *et al.* studied the effect of different types of finishing treatments (starch and elastomeric) on fabric drapeability in terms of the Polish standard method for drape coefficient. The mean standard deviation of starch samples was higher than elastomeric samples which means that they have lower stability. It was observed that elastomeric finishing had a significantly increased drapeability effect than starch treatment [67].

Agarwal *et al.* studied the effect of wash-ageing and use of fabric softener on viscose and polyester knitted fabric drapeability. Measurements were carried out after one and 40 washings with and without softener. In viscose fabrics the highest effect was for construction, followed by prolonged washing and then the use of softener. In the polyester fabrics they were the same factors, however the second(I am not clear what this means?) was replaced by fibre fineness. Using softeners decreased the drape coefficient of viscose and polyester knitted fabrics tested. Initial washing's effect on drape were not as significant as prolonged cycles. Maximum effect on drapeability was for the 20th washing using softener. The DC increased after that (at the 40th washing) the viscose fabrics however were more constant than the polyester fabrics. This increase was suggested to be due to the alteration of loop shape and/or deposited calcium and/or magnesium in the fabric. This means that: For the viscose fabrics, the influence of different parameters on drape coefficient follows the following order: knitting construction>prolonged wash ageing>use of laundry softener.

Commented [U62]: This means that:
For the viscose fabrics, the influence of different parameters on drape coefficient follows the following order: knitting construction>prolonged wash ageing>use of laundry softener.

While for the PET fabric the order is: knitting construction>fibre fineness>use of laundry softener.

While for the PET fabric the order is: knitting construction>fibre fineness>use of laundry softener [111].

4.4.2 Controlling drape behaviour of fabric

Tandon and Matsudaira compared static and dynamic drape coefficients and the indices of the drape fluidity of 20 wool fabrics and 4 types of shingosen fabrics. They found similarity between one of the wool fabrics and the shingosen fabrics which was characterised by smooth and fluid drape behaviour. This means that wool fabrics with high drapeability could be engineered using suitable production parameters for the fabric starting with the fibre content through the yarn to the fabric structure and mechanical properties endowed by the finishing process. This would be useful information for researchers working on engineering fabrics for certain purposes (fit for purpose), as they are able to engineer fabrics with high drapeability using the existing knowledge and rules with respect to the selection of fibre, yarn, fabric and finishing production and process criteria (see Table 3.1~~Table 4.1~~) [83].

Table 3.1 Levels to control the development of drapeable fabrics [83]

Fibre selection • Fibre type • Fibre denier(diameter) • Fibre cross sectional shapes • Fibre surface
Yarns (structure) • Yarn spinning route (woollen,worsted, cotton-spun, multifilament, SoloSpun,etc.) • Count • Twist • the number of plies (singles or two or three-ply)
Fabric construction • weave or knit type, • threads/cm (warp and weft sett,courses and wales/cm), • fabric cover • thickness • weight.

~~4.4~~3.4 Effect of test procedure on stability of drape values

Morooka and Niwa investigated the applied method for mounting samples on a drapemeter in terms of drape coefficient values reproducibility. Three methods of mounting tested specimens were used. These were D_j, D_n and D_f referring

Commented [R63]: I'm not sure this section is in the most-appropriate place .

Commented [R64]: Could this title be the development of controls for drape behaviour in fabric, or something similar to reflect the summary nature of its contents?

Commented [U65]: This is moved here as it would be kind of summing up and indicating the above headings concerned with fabric properties affecting drape including:
- Composition and structure
- Mechanical properties
- Finishing

respectively to drape coefficient with shaking the mounted sample together with the supporting disc up and down several times before testing, adjusting the tested sample before testing in state to produce four nodes and the last was mounting the sample without touching it by means of a board with a hole with similar diameter to the supporting disc. The last method exhibited the lowest deviation of drape coefficient followed by the second and the first method had the highest variation. The first (shaking) method exerted different forces on the measured sample in each measurement which made the ratio $\sqrt{\frac{2HB}{W}}$ highly scattered. This ratio which represented the hysteresis in bending per unit weight (frictional term) was found to have an effective role on the measured drape coefficient deviation. The higher this ratio was, the higher the deviation of DC values were [101].

Jeong proved practically that the initial state of the tested samples affects the drape parameters. Different methods of mounting the samples were applied i.e. without remounting on the supporting disc and also with remounting between successive measurements. The remounting method had higher node number variation. Therefore; it was worked out that the same drape shape could be obtained using the same initial state of the sample. The initial state affects the number of nodes which in turn has an impact on the drape values (drape coefficient and drape distance ratio).Consequently; the initial state of the fabric affects the drape values. He found that different fabrics have different sensitivity for mounting methods. Moreover, different methods of mounting fabrics gave different drape values. Drape distance ratio had lower variation than the drape coefficient; he referred this to the basis of measurement for each parameter, as the first is based on length units while the second on area units [47].

Behera and Pangadiya pointed to the importance and effect of sample placement method on result variance [44].

Mizutani at al compared the repeatability of their drape elevator and a conventional Japanese drapemeter. Drape coefficient values of the drape elevator were higher than the conventional tester and had lower standard deviations (less than half of the conventional rotational drape tester) which means that it had higher reproducibility. The high error for the conventional tester could be due to the falling movement with inertia of rotation of the rotated sample tested resulting from the sample rotation when placed/mounted on the tester. Therefore, drape shape resulted in complex unstable conditions. On the other hand the drape shape in the drape elevator was generated gradually during moving the table downwards which provided less disturbance than the conventional drape tester. This means that the rotation movement of the conventional Japanese drape tester caused disturbance of the drape shape which produced low repeatability. However, the drape elevator kept the sample tested more stable during testing [61].

Al-Gaadi *et al.* studied the effect of exerting dynamic impact on drape values measured as they simulated the real use of fabrics. Three annular discs with different inner diameters (21, 24 and 27cm) were used to push the sample tested. The test started with the sample lying on the tester's base and mounted on a circular supporting disc with 18cm diameter. It was found that the ring with the smallest inner diameter produced the lowest drape value deviation (higher reproducibility) and more even node distribution. Moreover, it had the most effect on the drape behaviour by producing lowest DC values and the highest number of nodes [59].

4.4.13.4.1 Supporting-disc size

Cusick found that the number of nodes increased as the supporting disc diameter decreased. The drape coefficient did not change as significantly as the number of nodes [41].

The effect of different supporting discs diameter (3 and 5 inches) on drape values obtained from measuring the same sample diameter was investigated by Collier in 1991. The 3 inch diameter disc produced longer overhanging parts of fabric than the 5 inch diameter's. They found experimentally that the drapeability of the fabrics tested increased with the smaller disc diameter. The coefficient of variation was lower for the 3 inch disc samples which means higher accuracy [54].

4.4.23.4.2 Test Duration

A draped fabric is subjected to the force of gravity which could produce a deformed shape over time. This change could be due to creep in fabric and yarn slippage (shear) [65]. Therefore, time is one of the factors affecting fabric drape behaviour.Consequently, textile and clothing researchers interested in fabric drape parameters were interested in studying time's effect on fabric drapeability.

Cusick in 1965 suggested tracing the projected shadow of sample tested immediately (within 15 seconds) after raising the supporting disc and repeating continually as fabric deformation changes with time [42].

Vangheluwe and Kiekens found that aten minute period of time was sufficient to work out the relationship between time periods. From their plots, drape coefficient decreased exponentially with time. Equation 3.44.4 theoretically governed the relationship between drape and time.

$$D(t) = A + \sum_{i=1}^{n} B_i \, e^{-t/T} \qquad 3.4$$

where: A, B, e, t varied according to the experimental values used and could be easily calculated using statistical software [65].

Jeong in 1998 studied the time dependence of drape coefficient using an image analysis method. He measured the drape coefficient of four fabrics over around eleven minutes period of time. His experimental results agreed with Vangheluwe and Kieken's that the drape coefficient decreases gradually with time and this reduction is due to the relaxation of fabric mechanical properties. The DC became stable at around the 7th minute. This steady state could be easily checked using an image analysis method [47].

Hearle and Amirbayat designed a multipurpose fabric tester, drape was one of the properties which could be measured using this device. It was devised to measure drape and other surface properties as a function of time [60].

Zunic-Lojen and Jevsnik studied the effect of time on drape parameters over a long period of time (24 hours). Drape coefficient, number of folds and maximum and minimum fold amplitudes of eight woven fabrics were measured using a Cusick drapemeter coupled with an image analysis system. These measurements were carried out for samples with two different diameters 30 and 36 cm for each fabric over four periods of time 2, 4, 6 and 24 hours after the first measurement (four intervals were used 0-2, 2-4, 4-6, 6-24 referred to as 1st, 2nd, 3rd and 4th interval respectively). They found that the drape coefficient decreased with time regardless of sample size (large or small). The most distinctive change (decrease) was in the first stage. The rate of the drape coefficient reduction was different from fabric to fabric. Reduction rates were similar in the first and fourth stages and the change rate was lower in the second stage than the first. Generally, the change was significant in the first three stages (0-6 hours) than the fourth (6-24). Plain weave fabrics with the lowest weight and bending rigidity had the highest percentage of decreasing rate, while weft rib fabrics with the highest weight had the lowest decreasing rate. They agreed with Vangheluwe and Kiekens that the exponential function ($y = A\ x^B$)was the best to represent the curves of drape coefficient change with time with R^2 values higher than 0.79, however large samples presented higher R^2 than small ones. They found that maximum and minimum amplitudes went down with time as the drape coefficient did, however the number of folds was constant. The change in the maximum and minimum amplitudes alone did not give evidence for the change of the drape behaviour as they were just parameters for two folds and their changes were insignificant. So, they could not depend on their results without connection with the rest of the parameters. The change for small and large samples were different. Smaller samples had higher drape coefficient values and rate of reduction than larger ones. However, the larger samples had higher weight of around 67.41%, there was not significant correlation observed between this increased weight and the change of drape coefficient with time [74].

Sun developed a tester to measure the angle of drape of a cross shaped sample in warp and weft directions from which the bending length was calculated. He suggested leaving the tested samples for 1 min to relax in order to obtain stable samples. He found a difference between readings of drape angles on mounting the samples and after 1 minute as the latter was lower in both main directions. Higher correlation coefficient was found between values of bending length using this tester after 1 minute and Shirley and FAST 2 bending meter's values than instant readings [112].

The factor of time plays an important role in the computer graphics area. Fabric drape researchers interested in virtual simulation have been working on the challenge of engineering a reliable, efficient and accurate model of draped fabric. Different computer techniques were developed to achieve this challenge. All of them were based on using drape parameters and variable factors affecting drape significantly [30, 113, 114]. Time was an important variable in the derived/applied equations which produce a time-variable deformation for virtual fabric drape simulation [71, 115-119].

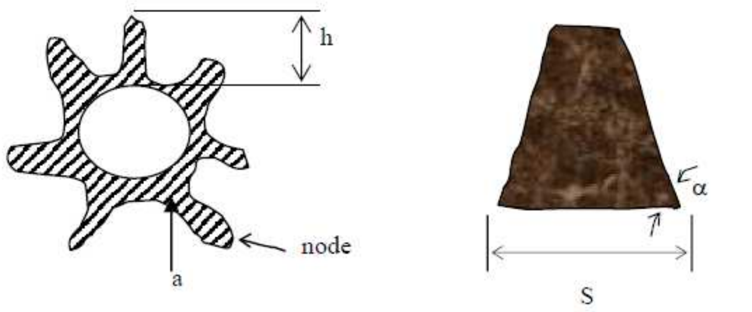
~~5~~4 Garment Drape

~~5.1~~4.1 Fabric Drape versus Garment Drape

Ng *et al.* investigated the difference between fabric and garment (flared skirt) drape supported on the same body (column). Two drape profile parameters, maximum hem angle of the front view (α) and the number of nodes did not show a difference (see Figure 4.1~~Figure 5.1~~). However, DC, area of cross-section top view (A), average wave the cross-section of the top view (h) and maximum width of hemline of the front view S showed a difference. Correlations between the fabric and garment drape difference and the sixteen mechanical properties measured on the KES–F showed that two compression properties (stress/thickness curve and compression energy) had strong negative correlations with the resultant differences. These results confirmed that garment drape will not be predicted precisely using the fabric drape parameters as they behaved differently in their study. Therefore, garment drape is independent of fabric drape assessment. They expected that their investigation would have positive impact on apparel design, end use of fabrics and its simulation in CAD systems [120].The complexity of garment drape is something that is difficult to control as existingtests cannot replicate how fabric will fall over all the complex curves of the human body.

Commented [R66]: Images would really be of benefit to this sentence/paragraph.

Commented [R67]: Reflections like this may help situate the reader in the narrative?



(a) Cross-sectional view **(b) Front view**

Figure 4.1 Parameters of drape profile (reproduced from [120])

In a series of papers from 2012 to 2015, Sanad et Al reported on a method for studying drape by making up garments (dresses)from the fabrics to be measured. Image analysis was then carried out on the images captured by camera from below the garments suspended on a mannequin. They proved conclusively that there was a very poor correlation between fabric and garment drape values.They went on to derive an equation to predict drape rank scores for garments depending on circularity and wavelength minimum [121-123]. Importantly existing tests of drape use templates which do not represent cross section of the body at even key locations. Even though slices from body scan data can be used to contrast against templates used in existing drape tests. This study shows the importance of understanding garment drape in wear, outside of controlled laboratory environments.

Commented [R68]: Slices from body scan data can be used to contrast against templates used in existing drape tests.

~~5.2~~4.2 Grain Alignment

Fabric grain line position on a pattern piece of agarment affects its appearance. The garment maker may needto tilt patterns off grain within the marker to increase the fabric efficiency and thus reducethe manufacturing cost. Positioning patterns incorrectly (off-grain) could cause undesirable drape appearance and the marker planner needs an awareness of what will be acceptable. Therefore a study was carried out by Orzada *et al.* to investigate the effect of grain alignment (tilt degree) of the pattern on fabric drape. Fabrics suitable for astraight skirt style (gabardine, light and heavy denim) were used in the investigation. Computer software was used to design and mark patterns on the fabric. Four different tilt angles (0, 3, 6, and 9) were applied to obtain 12 different combinations of two halves of a circular sample (sewn pairs) with similar or different tilt degrees. 0 tilt degree referred to a pattern aligned with the grain line. 0/0 tilt sample was used to present the seam effect on fabric. A seamless sample from each fabric was used as a control sample. Images for samples draped with their face up were used to simulate the action of the garment drape. There was not a significant correlation (consistent) found between tilt angle and drape coefficient. There was a significant effect on drape symmetry and appearance. There should be a correlation found between the tilt angle and the drape behaviour (as it presumed in text books as mentioned in this paper). So extending this study with a wider range of fabrics was suggested [124].

Commented [R69]: Please also see: Orzada, B. T. (2009). Effects of Grain Alignment on Fabric Mechanical Properties. doi:10.1177/0887302X0101900202
For more details on this study.

This investigation (Orzada et al.'s 1997) was extended by Orzada in 2001 using larger range of fabrics in terms of descriptive properties. Fabric properties related to drape were measured employing KES-F (namely: bending modulus and hysteresis and shear stiffness and hysteresis). Orzada et al.'s findings in 1997 were confirmed. There was found Insignificant negative correlation was found between tilt angle bending modulus and hysteresis properties. However, shear properties were found highly affected to variations in grain alignment than bending properties. Moreover, Orzada suggested that significant effect of tilt on shearing properties is for tilt angles above 4°[125].

5.34.3 Interfacings

Koenig and Kadolph studied the effect of seven different fusible woven, knitted and nonwoven interfacings (namely; plain woven; tricot warp knit; weft-insertion tricot, warp knit; random web, dry-laid nonwoven; oriented web and spunlaced nonwoven) on broadcloth fabric drape. All interlined fabrics had significantly higher DC values than the original fabrics. The least effect (especially on the drape configuration) was found for tricot knit and spun laced interfacings which had the lowest rigidity. The drape profile of interfaced fabrics were found draping parallel to the main direction with higher rigidity, however parallel to the bias direction with lower BR than two main directions with equal BR [126].

Collier *et al.* studied the effect of interfacing type on shear stiffness $\boldsymbol{G}$ as an indicator of its effect on fabric drapeability. Woven face fabrics (F) (having a range of weight and yarn type) were interlined with four different interfacing fabrics: fusible and nonfusible from woven and nonwoven to produce different composite fabrics (C) (interfaced fabric). They found that shear rigidity of the end product (interlined garment) was not just a sum of the components, as the interface type had an important impact on composite C shear stiffness. Therefore, ratio (composite shear rigidity) to Sum (sum of individual component shear rigidities) was proposed to study the relation between face and interface fabrics and how this relation affected composite behaviour. Ranking of interfacing fabrics' shear rigidity was as follows: nonwoven non-fusible >nonwoven fusible > woven fusible > woven non-fusible. Nonwoven non-fusible had the highest shear stiffness, woven fusible had the highest effect in increasing the composite shear stiffness as it had more than an additive effect (means G composite >G Sum, as the additive character results G composite = G Sum). This was due to adhered yarns which were free and able to slip over each other before joining to the face fabric. Therefore, the adherence increased the shear stiffness of the interface fabric itself and stiffened the face fabric as well. Moreover, the higher the face fabric stiffness was, the lower the resin penetration was, which decreased the effect of the adhesive material on changing the face fabric behaviour. Woven nonfusible interlinings were less than additive G composite <G Sum (G composite:G Sum < 1). The way of joining the face and interface fabrics together had an important role in this weak effect of Wn interlining on the produced composite as in this study the two layers were only stitched at the four corners of the squared samples. Therefore each of the joined layers behaved as independent layers rather than an identical composite which consequently reduced the load transference. One of the two layers became compliant (capable of being controlled) and the other noncompliant (controlled the composite shear behaviour). The stiffer layer provided more control in the composite behaviour. Two important factors dominated the effect of woven interlinings on composite shear stiffness: interconnection density (stitching or fusing) and the ratio G interfacing: G fusible.

The ratio between interlining and face fabrics shear stiffness GI: GF affected the G composite:G Sum ratio. This was obvious when one interlining fabric was used with two different face fabrics (in the first G interfacing /G fusible < 1and the second G interfacing /G fusible > 1). The first produced G composite:G Sum values close to 1 (slightly higher), while the second produced G composite:G Sum values significantly higher than 1. Therefore, the lower stiffness face fabric had a stronger impact on increasing the composite fabric shear stiffness than the Sum shear stiffness.

They determined that the existence of the nonwoven structure was more important than the resin existence and generated composite values were nearly additive (except in N nonfusible composites which had G interfacing /G fusible < 1). Negligible effect was found for the face fabric on composite$G$ values including nonwoven interlinings due to the very high shear stiffness of the latter, and limited effect of the fusible resin on the composite as it was applied using a dotted pattern rather than a continuous pattern which produced a composite with lower shear resistance [53].

According to Chung *et al.* and Hu *et al.*,Suda and Nagasaka found that, both bending rigidity and drape coefficient increased with the number of layers and width in circular samples with bonded circular edges, however, the number of nodes decreased. Four layers of radial bonded nonwovens affected the number of nodes significantly [90, 127].

Both woven and knitted interlinings increased the DC with a range of 33.5 - 129.18%. Woven interlinings had more effect than knitted. Shell fabrics' areal density affected the increment rate of DC due to fused interlining, the increment rate of DC decreased with increased weight of the shell fabrics [78].

5.44.4 Seams

Garment drape researchers found that it is unrealistic to study drape without taking into consideration different processes used to convert fabric into garments, as fabric must be sewn to be made into a garment. Seam existence, number, allowance, position, direction, type and stitch type effect on bending properties, drape coefficient, drape profile and number, length, size, maximum and minimum number of nodes were investigated.

5.5.04.4.1 Seam Addition

Jevšnik and Žunič-Lojen found that the addition of seams increased fabric DC, as seamed fabric is two fabric parts connected to each other by a thread. Additional fabric lies under the fabric's face and the thread used within garment seaming(not sure what this means)increased fabric bending rigidity [74]. The increment range was between 13.35-42.78% [78]. A possible example of this is trouser legs which twist around, usually from seaming with lap felled seams. Introducing seams decreased the number of nodes or kept it constant. In seamless fabrics, 2 nodes appeared in the warp

Commented [U70]: I mean the thread used in the sewing process (i.e. seaming) direction. However, 1 or 2 nodes appeared in the seam direction for most fabrics. The drape profiles of seamed fabrics were different from un-seamed samples in terms of node size (form) and distribution. In seamed samples, minimum fold amplitude was lower and maximum fold amplitude was greater than in un-seamed samples [74].

~~5.5.1~~4.4.2 Seam Allowance (SA)

Bending length was affected by seam allowance (SA). Vertical (VS) and horizontal seams (HS) (perpendicular and parallel to the hanging edge of cantilever BL strip respectively) were used. In VS samples, BL increased with increased SA initially between (0-1 mm) and remained constant while SA increased. In HS samples, an initial insignificant increase of seam allowance decreased the BL which then increased with increased SA. But this increment's magnitude was not comparable with the increment rate caused by VS. [90].

Chung *et al.* agreed with Hu *et al.* as they found that BL had initial rapid increase in the stage between 0-1 mm SA. The increment rate became less after that and reached the maximum at 5mm. Sometimes, the BL decreased after this stage or became constant. Fabric weight affected this increment rate as for light weight fabrics BL increased less than for heavy fabrics with increased SA [127]. The effect of the seam allowance was significant in vertical seam samples as 1 mm seam allowance increased the bending rigidity of the fabric with 3-4 times (9-11 times for the bending hysteresis) more than seamless fabrics. A seam allowance of 10 mm increased BR 14 - 16 times and bending hysteresis 26 - 33 times more than seamless fabrics [127, 128].

Dhingra and Postle found that bending rigidity (KES-F) was affected by seams but this was not true for shear rigidity and hysteresis. The effect on bending behaviour depended on seam allowance and direction. VS (with SA: 1 and 10mm) and HS (with SA: 1 and >2.5mm) were used. However, the horizontal seam increased the bending rigidity (with SA > 2.5mm), its increment rate was not comparable with the vertical seam effect which was 3-4 times higher. This was due to more free fabric in the horizontal seam sample than the vertical. As in apure bending tester, the sample tested was held between two clamps parallel to the bending axis during test. This made the movement of seam allowances restricted in the vertical seams and free in the horizontal seams. Therefore, samples with horizontal seam had lower bending rigidity than the vertical samples[128].

~~5.5.2~~4.4.3 5.4.3 Drape Coefficient

DC was increased with seam allowance then decreased after reaching a maximum. Its increment rate was lower than for bending length. Maximum DC was at 1 cm while the maximum BL was at around 2 mm. [90]. Heavy weight fabrics were more sensitive than light weight for increased DC due to increased SA [127]. Hu and Chung found that increased SA of radial seams (RS) (seam between two edges of a circular sample passing through the centre) slightly affected DC which had a rapid increase between

1-5 mm SA and insignificant increase after this period. DC trend curves of 1, 2 and 4 RS were similar; however the latter was the most stable and clear with variable SA [69].

5.5.34.4.4 5.4.4 Drape Profile (DP)

Variable SA was not effective on drape profile appearance and node orientation [69].

i) ***Number of nodes (NN)***

Increasing the SA reduced NN along the unseamed parts, and light weight fabrics were less sensitive than heavy weight fabrics with changed SA [69].

ii) ***Node size***

Increasing the SA produced large nodes along the seam but it was not a significant change [69].

5.5.44.4.5 Seam Position

Hu *et al.* found that in HS samples: The nearer the seam to the hanging edge was, the lower the BL was.[90]. Variable circular seams (CS) position in circular samples with respect to the sample centre had significant impact on DC values. The most significant increasing effect for DC was for a seam just off the supporting disc as seam allowance was still hanging on the sample disc and increased sample support. DC decreased with CS movement towards the sample edge to reach the lowest value when CS was at the edge of the fabric specimen [69].

5.5.54.4.6 Seam Direction

i) ***Bending length***

VS had higher effect than HS in increasing BL values. Seamless samples had BL values higher than HS samples. [90].

ii) ***Drape coefficient***

DC of knitted fabrics with seams in the wales direction was slightly higher than samples with courses direction seams as it raised the rigidity of the fabric in the wales direction [51].

iii) ***Drape profile***

Nodes were generated in seam direction because the seamed part had higher bending stiffness than other parts, so seams support their parts and generated nodes in its direction [90].. Seam in the courses direction made the fabric DP more stable in the courses direction and produced higher correlation between dependant (DC, NN) and independent (seam number, fabric density) variables as correlations in wales direction were lower than the courses direction due to the low rigidity in the former [51].

iv) ***Number of nodes***

Commented [R71]: Can this be shown visually?

In samples tested with radial seams (warp and/or weft directions), 2 and 4 folds dominated the warp or weft directions, and weft and warp directions respectively(is this correct?)[90]. Jevšnik and Žunič-Lojen found two or three nodes in the weft direction seam [74] (see Figure 4.2~~Figure 5.2~~) .

Commented [U72]: This is correct.
If there is one seam in the warp direction on a circular fabric, two nodes will be generated in this direction. Each node will be at one tip of the seam.

If there is one seam in the weft direction on a circular fabric, two nodes will be generated in this direction. Each node will be at one tip of the seam.

If there are two seams in the warp and weft direction on a circular fabric, four nodes will be generated in these directions. Each node will be at one tip of the seam.

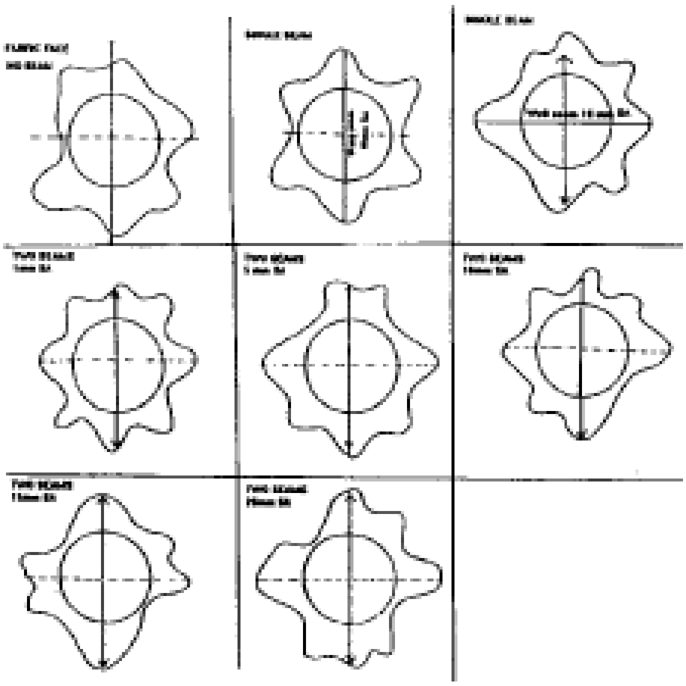


Figure 4.2 Nodes formed at seam positions at warp or/and weft (Nodes are more concentrated at the seamed area as seam allowances increases) (reproduced from[90]

~~5.5.6~~4.4.7 Seam Number (SN)

i) ***Drape coefficient***

Seam number increased fabric DC. The more added seams there were, the more obvious the effect [51]. Increased DC due to increased SA in 1 and 2 RS samples were not as effective as vertical seam on BL values. However, 4 RS had the highest DC values and their increment rate was similar to the BL samples which increased initially between 1 - 5 mm SA and became stable with increased SA after that. This increment rate was more stable and consistent in 4 RS samples than 1 and 2 RS samples [127].

Hu and Chung agreed with these findings as they found that DC increased with the addition of radial seams, but this effect was more obvious with increased seam number. Change in DC was higher and more stable and consistent in 4 seam samples than 1 and 2 seams samples. Fabric weight had an influence on the effect of SN on DC as increased SN had more impact on increasing DC of heavy weight fabrics than light weight ones. [69].

ii) ***Drape profile***

Unseamed fabrics had unstable DP. Adding a seam swung the highest node to the seamed part. One RS changed the DP of a seamless fabric and acted to locate the nodes but not exactly at its middle. It had irregular node orientation at the unseamed parts, while seamed parts stabilised the nodes at it. Number of radial seams had significant effect on DP. The more seams added to a fabric were, the more stable the drape profile was. Thus, drape profiles of fabrics with both two and four seams had more regular nodes arrangement than one seam. Four seams fabric drape profile was the most stable one and not affected by varied SA. They had stable nodes which were mostly found along the seamed directions orienting themselves regularly in the seams direction. The drape profile of fabric with circular seam was entirely different from the drape profile of fabric with RS as nodes did not stay at any specific position. Number of seams showed great effect on drape profile of heavyweight fabrics, but very little effect on lightweight fabrics [69].

iii) ***Number of nodes***

Unseamed and one seam fabric node numbers were unstable, the more added seams were the more stable NN was, as NN of 2 seam fabrics were more stable than seamless and one seam samples. In 2 seam fabrics, 4 nodes existed at the seamed parts. However, NN were fixed at 7 or 8 in an octagonal arrangement in 4 RS samples [69].

There were negative correlations between NN and SN. The addition of seams decreased fabric drapeability as seamed parts bent less than unseamed parts. This relation was slightly stronger than *the* DC - SN relation [51] .

iv) ***Node size***

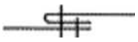
In fabrics with no seams, the greatest and smallest node lengths were found in any position on the draped fabric. Seamed parts always had the longest node lengths and did not have the lowest. In lightweight fabrics, node length was more sensitive when adding RS (Radial Seam) than DP and DC. Addition of circular seams did not affect the node length and was not so different from unseamed fabrics [69]. Seamed parts had wider nodes than other parts [51].

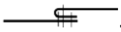
~~5.5.7~~4.4.8 Seam Type

i) ***Bending length***

SPS (side press seam) increased BL more than OPS (open press seam), this was considered to be because of the higher localised fabric weight generated due to pressing both sides of seam allowance on one side. For any seam type, heavy weight fabrics were more affected than light weight fabrics because of the increased stiffness [127].

ii) ***Drape coefficient***

Effect of four types of lockstitch seams (LS1  , LS2  , LS3  and LS4 ) on fabric drapeability were studied. LS1 had the lowest DC values while the others showed similar effect in raising the DC values.

Jevšnik and Žunič-Lojen studied the effect of two seam types on DC values and found that S2  seam type had higher DC (seam allowance turned in one direction) than S1 . The effect of seam type on NN was clear in bias and double warp and weft seams and it was different according to the fabric characteristics [74].

5.54.5 Girth Ease Allowance

Cui *et al.* studied the relation between fit of clothing and fabric properties (including drape). As it was noticed in the clothing industry that garments with similar size and style made from different fabrics produce different levels of fit. The relation between girth ease allowance (GEA) and fabric drape (in terms of traditional drape coefficient) was investigated. GEA is the difference between the body measurement and the pattern. The ease differs according to the type and style of garment.

Clothing samples (jacket) made from 12 different fabrics with the same size and style were scanned (using a 3D scanner) on a standard mannequin. Images for the mannequin wearing garments and naked were scanned to work out and analyse the GEA at different parts on the mannequin/garment (namely bust, waist, and hip). They determined that garment drape was more dependent on GEA of waist r =0.65 and hip r = 0.82 (linear relation) more than the bust (nonlinear relation r = 0.27). GEA at the waist and bust was significantly larger than the hip. Regression models/equations for these correlations were worked out and would provide important information for apparel industry workers [129].

5.64.6 Deformation in Garment Drape

5.6.14.6.1 Effects of Fabric Distortion on Garment Drape

Garment drape is expected to be equivalent along its sides but deformed/distorted fabric drape would affect garment degree of comfort and appearance. Some aspects of unpleasant drape would result from twisted seams at the front and back of the wearer's body or different number of nodes along the garment edge. A distorted drape profile could be a result of fabric skew and/or bow, incorrect position of fabric and/or pattern in the layout or on production markers, and inaccurate joined seams etc.

5.6.24.6.2 Effects of Fabric Skew on Garment Drape

Skew in woven fabric results when weft yarns are displaced from a line perpendicular to warp yarns expressed in percentage. Fabric skew causes garment twist which subsequently generates different drape shapes on each side of the body. Its impact is more obvious on garment drape rather than fabric drape. It could affect garment drape by producing different drape behaviour at the garment edge at each side of the garment (front, back, right and left).

Moore *et al.* studied the most significant factors affecting garment drape negatively. They studied the effect of skew on the drape profile using fabrics supplied with 5 levels of skew (0.2, 1.5, 2.3, 3.3, 4.4). They found that two parameters were sensitive to skew levels which were significantly linear. These were the asymmetry (at 4.4% skew level) and the distance between adjacent nodes across a seam (at 3.3 and 4.4% skew levels). Strong negative correlation was found between shear hysteresis in the weft direction and skew levels with $R^2 = 0.85$. They proposed several recommendations for further studies at the end of their paper. These were to increase the number of samples (skirts) for each level of skew than the number they used (3 skirts) and establishing a standard method for mounting the garment tested (skirt) on a mannequin to avoid error in placing the sample [84].

5.6.34.6.3 Effects of Asymmetrical Body Features

Lengthwise and crosswise grain lines of worn garments are ideally perpendicular on and parallel to the floor respectively. Asymmetrical body dimensions could create distortion in garment ideal symmetrical drape due to deforming the grain lines' ideal position. Ready-made garments would not be the most suitable clothes as for these bodies which could be dealt with by custom-made clothes to treat body errors [130].(see editor's comments)

Traditionally in guidance on garment development and fit assessment lengthwise and crosswise grain lines of worn garments are ideally perpendicular on and parallel to the floor respectively.Asymmetrical body dimensions (for instance a higher hip or higher shoulder on one side) would pull one side of the garment up. This would cause distortion for the cross grain position, as it will become no longer parallel to the floor. The lengthwise grain will be distorted as well. This will cause asymmetrical drape shape on each side of the body. Ready-made garments which often assume symmetry would not be the most suitable clothes for asymmetrical bodies which may require customisation to reflect individual variations[130].

Commented [R73]: In garments designed to fit a symmetrical shape……?

Commented [R74]: Most-suitable rather than 'proper'?

Commented [u75]: Please see the paragraph below in blue.

Commented [R76]: I would suggest the following change as the reference is dated and asymmetry is more the norm in bodies than clothing development literature would suggest.

~~5.6.4~~4.6.4 Effects of Pattern Layout and Production Markers

Sometimes, garment manufacturers rotate the pattern used in making markers or during layout to reduce fabric waste. Laying fabric and/or positioning a pattern on the marker incorrectly could affect garment drape negatively. If according to the layout instructions, the fabric should be folded lengthwise, the fold must be accurately along a lengthwise grain for all layers of fabric. Otherwise, the resultant garment would have different drape behaviour over different sides of the garment when worn [130].

~~5.6.5~~4.6.5 Effects of Sewing Operations

Error in feeding fabric during seaming (overfeeding) to the sewing machine due to machine error or operator mistake could affect garment drape. Excessive fabric on one side of the sewn garment will affected its drape negatively and the shorter side will tend to twist[130].Examples of this can be seen in….?

~~5.6.6~~4.6.6 Effects of Unbalanced Seams

Non-identical grain lines of two garment layers which should be identical affects the garment drape. The layer which is further from straight grain (morebias)will have limited stretchability (bias normally has better stretch?)which consequently causes inconsistent feeding [130].

Commented [R77]: Orzada reference?

Commented [R78]: During seaming?

Commented [R79]: Possible example is trouser legs which twist around, usually from seaming with lap felled seams

65 Subjective Assessment of Drape

Fabric drape behaviour is one of the garment qualitative attributes/characteristics which is assessed visually by the human eye and depends on fabric properties and surrounding atmospheres. Therefore, it was evaluated subjectively in the textile and apparel industry. Subjective assessments of fabric drape lack reproducibility and often cause controversy due to large variation in evaluators' perception and skill, this shortage ended with development of the quantitative measurement of drape [46, 49]. Subjective assessment was affected by individual preference, fashion trends [131] and the length of fabric on the pedestal (sample diameter)[114, 132]. Validation of fabric drape measurement objectively is based on comparing its results/output with subjective results. Subjective assessment of fabric drape behaviour was carried out by one of three approaches: viewing images of tested fabrics [51], displaying real draped samples on a supporting body [39, 40], and handling tested fabrics [111]. The evaluation process was carried out employing a paired comparison test within groups of fabrics [41, 42] or ranking a group of fabrics on a rating scale [133].

Commented [R80]: Great synthesis here, other sections would benefit from this type of grouped discussion with clear references.

The first 3-D drapemeter was inspired by the way individuals view fabrics. A circular pedestal was used to support and drape the fabric tested. This was similar to draping fabrics shown in the shop windows[37].

Chu and others found good correlation (R^2 = 0.78) between drape coefficient measured on an F. R. L. drapemeter and subjective assessment (ranking) carried out by a panel consisting of 57 assessors with different backgrounds in textiles. This meant that their drapemeter worked efficiently [68].

Cusick in 1962 assessed drape grades of 8 half skirts (semi circular pieces) made from different fabrics using a panel of 5 textile specialists. Fabrics were mounted on mannequins and the paired comparison method was applied. Another test was carried out using photographs instead of using direct views of the half skirts to avoid differences in mounting the fabrics in the previous test and using a higher number of assessors (12 persons). In both tests, it was found that subjective assessment of fabric drape correlated significantly with the drape coefficient values at a level higher than 5%. The subjective assessment showed that there was a relationship between the fashion trend and individuals' evaluation with regard to preference. Subjects preferred stiff fabrics which was the fashion at that time. Drape coefficients presented high positive correlation with each subjective drape amount and preference with r = 0.83 and r = 0.81 respectively. [41, 42].

Brand proposed that fabric drape could be expressed subjectively through: the way it is perceived by individuals using secondary attributes and polar characteristics (opposite pairs) or objectively using measurements. He proposed avoiding using "good – bad" expressions in drape assessment. Polar difference words and attributes such as limp - stiff could be used more efficiently as they were simple words which could be understood easily rather than concept words [99].

Ranganathan *et al.*'s dynamic apparatus for measuring fabric drapeability was based on a principle similar to that of average customers' assessment. Customers were used to assess fabric drape while the fabrics were draped vertically downwards generating folds. In their test a fold similar to a real fabric fold was formed [55].

Mahar *et al.* in 1990 stated that fabric descriptive words called "Fabric handle attributes" such as smooth, soft, full and drape etc., used in the textile and clothing industry were more expressive for fabric than grading them as good/poor. They studied the subjective measurement of fabric handle attributes and quality descriptors. A panel with experience in fabric handle evaluation were asked to evaluate fabric handle on a 6 step rating scale from unsatisfactory to excellent handle. The judges were also asked to rank fabrics tested on a 10 step scale according to intensity of each of six attributes; sleekness, fullness, firmness, warmth, durability, and drape. Japanese standards defining the first three qualities were provided for the judges. Drape had the best correlation with the overall handle ($r = 0.9$), sleekness ($r = 0.79$), fullness ($r = 0.72$) and firmness ($r = -0.74$), warmth ($r = 0.6$) and durability ($r = -0.1$); 35% of the overall handle assessment deviation was due to drape evaluation. However, there were many words used in describing winter suiting fabric handle, a combination of 4 characteristics were useful. These were sleekness, fullness, firmness, and drape. [133].

Collier investigated the validity of objective drape values proposed by Collier *et al.* in 1988 by studying the correlation between them and subjective grades. A subjective assessment process was designed to use a panel consisting of 13 evaluators with expert backgrounds and knowledge of textile and apparel design. The aim of the study was to determine the impact and importance of drape prediction in apparel design. The individuals ranked the fabrics tested on a 7 level scale according to amount of drape and their preference due to the aesthetic drape behaviour. Before the evaluation process the assessors were shown two extreme drape behaviour fabrics on the rating scale. The panel assessment of drape behaviour based on the amount and preference were well correlated at around $r = 0.9$, $p < 0.0001$. Both of these subjective assessments correlated strongly with objective drape values measured on a digital drapemeter at spearman rank correlation coefficient around $r = 0.8$. His study indicated that the preferred drape behaviour was affected by fashion and popular clothes' style. As highly drapeable fabrics were preferred by the panel which were the trend at that time [54].

Stylios and Zhu defined aesthetic attributes using the natural psychology of consumers. It was found that although drape coefficient is an important property for the assessment of fabric, it is not an accurate and complete measure of drape since two fabrics can have the same drape coefficient but different drape behaviour. Consequently a number of aesthetic attributes were added to the drape coefficient such as the number of folds, variation of the folds and depth of fold which represent how humans interpret drape aesthetically [56].

Orzada *et al.* in 1997 assessed fabric and garment drape using a 7 point Likert scale. Two groups of subjective assessors with two levels of experience of apparel design were asked to carry out the assessment. Fabric drape assessment was conducted using circular fabric samples on a pedestal according to drape amount and preference. However, 12 skirts with different tilt combinations for the front and back sides were hung on a mannequin for the assessment of garment drape. Skirt evaluation was carried out according to drape amount, preference for purchase, and accuracy of pattern layout (visual and close up with touch). These four aspects of assessment were averaged for each skirt and their score converted into ranks. Drape was defined and two extreme samples with regard to drape amount were shown to the judges prior to the test.

In the fabric test, drape amount and preference of most of the fabrics tested showed significant positive correlations ($r > 0.6$). The more experienced individuals rated the fabrics at lower levels and exhibited higher preference consistency than the less experienced did. However, drape amount assessment by the two groups showed higher similarity than preference evaluation. However, the more experienced group had stronger correlation with objective values of drape with regard to drape amount than the less experienced. Drape amount was correlated higher than drape preference with the 8 fabric properties measured. In the garment test, 12 skirts were ranked by the researcher according to the tilt degree. Advanced judges had higher agreement between themselves and with the researcher's rank and sensitivity than less experienced individuals [124].

Uçar *et al.* evaluated 30 fabrics' drapeability subjectively using images captured for the corresponding fabrics. Five assessors (with a textile ranking and rating background) viewed the images and ranked them according to drape amount and after that were rated on a 10 step scale, with 1 being the highest drapeability. Subjective drape ratings were highly correlated with theoretical drape ratings resulting from their developed equations including drape coefficient and number of nodes as independent variables ($r = 0.86$) which was higher than the correlation using drape coefficient only [51].

Shyr *et al.* carried out subjective evaluation for the number of nodes formed by pure wool fabrics using photos for measured fabrics and the results were used as a basis for developing an equation for objective assessment of number of nodes. The assessment started with 19 individuals with a background in textiles and fabrics. Inconsistent evaluators (whose number of nodes showed high variance within the results) were removed from the results and the subjective assessment was proved by the13 assessors whose results were highly consistent [76].

Agarwal *et al.* asked 6 individuals to rank 52 knitted fabrics according to their drapeability using the two paired comparison technique to rank them from 1 to 52. They were asked to handle the fabrics by laying them on the back of their hands. They established the relation between measured mechanical properties (tensile, shear and bending) and a drape grade resulting from the subjective assessment using Equation 5.16.1.

$$T_{YZ} = \frac{2\sum_{i \neq j} t_{YZ}(i,j)}{q(q-1)} \qquad 5.1$$

where: $t_{YZ}(i,j) = \frac{|Y_i - Y_j|}{|Z_i - Z_j|} + \frac{|Z_i - Z_j|}{|Y_i - Y_j|}$, where Y_i and Y_j denoted the normalised value of the mechanical parameter for the ith and jth samples, respectively, Z_i and Z_j denoted the normalised sensory score for the relevant attribute and q was the total number of samples. The smaller the T_{YZ} parameter was, the higher the agreement between the subjective ranking and mechanical properties. The best correlation was between shear rigidity G and bending hysteresis 2HB and drape grade [111].

76 Prediction of Drape Coefficient

Assessment of fabric drape has been investigated theoretically for a long time by researchers in the textile area as using equations is easier, less tedious and quicker than carrying out experiments. It takes a long time and several steps have to be done to obtain fabric drape values (static or dynamic) even by image analysis techniques or cut-and-weigh conventional methods. Moreover, prediction of fabric drape was important in the development/improvement of textile product characteristics [72]. Most equations include independent variables; namely fabric physical and the mechanical properties used to calculate the fabric drape coefficient.

Cusick in 1965 studied theoretically the relationship between fabric drape coefficient, bending length and shear stiffness. Simple and multiple regression analyses were applied to investigate this relation for 130 fabrics. Regression of drape coefficient on bending length (c), shear rigidity (A) and combinations of them were calculated and produced 7 regression equations. The model included a combination of 4 variables c, c^2, A and A^2 which had the lowest residual value which means that it was the best fitto the data (experimental values) (see Equation6.17.1).

$$\mathrm{DC} = 35.6\mathrm{c} - 3.6\mathrm{c}^2 - 2.59\mathrm{A} + 0.0461\mathrm{A}^2 + 17 \qquad 6.1$$

Cusick also studied in his paper the theoretical relation between the drape coefficient and bending length and neglected the shear rigidity. Because of the obviation of the shear rigidity, the experimental drape coefficient values were higher than the theoretical values and that was shown when both observed and theoretical values were plotted on one graph [42].

Gaucher *et al.* used multiple regression analysis to predict knitted fabric drape coefficient using physical and mechanical properties. It was found that bending length is the best predictor for all knits. BL had good prediction level when it was combined in equations with: thickness and shear properties in the overall group, thickness and extensibility in the warp knitted subgroup and only with shear in the weft knitted subgroup. It was observed that using mechanical property values of different face direction or average resulted in prediction equations with different reliability degrees. In other words, the overall mean did not always exist in the best predictive equation [134].

Postle and Postle proposed using a static cantilever bending length differential equation in modelling fabric buckling including drape [135]. This indicates the importance of the bending length contribution to drape profile.

Hu and Chan employed stepwise regression analysis using four different models to find the best basic parameters combination to predict drape coefficient theoretically. Only one parameter from each interrelated (blocked) mechanical properties group correlated strongly with each other and highly correlated with drape coefficient was used in establishing predictive equations. Equation 6.27.2 produced the best regression coefficients and residual values using values of 2HB, G, LT and MMD (BR could replace 2HB).

$$\ln \mathrm{DC} = \mathrm{b_0} + \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{b_i} \ln \mathrm{x_i} \qquad 6.2$$

where: DC was the Drape coefficient, b_0 and b_i were arbitrary constants, n was the number of parameters closely related to the Drape Coefficient, n ($1 < n < 16$), x_i represented a mechanical property parameter, which means that these were the most important predictors for the drape coefficient [107].

Postle and Postle pointed to the possibility using mathematics for modelling fabric deformation and described fabric surface using differential geometry parameters such as curvature. Mathematically, its deformation could be expressed by its transformation as invariants and exhibited the inherent properties of the fabric [136].

Lo *et al.* developed a model for predicting fabric drape profile. This model was established using the trigonometric Equation6.3~~7.3~~.

Formatted: Font: (Default) +Body CS (Arial), Check spelling and grammar

$$\mathrm{r} = \mathrm{p} + \mathrm{q} \sin(\mathrm{k}\theta + \alpha) \qquad 6.3$$

where: r was the radius of the projected drape profile, p was the mean of radial length between peaks and troughs, q was half-depth of node, k was the number of nodes, α was a constant representing an angle between the fabric main direction and its adjacent peak. The constants p, q and k were calculated using the polar coordinate fitting technique to obtain a theoretical drape profile. This process included providing computer software with the experimental results of (r, θ), where, r was the radial length of the drape profile at 7.5°θ interval from 0° to 352.5°, to obtain the constants. Moreover, the drape coefficient, node number and location for each specimen were calculated. Theoretical and experimental drape profiles and values showed good correlation which means that the developed model was valid to predict those values.

They also studied the availability of calculating these constants p, q and k using the mechanical properties measured on KES - F. Stepwise regression analysis of constants on the bending and shear hysteresis properties produced equations which were used efficiently to calculate the constants of their developed models. Strong correlations were found between constants and the mechanical properties used. The average mechanical properties of warp, weft and bias direction produced higher correlation with the constants than using the mean of warp and weft only [137].

Stylios and Powell studied the engineering of the drapeability of textile fabrics using neural networks. In their system the relationships between fabric: mechanical properties, drape values (drape coefficient, fold depth, number of nodes and evenness), drape grade (from subjective evaluation) and its end-use were established. This system was successfully used in forward (prediction of drape grades and end use employing fabric mechanical properties) and backward (using a feedback system to adjust the drape behaviour of a product by modifying the fabric mechanical properties) predictions. This model predicted the drape grades of 90% of the samples and was claimed to be better than the traditional predictive techniques (namely; regression and discriminate analysis) [40].

Uçar *et al.* developed a prediction equation for the drape coefficient of seamed heavy weight knit fabrics using a regression analysis method (see Equation 6.4~~7.4~~).

$$DC_1 = 18.5 + (0.65\ DC_0) + 0.889\ NS \qquad 6.4$$

where: DC_1 was the drape coefficient of seamed fabric, DC_0 was the drape coefficient of seamless fabrics, NS was the number of seams on the sample. This theoretical DC exhibited high correlation with experimental DC with r = 0.8. Equations 6.5~~7.5~~ and 6.6~~7.6~~ were developed for prediction of fabric rating with regard to their drapeability degree.

Formatted: Font: (Default) +Body CS (Arial), Check spelling and grammar

$$R_1 = -28.5 + (0.61\ DC) \qquad 6.5$$

$$R_2 = -7.86 + (0.39\ DC) - (1.27N) \qquad 6.6$$

where: R_1 and R_2 were the ratings, DC the drape coefficient, N the number of nodes. The second equation produced higher correlation with the subjective rating than the first one which included only the drape coefficient value [51].

Yang and Matsudaira (between 1998 and 2001) developed regression equations to predict fabric drape theoretically, namely: Static drape coefficient (D_s), revolving drape increase coefficient (D_r), dynamic drape coefficient (D_d), Dynamic drape coefficient at 200 r.p.m (D200) and dynamic drape coefficient with swinging motion D_{sm}. These equations were applied in several further studies investigating drape in terms of studying different features of fabrics [57, 80-83] and the effect of finishing on fabric drape behaviour [92, 110].

Static drape coefficient Ds and node number nwere calculated using Equations 6.7~~7.7~~ and 6.8~~7.8~~ respectively.

$$Ds = \frac{4a^2 + 2b^2 + 2a_m^2 + b_m^2 - 4R_0^2}{12R_0^2}, \qquad 6.7$$

$$n = 12.797 - 269.9\sqrt[3]{\frac{B}{W}} + 38060\frac{B}{W} - 2.67\frac{G}{W} + 13.03\sqrt{\frac{2HG}{W}} \qquad 6.8$$

where: $R_0$was the radius of a circular supporting stand (63.5 mm), awas a constant showing the total size of the two-dimensionally projected area (mm), b was a constant showing the height (amplitude) of a cosine wave of the two-dimensionally projected shape (mm), $a_m$and b_m were constants forthe anisotropy of fabrics. These constants were calculated using mechanical parameters measured by the KES system in Equations 6.9~~7.9~~ - 6.12~~7.12~~.

$$a = 35.981 + 1519\sqrt[3]{\frac{B}{W}} - 204300\frac{B}{W} + 23.27\sqrt[3]{\frac{G}{W}} + 0.0178G \qquad 6.9$$

$$b = 29.834 - 1.945n - 0.0188G - 91.84\frac{2HG}{W} \qquad 6.10$$

$$a_m = 9063 - (\frac{B_1 - B_2}{W})^{2/3} \qquad 6.11$$

$$b_m = 6224 - (\frac{B_1 - B_2}{W})^{2/3} \qquad 6.12$$

where: B=bending rigidity (mN.m^2/m), G = shearing rigidity (N/m/rad), 2HG=hysteresis in shearing force at 0.0087 radians (N/m), W=fabric weight (mg/cm^2); B1, B2=bending rigidity in the warp and weft directions respectively.

The revolving drape increase coefficient D_r (the slope of the curve of correlation between revolving drape coefficient with revolutions in the range between 50-130 rpm) was calculated using Equation 6.13~~7.13~~.

Formatted: Font: 12 pt, Check spelling and grammar

$$D_r = 0.792 + 2.374\sqrt{\frac{2HG}{W}} - 0.6305\sqrt[3]{\frac{G}{W}} - 6.762\sqrt[3]{\frac{B}{W}} - 2.673\frac{2HG}{W} + 0.0005W \qquad 6.13$$

The dynamic drape coefficient at 200 rpm, D_{200}, was calculated using Equation6.14~~7.14~~.

Formatted: Font: 12 pt, Check spelling and grammar

$$D_{200} = 61.475 - 37.02\frac{G}{W} + 0.1411G + 40.88\sqrt[3]{\frac{G}{W}} + 0.049W + 436.8\frac{2HB}{W} \qquad 6.14$$

where: 2HB is the hysteresis in bending moment at 0.5 cm^{-1} (mN·m/m).

Gider derived equation for predicting the drape coefficient using mechanical properties measured on KES-F. Stepwise regression analysis produced Equation 6.15~~7.15~~.

Formatted: Font: (Default) +Body CS (Arial), Check spelling and grammar

$$DC = 69.17 + 25.51(2HB) - 35.69MIU + 3.50G + 0.00049RT + 21.13WC - 0.492RC - 13.04t + 0.303EMC + 0.51W \qquad 6.15$$

where: $2HB$ was bending hysteresis, MIU was mean frictional coefficient, G was shearing stiffness, RT was the tensile resilience, WC was the compressional energy, RC was the compressional resilience, t was the fabric thickness EMC was the compression rate , W was the weight.

He also developed an online database search engine to help select fabrics for certain end-uses with intended mechanical properties and drape especially. This system predicted a drape coefficient with 94% accuracy compared with measured values [31].

Lam *et al.* used drape coefficient and circularity as drape parameters in neural networks to predict fabric drape. In the proposed model, 7 mechanical properties showed strong correlations with fabric drape. These were weight, thickness, bending rigidity, shear rigidity, hysteresis of shear force at 0.5 degree, linearity of load-extension curve, and weave. Their model was comprehensive in predicting the output data and the difference between desired and resulting outputs. This system worked efficiently, however they pointed to the key to improving this model which was to establish a huge data base with input and output data [138].

Jeddah *et al.* investigated the prediction of drape coefficient using two alternative theoretical models: Regression and neural models. Bending and shear stiffness were the best predictors for the drape coefficient followed by the thickness. Predicted and measured DC were highly and strongly correlated, however, the neural model (with error 2.7%) had higher accuracy than the regression models (error 3.9%). Fabric structure had no effect on the correlation between the measured mechanical properties and the DC, however twill fabrics had higher correlation than plain fabrics [139].

Agarwal *et al.* modelled a fuzzy logic system to predict drape grade. They used shear rigidity (G) and hysteresis in bending moment (2HB) as inputs because they had the best correlation with subjective assessments [111].

87 Drape Simulation

Since the mid-1980s, researchers have been developing alternative numerical techniques for simulating the draping process for fabrics and garments[71, 77, 113, 116, 118, 137, 140-153]. Prediction and simulation of fabric and garment drape allowed drape researchers to know how fabric properties affected drape shape rather than comparing between drape coefficients of different fabrics. Different combinations of fabric mechanical properties were used as input data to obtain a drape model shape [152].

Ngoc and Anh used pictures captured from front, back and side views for skirts worn by a mannequin to obtain virtual simulation for them using 3D simulation software (V-Stitcher 4.3). They found similarity between actual and virtual skirts; however the first had bigger and deeper folds than the second [75].

The importance of accurate fabric drape simulation (3D presentation) methods and technologies used to accomplish this is reflected in computer graphics (fabric representation) and the textile and apparel industries [154].

In computer graphics, the generation of satisfactory simulated/virtual output could improve this industry and satisfy users, manufacturers and designers. Workers in the apparel industry (including: design, product development and manufacturing) would be able to simulate, quantify and compare the drape of apparel virtually, consequently producing improved products with high success rates; reduced quantities of incorrect prototype products and enhanced business processes.

In design and product optimisation and development areas, it is becoming more difficult to depend on specialists' experience to evaluate and predict the drape behaviour of fabrics with the increasing number of new fibres, yarns and fabrics with different properties[85]. This makes predicting and modelling fabric appearance, including drape prediction, highly important for end product aesthetics and manufacturing. Virtual 3D modelling would be at the base of producing improved accuracy, efficient and quick clothing Computer Aided Design (CAD) systems as CAD software users always expect accurate and rapid fabric drape simulation [118, 148]. CAD systems provide designers with virtual environments by which they can view their designed garment before making it which guides them to the appropriateness of fabric and garment fit [155].

Moreover, researchers proposed using dynamic fabric simulation as a way of coping with low sales of fabric products due to design and/or style faults. The designer could visualise his design using the proposed fabric which would give him a reliable 3D presentation before production could obviate designers having to make prototypes. Development of products using conventional methods is time and resource consuming, however employing simulation methods for visualising developed garment saves time and cost [85]. It was supposed that this system could be used by designers and technologists to develop their new materials (fabrics) by the process of reverse engineering [71].

In communication within the textile and apparel industry, simulation of fabric and garment drape could allow different departments or organisations to exchange and share viewing draped garment which would enhance apparel design, manufacture and management.

E-commerce is increasingly being used all over the world. However, the percentage of sold apparel online is very low compared to apparel being sold by conventional methods. Accurate product characterisation is one of the factors which causes this small portion of selling apparel online [85]. Therefore, improving virtual simulation of fabric drape could affect the global retailing systems and enhance competiveness in the textile and apparel market over the world [71].

From this review the importance of the input data to achieve the best visualisation of fabric drape is obvious. Therefore working on revealing the combination of fabric properties which would be used as input data for this simulation is essential.

~~9~~8 Priorities for Future Research

Further studies are recommended and required into measurement of fabric drapeability:

• As recently a variety of nonwoven fabrics have become available in the fabric market, a wider range of fabrics including different commercial nonwovens, which would give acceptable drapeability for garment use, could be investigated.

• Investigating the reliability of the proposed drape parameters in this study by fabric simulation is recommended.

• Development of alternative drape parameters using image analysis methods providing representative and reliable parameters for apparel making is required.

• Studying durability and comfort of nonwoven garments.

• Investigating the effect of laundry and softening treatment on nonwoven drape.

~~10~~9 References

[1] D.P. Bishop, Textile Progress 26 (1996) p. 1.
[2] S. Saleh, *Low stress mechanical properties of hydroentangled fabrics*, in *School of Textiles and Design*, The university of Leeds, Leeds, 2003.
[3] V.H. Elsasser, *Textiles: concepts and principles,* 2nd ed., Fairchild, New York, 2005.
[4] B.P. Corbman, *Textiles: fiber to fabric,* 6th ed., McGraw-Hill, New York, 1983.
[5] J. Booth, *Principles of textile testing : an introduction to physical methods of testing textile fibres, yarns and fabrics,* 3rd ed., Heywood Books, London, 1968.
[6] British standard Institution, *Determination of mass per unit area using small samples*, in *Textiles. Fabrics.*, BSI, London, 1998.
[7] B. Saville, *Physical testing of textiles*, Woodhead Publishing, Cambridge, 1999.
[8] F.T. Peirce, Journal of the Textile Institute Transactions 21 (1930) p. T377.
[9] J.W.S. Hearle, *Structural mechanics of fibers, yarns, and fabrics* Vol. 1, Wiley Interscience, New York, 1969.
[10] CSIRO, *Fabric assurance by simple testing: instruction manual*, Cisro, Australia., 1991.
[11] G.E. Cusick, J.W.S. Hearle, R.I.C. Michie, R.H. Peters and P.J. Stevenson, Journal of the Textile Institute Proceedings 54 (1963) p. 52.
[12] British standard Institution, *Method for determination of bending length and flexural rigidity of fabrics*, BSI, London, 1990.
[13] S.J. Russell, Journal of the Textile Institute 85 (1994) p. 82.
[14] L.J. Winn and E.R. Schwarz, Textile Research Journal 10 (1939) p. 5.
[15] N.J. Abbott, Textile Research Journal 21 (1951) p. 435.
[16] I.M. Stuart and K. Baird, Textile Research Journal 36 (1966) p. 91.
[17] I.M. Stuart, British Journal of Applied Physics 17 (1966) p. 1215.
[18] T. Cassidy, C. Cassidy, S. Cassie and M. Arkison, International Journal of Clothing Science and Technology 3 (1991) p. 14.
[19] C. Cassidy, *An investigation of the mechanical and surface properties of weft knitted fabrics and their influence on sewability during garment assembly*, in *Faculty of Computing Science and Engineering*, De Montfort University, Leicester, 2002.
[20] E.R. Schwarz, Textile Research Journal 9 (1939) p. 216.
[21] L.J. Winn and E.R. Schwarz, America dyestuff reporter 29 (1940) p. 469.
[22] H.F. Schiefer, Textile Research Journal 3 (1933) p. 388.
[23] T. Mori and D.W. Lloyd, Textile Research Journal 64 (1994) p. 397.
[24] L.J. Winn and E.R. Schwarz, Textile Research Journal 9 (1939) p. 216.
[25] L.J. Winn and E.R. Schwarz, Textile Research Journal 10 (1940) p. 453.
[26] W.J. Hynek and G. Winston, Textile Research Journal 23 (1953) p. 743.
[27] A.R. Kalyanaraman and A. Sivaramakrishnan, Textile Research Journal 54 (1984) p. 479.
[28] N. Zhou and T.K. Ghosh, Textile Research Journal 68 (1998) p. 533.
[29] M. Ayhan Haji, C. Thomas, B. Alan and H. Dave, Measurement Science and Technology 23 (2012) p. 055602.
[30] P. Pandurangan, *Mechanics of fabric drape*, in *Department of Mechanical and Aerospace Engineering*, North Carolina State University, Raleigh, NC, 2003, p. 60
[31] A. Gider, *An online fabric database to link fabric drape and end-use properties*, in **The School of Human Ecology**, Louisiana State University 2004.
[32] K. Slater, Journal of the Textile Institute 88 (1997) p. 79.

[33] J. Fan, *Clothing appearance and fit: science and technology*, Woodhead Publishing in association with The Textile Institute, Cambridge, 2004.
[34] British Standards Institution, *Textiles. Test methods for nonwovens.* , in *Determination of drapability including drape coefficient*, BSI, London, 2008.
[35] British Standards Institution, *Textiles - Test methods for nonwovens. Part 9: Determination of drape coefficient*, BSI, London, 1998.
[36] British standards Institution, *Method for the assessment of drape fabrics*, BSI, London, 1973.
[37] C.C. Chu, C.L. Cummings and N.A. Teixeira, Textile Research Journal 20 (1950) p. 539.
[38] W. Zurek, D. Jankowiak and I. Frydrych, Textile Research Journal 55 (1985) p. 113.
[39] G.K. Stylios, N.J. Powell and L. Cheng, Transactions of the Institute of Measurement and Control 24 (2002) p. 33.
[40] G.K. Stylios and N.J. Powell, International Journal of Clothing Science and Technology 15 (2003) p. 211.
[41] G.E. Cusick, *A study of fabric drape*, in *Faculty of technology*, Univeristy of Manchester, Manchester, 1962.
[42] G.E. Cusick, Journal of the Textile Institute Transactions 56 (1965) p. 596.
[43] G.E. Cusick, Journal of the Textile Institute 59 (1968) p. 253.
[44] B.K. Behera and A. Pangadiya, Textile Asia 34 (2003) p. 45.
[45] B.K. Behera and A.K. Pattanayak, Indian journal of fibre and textile research 33 (2008) p. 230.
[46] B.K. Behera and R. Mishra, Journal of the Textile Institute 97 (2006) p. 147.
[47] Y.J. Jeong, Journal of the Textile Institute 89 (1998) p. 59
[48] Y.J. Jeong and D.G. Phillips, Journal of the Textile Institute 89 (1998) p. 70.
[49] N. Kenkare and T. May-plumlee, Journal of Textile and Apparel, Technology and Management 4 (2005) p. 1.
[50] K.H. Tsai, M.C. Tsai, P.N. Wang and T.W. Shyr, Fibres and Textiles in Eastern Europe 17 (2009) p. 54.
[51] N. Uçar, F. Kalaočlu, D. Bahtiyar and O.E. Blaç, Textile Research Journal 74 (2004) p. 166.
[52] S. Farajikhah, K. Madanipour, S. Saharkhiz and M. Latifi, *3D reconstruction of fabric drape using shadow moiré topography*, 1986, p. 1.
[53] B.J. Collier, V.A. Paulins and J.R. Collier, Clothing and Textiles Research Journal 7 (1989) p. 51.
[54] B.J. Collier, Clothing and Textiles Research Journal 10 (1991) p. 46.
[55] T.S. Ranganathan, D. Ramaswamy, K.S. Jayaraman, R. Sanjeevi, V. Arumugam, S. Das and A. Vaidyanathan, Journal of the Textile Institute 77 (1986) p. 226.
[56] G.K. Stylios and R. Zhu, Journal of the Textile Institute 88 (1997) p. 465.
[57] M. Matsudaira and M. Yang, Journal of the Textile Institute 91 (2000) p. 600.
[58] J.Y. Lin, P.N. Wang and T.W. Shyr, Textile Research Journal 78 (2008) p. 911.
[59] B. Al-Gaadi, F. Göktepe and M. Halász, Textile Research Journal 82 (2011) p. 1.
[60] J.W.S. Hearle and J. Amirbayat, Journal of the Textile Institute 79 (1988) p. 588.
[61] C. Mizutani, T. Amano and Y. Sakaguchi, Textile Research Journal 75 (2005) p. 81.

[62] G. Grover, M.A. Sultan and S.M. Spivak, Journal of the Textile Institute 84 (1993) p. 486.
[63] J.O. Kim and B.L. Slaten, Textile Research Journal 69 (1999) p. 59.
[64] N. Pan, The International Journal of Design and Nature and Ecodynamics 1 (2007) p. 48.
[65] L. Vangheluwe and P. Kiekens, International Journal of Clothing Science and Technology 5 (1993) p. 5.
[66] J.E. Ruckman, K.B. CHENG and R. Murray International Journal of Clothing Science & Technology 10 (1998) p. 56.
[67] I. Frydrych, G. Dziworska and M. Matusiak, Fibres and Textiles in Eastern Europe 11 (2003) p. 31.
[68] C.C. Chu, M.M. Platt and W.J. Hamburger, Textile Research Journal 30 (1960) p. 66.
[69] J.L. Hu and S.P. Chung, Textile Research Journal 68 (1998) p. 913.
[70] H. Rodel, V. Ulbricht, S. Krzywinski, A. Schenk and P. Fischer, International Journal of Clothing Science and Technology 10 (1998) p. 201.
[71] G.K. Stylios and T.R. Wan, International Journal of Clothing Science and Technology 11 (1999) p. 10.
[72] D. Robson and C.C. Long, Clothing and Textiles Research Journal 18 (2000) p. 1.
[73] S. Jevšnik and J. Geršak, Fibres and Textiles in Eastern Europe 12 (2004) p. 47.
[74] S. Jevšnik and D. Žunič-Lojen, Fibers and Polymers 8 (2007) p. 550.
[75] N.T.T. Ngoc and H.N. Anh, World Journal Of Engineering 7 (2008) p. 1.
[76] T.W. Shyr, P.N. Wang and J.Y. Lin, Textile Research Journal 79 (2009) p. 1223.
[77] P. Fischer, S. Krzywinski, H. Rodel, A. Schenk and V. Ulbricht, Textile Research Journal 69 (1999) p. 331.
[78] K.R. Sharma, B.K. Behera, H. Roedel and A. Schenk, International Journal of Clothing Science and Technology 17 (2005) p. 75.
[79] L. Kokas-Palicska, I. Szücs and Z. Borka, Journal of Applied Sciences 5 (2008) p. 75.
[80] T.W. Shyr, P.N. Wang and K.B. Cheng, Fibres and Textiles in Eastern Europe 15 (2007) p. 81.
[81] M. Matsudaira, M. Yang, T. Kinari and S. Shintaku, Textile Research Journal 72 (2002) p. 410.
[82] M. Matsudaira and M. Yang, Textile Research Journal 73 (2003) p. 250.
[83] S. Tandon and M. Matsudaira, Research journal of textile and apparel 14 (2010) p. 62.
[84] C.L. Moore, L.M. Gurel and M. Lentner, Clothing and Textiles Research Journal 13 (1995) p. 131.
[85] N.s. kenkare, *Three dimensional modeling for garment drape*, in *Textile Technology Management*, North carolina state, Reliegh, 2005.
[86] S. Backer, Textile Research Journal 18 (1948) p. 650.
[87] V. Werner and W. James, Textile Research Journal 22 (1952) p. 123.
[88] H.M. Elder, S. Fisher, K. Armstrong and G. Hutchinson, Journal of the Textile Institute 75 (1984) p. 99.
[89] M. Matsudaira, Y. Tan and Y. Kondo, Journal of the Textile Institute 84 (1993) p. 376.
[90] J. Hu, S. Chung and M.T. Lo, International Journal of Clothing Science and Technology 9 (1997) p. 220.

[91] I. Frydrych, G. Dziworska and A. Cieslinska, International Journal of Clothing Science and Technology 12 (2000) p. 171.
[92] M. Matsudaira and M. Yang, Journal of Textile Engineering 49 (2003) p. 27.
[93] V. Sidabraitė and V. Masteikaitė, Materials science 9 (2003) p. 111.
[94] E. Önder, F. Kalao and B. Özipek, Textile Research Journal 73 (2003) p. 854.
[95] M. Matsudairaa, S. Yamazaki and Y. Hayashi, Indian journal of fibre and textile research 33 (2008) p. 223.
[96] R. Chattopadhyay, Journal of Textile Engineering 54 (2008) p. 179.
[97] M.M. Quirk, T.L. Martin and M.T. Jones, *Inclusion of fabric properties in the e-textile design process*, in *13th IEEE International symposium on wearable computers*, IEEE, Linz, 2009, p. 37.
[98] G. Ramakrishnan, D. Bhaarathi and S. Mukhopadhyay, Journal of Textile and Apparel, Technology and Management 6 (2009) p. 1.
[99] R.H. Brand, Textile Research Journal 34 (1964) p. 791.
[100] N.R.S. Hollies, Journal of the Textile Institute 80 (1989) p. 1.
[101] H. Morooka and M. Niwa, The Journal of the Textile Machinery Society of Japan 22 (1976) p. 67.
[102] J. Amirbayat and J.W.S. Hearle, Journal of the Textile Institute 80 (1989) p. 51
[103] J. Amirbayat and J.W.S. Hearle, International Journal of Mechanical Sciences 28 (1986) p. 339.
[104] J. Amirbayat and J.W.S. Hearle, International Journal of Mechanical Sciences 28 (1986) p. 359.
[105] A. Okur and T. Gihan, Textile Asia 33 (1993) p. 28.
[106] J.L. Hu, Researech journal of textile and apparel. 1 (1997) p. 126.
[107] J. Hu and Y.F. Chan, Textile Research Journal 68 (1998) p. 57.
[108] O. Tokmak, O.B. Berkalp and J. Gersak, Fibres and Textiles in Eastern Europe 18 (2010) p. 55.
[109] R.I.C. Michie and P.J. Stevenson, Textile Research Journal 36 (1966) p. 494.
[110] M. Matsudaira, M.Z. Yang, T. Kinari and S. Shintaku, Textile Research Journal 73 (2003) p. 59.
[111] G. Agarwal, L. Koehl and A. Perwuelz, Textile Research Journal 81 (2011) p. 1100.
[112] M.N. Sun, Textile Research Journal 78 (2008) p. 761.
[113] J.R. Collier, B.J. Collier, G. O'Toole and S.M. Sargand, Journal of the Textile Institute 82 (1991) p. 96.
[114] D. Zunic-Lojen and S. Jevsnik, Fibres and Textiles in Eastern Europe 15 (2007) p. 39.
[115] D.E. Breen, D.H. House and M.J. Wozny, Textile Research Journal 64 (1994) p. 663.
[116] J.L. Hu, S.F. Chen and J.G. Teng, Textile Research Journal 70 (2000) p. 593.
[117] D. Xiaoqun, F. Takao, M. Shigeru, T. Masayuki and S. Yoshio, International Journal of Clothing Science and Technology 13 (2001) p. 23.
[118] S.F. Chen, J.L. Hu and J.G. Teng, Finite Elements in Analysis and Design 37 (2001) p. 513.
[119] N. Magnenat-Thalmann and P. Volino, Visual Computer 21 (2005) p. 506.
[120] S.F. Ng, C.L. Hui and F.Y. Tam, Research journal of textile and apparel 6 (2002) p. 65.
[121] R. Sanad and T. Cassidy, Journal of Fiber Bioengineering and Informatics 8 (2015) p. 47.

[122] R. Sanad, T. Cassidy and V. Cheung, Journal of Fiber Bioengineering and Informatics 5 (2012) p. 341.
[123] R. Sanad, T. Cassidy, V. Cheung and E. Evans, Journal of Fiber Bioengineering and Informatics 6 (2013) p. 1.
[124] B.T. Orzada, M.A. Moore and B.J. Collier, International Journal of Clothing Science and Technology 9 (1997) p. 272.
[125] B.T. Orzada, Clothing and Textiles Research Journal 19 (2001) p. 52.
[126] S.K. Koenig and S.J. Kadolph, Textile Research Journal 53 (1983) p. 341.
[127] S.P. Chung, J.L. Hu and M.T. Lo, *The relationship between fabric drape and seam parameters*, in *The 78th world conference of the textile institute in association with the 5th textile symposium of Seve and Sepve*, The Institute, Thessalonika, 1997, p. 175.
[128] R.C. Dhingra and R. Postle, Clothing Research Journal 8 (1980) p. 59.
[129] F.F. Cui, X. Zhang and L.S. Wang, *Study of the relationship between jacket - business wear fitness and fabric drape*, in *The 3rd International Symposium of Textile Bioengineering and Informatics*, Li, Y. Q. Y. P. L. X. N. L. J. S., ed., 2010, p. 1299.
[130] C.L. Moore, Journal of Home Economics 84 (1992) p. 31.
[131] J.W.S. Hearle and J. Amirbayat, Textile Research Journal 56 (1986) p. 727.
[132] J. Hu, *Structure and mechanics of woven fabrics*, Woodhead Publishing, Abingdon, 2004.
[133] T.J. Mahar, P. Wheelwright, R.C. Dhingra and R. Postle, Textile Research Journal 60 (1990) p. 7.
[134] M.L. Gaucher, M.W. King and B. Johnston, Textile Research Journal 53 (1983) p. 297.
[135] J.R. Postle and R. Postle, Textile Asia 24 (1993) p. 63.
[136] J. Postle and R. Postle, Textile Asia 31 (2000) p. 30.
[137] W.M. Lo, J.L. Hu and L.K. Li, Textile Research Journal 72 (2002) p. 454.
[138] A. Lam, A. Raheja and M. Govindaraj, *Neural network models for fabric drape prediction*, in *IEEE International Symposium on Neural networks*, IEEE, Budapest, 2004, p. 2925.
[139] H. Jedda, A. Ghith and F. Sakli, Journal of the Textile Institute 98 (2007) p. 219.
[140] B. Chen and M. Govindaraj, Textile Research Journal 65 (1995) p. 324.
[141] D.M. Stump and W.B. Fraser, Textile Research Journal 66 (1996) p. 506.
[142] B.P.V. West, R.B. Pipes and M. Keefe, Journal of the Textile Institute 81 (1990) p. 448
[143] P. Potluri, S. Sharma and R. Ramgulam, Composites Part a-Applied Science and Manufacturing 32 (2001) p. 1415.
[144] J. Mccartney, B.K. Hinds, B.L. Seow and D. Gong, Journal of Materials Processing Technology 107 (2000) p. 31.
[145] W.R. Yu, T.J. Kang and K. Chung, Journal of the Textile Institute 91 (2000) p. 285.
[146] P. Pandurangan, J. Eischen, N. Kenkare and T.A.M. Lamar, Journal of the Textile Institute 99 (2008) p. 219.
[147] N. Kenkare, T.A.M. Lamar, P. Pandurangan and J. Eischen, Journal of the Textile Institute 99 (2008) p. 211.
[148] G. Stylios, T.R. Wan and N.J. Powell, International Journal of Clothing Science and Technology 7 (1995) p. 10.
[149] I. Hwan Sul, T. Jin Kang, S. Min Kim and Y.S. Chi, Textile Research Journal 76 (2006) p. 712.

[150] F. Bendali, J. Koko and A. Quilliot, Journal of the Textile Institute 90 (1999) p. 177.
[151] J.R. Postle and R. Postle, Textile Research Journal 69 (1999) p. 623.
[152] G. Stylios and T. Wan, *The modelling of fabric drape on humans for virtual wear trials: the next generation of fashion technologies*, in *The 78th world conference of the textile institute in association with the 5th textile symposium of Seve and Sepve*, The Institute, Thessalonika, 1997, p. 163.
[153] L. Gan, N.G. Ly and G.P. Steven, Textile Research Journal 65 (1995) p. 660.
[154] B.J. Collier and J.R. Collier, Clothing and Textiles Research Journal 8 (1990) p. 7.
[155] C.H.M. Hardaker and G.J.W. Fozzard, International Journal of Clothing Science and Technology 10 (1998) p. 114.