MANUFACTURE, ANALYSIS AND CONSERVATION STRATEGIES FOR HISTORIC TAPESTRIES

A thesis submitted to the University of Manchester for the degree of

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SCHOOL OF MATERIALS

"Well, it is a fabric, no more nor less than a fabric. But it is a coarse, vigorous, organic fabric; supple, certainly, but of a less yielding suppleness than silk or linen. It is heavy... It is heavy with matter and heavy with meaning. But it is more, it is heavy with intentions. It is this which secures its magnificence to man..."

Jean Lurçat, *Le travail dans la Tapisserie au Moyen Age,* 1947

TABLE OF CONTENTS

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TABLE OF FIGURES

ABSTRACT

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Manufacture, Analysis and Conservation Strategies for Historic Tapestries

This project aimed to address the lack of research into the mechanical properties and degradation mechanisms for historical tapestries at the fabric level and understand how effective conservation support strategies can be in the preservation of these artifacts. The research incorporated a large range of techniques from diverse disciplines including weaving, ageing, computer modeling, biochemistry and conservation science. The successful manufacture and ageing of relevant samples provided an excellent opportunity to include testing of historical samples for comparison.

Tensile testing of all samples provided a valuable insight into the characteristics of degraded historical samples compared to artificially aged samples. Although individual ageing processes – including UV ageing, Relative Humidity (RH) – thermal cycling and mechanical strain ageing produced a reduction in strength, the historical samples showed a far greater loss of strength due to the combination of all types of ageing in addition to handling and pollution damage.

A proteomic analysis of the wool fibres resulted in a greater understanding of the degradative “dark” wool ageing process which suggests that wool yellowing and tendering can be produced not just through photo-chemical reaction. Additionally, the chemical analysis laid an important foundation for future research into linking chemical mechanisms of damage with mechanical loss of strength. Analysis using electron paramagnetic resonance spectroscopy (EPR) provided an insight into the free radical chemistry of a range of wool/wool samples. It was observed that the light aged samples produced thiyl radicals whereas thioperoxy radicals were seen in the heat-humidity aged samples. This implies separate chemical reactions occur to produce degradation in the different ageing regimes. EPR analysis of some historical samples produced a carbon-based radical peak linked to a soot calibration signal. Further research on historical samples found phenolic radicals, possibly linked to the complex dye chemistry. Further research needs to be undertaken to fully clarify these findings.

A world-wide questionnaire to textile conservators has provided a useful resource in terms of a survey of methods and materials used across the world – including technical data as well as more “ethical” motivations for conservation. The results of this survey were used along with the physical data collated in the mechanical testing as information inputted into a finite element model (FEA) to undertake the digital modeling of a tapestry hanging under its own weight. Although more research is needed to fully develop this model, a preliminary investigation has been established which can be used in future research as a tool for textile conservators across the world.

DECLARATION

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1.0 INTRODUCTION

This PhD is part of the Science and Heritage Programme, which is jointly funded by the Arts and Humanities Research Council (AHRC) and the Engineering and Physical Sciences Research Council (EPSRC). The programme aims to develop links between heritage institutions and collaborative research partners such as the University of Manchester and to advance and promote interdisciplinary projects and research.

Historical textiles are among the most vulnerable objects in heritage collections, owing to their inherent long-term chemical and physical instability caused by a number of deterioration mechanisms. In the past, large-scale textiles were often overlooked as they were thought to be more stable and robust than smaller, more intricate textiles. However, recent research has highlighted that many of these large-scale textiles are not as durable as expected. Conservation of large-scale textiles often requires significant time and resources, and there are a number of methods used by different conservators – especially in the area of support methods. Due to their size, many large-scale textiles, tapestries in particular, are heavy and additional support is necessary to reduce the mechanical forces on the historic textile itself.

1.1 BACKGROUND TO PROBLEM

In general, research on historical textiles and their conservation has focused on the chemical state of the fibres and the conservation treatments to stabilise them. This research includes a large body of work to investigate dyes and their deteriorating

effect on the life of a textile. Less work has been done on the mechanical strength of tapestries, however this area is beginning to be more of interest as research has highlighted how potentially fragile these previously thought robust textiles really are. Although relatively smaller research projects have been undertaken to investigate the mechanical properties and strength of large textiles no large study has been dedicated to this topic. This research intends to increase the understanding of these highly complex and valuable objects.

1.2 Structure of project and thesis

This section will describe the original project aims and research questions (as well as their development) and the thesis structure.

1.2.1 Aims of project

The original aims of the project were set out as research questions, as below. However, as the research progressed the direction of the research changed to better understand the results and mechanisms of degradation that were seen developing. Therefore, the aims were modified slightly, as can be seen in the updated aims.

Original research questions:

Can we improve the "model tapestry" sample production technique?

Previous studies had difficulty producing an "authentic" tapestry weave on a large scale

What type of tapestry support is best?

- Many different types of support are used including: full support, patches, straps and none at all

What stitches should be used and how much?

- With the conservation ethos of "minimum intervention" how much stitching is necessary to be effective?

What materials should be used for support fabric and stitching?

- Should the support fabric and stitching threads resemble the original materials or provide different properties?

Updated research questions:

How do different types of artificial ageing affect the mechanical strength of textiles?

Recent research highlights the importance of relative humidity ageing – but can this be quantified?

How does the mechanical behaviour of aged textiles relate to their chemical degradation?

- Is it possible to relate the damage caused by different types of ageing to specific chemical mechanisms of damage?

How effective is artificial ageing?

- By using historical samples as markers, can we discover how efficient or realistic our artificial ageing techniques are at replicating historical damage?

The updated research questions were necessary as the project developed. At an early stage, after sample production and mechanical testing had been undertaken, it was found that to proceed further with the questions on structural analysis it was necessary to understand the mechanisms of damage more thoroughly, hence the evolution of the further research questions.

1.2.2 Thesis structure

This thesis does not take the form of a "traditional" thesis or scientific report; rather than all methods and materials grouped together, and all results grouped together, the work is structured into distinct topics of research. Each of these will have its own introduction, methods, results and discussion for ease of presentation and understanding; and a final conclusions chapter places the results and discussion in overall context.

The introductory chapter explains the background to this research project and the partners involved. A brief history of tapestry and tapestry conservation is included.

Chapter Two covers the sampling of tapestry samples. This includes a study of the tapestry collection at Hampton Court Palace, as well as methods and materials in the production of replica tapestry fabric.

Chapter Three examines the mechanical properties of historical textiles and artificially aged textiles. This includes a review of what is known about the mechanical behaviour of tapestry materials (wool and silk) as well as the results of mechanical testing.

Chapter Four is similar in structure to Chapter Three except that it discusses the chemical properties and effect of ageing on historical textiles. This chapter concludes with a discussion of how this research has established some links between mechanical behaviour and chemical degradation of fabric.

Chapter Five moves onto the conservation of tapestries – specifically the support strategies used across the world. It includes the results of a worldwide survey conducted to better document methods and treatments used by textile conservators. The second half of this chapter presents the finite element analysis undertaken of tapestries and potential for future work in this area.

The thesis is concluded in Chapter Six with contextual conclusions, along with suggestions for future research leading out from this study.

1.3 Why conserve?

The field of conservation is one which has existed in some form since man began to make and form objects and art. The origin of conservation was restoration where objects were restored to make them still practical and useful. However, in the last one hundred years the ethics of conservation and restoration has shifted towards less interventive methods and takes the consideration and values of the object into account during treatment planning. Objects are often left much in the same state aesthetically but given stability and support to preserve them in their current form. Respect is given for both the original artist as well as previous restorations, with historical value themselves.

Conservation is important in the field of heritage in order to preserve objects and cultural heritage for the future and future generations. As a relatively “young” field, questions over methods, materials and ethics are constantly being explored and this research contributes to all three of those areas; which methods to use, which materials are best and how "far to go" during conservation.

1.4 Historical background

The art of tapestry is one which has been practised for over 3500 years, with the oldest known surviving tapestry recorded from 1400 B.C. (Campbell, 2002). A tapestry is the result of a weaving technique that has not seen much change since its inception. The thriving era of the western tapestry weaving began in the fifteenth century although European attempts at tapestry making were made as early as the twelfth century (Candee, 1935). The main centres for tapestry weaving were France, Flanders, England and Spain with different workshops flourishing at different historical periods under various patronages from wealthy and highly connected families.

Although “tapestry” technically refers to a type of weave, the term is commonly applied to objects which portray a decorative image or story; often biblical, mythical or commemorative.

Tapestries were arguably "the" status symbol of the past. More expensive than paintings or sculpture, and with an opportunity for self-appreciation; they were a way of showing the world your wealth and power and assuming an association with historic events or myths. Henry VIII commissioned a large number of tapestries to

emphasise his new power and position as the head of the Church of England in the 1540s (Campbell, 2002). They were often commissioned to commemorate historic events such as a set of tapestries at Blenheim palace, a gift to the first Duke of Marlborough from Queen Anne for his leadership and victory during the War of the Spanish Succession; in particular the battle of Blenheim in 1704.

Tapestries can be found at all the major courts of Europe. The finest tapestries of the medieval and renaissance era were the result of the patronage of the royal families, leading nobility and the Church – due to the huge costs involved these were the only people who could realistically afford to be a patron of this art. The tapestries at the Vatican (Acts of the Apostles – ten tapestries) cost five times the amount that the Sistine chapel ceiling, giving an indication of their importance and value (Vasari, 1568).

Although only the very powerful and wealthy could afford tapestries, they did have a practical function, which was to provide warmth and decoration wherever the household was travelling. In the days before central heating and electricity they would also act as draught excluders and provide insulation on bare stonewalls! They would be rolled up and transported along with the other items of the household such as beds, hangings and personal wardrobes (Campbell, 2002).

Hampton Court Palace is a royal palace near London, UK. The first royal to live in the palace was Henry VIII in 1529 and is still owned by the crown today, although the British royal family has not lived there since the 18th century. The palace is maintained by Historic Royal Palaces, the collaborator in this research and it is appropriate that the focus of this research was on their collection.

The collection of tapestries at Hampton Court Palace is focused primarily around the commissions of Henry VIII (1509-1547) and the Tudor period.

Hampton Court houses a number of important sets of tapestries including: History of Alexander (7 tapestries, early 18th Century, Brussels), History of Abraham (10 tapestries, early 16th century, Flemish) and Acts of the Apostles (9 tapestries, 17th Century, Brussels).

FIGURE 1.1: ALEXANDER'S TRIUMPHAL ENTRY INTO BABYLON HANGING IN THE QUEEN'S GALLERY, HAMPTON COURT

1.5 TAPESTRY CONSERVATION

This section discusses the manufacturing and weave of a tapestry as well as the conservation of tapestry and its historical development.

1.5.1 STRUCTURE AND WEAVING OF A TAPESTRY

Tapestry is a discontinuous plain weft-faced weave, with the weft yarns forming the design from the cartoon in a variety of colours (Figure 1.2).

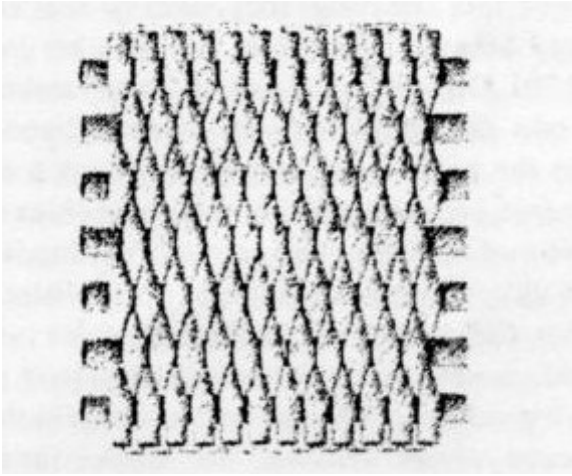


FIGURE 1.2 TAPESTRY WEAVE (VERLET ET AL., 1978)

Unlike other forms of plain weave, the weft does not stretch from selvedge to selvedge but only for the section of design in question. As a result, there are a number of slits in the weave structure, which were traditionally sewn up by ladies or children working in the workshop after the main weaving process is completed.

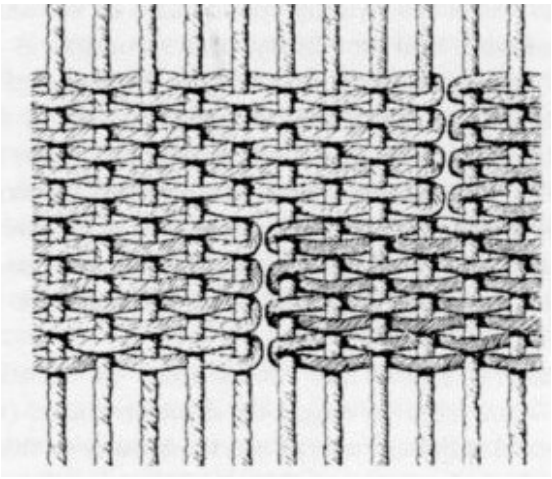
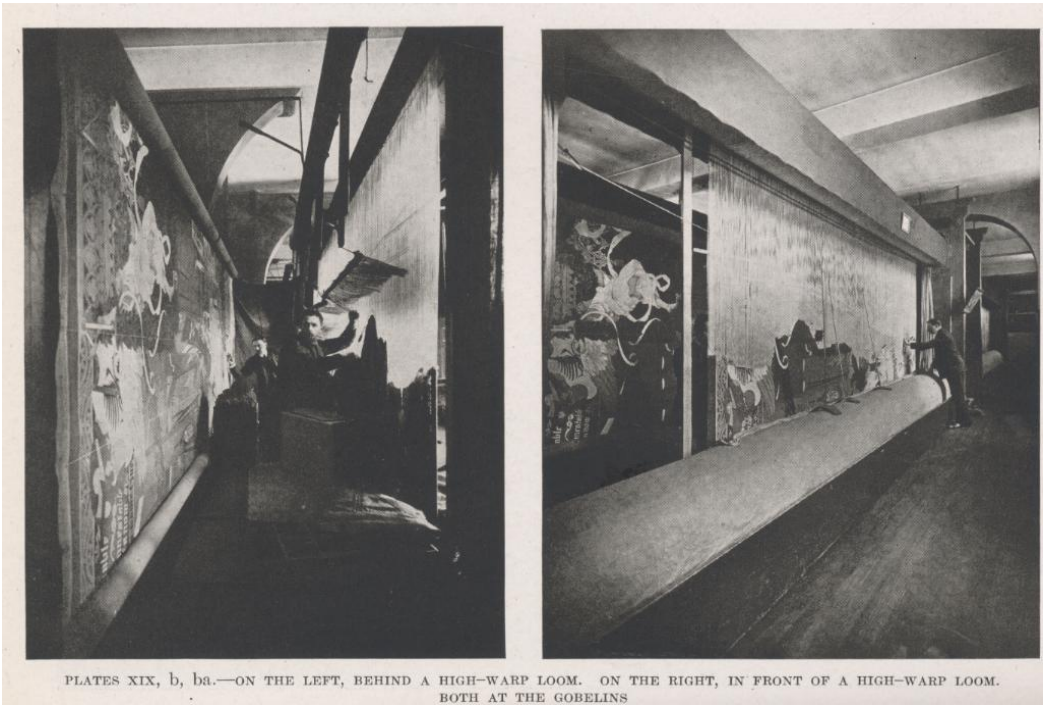


FIGURE 1.3 SLITS IN TAPESTRY WEAVE STRUCTURE (VERLET ET AL., 1978)

The warp yarns were usually wool, and were not dyed. Both fine wools and silk were used for the weft yarns, and for the finest tapestries metal threads of gold and silver (wrapped around a core of silk) were also used.

Tapestries are conventionally woven on either *haute lisse* (high leash) or a *basse lisse* (low leash). Also known as high-warp and low-warp looms, respectively, the main difference is the direction of warps for weaving. On a *haute lisse* the warps are strung vertically whereas on a *basse lisse* loom the warps are horizontal, Figures 1.4 and 1.5 (Hunter, 1925). Although the position of the warp, weaver and cartoon is different for each set-up, the result is the same and unless original evidence exists, the precise method that was used for a particular tapestry cannot be discovered through inspection of the tapestry itself.



PLATES XIX, b, ba.—ON THE LEFT, BEHIND A HIGH-WARP LOOM. ON THE RIGHT, IN FRONT OF A HIGH-WARP LOOM. BOTH AT THE GOBELINS

FIGURE 1.4: HAUTE LISSE (HIGH WARP LOOM) (HUNTER, 1925), P.270)


PLATE XIX, d.—TAPESTRY WEAVING. GENERAL VIEW OF LOW-WARP LOOM. SHOWING THE WEAVER AT WORK

FIGURE 1.5: BASSE LISSE (LOW WARP LOOM) (HUNTER, 1925), P. 270)

Once the customer chose a design, a cartoon was drawn by an artist or a replica made from a well-known set. This was then placed either behind the weaver viewed by a mirror (*haute lisse*) or underneath the warps (*basse lisse*). All tapestries were woven from the reverse of the tapestry. One advantage of a high-warp loom was that the weaver could monitor the progress of the tapestry front by walking in front of the loom whereas the face of the tapestry woven on a low-warp loom was only seen for the first time when it was completed and unfurled.

The tapestry industry during the 15-17th centuries was a major source of income and employment in those centres where it was carried out, in particular Flanders with Brussels at its centre as the leading manufacturer of fine tapestries (Campbell, 2002).

1.5.2 History of tapestry conservation

Tapestries were made to be functional as well as a show of wealth and power. Therefore they were considered portable objects and travelled around Europe with the households of the nobility. As a result, almost as soon as they had been woven, repairs were needed as a result of general wear and tear, handling, poor environmental conditions and insect damage.

Some very wealthy households could afford to keep their own repairer, or *rentrayeur* as part of their staff. The expense that was taken to commission a tapestry implies that the relatively small expenditure to have repairs done would be worthwhile to extend their lifetime. Often weavers had a unit responsible for repairs and re-weaving, such as in the renowned Gobelins manufactory in Paris and Morris & Co. in London (Ysselsteyn, 1969). This was also reflected in the British royal household as well: records show that as part of the kings' staff, at least one "master re-weaver" was employed to carry out repairs and re-weaving of the tapestries in Henry VIII's court (Brewer et al., 1861-3).

These repairers would use traditional techniques to clean the tapestries and to restore areas of loss. The main method used to restore damaged areas was re-weaving. When this re-weaving was of the highest quality, the only way it can be differentiated from the original weave today is through the fading of the dyes over time. Often newer, more modern dyes are not as light-fast as the original dyes used, so even if colours were matched during re-weaving, differential fading of

original and replacement yarns will take place over time highlighting areas of restoration (Fiette, 1997).

The aim of restoration was to re-create the image and weave so that any areas of loss were not visible to the observer. Although modern conservation theory and practice have concerns over loss of original material, in the past it is likely that the primary concerns were functionality and aesthetics. It was important that the tapestry appeared to be in good condition, and the pictorial image was kept intact.

This tradition was upheld until the 1960s (Lennard and Hayward, 2006) when the concept of restoration began to shift towards an outlook of conservation, with this view prevalent within the museum field. Rather than replacing large sections through re-weaving techniques, the work carried out aimed to keep as much original material as possible and provide stability and support to the tapestry as a structure. Thus the modern tapestry conservation practice was born. It should be noted that commercially, re-weaving was still encouraged as the priority was often preserving the pictorial image and therefore increasing monetary value.

The changes in tapestry conservation have been influenced by a general change in the outlook of cultural heritage conservation brought about in the 1970s with the concepts of “minimal intervention” and “reversibility” gaining favour (Munoz-Vinas, 2004). However textile conservation, unlike some conservation specialities, struggles with the concept of complete reversibility. The likelihood of stitches being unpicked and supports unmounted is small and presents a problem of causing more damage. Instead, the motion of carrying out as little as possible with maximum effect: i.e. minimum intervention is encouraged as well as an associated

significant increase in the standard of documentation. Tapestry conservation, as a specialist field within textile conservation, is considered to have slightly different practices. It is generally accepted that a large proportion of the object's entity and value is in the image and design, and when large sections of the image are missing or distorted conservation does aim to restore or partly-restore the image so that the integrity of the image and message remain (Lennard, 2007).

As tapestries are composed of natural fibres they are innately susceptible to damage through light, humidity fluctuations and insect attack (Timár-Balázsy and Eastop, 1998). They also suffer physical damage as a result of handling and hanging under their own considerable weight. Therefore tapestry conservation is focused on two primary areas. Firstly, the consolidation of damage, in some cases re-warping and preserving the image; secondly in providing a support structure to prolong the lifetime of the tapestry whilst it is on display or in storage.

This project is especially concerned with the latter area of conservation although the activities undertaken in the primary area will be of importance as the degradation of the fibres will inherently weaken them and therefore their physical properties will be altered. The precise methods used, such as stitches, stitching patterns, materials used for repair and replacement yarns vary depending on the country, institution and conservator carrying out the work. Every tapestry will be in a slightly different condition and need a different approach or amount of conservation work. Some may be in very sound condition generally but have lost a large area of the image through insect attack or vandalism. Others may be aesthetically intact but structurally very weak with severely degraded and soiled

yarns. The costs involved in conserving tapestries are large, owing to the size of the objects and the specialist equipment, materials and skills needed. Of course, with such large objects the work is extremely labour intensive and costs mount due to the time needed to conserve the object properly.

1.5.3 Tapestry Conservation Support Systems

There is no one universal rule in conservation when it comes to supporting tapestries. Many different methods are used, some of which are opposing in theory.

For the most part, the two common materials used as a support fabric are linen and cotton (Graaff and Boersma, 1997, Graaff and Boersma, 1998). They are used mainly because of their response to environmental changes, and their mechanical strength. It is thought that linen will allow the tapestry to "move" with changing environmental conditions. That is, the physical dimensions of the tapestry will change as the local humidity changes. This is due in the most part to the properties of wool fibres in the original tapestry.

An extensive survey and scientific investigation was carried out in 1996 by the Netherlands Institute for Cultural Heritage (ICN) which addressed the issues of cotton versus linen as a support fabric; however, no conclusive decision as to the more effective fabric was reached (Graaff and Boersma, 1997). This was the first survey of its type (to the author's knowledge), which addressed differences in tapestry conservation; specifically support methods. 28 replies were received from their original survey.

In 1999 a survey of tapestry conservation methods and evolution in the United States was performed which revealed that the primary support method used in the USA is strapping; whilst a full support is referred to as the "English Method"(Breeze, 2001). However, it was clear from the survey that even though strapping – something which is considered to define American tapestry conservation – is itself under critical assessment by conservators. Some believe that using narrow straps (3") and stitching along the edge of the straps is better; however, others believe that using wider (and fewer) straps and also stitching across the straps, is preferable. Clearly, new methods are being developed and older methods reassessed, with this process ongoing across the world in tapestry conservation studios. The profession is still a relatively young and is constantly developing its methods using research, testing and experience.

However, one conservator in the UK opposes the concept that the support fabric should allow the tapestry to "move" with changing environmental conditions. Landi proposes that the supporting material should be rigid to restrain the tapestry from moving and fixing it in one position. The material of choice is polypropylene although she acknowledges that this method is not appropriate for all conservation situations (Landi, 2006). It is not known how many other conservators subscribe to the opinion that a tapestry should be restrained or not: however this will be addressed in the questionnaire undertaken as part of this study.

The type of support used also varies. Some will use a full support, others just patches over the areas of more severe degradation and others a strapping system, Figure 1.6.

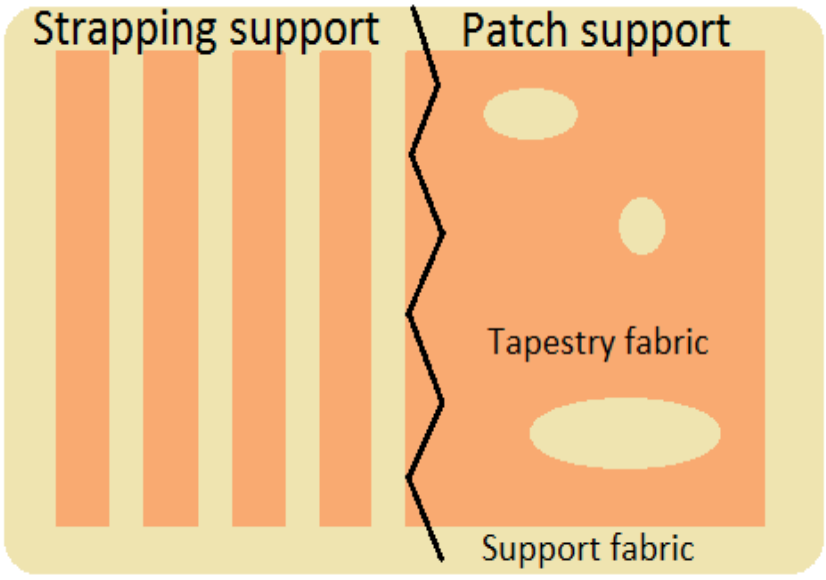


FIGURE 1.6 DIAGRAM SHOWING 2 SUPPORT SYSTEMS; STRAPPING ON THE LEFT, PATCH ON THE RIGHT

The strapping system is used primarily in the USA. The differences between a full and patch support is likely to be related first and foremost to the condition of the tapestry but also to the pressures of time, money and other resources. Conservation is a time-intensive process with any object, and considering the size and complexity of tapestries the conservation period commonly stretches into years – sometimes more than 10. The extra time and materials needed to apply a full support is often not plausible, especially on a restricted budget or time-scale. To patch the areas of most severe weakness is frequently the most appropriate treatment solution.

Some of the original methods of hanging tapestries can also be extremely damaging to the fabric of a tapestries. For instance, many were originally nailed to the wall and over time the tapestry can sag and pull on the area surrounding the nails. This can cause areas of local stress and strain concentration which eventually leads to

slitting of the object. Other traditional hanging techniques include studs into original panels (similar to nails) or loops attached to a pole. Both these methods would have a similar effect on stress concentration. Modern textile conservation commonly uses hook-and-loop fasteners such as Velcro® across the top of a tapestry which distributes the load more evenly than a point support such as a nail. However, this method was only introduced relatively recently as far as the age of the tapestry is concerned so the areas of weakness around the original hanging methods should be taken into account when undertaking conservation and also in this project when modelling stresses in the object.

2.0 Sampling: Replica and Historic sample characterisation and production

When conducting research in the field of heritage science one area of difficulty when compared to other areas of research is sampling. Often samples cannot be taken from original items of historical value or if they can be taken, commonly they are as small as possible. For this project, large samples were necessary as the bulk fabric properties needed to be characterised. Therefore replica samples were required: this chapter describes their production, artificial ageing and validation. Historic samples were also supplied by the textile conservation studio at HCP and they provided validation and comparative data for the project.

2.1 Tapestry collection research carried out at Hampton Court Palace (HCP)

The digital modelling in the later stages of this project will involve an input of certain known physical parameters of tapestry before a prediction of the mechanical behaviour can be made. Therefore, collection of this data took place through archival research and direct measurements.

Physical data collation

A survey of the warp and weft counts of the tapestry collection at Hampton Court was carried out using conservation and archival records. The most common parameter noted in condition reports is the warp count (warps per centimetre). Not all records contained information on the weft count, so the warp count will be used as a measure of fineness. The warp count varied between 30.5 – 61 warps/cm

from the coarsest to finest tapestries. Generally, sets of tapestries will have the same warp count. For instance, all six of the History of Abraham tapestries have 46 warps per centimetre. The main sets of tapestries and their respective warp counts are shown in Table 2.1.

Tapestry series	Number of tapestries	Warps per cm
Acts of the Apostles	8	50.8
History of Alexander	7	53.34
History of Abraham	10	45.72
Dido and Aeneas	5	38.1
Seasons	3	60.96

TABLE 2.1: WARPS PER CENTIMETRE OF PRIMARY TAPESTRY SETS AT HCP

Tapestries are large objects; often averaging 4 m x 6 m with their exact weight historically not being determined. Bilson et al. made several predictions in their models of the estimated weight of a tapestry which depended on the dimensions of the object alone (Bilson et al., 1997). The predicted results are included in Table 2.2: the predicted weight by Bilson et al is in the final row of the table.

During a relocation of ten tapestries into storage at Hampton Court, a method was developed to weigh the objects to establish a range of weights for modelling.

The weights of the ten tapestries ranged from 29 kg - 82 kg. Table 2.2 and Figure 2.1 present the results obtained from the preliminary weighing of the ten tapestries.

Tapestry	Weight of tapestry (kg)	Area (m^2)
Elymas RC1922	82	36.05
Time over fame - RC1270.3	70	35.64
Death over chastity - RC 1270.1	66	32.84
Death over chastity - RC 1270.4	63	25.25
Solebay - Fireships in action HRP 3003477	62	14.84
Tobit - RC 1364	62	30.24
Solebay - Fleets drawn up HRP 300476	57	27.78
Solebay - English and Dutch warships RC 1145.2	51	21.37
Peter and John - RC 1223.3	38	26.26
Verdure	29	11.43
Bilson et al. model tapestry	24	24.00

TABLE 2.2: WEIGHTS AND AREAS OF TAPESTRIES IN HAMPTON COURT PALACE COLLECTION

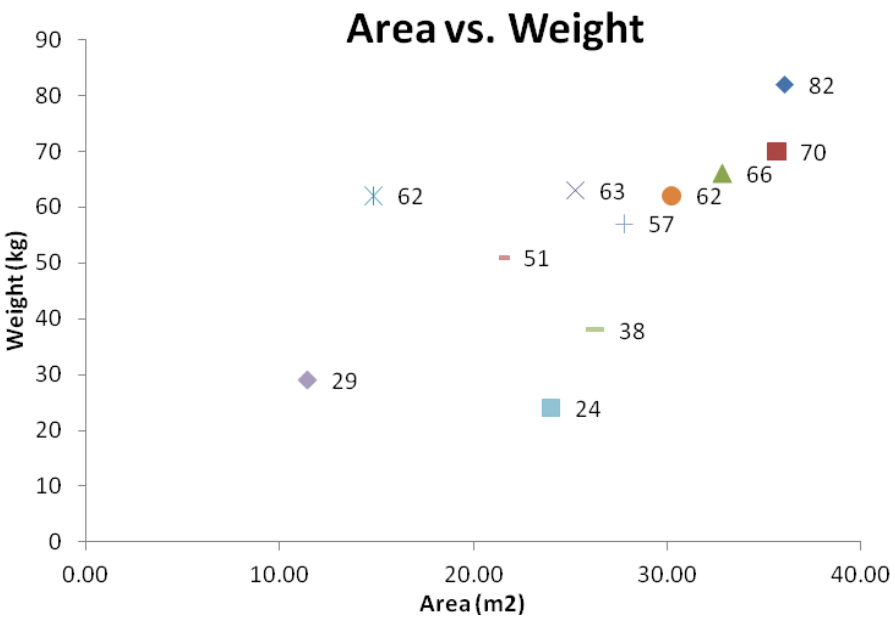


FIGURE 2.1: AREA VS. WEIGHT OF A TAPESTRY

From the data in Table 2.2 and Figure 2.1, it is unsurprising that there is correlation between increasing area and weight. However, it is not entirely linear as different tapestries have varying levels of fineness (see Table 2.1) and also materials. Those finest tapestries which included large areas of metal thread will be heavier than those which contain large areas of silk and no metal thread. If a tapestry contains a significant portion of metal thread then it can be predicted that its weight will be more than that estimated by Bilson et al.

Tapestries were often made for specific rooms, which are measured beforehand for size. Therefore, a set of tapestries may vary in size even if they are part of a series commissioned at the same time. The average area of HCP tapestry is 25.6 m^2 with a range of 6 m^2 – 45 m^2.

2.2 SAMPLING

In this section, the study of the tapestry collection at Hampton Court Palace, the historic samples supplied by the tapestry conservation team at Hampton Court Palace and subsequent production of replica tapestry materials is discussed.

2.2.1 HISTORIC SAMPLES

The textile conservation studio has been at Hampton Court for over one hundred years. During that time, many samples of tapestry have been collected from a variety of sources; such as removed repairs, mis-matched borders and remains from tapestries beyond repair. This resource is in itself historic – and this project was granted access to this collection to gather historic samples for investigation and comparison.

Ten samples were removed for analysis and testing. A description of these samples is given below and the coarseness of the weave is given. This is a rough estimate which was judged so that there was a range of weave structures tested.

Sample 1

Fine weave and multiple colours, possibly a section from an Abraham tapestry, which has a very similar weave and colours, with part of a lion head on the complete piece.

FIGURE 2.2 HISTORICAL SAMPLE 1

Sample 2

Medium weave, multiple colours. Verdure tapestry with intricate leaf detail.

FIGURE 2.3 HISTORICAL SAMPLE 2

Sample 3

Medium fine weave, lost most of its colour, with some blue remaining. Linen section observed of base of complete sample. Clear repairs along slits.

FIGURE 2.4 HISTORICAL SAMPLE 3

Sample 4

Medium/fine weave with multiple colours. Decorative border - small sample, so removed as a whole piece. No image.

Sample 5

Medium weave, mainly yellow with blue detail, thought to be a verdure tapestry. Quite dirty.

FIGURE 2.5 HISTORICAL SAMPLE 5

Sample 6

Very coarse weave. Yellow and blue sample – possibly a border piece. Bright colours.

FIGURE 2.6 HISTORICAL SAMPLE 6

Sample 7

Very coarse weave, blue/green colour. Possibly a verdure tapestry section.

FIGURE 2.7 HISTORICAL SAMPLE 7

Sample 8

Fine weave, uniform yellow and green sections. Probably taken from a tapestry border. No image.

Sample 9

Medium/coarse weave, continuous uniform red colour. Large section of border. No slits. No image.

Sample 10

Medium weave, plain yellow/green colours. Probably part of a tree or decorative border.

FIGURE 2.8 HISTORICAL SAMPLE 10

2.2.2 REPLICA TAPESTRY SAMPLES

This section describes the background development and manufacture of the replica tapestry samples produced for this project.

2.2.2.1 MODHT

The MODHT project developed model tapestry fabric, woven at the University of Manchester, whose construction and relevance were validated by the project partners. However, one of the limitations of the samples produced by the MODHT project was the physical behaviour of the fabric in replicating a tapestry. The weave structure was very similar and although approved by conservators, it was recognised that the fabric was more flexible and extensible than an authentic historical tapestry. These properties were not considered important at the time because the project focused on the chemical properties of the fibres and their

damage. However, in the current project mechanical properties are of paramount importance. Therefore, various changes were made during the weaving process in this study to develop a model fabric that better replicated the historic tapestry weave; as described in Section 2.2.

2.2.2.2 Weaving

The majority of tapestries have a wool warp and a mixture of wool and silk weft (occasionally with metal threads for the finest tapestries). The wool/wool samples were woven using neutral, un-dyed wool yarns for both warp and weft and the silk/wool samples were woven with a wool warp and a silk weft (so the result was the silk yarns covered the wool yarns). The MODHT project and other research projects (Quye et al., 2009) (Smith et al., 2005) focused on the effect of dyes on the long-term stability and strength of yarns and fibres. However, this project will focus on the mechanical behaviour and properties of fabric and therefore the additional parameters of dyeing and the effects of dyeing will not be investigated.

Methods and Materials

The wool yarns used were English wool, 158 tex, 3/18 with the crimp and twist being investigated at a later stage of the project. The silk yarns used in the silk/wool samples were un-dyed 66 Tex 2-ply Italian silk yarns. Wool yarn was sourced from Orme & co. (manufactured by W and J Whitehead). Silk yarn was sourced from H.T. Gaddum & co. Ltd.

The weaving of replica material followed the method successfully developed by the MODHT team in 2005 and was independently approved by tapestry conservators at Hampton Court Palace (Hacke, 2006). However, the comments taken after the MODHT project and described in Section 2.1.2 were accepted and acted upon.

Following preliminary studies examining tapestries, it was concluded that the yarns used for the MODHT project and this project were relatively fine compared to some historic tapestries. It was therefore decided to increase the fineness of the weave so that this carried through to all levels of the structure. The coarser tapestry weaves, such as 12 at the lowest end of the scale, have corresponding coarse warp yarns. Generally the finer the weave of a tapestry, the finer the warp and weft yarns with therefore, the warp density being increased.

Weaving of the replica tapestry material was performed on a Northrop single shuttle loom with the fabric having 63.5 wefts per centimetre and 89 warps per centimetre. In weaving the tapestry on the Northrop loom it was necessary to reverse the warp and weft. This is because when the tapestries were hand-woven originally, a comb and mallet was used to “beat-down” the weft over the warp yarns. This resulted in the weft-faced weave that is familiar as a tapestry. However, there are no options to recreate such a compact weave using modern looms. This problem was overcome by threading up the loom with a very high density of warps. These warps are then interweaved with weft. However, when taken off the loom, the large number of loom warps became the fabric weft and the loom weft became the fabric warp. So the tapestry fabric could be consistently replicated at 63.5 warps per centimetre and 88.9 wefts per centimetre. From this

point on, when referring to “weft” the terminology means the tapestry weft (loom-warp) and vice versa. This is possible with tapestry because it is a plain weave fabric – the weft goes over one warp and under another. Therefore there is no difference in the weave structure when reversed in this fashion.

This replica material was approved by the Hampton Court conservators and scientists who unanimously agreed that the new samples were closer in texture and behaviour to a historic finely woven tapestry. It was therefore concluded that even if the fineness of the weave was slightly greater than any tapestry at Hampton Court, this was preferable to a sample with dissimilar physical behaviour to tapestry material in a physical behaviour investigation.

FIGURE 2.9: WEAVING OF TAPESTRY SAMPLES ON NORTHROP LOOM

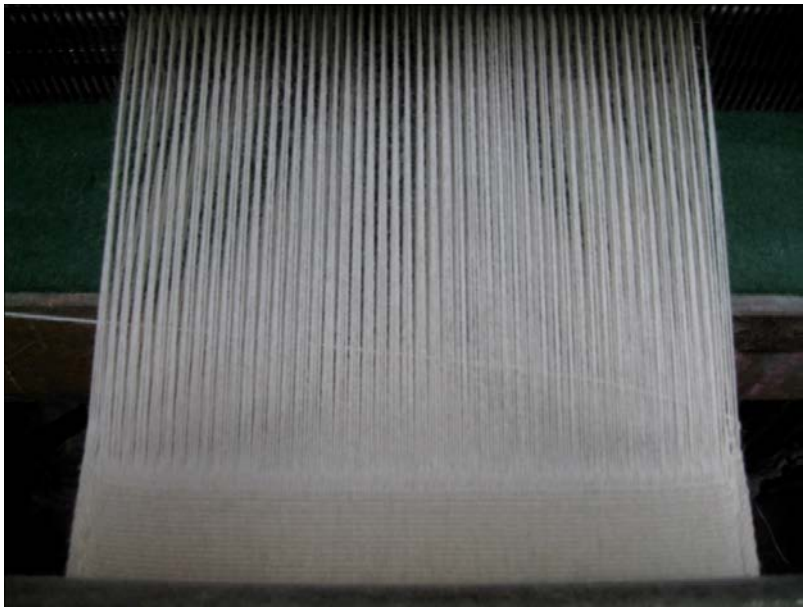


FIGURE 2.10: SAMPLE BEING WOVEN. THE INSERTION OF THE WEFT CAN BE SEEN IN PROGRESS.

2.3 Characterization of samples

The characterisation of the replica and historic samples was vital in order to validate the weave against that of historical tapestry and tapestry made in the traditional hand-woven manner. The following sections describe the tests undertaken to achieve this.

2.3.1 Crimp

Weave crimp was measured using a crimp meter after removing 10cm lengths of warp and weft yarns from the fabric. The samples were then tensioned with a weight specified for their tex value (following the standard) and the extension measured under that force.

The resulting change in length is the crimp value for the yarn given as a percentage value. The results presented are the average of 10 measurements. Crimp was calculated using the following expression:

$$C = \frac{L - L_o}{L_o} \times 100\%$$

Where:

C is the percentage crimp;

L is the mean straightened length of 10 threads removed from the fabric, in mm;

L_o is the length occupied by the threads in the fabric (i.e. original length), in mm.

The procedure followed the ISO standard (ISO 7211/3 – 1984 (E)) and the recommended straightening force for woollen and worsted spun, shown below.

Yarn	**Linear density (tex)**	**Straightening tension (cN)**
Woollen and worsted spun	15 tex to 60 tex 61 tex to 300 tex	(0.2 x tex value) + 4 (0.07 x tex value) + 12

TABLE 2.3 CRIMP TENSIONS FOR TESTING

The higher the crimp value, the more bends in the yarn per unit length. Measurements of both replica fabric and historic fabric were taken to make a comparison and to validate the manufacturing method of the replica fabric.

Sample Type	Warp Crimp value (%)	Weft Crimp value (%)
Wool/wool unaged	1.72	8.11
Silk/wool unaged	3.02	5.50
Historic wool	3.17	25.2

TABLE 2.4 CRIMP VALUES OF DIFFERENT SAMPLE TYPES

A comparison of the elastic behaviour in both directions for the wool/wool samples (Figure 2.15) clearly showed the effect of weave crimp on the tensile properties of the fabric. The warp direction has less crimp in the fibres and this is reflected in the length of the de-crimping region, characterised by the shape of the curve pre-elastic region. Throughout the elastic region, force is proportional to extension so

the plot region is approximately a straight line. Before this region of the graph, the force applied is straightening out the fibres (called de-crimping). The crimp measured for each direction was 1.72% for warp and 8.11% for weft in wool/wool fabric. This shows the difference between directions which was successfully reflected in the tensile tests, Figure 2.15.

The historic weft crimp value is significantly larger than the replica samples which was possibly an effect of the weaving method or an ageing effect. However, most importantly the trend was the same: weave crimp was introduced in the weft yarns in both historic and replica fabric samples.

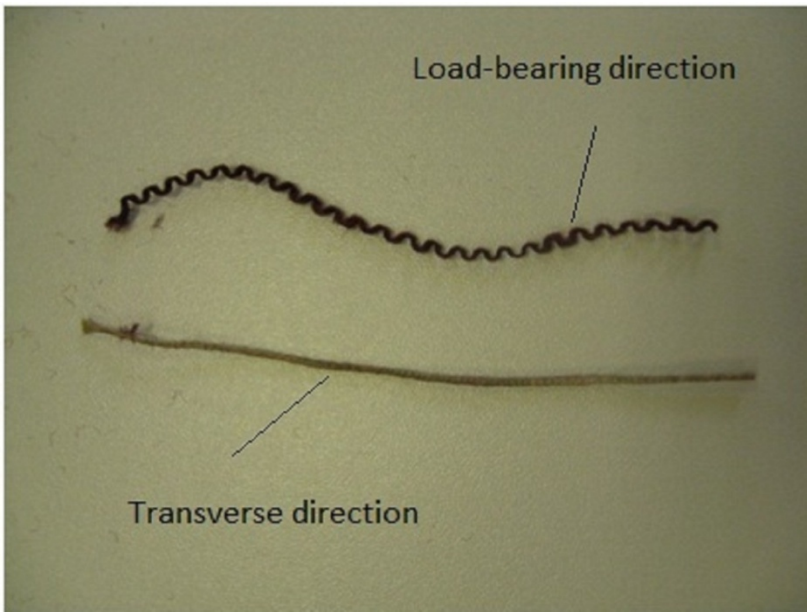


FIGURE 2.11 EFFECT OF WEAVING ON CRIMP OF WOOL FIBRES: HISTORIC WARP (BELOW) AND WEFT (TOP)

2.3.2 CROSS-SECTIONING

Optical microscopy was used to ascertain the weave angle for both virgin wool/wool and historic samples. Samples were set in resin and polished using

diamond paste and polishing mats at the University of Manchester. Figure 2.12 and Figure 2.13 show optical microscope images for both virgin wool/wool and historic samples. The average virgin wool sample weave angle was 42°, and for the historic samples was 38°.

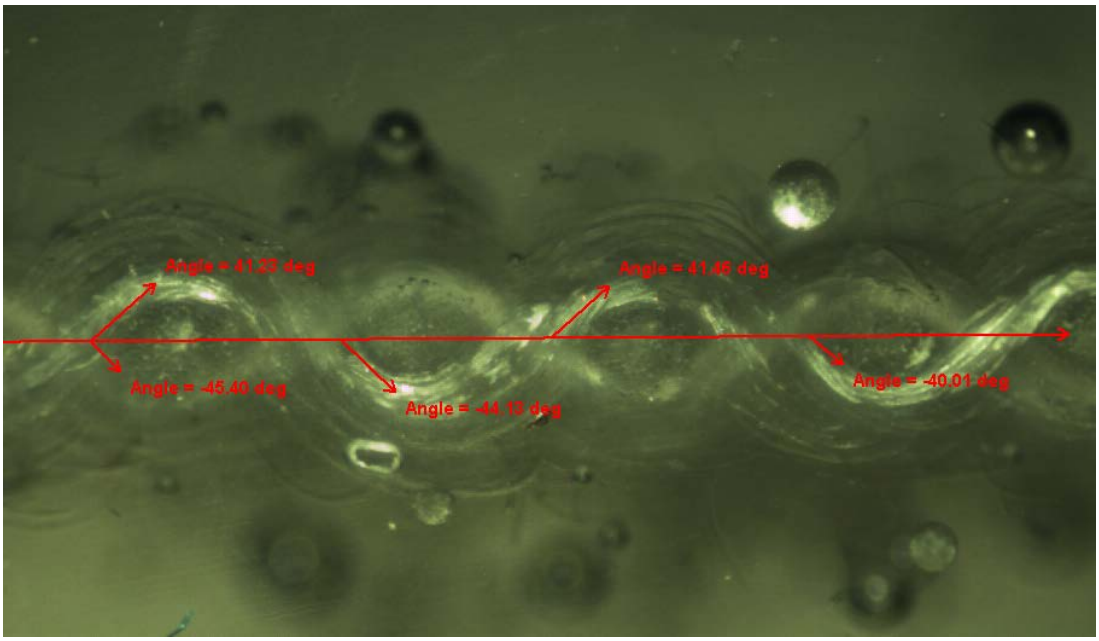


FIGURE 2.12 VIRGIN WOOL SAMPLE WEAVE ANGLE

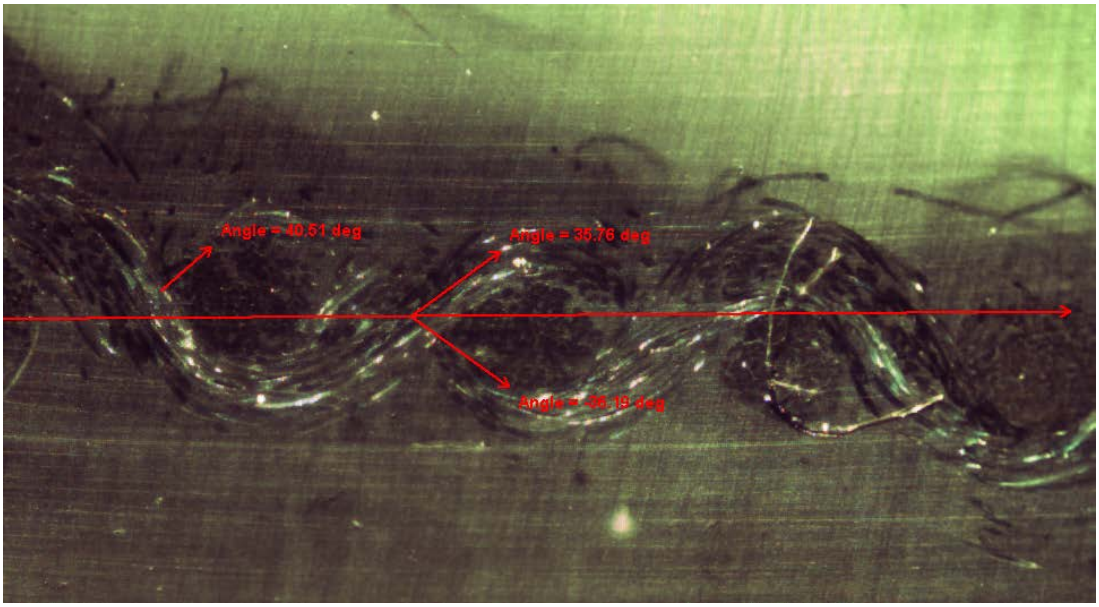


FIGURE 2.13 HISTORIC WOOL SAMPLE WEAVE ANGLE

2.3.3 TENSILE TESTING

Uni-axial testing was undertaken for machine woven samples to characterise the tensile behaviour for bulk, unaged fabric.

Samples were 135 mm by 45 mm and were uni-axially tensile tested on an Instron 4411 in a conditioned room at 65% ± 5% RH and 20°C ± 2°C. Samples were conditioned for 24 hours prior to testing. Tests were carried out at a constant rate of extension of 200mm/min using a load cell of 5kN and a gauge length of 50 mm. Results presented are the average of a minimum of five replicate measurements. These tests are carried out according to ISO 9073.3:1989 – Determination of tensile strength and elongation (Textiles).

2.3.3.1 WOOL/WOOL SAMPLES

Wool/wool samples were tested in both warp and weft directions and the average of 5 repeat samples taken. The results of these tests are presented in Figure 2.14. The behaviour exhibited by the wool/wool fabric was representative of the standard behaviour of wool; large breaking extensions but low strength resulting in a characteristic curve with a long plateau and initial Hookean region (elastic region).

The weft direction exhibits higher strength and a larger de-crimping region (Figure 2.15). This is likely to be due to a number of different factors. Firstly, the crimp introduced by weaving (section 2.2.2.2) is higher in the weft direction than the warp so the straightening out of the fibres takes more force. Additionally, the tapestry weave, being weft-faced results in a larger number of weft yarns per unit

length than warp. Therefore, when force is applied in the weft direction there are a larger number of yarns to spread the force over a unit area. Therefore, the weft direction will be stronger, as reflected in the results presented.

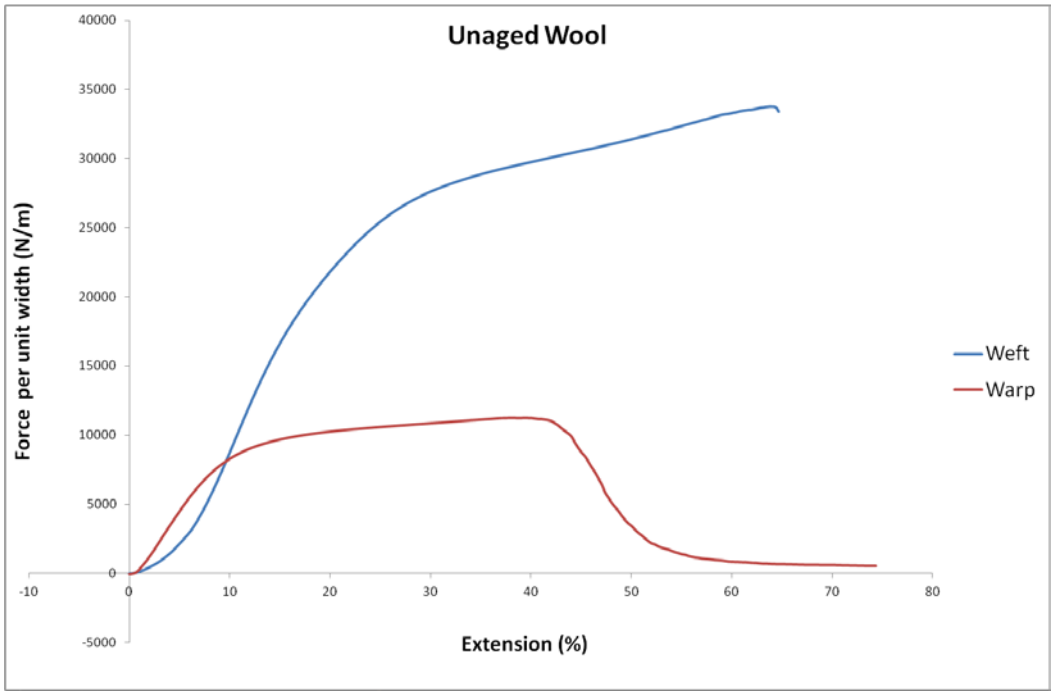


FIGURE 2.14 TENSILE BEHAVIOUR OF REPLICA TAPESTRY FABRIC, UNAGED WOOL/WOOL SAMPLES

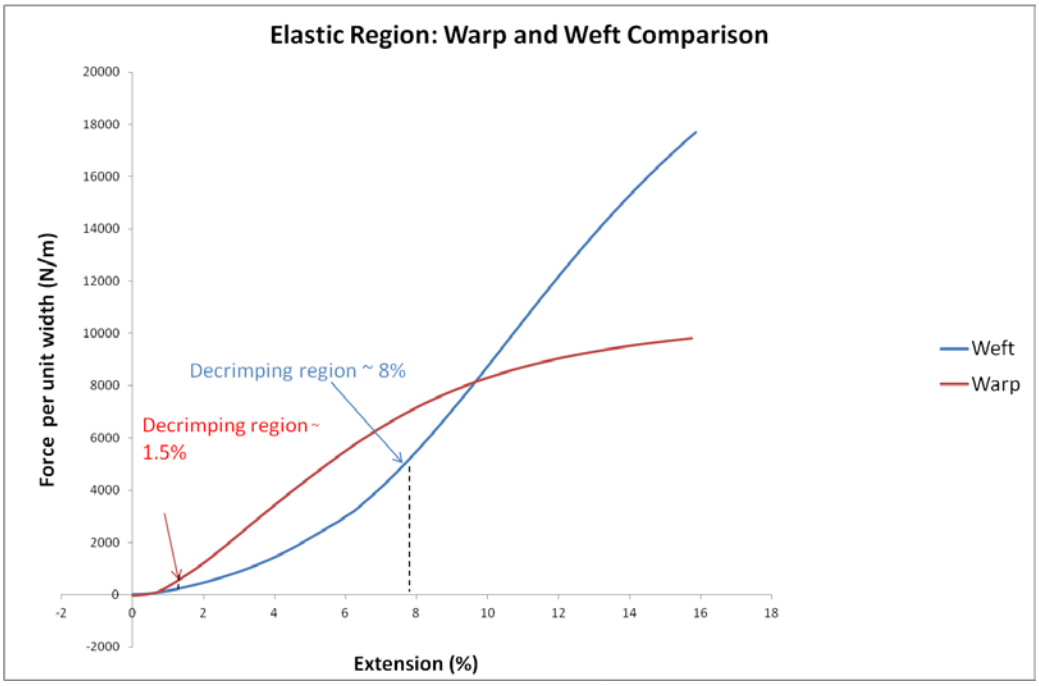


FIGURE 2.15 ELASTIC REGION OF UNAGED WOOL/WOOL SAMPLES SHOWING DE-CRIMPING REGIONS

Figure 2.15 concurs with the results obtained with the crimp measurements. The de-crimping region of warp ends at ~ 1.5% and the weft region at ~ 8% which corresponds to the measured values of 1.72% and 8.11%, respectively.

2.3.3.2 SILK/WOOL SAMPLES

Silk/wool samples were tested in both warp and weft directions. The fabric was constructed with a silk weft and wool warp. The behaviour of warp and weft was significantly different – which was reflected in their different material of construction.

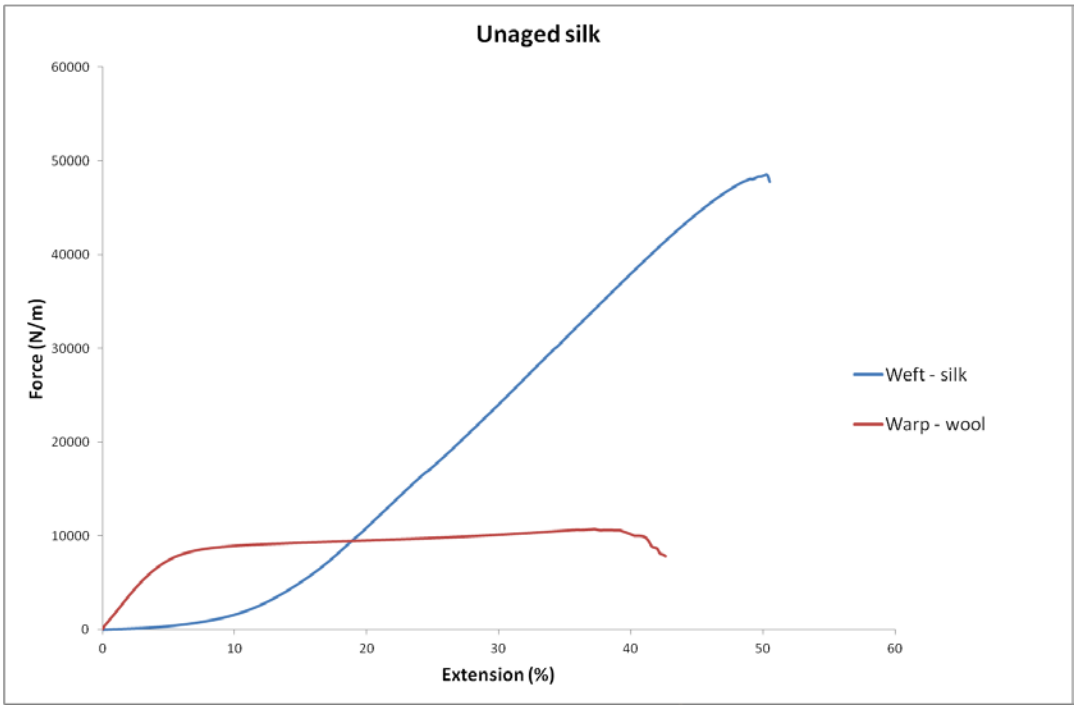


FIGURE 2.16 TENSILE DATA FOR REPLICA TAPESTRY FABRIC, SILK/WOOL SAMPLES

The weft, constructed with silk yarns exhibited a large linear region and a brittle break point. The warp, constructed with warp yarns exhibited large breaking extension and low strength, characteristic of wool fabrics.

2.4 Ageing

Artificial ageing was carried out to simulate the ageing of historic tapestries. Three different types of artificial ageing were undertaken on different samples (not consecutively on the same samples).

Previous studies have focused on using light ageing for accelerated ageing however recent research has begun to highlight the importance of relative humidity in the degradation of textiles (Luxford, 2009, Dulieu-Barton et al., 2007, Ballard, Howell, 1996). Therefore this project used three forms of artificial ageing in order to quantify and understand more thoroughly the different types of ageing which can occur within a textile fabric.

2.4.1. Light Ageing

Samples were aged in a Xenotest 150S Light Ageing Chamber with an Atlas Xenon lamp and a filter with UV cut-off at 320nm. The spectral distribution closely resembles that of sunlight according to the CIE 85/1989. Relative humidity was maintained at 65% within the chamber, and temperature was uncontrolled but monitors show it varied between 18°C and 22°C. The illumination provided by the lamp had recently been measured at 180,000 lux (Gibb, 2010). Samples were aged for 500 hours with a total exposure of 90 Mega lux hours. This is approximately the equivalent of 400 years of exposure in the Great Hall at Hampton Court Palace.

The calculation for lux exposure was carried out by the calculation below:

$$\text{Number of hours in Xenotest} = \frac{\text{Light level in room x total hours of exposure}}{\text{Level of exposure in Xenotest}}$$

The total hours of exposure = **4486 hrs** (calculated from the average number of sunlight hours in a year for London[1])

Estimating that they are exposed for half these hours (through being in storage/curtains closed/palace closed for winter etc.): **2243 hrs**

Average lux value in Great Hall (provided by HCP) = **100 lux**

Total lux hours after 400 years = 100 x 2243 x 400 = **89,720,000 lux hours**

Exposure time = 89,720,000/180,000 = **498.4 hrs (**

2.4.2. Relative Humidity and Thermal Ageing

Relative humidity and thermal ageing was carried out in a Binder MKF 240 environmental chamber for both wool/wool and silk/wool samples. Relative humidity was cycled between 20% and 90% (Luxford, 2009), with an hour "fixed soak" at each extreme and a half hour ramp between (Figure 2.18). The temperature was set at a constant of 80°C to accelerate the effects of deterioration according to the Arrhenius equation (Atkins and De Paula, 2002).

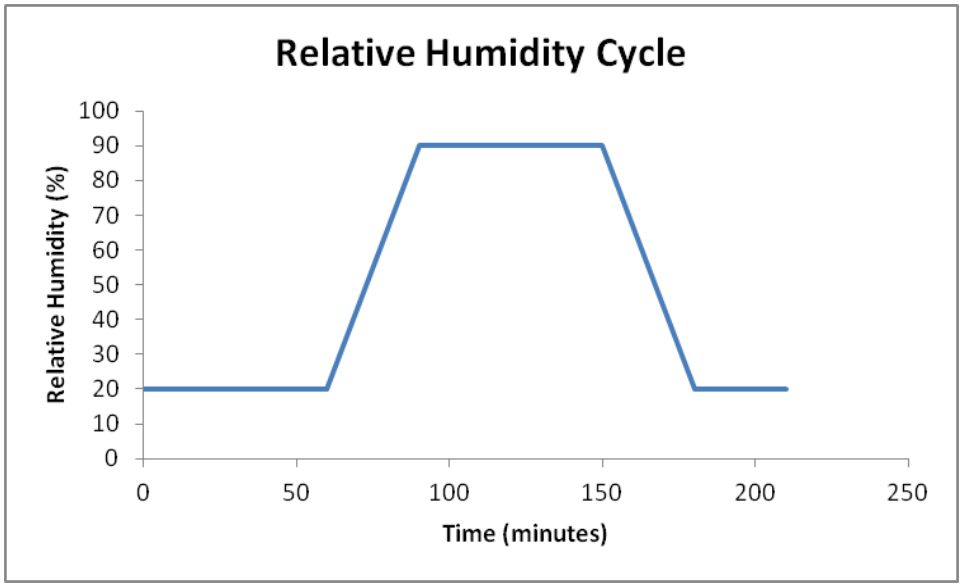


Figure 2.18 Single cycle of Relative humidity and thermal ageing

Figure 2.18 shows that one complete cycle takes 3 hours so 8 cycles were completed in one day. Samples were aged for a progressive number of cycles: 100, 170 and 240 cycles. 5 samples were used for each group of cycling.

2.4.3. Strain Ageing

In order to investigate the effect of relative Humidity (RH) ageing under strain, samples were placed in the chamber with 10 samples hanging under a weight. Working on a "worst-case scenario" basis and the information gathered from Table 2.2, the weight necessary for a sample of this size (0.00675 m^2) of a historic tapestry was 45g (tapestry area 15 m^2, weight 100 kg). As this was an accelerated ageing test this weight was overestimated (100g) to exaggerate any effects which may occur. Samples were secured across the top and a pocket was designed to carry the weight so that the weight was evenly distributed across the width of the sample. The samples were subjected to the same conditions outlined in section 2.4.2: Relative Humidity and Thermal ageing. The samples underwent 240 cycles of RH conditioning.

Figure 2.19 Interior of RH ageing chamber showing both hanging and static samples

3.0 Mechanical Effects of Artificial and Historic Ageing

This chapter presents the work undertaken to investigate the mechanical properties of the replica tapestry material, historical samples as well as an overview on the general mechanical properties of wool and silk fibres and fabrics.

3.1 Mechanical properties of wool literature review

Wool is the primary material used in tapestries for both warp and weft. For historical tapestry, the wool used would have been English but in some cases it was sourced from Spain.

Wool is a proteinaceous fibre - primarily the hair produced by domesticated sheep (Corbman, 1983). The properties of wool fibres, such as fibre length, diameter, crimp and precise chemical structure vary and can be affected by the breed, health, age, diet and habitat of the sheep in question.

3.1.1 Basic morphology of wool fibres and chemical composition

All mammalian hairs are proteinaceous and belong to the keratin family; in the case of wool, the α-keratin. Both the chemical and physical structures of wool fibres are complex and heterogeneous. Wool fibres can be considered to be an assembly of three main types of cell: the cuticle, cortex and cell membrane complex. The exterior cuticle cells provide wool with its unique scale-like appearance. The cortical cells form the bulk (90%) of the fibre. The cell membrane complex (CMC)

holds the cells together and is the only continuous phase in the fibre (Rippon, 1992). In addition within these morphological features are finer structures and different types of cell, Figure 3.1, with their component by weight % listed in Table 3.1.

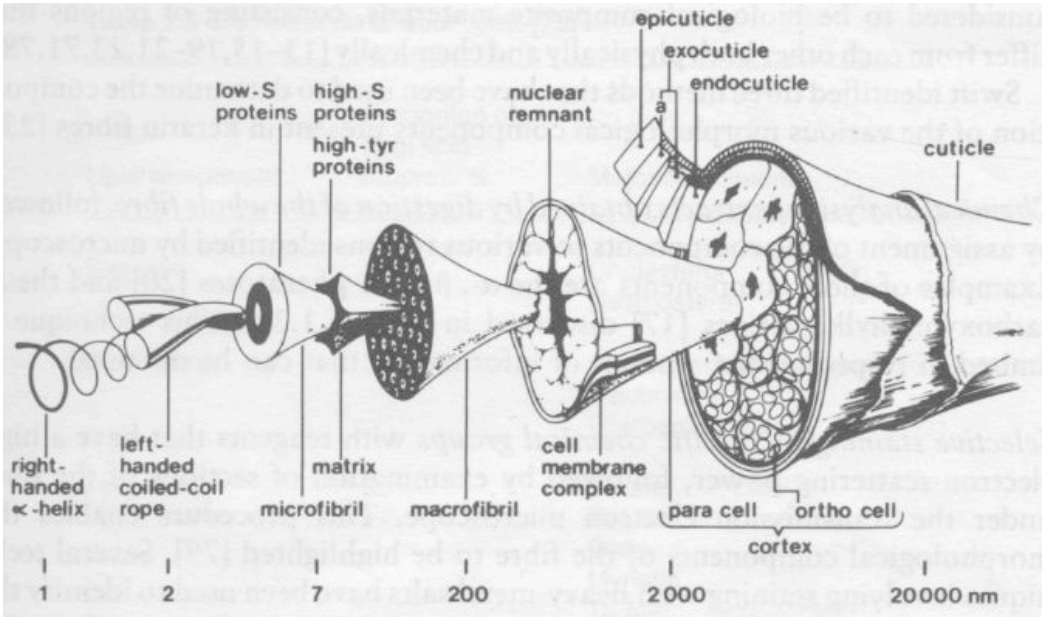


FIGURE 3.1: THE MORPHOLOGY OF WOOL (RIPPON, 1992 P.16)

Component	Keratinous proteins	Non-keratinous proteins	Non-protein material
Cuticle(a)			
exocuticle	6.4		
endocuticle		3.6	
Cortex (b)			
Microfibrils	35.6		
Matrix	38.5		
Nuclear remnants and intermacrofibrillar material		12.6	
Cell Membrane Complex (CMC, c)			
Soluble proteins from the cell membrane complex		1.0	
Resistant membranes (d)	1.5		
Lipids			0.8
Total	82.0	17.2	0.8

Total cuticle 10%

Total cortex 86.7%

Total cell membrane complex 3.3%

Including the epicuticle (0.1%)

TABLE 3.1 MORPHOLOGICAL COMPONENTS OF WOOL FIBRE (ADAPTED FROM RIPPON, 1992, P.16)

The cortical cells and CMC are most responsible for the tensile properties of wool fibres.

The cortex forms the bulk of the fibre, around 90%. It consists of closely packed, overlapping cortical cells surrounded by the continuous phase CMC. Cortical cells are approximately 100μm long and 3-6μm wide (MacLaren and Milligan, 1981, Rippon, 1992). Cortical cells consist of rod-like, low sulphur fibres (microfibrils or intermediate filaments (IF)) in a sulphur-rich amorphous matrix). Groups of microfibrils bundle together to form cylindrical macrofibrils within the cortex. The cortex is segregated into two (sometimes three) types of cell: orthocortical, paracortical and sometimes additionally mesocortical cells. The orthocortical and paracortical cells are characterised by the distribution of the non-keratinous material – the nuclear remnant and intermacrofibrillar material. The non-keratinous material is derived from the remains of dead cells' nuclei and cytoplasm. In orthocortical cells, this material is distributed amongst the macrofibrils whereas in paracortical cells the non-keratinous material groups together in specific regions. Additionally, paracortex cells contain a higher proportion of matrix (therefore sulphur-rich proteins) as compared to orthocortical cells. This affects the chemistry of each cell and therefore potentially the mechanical properties of the fibre. The orthocortex and paracortex is often in a bilateral arrangement for fine wools (see Figure 3.2) but in some coarser wool fibres, such as a Lincoln fibre, the arrangement is cylindrical. In the bilateral arrangement, the orthocortex is always orientated so that it faces the outside of the crimp in the fibre.

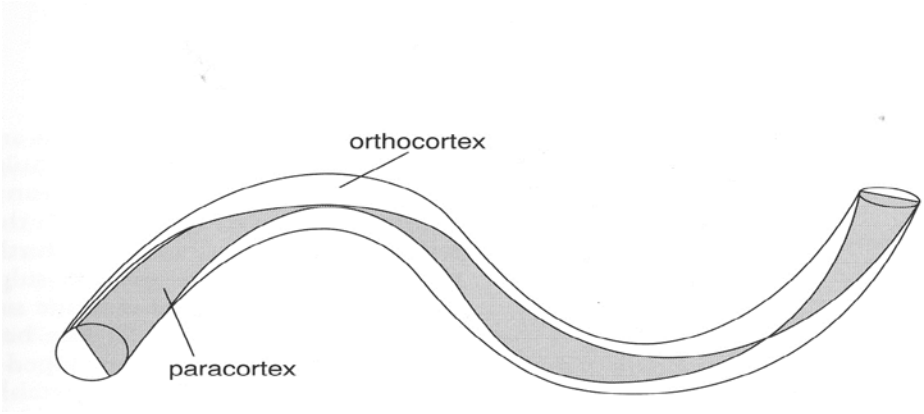


FIGURE 3.2: BI-LATERAL STRUCTURE OF PARA- AND ORTHOCORTEX CELLS WITH THE PARACORTEX CELLS ALWAYS ON THE INSIDE OF THE CRIMP OF THE FIBRE AND VICE VERSA FOR THE ORTHOCORTEX (TIMÁR-BALÁZSY AND EASTOP, 1998)

Finally, the CMC is considered to be the "cement" which holds together all the different parts of the fibre, forming a definitive layer between the cuticle and cortex up to 25nm thick. Little is known about its precise composition or properties; however, Rippon believes it to be composed of three main components: 'intercellular cement (lightly cross-linked non-keratinous protein), a lipid component and a chemically resistant membrane which surrounds each cortical cell' (Rippon, 1992).

3.1.2 DIMENSIONS

Wool fibre lengths and diameter vary considerably. Cook reported that the fibre length of wools vary from 28-375 mm depending on whether the wool if fine, medium or long.

The width of fibres varies from 17μm for the finest wools to 40μm for a coarser wool and have an oval cross-section.

Crimp, one of the most important characteristics of a wool fibre in terms of mechanical properties, varies from 12 waves/cm in the finest merino wools down to 2 waves/cm in the lower quality wools (Cook, 1993).

3.1.3 Intermolecular forces in the wool structure

The mechanical properties of wool, indeed any polymeric structure, will be dictated by the molecular interactions and bonding. The main polypeptide chain in the α-keratin fibre is covalently bonded; however, there are other, weaker interactions that also contribute to the structural chemistry, which dictates the behaviour of the material under mechanical stress.

3.1.3.1 Disulphide cross-links

The presence of cysteine along the polypeptide chains promotes the formation of disulphide cross-links between the chains forming cystine and stabilising the structure by forming a single network molecule (a highly cross-linked polymer structure).

The disulphide links, unusually for a covalent bond, can reorganize themselves along a chain under mechanical stress, in the presence of water and increased temperature or a combination of both. This can have significant effects on the mechanical properties of the fibre (Morton and Hearle, 1993).

3.1.3.2 SALT-BRIDGES

The wool fibre contains a number of ionised side groups, some acidic and some basic (e.g. NH_3^+ and COO^-). Therefore, salt-bridges form between these side groups due to the combination of electrostatic attractive forces and hydrogen bonds. This combination is commonly referred to as a salt-bridge. These forces are significant although not as strong as a covalent bond.

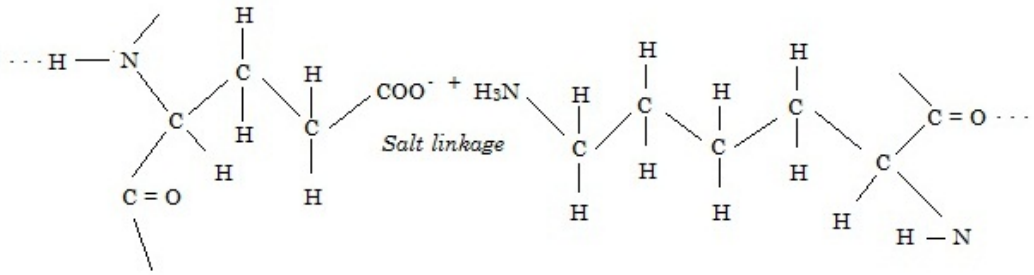


FIGURE 3.3 SALT LINKAGE BETWEEN TWO POLYMER CHAINS (ADAPTED FROM GOHL AND VILENSLAY, 1983)

3.1.3.3 HYDROGEN BONDING (H-BONDING)

There are a number of H-bonding sites which occur along both the main chain and the side groups in the wool structure. In the main chain, the –NH- group and –CO- group in adjacent chains form a hydrogen bond. Additionally, in side groups the hydroxyl (-OH-) groups can form hydrogen bonds. The prevalence of hydrogen bonds in the wool structure has a significant influence over the wool properties and the associated interaction with water.

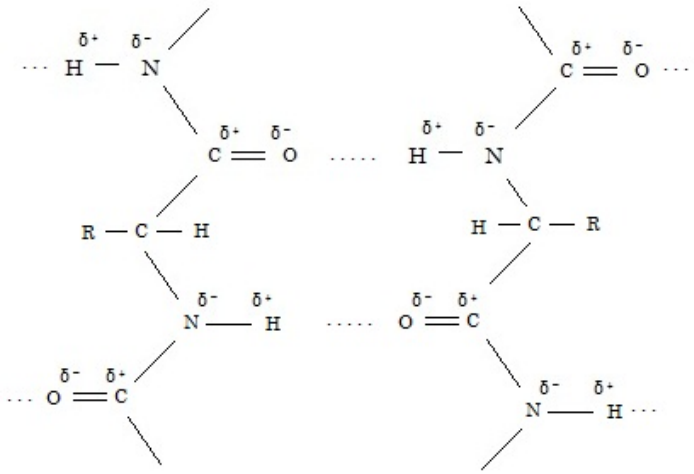


FIGURE 3.4 HYDROGEN BOND BETWEEN TWO WOOL PROTEIN CHAINS (ADAPTED FROM GOHL AND VILENSLAY, 1983)

3.1.4 TENSILE PROPERTIES

In comparison to other textile fibres, wool is characteristically of a low strength but high extensibility (see Figure 3.5). The high elasticity of wool is explained by the high natural crimp of the fibres on a “macro” scale but also the highly folded structure of the polymer chains at all levels of microstructure.

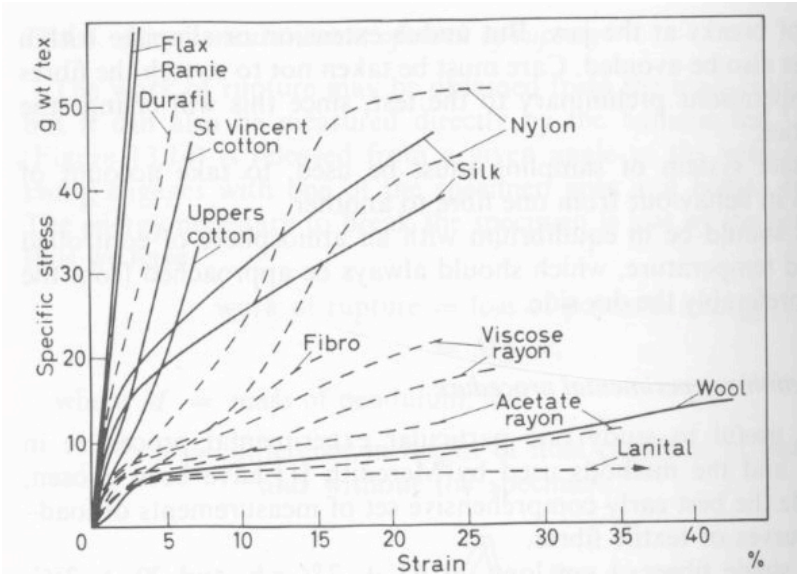


FIGURE 3.5: RELATIVE TENSILE PROPERTIES OF DIFFERENT TEXTILE FIBRES (MORTON AND HEARLE, 1993, P.282)

The reported tenacity of wool is 8.8-15 cN/tex for dry fibres, and 7-14 cN/tex when wet. The elongation at break under standard conditions is 25-35% and 25-50% when wet. It has an elastic recovery of 99% at 2% extension and of 63% at 20% extension (Cook, 1993).

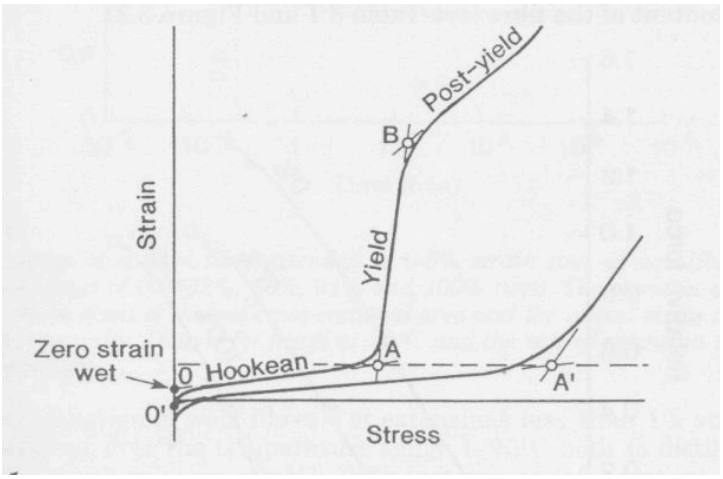


FIGURE 3.6: STRESS-STRAIN GRAPH FOR A WET WOOL FIBRE AND THE LOWER LINE IS A FIBRE AT SOME HUMIDITY LESS THAN 100% (FEUGHELMAN, 1997B)

One of the most important properties when considering the elasticity of wool is the change in mechanical behaviour of a fibre at varying humidity (therefore moisture content). The extension of wool can be more than doubled when increasing the humidity from 0-100% (Alexander et al., 1963, Morton and Hearle, 1993).

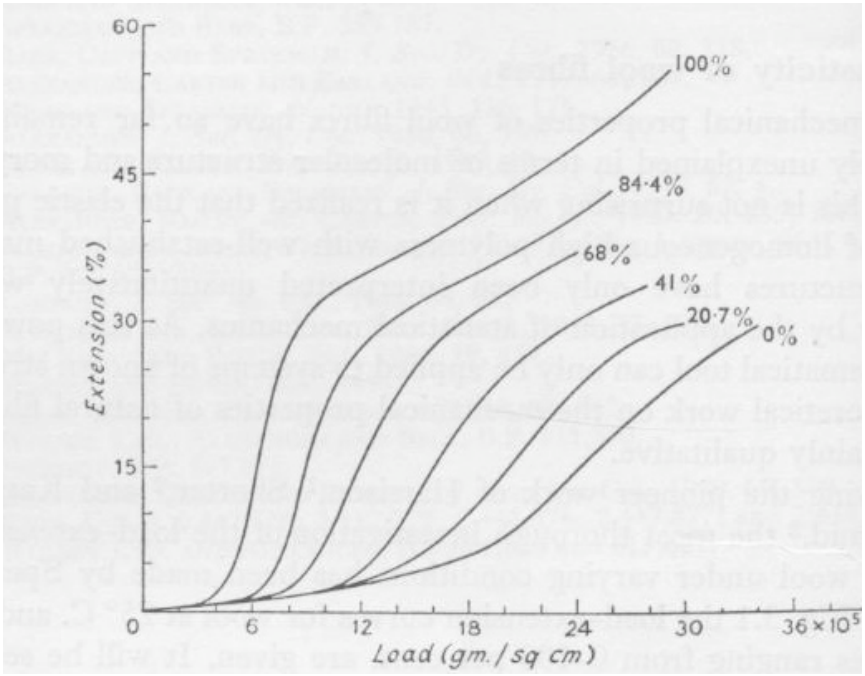


FIGURE 3.7: EFFECT OF RH ON THE TENSILE PROPERTIES OF A WOOL FIBRE (ALEXANDER AND HUDSON, 1963 P.56)

The theories behind the mechanical behaviour of wool have developed over time and the subject is considered to be complex and still under discussion (Speakman, 1941, Feughelman, 1997b, Feughelman, 1997a, Feughelman, 2002, Wortmann and Zahn, 1994, Shiloh et al., 1982, Chapman, 1969, Kreplak et al., 2004, Hearle, 2000).

Although variable, the basic stress-strain properties of wool can be simplified to three main regions of a stress-strain curve:

- an initial linear Hookean region up to 2% strain;
- a yield region of very low gradient slope between 2 and 30% strain;
- a post-yield of greater slope up to a breaking extension of around 50%.

The fibres have been shown to exhibit viscoelastic behaviour during the yield and post-yield regions but behaviour in the Hookean region is less time-dependent (Chapman, 1969, Morton and Hearle, 1993).

Speakman, and later Feughelman and Wortmann investigated the effect of changing humidity on the stress-strain curve of wool (Speakman, 1941, Feughelman, 1997b, Feughelman, 1997a, Feughelman, 2002, Wortmann and Zahn, 1994) and many interesting phenomena were found as a result of these experiments, and some important conclusions drawn. Two of these are of interest and value to this study:

Irrespective of relative humidity, the transfer from the Hookean region into the yield region occurs at the same absolute length of the fibre. This suggests that the α-helix structure begins to unfold at the same fibre length independent of moisture content;

The stress at this yield point is almost a linear function of relative humidity; with the stress decreasing with increasing RH. To a first approximation, decreasing the relative humidity from 100% is equivalent to adding a constant component of stress for all extensions past the yield point.

3.1.4.1 TENSILE STUDY OF HISTORICAL AND AGED WOOL FIBRES

As part of the Monitoring of Damage to Historic Tapestries (MODHT) project, Hacke investigated the stress-strain relationship of unaged, aged and historic wool fibres. The samples were aged using a Xenotest 150S for 400 hours (400 years equivalent) and the historic samples taken from tapestries across Europe by the MODHT team. The results of these tests showed that both the aged and the historic samples followed the curves of the unaged samples but ruptured at a lower strain and therefore lower stress. However, scant attention has been paid to the tensile behaviour of historic or aged fabrics (Hacke, 2006).

3.2 MECHANICAL EFFECTS

YARN TESTS

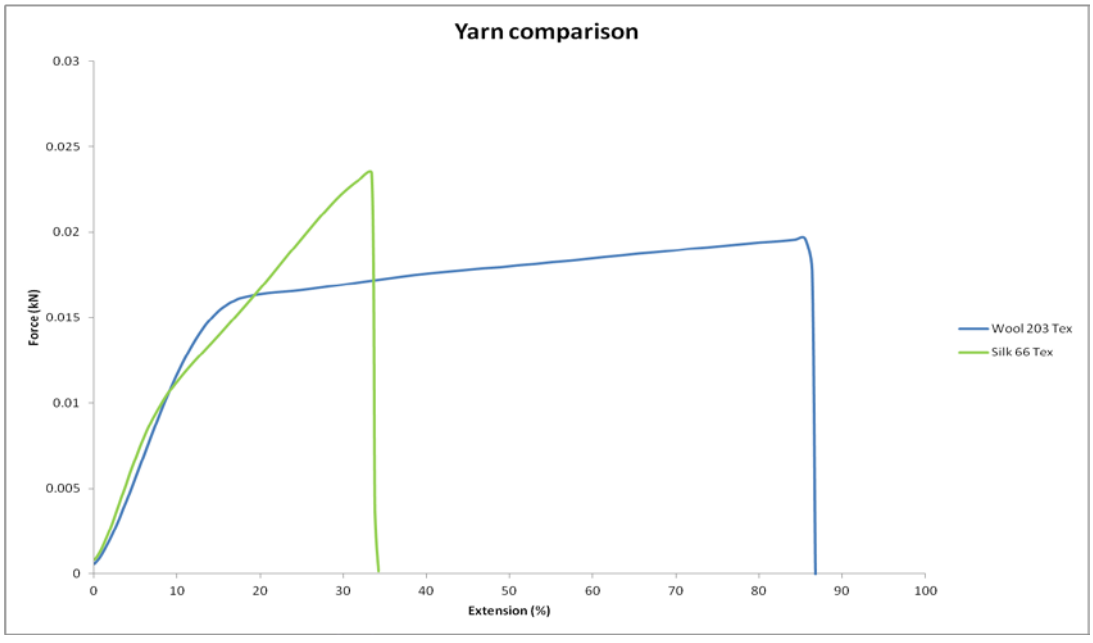


FIGURE 3.8 TENSILE BEHAVIOUR OF WOOL AND SILK YARNS

The tensile behaviour of the wool and silk yarns was tested before weaving to check that the yarn displayed the expected behaviour and strength. Figure 3.8 presents the results for both wool and silk yarn tests. Both silk and wool display the characteristic tensile properties for their respective fibres. Wool displays elastic extension to around 13% and then a long extension plateau to failure at 85%. Silk displays a greater ultimate tensile strength but at a lower extension (30%).

3.2.1 Stiffness calculations

For all samples, stiffness was calculated in order to compare between different types of sample and for inputting into the digital model, section 5.2. The stiffness of the fabric was calculated from the force per unit area (N/m) – engineering strain graphs, Figure 3.9.

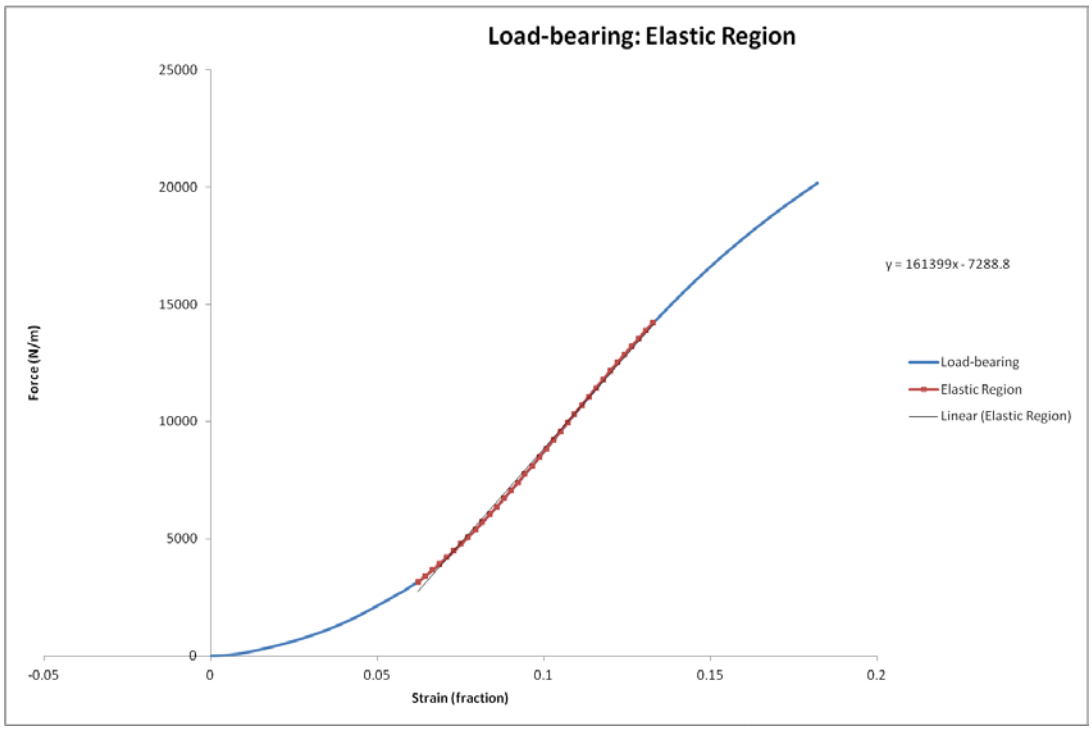


Figure 3.9 Example of a stiffness calculation

The values obtained for stiffness' in this study are useful as a comparative tool between the different samples investigated here, however it would not be possible to use these exact values to compare with other materials, e.g. iron. These methods have been used here as they are appropriate to the material and usage within this project however they are not "SI" so could not be used in a direct comparison to other materials. It should be noted that although stiffness was calculated using engineering strain, the majority of the graphs presented here in this thesis use extension as a percentage. This is because in the literature this is often how textile tensile graphs are presented (see figure 3.7 for one example), where Extension (%) = increase in original length (%) and Engineering strain = $\Delta L/L_0$ (fraction) (Hibbeler, 2008). Engineering strain is the fractional increase compared to the original length whereas extension is an absolute value obtained during testing.

3.2.2 Light Ageing

Below are presented the results of 500 hour light ageing on both wool/wool and silk/wool fabrics.

3.2.2.1. WOOL/WOOL SAMPLES

FIGURE 3.10 FABRIC TENSILE BEHAVIOUR OF UN-AGED AND 500 HOURS LIGHT-AGED WOOL/WOOL FABRIC

The effect of 500 hours ageing on both the weft (load-bearing) and warp (transverse) directions for wool/wool fabrics (Figure 3.10) was a loss of overall strength; the ageing process having a larger effect on the loss of strength in the weft direction (42%) than in the warp direction (27%). Although there was a change in stiffness for both directions; these changes are small and for the warp direction within the expected error range (Figure 3.12). In general, the aged curves follow a similar path to the unaged fabric curves except they rupture at a lower force and therefore extension. The extensibility of both directions was halved. This can probably be attributed to the extensive cross-linking of the wool protein

structure during ageing which inhibits the extension of the matrix during loading and the α-β transition however this needs further investigation[2].

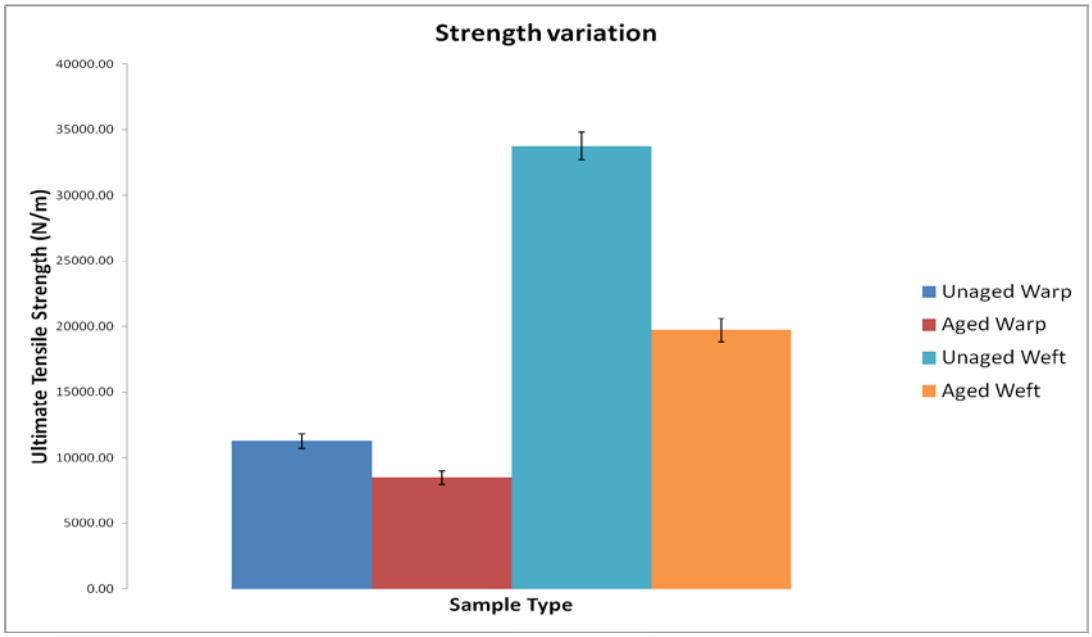


FIGURE 3.11 VARIATION IN STRENGTH OF UNAGED AND LIGHT AGED WOOL/WOOL FABRIC

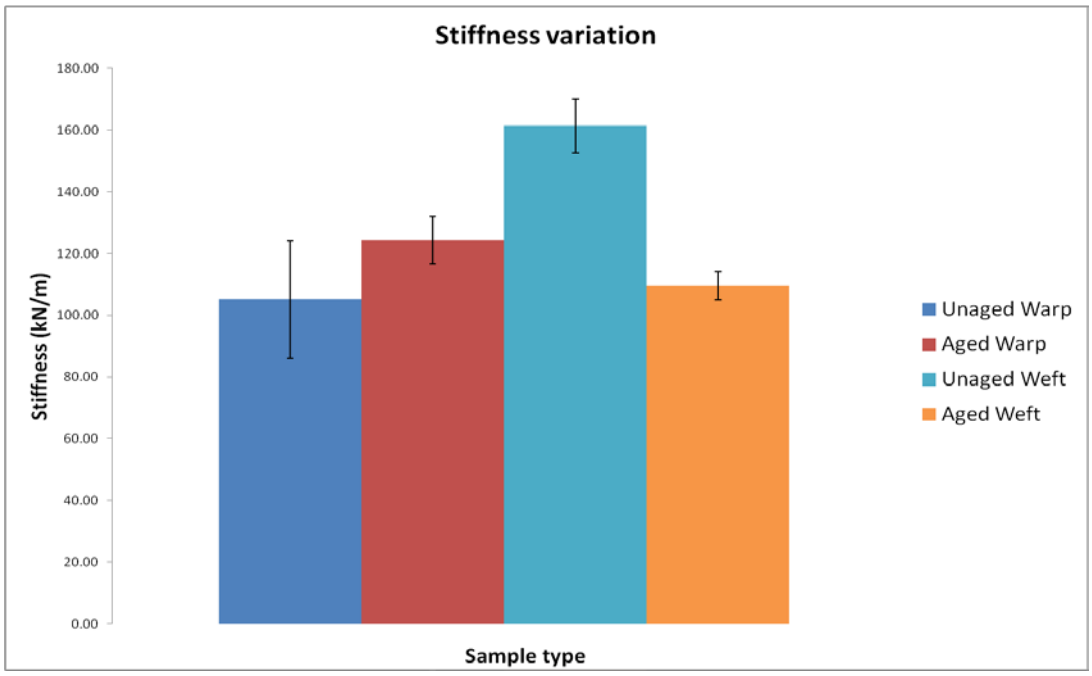


FIGURE 3.12 VARIATION IN STIFFNESS OF UNAGED AND LIGHT-AGED WOOL/WOOL FABRIC

[2] Hearle, J.W.S.,` A critical review of the structural mechanics of wool and hair fibres` *International Journal of Biological Macromolecules* 27 (2000) 123-138

3.2.2.2. SILK/WOOL SAMPLES

The effect of 500 hours of light ageing on silk/wool samples can be seen in Figure 3.13. Only the effect of ageing in the one (weft) direction is shown because the warp direction is wool yarns so follows the same pattern as section 3.2.1.1.

The effect of light ageing on the silk/wool fabric is a 85% decrease in the ultimate tensile strength of the fabric. The extensibility of the fabric was only 32% of the original, un-aged fabric. The photo-degradation of silk is well documented (Hallett and Howell, 2005, Luxford, 2009, Quye et al., 2009, Howell, 2005) and it is generally considered that the addition of UV in the ageing process further increases mechanical degradation (Luxford, 2009, Korenberg, 2007). The damaging effect of sunlight (with or without UV) on the silk fibres is attributed to the breaking of the polypeptide chains which in turn increases the amorphous content of the fibre – therefore decreasing the mechanical strength (Okamoto and Kikuchi, 1958).

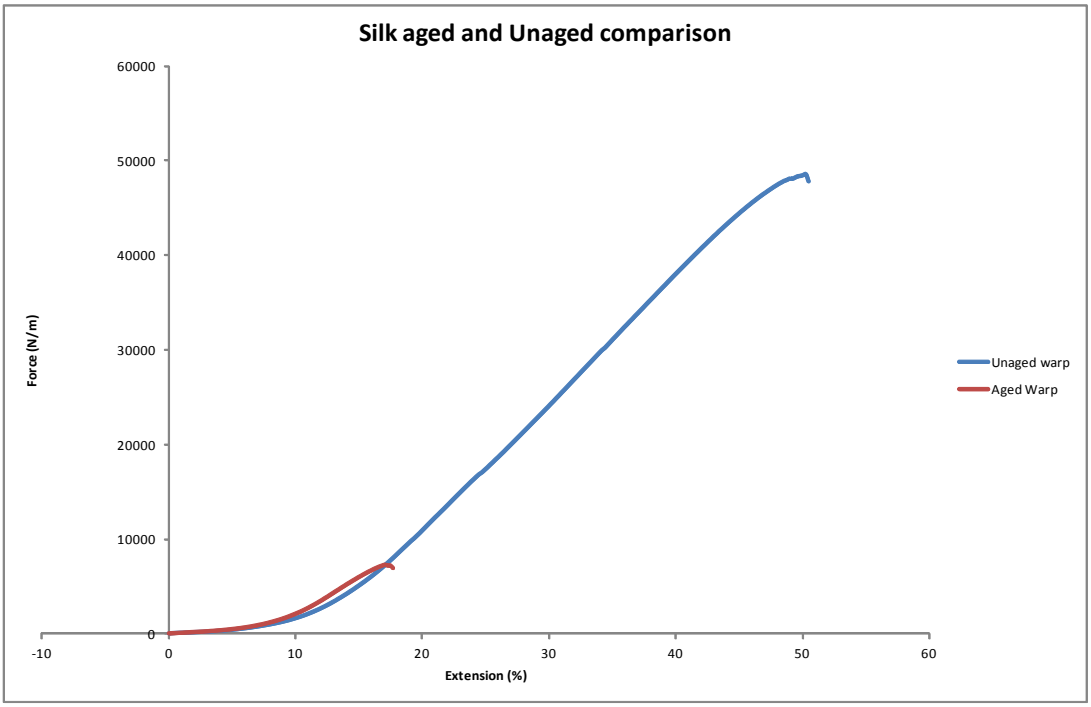


FIGURE 3.13 A TENSILE COMPARISON OF UN-AGED AND AGED SILK/WOOL FABRIC

3.2.3 RELATIVE HUMIDITY AND THERMAL AGEING

Below are presented the results of relative humidity/thermal ageing on both wool/wool and silk/wool fabrics.

3.2.3.1 WOOL/WOOL SAMPLES

Figure 3.14 shows the results of increasing the number of cycles of RH ageing on the tensile strength of wool/wool fabric. When an increasing number of cycles are applied to the wool/wool fabric an increasing loss in fabric strength and extensibility can be observed. The stiffness of the fabric also increased as indicated by the increase in gradient in the elastic region of the graph in Figure 3.14.

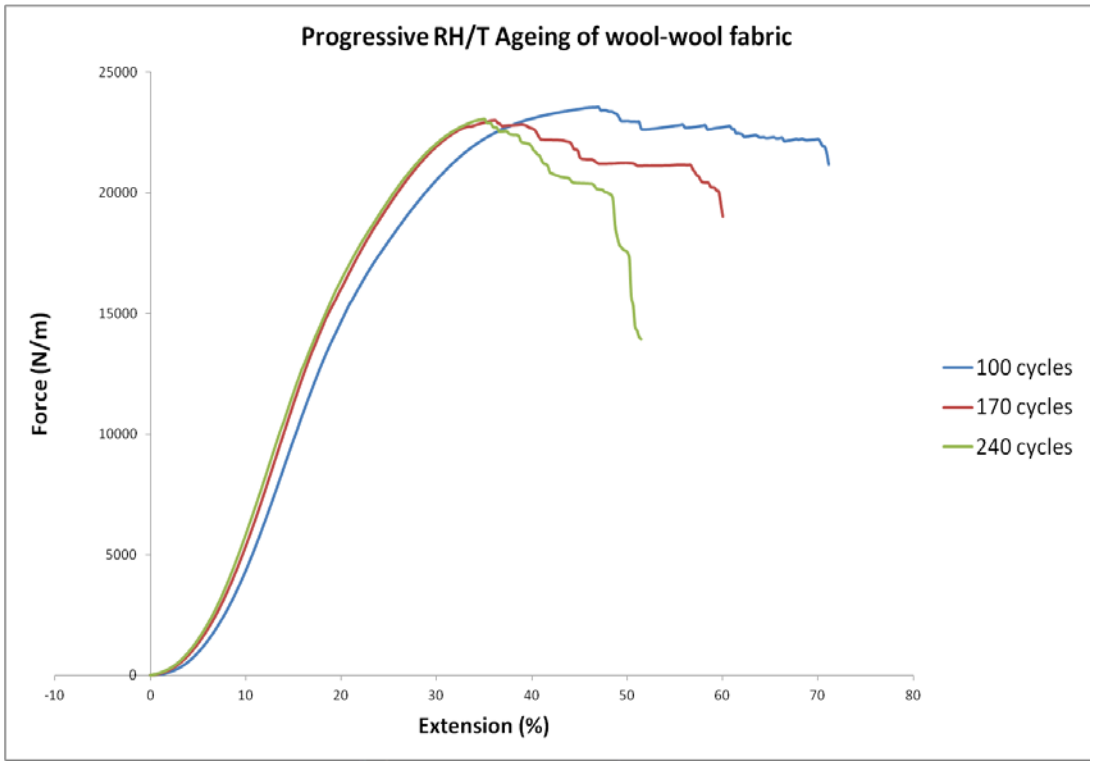


FIGURE 3.14 EFFECT OF NUMBER OF RH CYCLES ON TENSILE STRENGTH OF WOOL/WOOL FABRIC

3.2.3.2 SILK/WOOL SAMPLES

The tensile results for RH ageing of silk/wool samples are presented in Figure 3.15. Overall, progressive cycling of RH at an elevated temperature resulted in a loss of strength and a decrease in stiffness. However, compared to the wool/wool fabric, the effect of RH ageing was slower to take effect, with the first significant decrease in strength observed after 240 cycles.

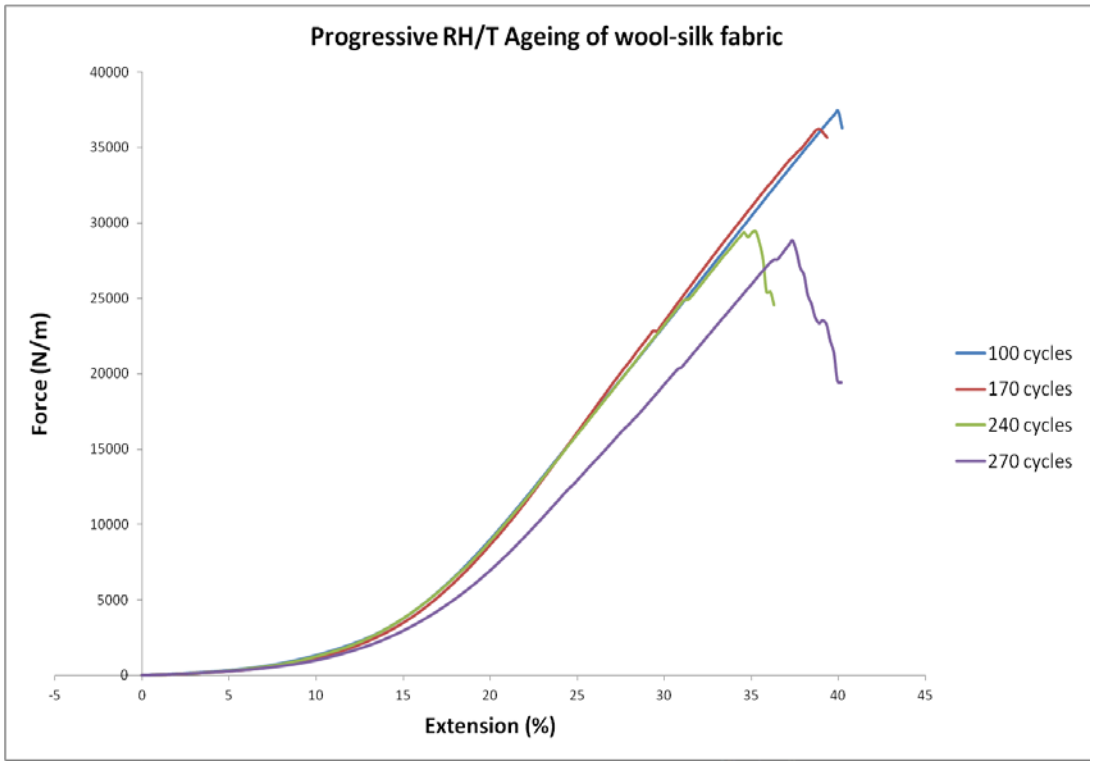


FIGURE 3.15 RH/T AGEING OF SILK/WOOL FABRIC

From a comparison of the effect of RH/T ageing on wool/wool and silk/wool fabrics, it is clear that both fabrics experienced a loss in strength. However, the stiffness changes observed in the fabrics is contrasting in behaviour with the stiffness increasing in wool/wool and stiffness decreasing in silk/wool.

One possible reason for this difference is that in the silk fibres, the ageing treatment breaks the peptide bonds converting a larger portion of the fibre into an amorphous region which will decrease the stiffness of the fibre (it is able to extend more readily). However, in the wool fibres the effect of the treatment converts the disulphide bonds into rigid cross-links which effectively "lock" the fibre structure in place making it more difficult to extend – therefore increasing the stiffness. This possibility is further explored in the chemical analysis later in this thesis.

3.2.4 Strain Ageing

Understanding the effect of ageing under strain is important in the field of tapestry conservation. These objects were made to be hanging on display for long periods of time and in some cases have been hanging for a significant portion of their lifetimes.

In other materials, ageing under strain or force can cause creep and other mechanical effects (Hibbeler, 2008) so a preliminary study to investigate the effect of strain ageing was extremely relevant in this case.

Figure 3.16 presents the results of strain ageing for both wool/wool and silk/wool fabrics, alongside the un-aged results for comparison.

The effect of strain ageing is apparent in the plots for both the wool/wool and silk/wool fabrics. An increase in stiffness for both fabrics is observed, which contributes to an overall loss of extensibility and increase in brittleness. An increase in the brittleness of a historical fabric is extremely important in the field of conservation and this is the first time we have quantifiable evidence that the effect of strain whilst ageing increases this degradation mechanism. When a fabric becomes more brittle, it is more easily torn or split as instead of the fibres stretching out under a force they will rupture instead. This increases the risk of hanging a brittle fabric on display as the danger of damage is increased.

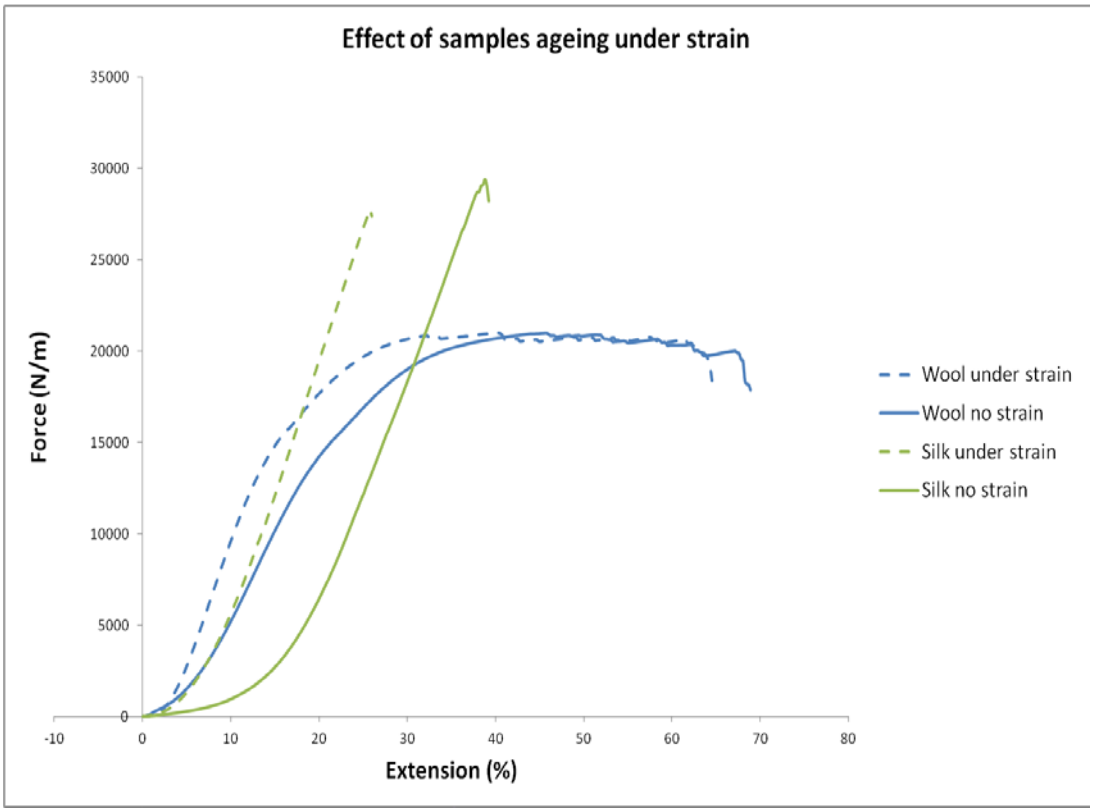


FIGURE 3.16 EFFECT OF STRAIN AGEING ON WOOL AND SILK FABRICS

Interestingly, an increase in the stiffness for the silk/wool fabric was observed even though a decrease in stiffness was observed under identical RH/T ageing conditions with no strain.

This implies that the addition of force whilst ageing affects the silk/wool fabric in a different way to the wool/wool fabric. This will need further investigation of the silk/wool fabrics to understand the link between the chemical and mechanical changes taking place.

3.2.5 Historic Samples

Studying the tensile behaviour of historic reference samples was an important element to this research study. This type of information is rarely collected as historic samples are not readily available.

The results below present the tensile data for both weft and warp directions for the historic samples described in section 2.2.1: Historical Samples.

Weft

The force-extension curves for historic samples in the weft direction are presented in Figure 3.17. Although there were ten samples, only eight sample plots can be seen in Figure 3.17. This is due to samples 4 and 8 rupturing during the pre-loading period of the tensile test and therefore failing the automated system. Their results are not included as their behaviour is classed as catastrophic in engineering terms.

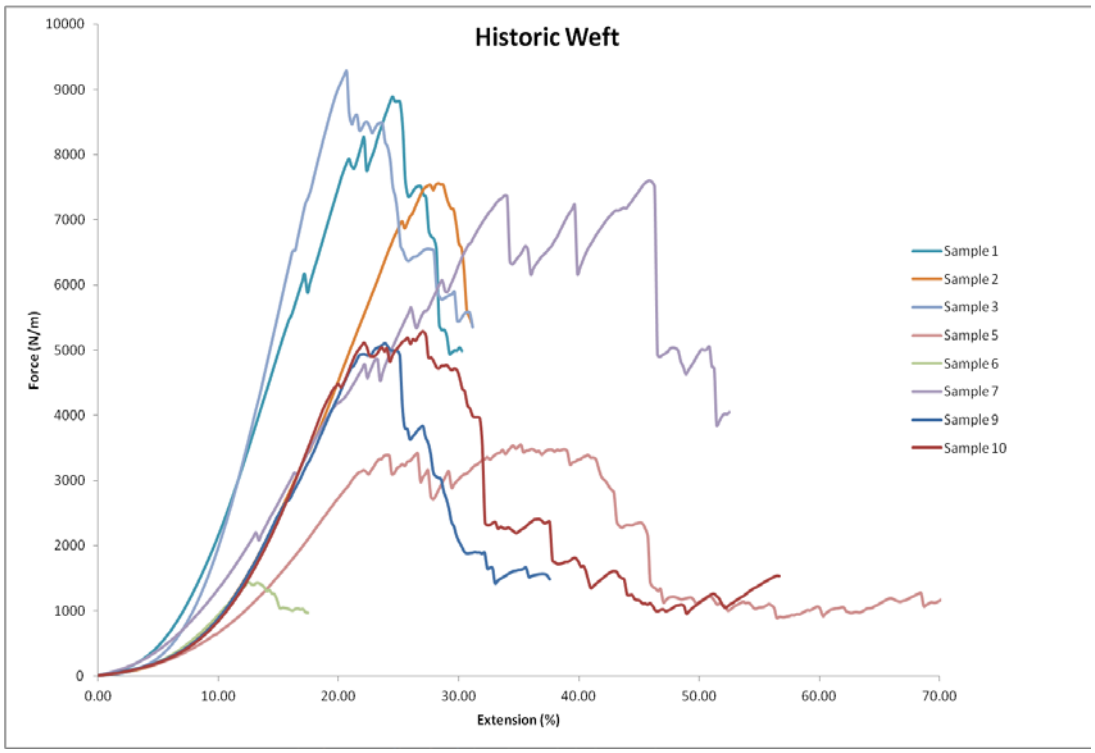


FIGURE 3.17 HISTORIC WEFT TENSILE RESULTS

WARP

The force-extension curves for historic samples in the warp direction are presented in Figure 3.18. Once again, not all samples were suitable for presentation; samples 4 and 10 failed during pre-loading and sample 1 was not large enough to create samples in both directions.

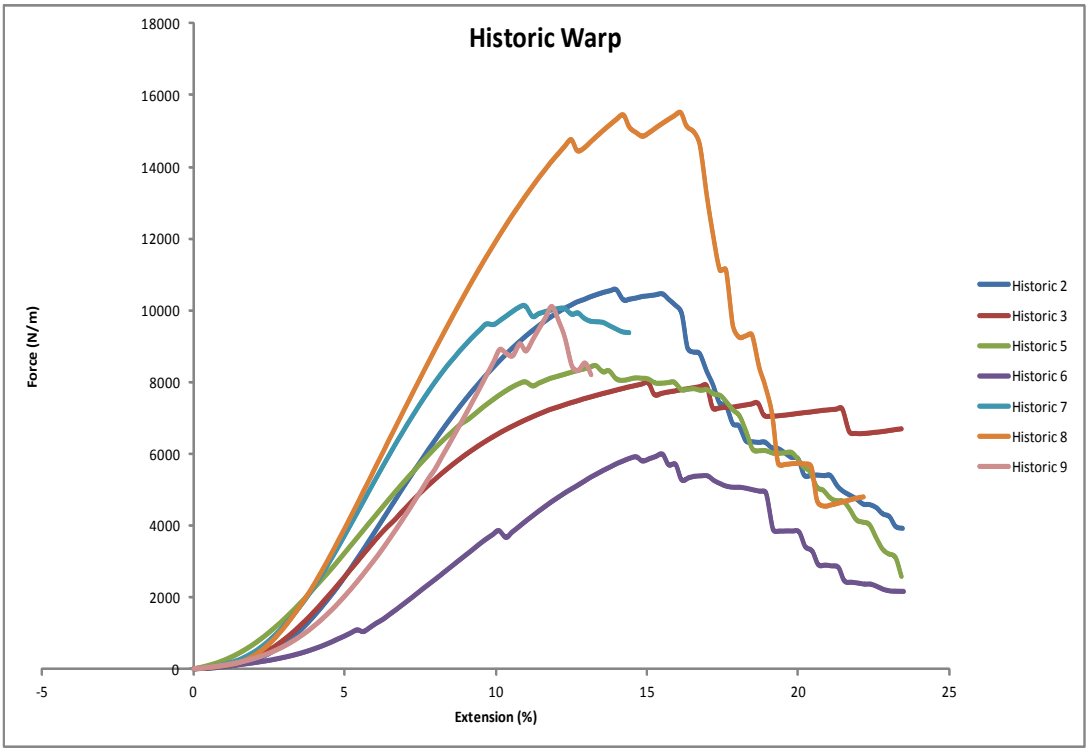


FIGURE 3.18 HISTORIC WARP TENSILE RESULTS

A number of features and effects can be observed and concluded from Figures 3.17 and 3.18:

An important observation is that the weft direction yarns are more affected than the warp yarns indicating the effect of ageing under strain has an influential role in determining mechanical performance. Additionally, the reduction in the strength of the historic wefts could also be attributed to the effect of dyes on the yarns. The weft yarns are traditionally dyed whereas the warp yarns are not dyed. None of the replica samples produced for this study were dyed and therefore a quantitative value for the contribution of reduction in strength from dyes cannot be provided at this stage although a thorough investigation into the effect of historical dyes on the chemistry of wool and silk fibres can be found elsewhere (Hacke, 2006);

A “cross-over” effect was observed in relation to strength – illustrated in Figure 3.19. Whereas the weft is originally stronger than the warp (un-aged and artificially aged samples see Figure 3.10), after “historic ageing” they are weaker (observing Figures 3.17 and 3.18). The historic fabrics show serious degradation which is not replicated in artificial ageing. Effectively the accelerated ageing regime used in this study was not aggressive enough to fully match real time ageing, Figure 3.19. This is further discussed in the next section: Ageing Comparison.

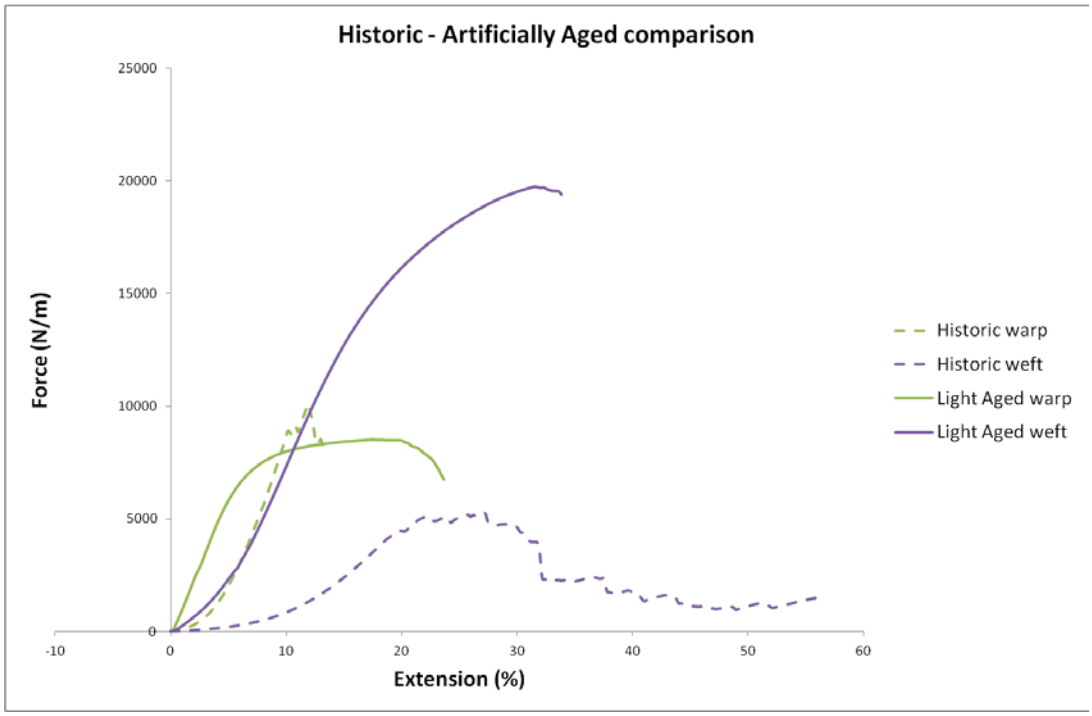


FIGURE 3.19 TENSILE COMPARISON BETWEEN HISTORIC AND ARTIFICIALLY LIGHT AGED FABRICS

3.2.6 AGEING COMPARISON

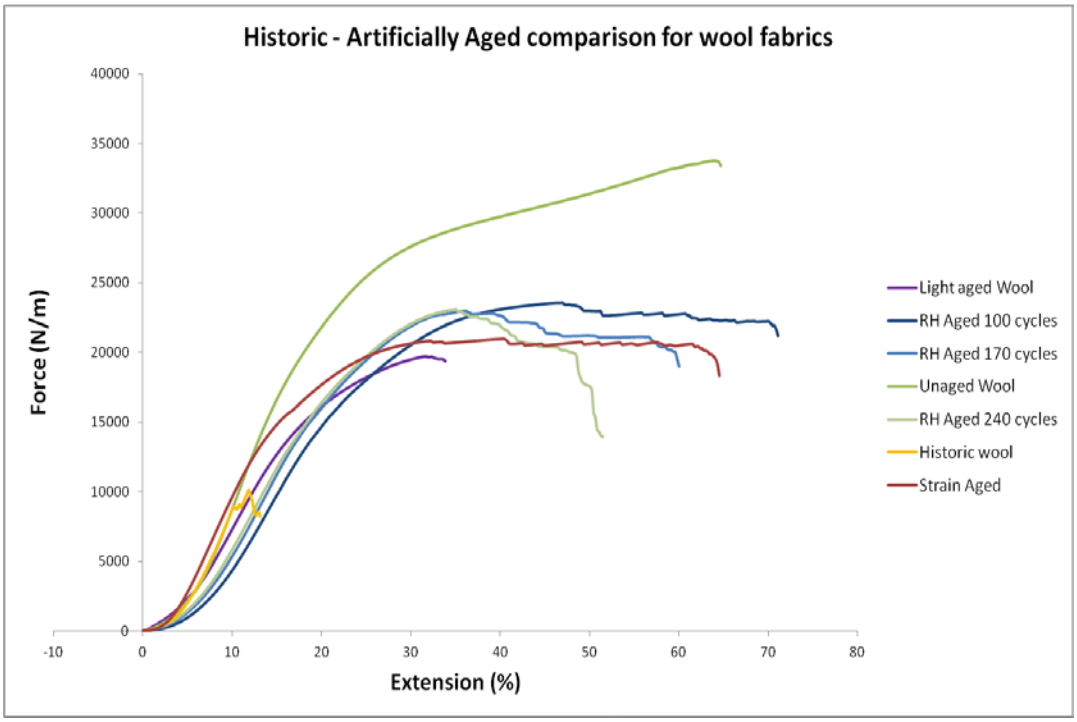


FIGURE 3.20 STRENGTH COMPARISON BETWEEN DIFFERENTLY AGED FABRICS

Examination of the force-extension curves in Figure 3.20 indicated that historic samples were far weaker than any artificially aged materials by a factor of at least 2. Light ageing appears to give significant loss of extensibility as well as UTS and RH ageing produced a loss of strength but still possesses comparable extensibility to the virgin wool samples.

The low overall strength of the historic samples compared to artificially aged samples shows that historic tapestries were weaker than expected through previous predictive ageing methods. In contrast the historic samples were also considerably weaker in the weft direction than in the warp: the opposite of all the artificially aged replica samples.

This is likely to be a cumulative effect of all the ageing mechanisms the historic fabrics experience, in particular; photo-degradation, chemical changes due to dyeing and dye degradation, relative humidity damage, ageing under strain, as well as pollution, insect and handling damage. The combination of all of these degradation mechanisms will affect the weft yarns more than the warp yarns with the overall effect being that the load-bearing (hanging) direction becomes much weaker. This will also affect the overall strength of a tapestry as the weakest structural direction is also the direction bearing the weight of the object.

4.0 Chemical Effects of Artificial and Historical Ageing

This chapter reviews the chemistry of wool fibre and the chemical investigation undertaken as part of this study. The aim of undertaking a chemical investigation was to establish links between mechanical damage which occurred as a result of artificial and historical ageing and chemical degradation processes.

4.1 Chemical properties of wool literature review

This section will summarise the chemical composition and protein chemistry of wool as a basis for the chemical analysis for virgin, historic and artificially aged samples.

Wool, as previously discussed in Section3.3.1, is a complex fibrous keratinous protein which occurs in the α-keratin form (3-12% sulphur content).

Primary structure of wool protein

The primary structure of a protein is governed by: the type of amino acids that make up the protein chain; the proportion of each amino acid; the sequence (order) of the amino acids and the covalent cross-links between protein chains.

Wool is composed of mainly 18 amino acids, and unlike other naturally occurring proteinaceous fibres (such as fibroin, silk) there is no one major component but rather many minor components as shown in Table 4.1. This amino acid composition is obtained by hydrolysing clean wool, and the relative quantity of each amino acid

will vary from sample to sample depending on both sheep breed and sample history.

Amino acid		**content (µmol/g)**		
		a	*b*	*c*
Lysine	Lys	193	277	269
Histidine	His	58	76	82
Arginine	Arg	602	613	600
Tryptophan	Trp	*d*	*d*	*d*
Aspartic acid	Asp	503	602	560
Threonine	Thr	547	564	572
Serine	Ser	860	892	902
Glutamic acid	Glu	1020	1046	1049
Proline	Pro	633	561	522
Glycine	Gly	688	815	757
Alanine	Ala	417	512	469
Cysteine	1/2 Cys	943	1120	922
Valine	Val	423	546	486
Methionine	Met	37	47	44
Isoleucine	Ile	234	318	275
Leucine	Leu	583	721	676
Tyrosine	Tyr	353	380	349
Phenylalanine	Phe	208	268	257
Ammonia	NH_3	887	855	-

a *results of Simmonds, 1955(Simmonds, 1955),* **b** *calculated from the results of O'Donnell and Thompson 1962***,c** *results of Bradbury et al 1965***,d** *tryptophan is destroyed under the conditions of hydrolysis used for these analyses*

TABLE 4.1 AMINO ACID CONTENT OF MERINO 64S WOOL (MACLAREN AND MILLIGAN, 1981), P.6)

These amino acids join together to form peptides, polypeptides and ultimately proteins. The sequence of amino acids forming the polypeptide chain is characteristic of the specific wool protein.

One of the most important amino acids in wool is the sulphur containing cystine (Cys). This particular amino acid is responsible for a significant part of the distinctive properties of the wool and is particularly relevant for this research. The specific contribution of cystine especially in the formation of disulphide cross-links will be discussed later in this chapter.

The wool genome for sheep has not yet been fully sequenced and therefore precise protein sequence is not precisely known. This makes comprehensive structural analysis of wool particularly difficult, although recent research is making progress in this field (Clerens et al., Plowman, 2003).

The covalent cross-links between chains in a protein affect the molecule structure (secondary structure) as well as providing significant strength to the fibre. In the wool protein chain, cross-links are formed by cystine both along the chain and between neighbouring chains (Figure 4.1).

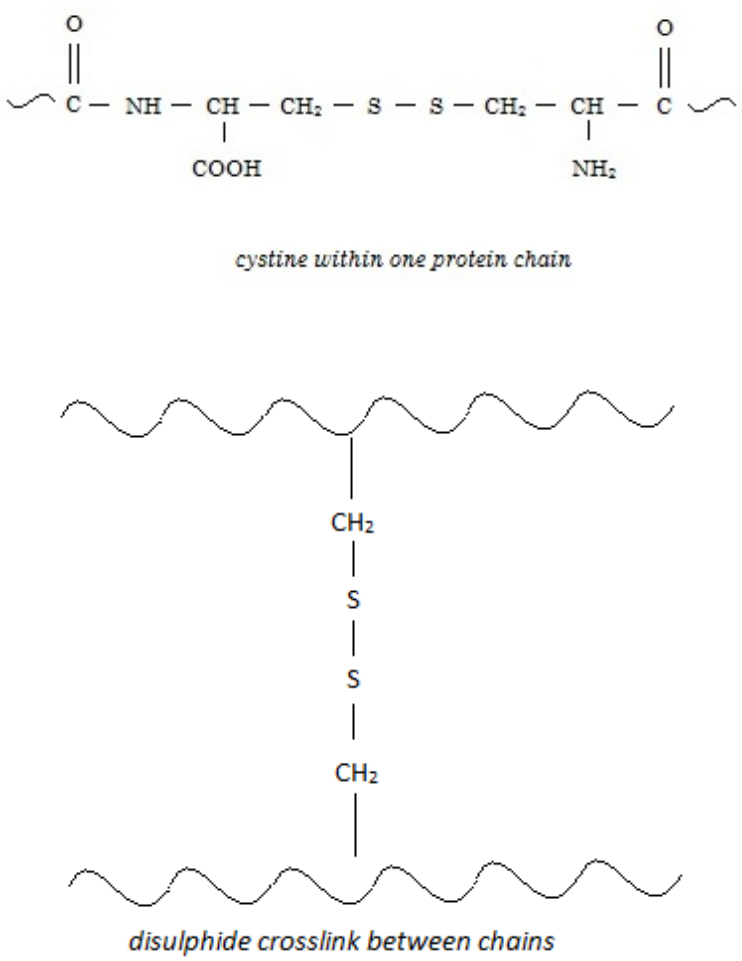


FIGURE 4.1 FORMATION OF CYSTINE CROSS-LINKS ALONG A CHAIN AND BETWEEN CHAINS (ADAPTED FROM GOHL AND VILENSLAY, 1983)

SECONDARY STRUCTURE OF WOOL PROTEIN

The secondary structure of proteins is the arrangement of the chains into a specific stable structure, and the intra-molecular forces which are weaker than the covalent primary and cross-link bonds but are still important in terms of the structure and properties of the fibre (Price and Nairn, 2009).

In the case of wool, the chains arrange themselves into an α-helix (or more rarely a γ-helix) so that the large bulky side chains (such as cystine) are on the outside (similar to the stairs in a spiral staircase). The helix structure is stabilised and strengthened by secondary bonding including: hydrogen bonds; polar bonds and salt linkages. These bonding types are discussed in more detail in section 3.1.3. Polar bonds between –CO of carbonyl groups (negatively charged) and –NH of amino group (positively charged), salt linkages between ($-COO^-$) and ($-NH^+_3$) (acidic and basic) are formed.

TERTIARY STRUCTURE OF WOOL PROTEIN

The tertiary structure of a protein is governed by the inter-molecular bonds which stabilise the structure of multiple chains of protein molecule, building up to a macromolecule.

In the wool fibre, the tertiary structure consists of both crystalline and amorphous regions. In the crystalline, organised structure, multiple α-helixes arrange themselves into a tight spiral cord. Most commonly, three helixes twist together to form one super-helix (protofibril). The protofibril structure is held together by hydrogen and polar bonds as well as salt linkages; provided the protein is in the correct pH to lie within its isoelectric range (see below). Eleven protofibrils make up a microfibril which are then organised into macrofibrils and cortex cells. The remaining non-helical keratin material forms the amorphous component of the fibre which acts as a matrix and cement between the well-organised helical crystalline micro- and macro-fibrils. The majority of the properties of the wool fibre

are controlled by the cortex (section 3.1.1) which itself is split into two parts: para- and ortha-cortex. The orthocortex has a large number of protofibrils (i.e. crystalline regions) and less amorphous cement whereas the paracortex has less protofibrils but more amorphous regions and a larger number of disulphide cross-links.

This highlights an important feature of the wool structure: most of the disulphide bonds are in the amorphous regions and therefore are more exposed to the effects of chemical and physical agents of deterioration. However, once the fibre begins to deteriorate and is exposed to agents of deterioration (including photolysis) it opens the more tightly-packed crystalline regions to damage as well.

Isoelectric point

The isoelectric point (IEP) of a molecule is the pH at which the molecule carries no overall (net) charge, i.e. the charge is zero. This value (IEP) is particularly important when using certain analytical techniques such as gel electrophoresis (Price and Nairn, 2009).

The IEP of wool keratin is pH 5.6 (Timár-Balázsy and Eastop, 1998). Common practice in textile conservation is to endeavour to maintain a woollen fabric between pH 5-7. This minimises the chemical damage that occurs, although it cannot prevent it. The accumulation of dust and pollution on the surface of a fabric will decrease the pH and often reduce the fabric pH to quite acidic conditions.

EFFECT OF MOISTURE ON THE WOOL FIBRE

The moisture regain of a fibre is the amount of moisture contained within a textile fibre in a standard atmosphere as a percentage of the dry weight of the fibre. The wool fibre has one of the largest moisture regains of any textile fibre, Table 4.2. In ambient humidity, a wool fibre has moisture absorption of 16-18% which increases to 33% at 100% relative humidity.

Fibre	**Moisture regain (%)**
Cotton, raw	8.5
Cotton, mercerized	8.5-10.3
Flax (linen)	12.0
Hemp	12.0
Jute	13.75
Ramie	6.0
Silk	11.0
Wool	13.6-16.0
Viscose Rayon	10.7-16.0
Acetate	6.5
Triacetate	3.2-3.5
Acrylic	1.0-2.5

Modacrylic	0.4-2.5
Nylon	3.5-5.0
Polyester	0.4-0.8
Polyethylene	0.0-0.1

TABLE 4.2 MOISTURE REGAIN OF SOME COMMON TEXTILE FIBRES (65% RH AND 21.1°C ± 0.1°C) (JOSEPH, 1977)

Wool will swell with water in the transverse direction as opposed to the longitudinal direction (Cook and Fleischfresser, 1986, Shiloh et al., 1982). On average, it can swell up to 40% in transverse and only 1-2% in the longitudinal direction. This directionality is due to the anisotropic nature of the cortical cells, which are long and thin along the fibre. The absorbent nature of wool is accredited to the combination of a large number of hydrogen bonds and salt linkages with a primarily amorphous structure. The (polar) water molecules are attracted to the polarity of the peptide groups and salt linkages, and due to the amorphous nature of the wool fibre they can easily enter the structure to hydrolyse the salt linkages and hydrogen bonds. The result is an increased number of molecules attached to the protein structure and therefore an overall swelling.

PHOTO-DEGRADATION OF WOOL

Wool is susceptible to photo-degradation and the effects of irradiation from various wavelengths of UV and visible light have already been well documented, although

the precise chemical mechanisms for the effects are often still under discussion (Davidson, 1996, Dyer et al., 2009, Millington, 2006a, Smith, 1995).

There are three main types of photo-degradation in wool: photoyellowing; photobleaching and photo-tendering. Irradiation effects from different wavelengths are presented in Table 4.3.

Wavelength (nm)	**Effect**
290-310	Photoyellowing
> 400	Photobleaching
< 300	Photo-tendering (not limited to this range)

TABLE 4.3 EFFECT OF DIFFERENT IRRADIATION WAVELENGTHS ON THE PHOTO-DEGRADATION OF WOOL (MACLAREN AND MILLIGAN, 1981)

Photoyellowing and photo-tendering are of most interest to this research. Photoyellowing is thought to occur due to the irradiation and consequent degradation of the amino acid tryptophan. Tryptophan degrades to form kynurenine and related degradation products which are bright yellow therefore contributing to the yellowing of wool. Water is known to greatly increase the rate of photoyellowing (Dyer et al., 2009, Millington, 2006a, Millington, 2006b, Millington and Church, 1997)

Photo-tendering, the loss of strength due to irradiation to light is known to be an issue with wool fibres (Millington and Church, 1997). Hacke investigated the effect on artificially aged and historic fibres and found the loss of strength and extension

to be significant at the fibre level. Wool extension fell from 38% to 11% (Hacke, 2006). It is likely that photo-tendering is a complex mixture of mechanisms but it is thought to be mainly attributed to: the scission of the main protein chain; breaking of both disulphide bonds (and cross-links) and the peptide bonds (Millington, 2006b).

4.2 Methods

4.2.1 Electron Paramagnetic Resonance Spectroscopy

Electron Paramagnetic Resonance (EPR) was used in this study to detect free radicals within the wool protein chain. Electron Paramagnetic Resonance (EPR) and Electron Spin Resonance (ESR) are the same technique known by two different names. EPR has been used previously in the study of wool radicals and associated additive free radical species (Nicholls, 1980, Carr et al., 1987, Shao et al., 1997, King, 2011). These studies mainly investigated the effect of light degradation and free radicals associated with metals and their effect on light degradation rather than historical wool samples but the technique is still very relevant to cultural heritage studies.

The samples which were examined were: virgin wool, 500 hours UV-aged wool, Relative humidity and thermal aged 100 cycled wool, Relative humidity and thermal aged 270 cycled wool, Relative humidity and thermal aged 270 cycled wool plus strain ageing, and two historic samples (5 and 8).

By applying a magnetic field (B_0) to a material, the magnetic moment of an electron within the material aligns itself either parallel (m_s = -1/2) or anti-parallel (m_s = + 1/2) to the field. An unpaired electron, such as those associated with free radicals, can move between these two states. As it moves between the states it will either emit or absorb a characteristic amount of energy, ΔE and this change in energy is detected, Figure 4.2.

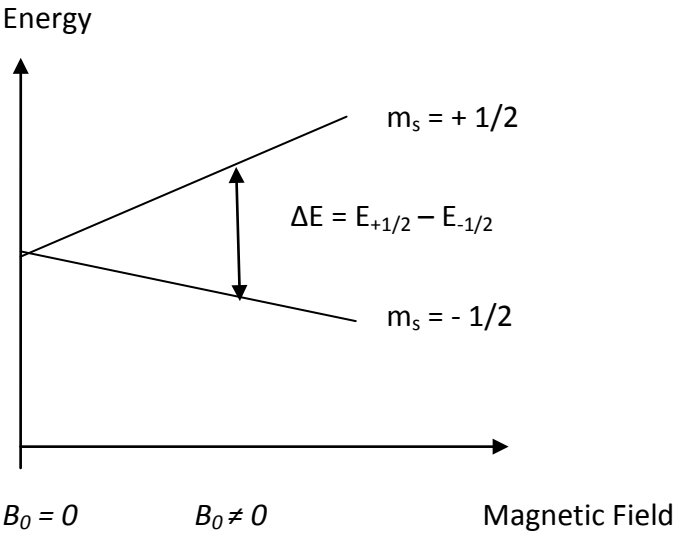


FIGURE 4.2. THE RELATIONSHIP BETWEEN THE INCREASE OF MAGNETIC FIELD AND THE SPLITTING OF ENERGY LEVELS. (ADAPTED FROM MEYBECK AND MEYBECK, 1978)

These characteristic changes in energy can be matched to specific known radical spectrum and changes in the protein chain structure can be identified.

Continuous wave X-band (approximate microwave frequency 9.4 GHz) electron paramagnetic resonance (EPR) spectra were obtained at the University of Manchester using a Bruker ELEXSYS E500 EPR spectrometer equipped with a Super High Q (SHQE) cylindrical EPR resonator. An experimental temperature of 10 K was maintained using liquid helium boil-off gas flow via an Oxford Instruments ESR900

helium flow cryostat and LT600 helium transfer line. The temperature was determined using a Cernox sensor within the cryostat linked to an Oxford Instruments ITC503 temperature controller. For the detection of high spin iron signals, the microwave power was 0.5 mW (milliwatts), the modulation amplitude was 5 G (gauss) and the sweep width was 4000 G. For the detection of radical signals the microwave power was 20 μW, the modulation amplitude was 1.5 G and the sweep width was 150 G.

Previous studies have demonstrated that intense uv/ozone exposure of wool produces relatively high concentrations of free radicals (Carr et al., 1987, Shao et al., 1997). In this study treatment of wool samples using a 42-220 Jelight UV/Ozone (UVO) system provides a "benchmark" of characteristic free radical species produced in tapestry wool material and photo-oxidative damage. The treatment of textile materials using UVO is a well-established technique and has been used within the heritage field previously when investigating the effect of using UVO as a cleaning treatment for tarnished silver threads (Hacke et al., 2003, Vig, 1985).

The UVO treatment irradiates the samples at 184.9nm and 253.7nm. Atmospheric oxygen will absorb the radiation at 184.9nm to generate ozone (and atomic oxygen). The ozone acts as a strong oxidising agent. Further reaction of ozone absorbing 253.7nm radiation produces more atomic oxygen which continues to act as an ozonizer. It is in this way that the wool fibres are oxidised with this treatment (Hacke et al., 2003, Shao et al., 1997)

4.2.2 Electrophoresis

Gel electrophoresis is a widely used technique in protein chemistry which enables the separation of individual proteins for further characterization. Proteins can be separated according to their size, overall charge or a combination of both depending on the specific technique chosen (Hames, 1998).

Protein Extraction and Concentration

The extraction of wool can be difficult owing to the large number of cross-links which can limit the protein solubility. In addition, the lack of information relating to the sequence of the wool genome results in difficulty establishing the precise sequence and structure of the wool protein (Clerens et al., Plowman, 2003). When separating the proteins in wool, there are two main groups: the intermediate filament proteins (IFPs) and the keratin associated proteins (KAPs). The IFPs in wool are Type I and Type II (acidic and basic keratins) and are generally the larger proteins which account for around 50% of the structure. The KAPs are the rest of the smaller proteins including the sulphur-containing proteins, which are of particular interest in this research. In standard extractions, the IFPs tend to dominate the electrophoresis gels and it is difficult to study the less abundant KAPs, so it is useful to choose an extraction buffer which enriches for the KAPs.

Following the work of Plowman et al. 2010 a range of buffers were evaluated in order to determine the most suitable conditions for KAP enrichment. The following buffers were tested:

Buffer A: Varying DTT concentration

8M Urea, 50mM Tris with 1mM, 2.5mM, 5mM, 7.5mM and 10mM DTT solutions, respectively, at pH 7.5

Buffer B: Varying Urea concentration

50mM Tris, 50mM DTT with 1M, 2M, 3M, 4M and 5M Urea solutions, respectively, at pH 9.3

An example 1-DE gel of Virgin wool, obtained from DTT and varying buffer is shown below:

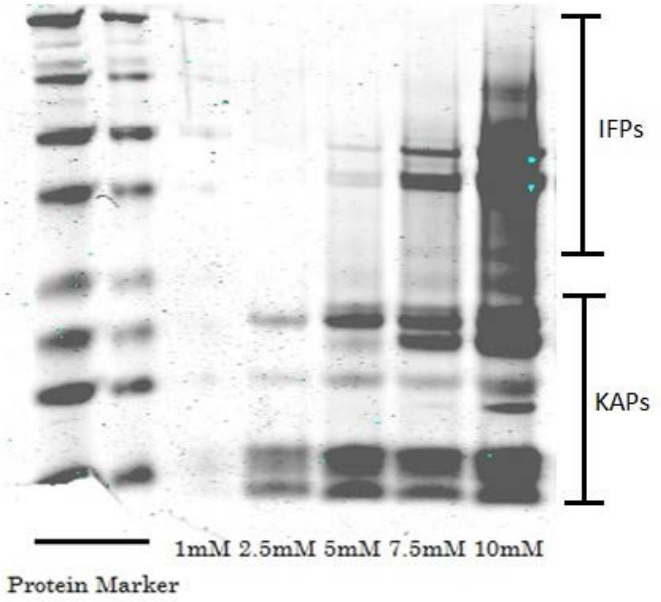


FIGURE 4.3 EXAMPLE 1-10MM DTT 1-DE GEL MAP SHOWING THE DOMINANCE OF IFPS AT HIGHER CONCENTRATIONS OF BUFFER

For the above gel, it was determined that a concentration of 2.5mM DTT was the most suitable for KAP enrichment.

In general, for most of the samples extracted, 2.5 mM DTT and 1M or 2M Urea were the optimum concentrations for KAP enrichment.

The wool sample was finely chopped (using scissors) and added to 10ml of the extraction buffer (as described previously, Buffer A or B) in a 15ml tube. The tubes were agitated overnight. 1ml of 1M iodoacetamide was added to the solutions and left in the dark for 30 minutes. The solutions were then centrifuged at 2500g for 10 minutes and the sample pipetted into fresh labelled 15ml tubes for freezer storage.

ONE-DIMENSIONAL SDS-PAGE

Sodium dodecyl sulphate -polyacrylamide gel electrophoresis, SDS-PAGE, is one of the most widely used electrophoretic systems in protein analysis (Bollag et al., 1996). One-dimensional SDS-PAGE separates proteins according to their size. After extraction of the protein, it is treated with SDS which binds to the primary protein structure. The SDS confers a constant negative charge: size ratio (1.4 mg SDS: 1 mg protein) to the protein and the SDS-protein complex is uniform in nature (in terms of charge and dimension) so the variable of interest between different proteins is their size.

The SDS-treated proteins are loaded into a polyacramide gel (see Figure 4.4) and an electric field is applied across the gel. The negatively charged proteins migrate through the gel towards the positive electrode (anode). The smaller proteins can migrate through the gel more quickly so the proteins separate out down the gel according to their molecular mass. Protein calibration markers are used (usually in

the end well) to estimate the mass of the unknown protein sample. The molecular masses are generally indicated in kDa (Da = Dalton). After electrophoresis, the gel is stained using Coomassie Brilliant Blue which will enable the proteins to be visualised.

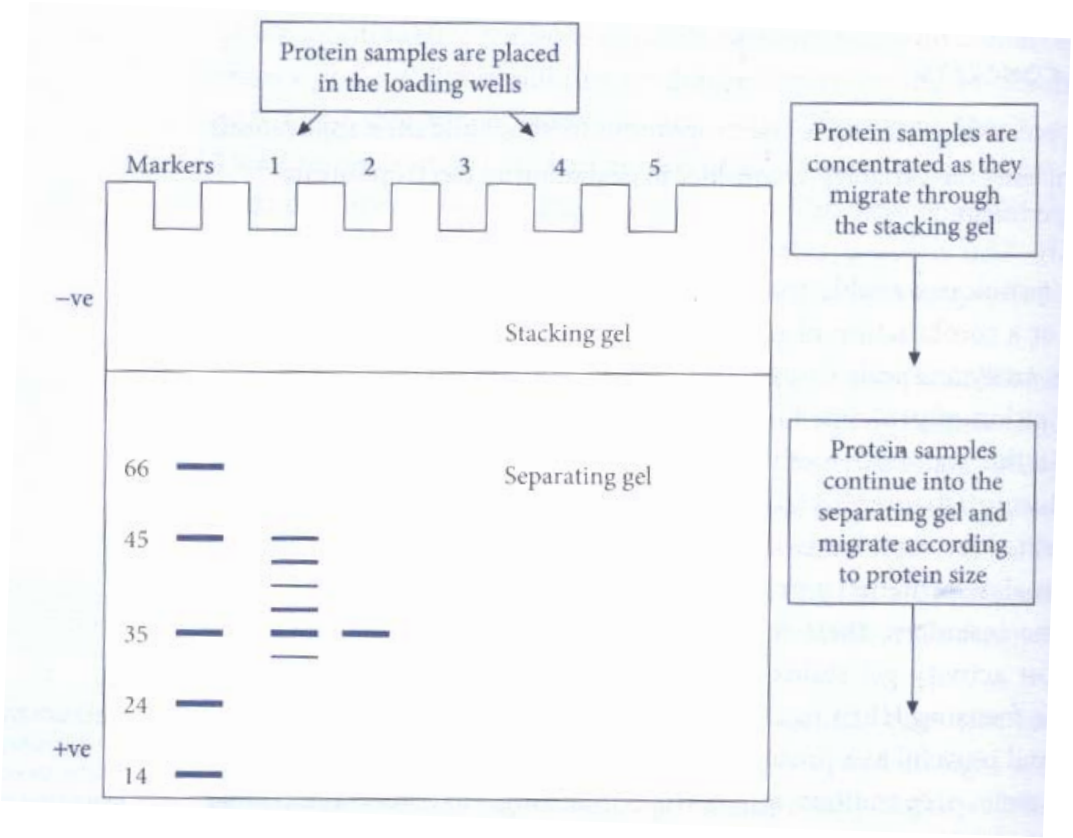


FIGURE 4.4 ONE-DIMENSIONAL SDS-PAGE (PRICE AND NAIRN, 2009)

METHOD

Sodium dodecyl sulphate - polyacrylamide gel electrophoresis, SDS-PAGE, was used to separate proteins in wool to enable comparisons between samples. Wool can be difficult to work with when compared to different proteinaceous substances (Koehn et al.), so a variety of buffers and methods were tested with the samples to ascertain the best-suited overall experimental method.

NuPAGE® Bis-Tris gels and electrophoresis buffers and cells were used to undertake all 1-D SDS-PAGE experiments.

A pre-cast 10% Bis-Tris polyacrylamide gel was used to separate proteins. 20µL of each protein extraction was added to 5µL of sample buffer (60 mM Tris–HCl, pH 6.8, 2% (w/v) SDS, 1% CHAPS (3-[(3-cholamidopropyl) dimethylammonio]-1-propanesulfonate)), 3% (v/v) mercaptoethanol, 10% glycerol and a trace of bromophenol blue (all Sigma sourced) and briefly mixed using a vortex. A litre of SDS running buffer was prepared and poured into the cell. Samples were loaded into the wells (up to 10) and Molecular Weight (MW) marker added (Unstained Precision Plus standard from Bio-Rad). The system was run at 200V for one hour, or until the dye front was ~10 mm from the bottom of the gel. The gel was then removed and stained using Coomassie Brilliant Blue (0.1% Coomassie G-250, 10% ammonium sulphate, 20% methanol, 3% phosphoric acid).

After staining, the gel was left agitating in MilliQ water overnight, ready for examination and digital scanning.

TWO-DIMENSIONAL SDS-PAGE

Two-dimensional SDS-PAGE was performed in two parts: firstly the proteins were separated by charge in isoelectric focusing, and then SDS-PAGE was carried out to separate them according to mass. Therefore the final gel contains a “plot” of protein spots which can be characterised by their placement according to both charge and size.

Part 1: Isoelectric focusing

Isoelectric focusing (IEF) is an electrophoresis method which separates proteins according to their net charge. Proteins carry a charge which depends upon their conformation, composition and the surrounding environmental pH.

Each protein has an individual isoelectric point (see section 5.1: Isoelectric point) – the pH at which it carries no overall charge. In IEF, proteins are exposed to a voltage across a pH gradient. Proteins carrying a net positive charge migrate towards the negative electrode (cathode) and those with an overall negative charge towards the positive electrode (anode) until they come to a stop when the pH matches that of their IEP. Once at their isoelectric point, the protein can be "focused" and resolved in order to proceed to the second part of the experiment: SDS-PAGE.

Part 2: SDS-PAGE

The next stage of the experiment is as described previously in "one-dimensional SDS-PAGE", where proteins are separated according to their size. The focused gel strip from the IEF stage was inserted into the top of the 10% Bis-Tris polyacrylamide gel and electrophoretic separation was performed with the following programme: 175V for 15 minutes, 175-2000V ramp for 45 minutes followed by 2000V for 30 minutes.

4.2.3 Gel-top Analysis

Gel-top analysis is a mass spectrometry technique where gels are prepared as for 1-D SDS-PAGE but the electric field only applied long enough for the dye band to

travel out of the gel wells and into the gel proper. Then the gel is stained and the bands cut out and analysed using mass spectrometry.

4.2.3.1 SAMPLE PREPARATION

Pre-cast 10% bis-tris polyacrylamide gels (Invitrogen) were run for 8 minutes at 200V to carry the sample a short distance into the resolving gel. The gel was stained using colloidal Coomassie Blue G250. The stained gel top band was excised using a disposable glass pipette, reduced using 10 mM DTT in 25 mM ammonium bicarbonate at 56^0C for 1 hour, and alkylated with 55 mM iodoacetamide, 25 mM NH_4HCO_3, 45 minutes at room temperature in the dark. After washing in acetonitrile, in-gel digestion was carried out overnight using 5 µl of 12.5 ng/µl trypsin (sequencing grade, Promega) in 50 µl 25 mM NH_4HCO_3. Peptides were extracted from the gel using 50 µl of 20 mM NH_4HCO_3 for 20 minutes, with further extraction using 5% formic acid in 50% acetonitrile for 20 min.

4.2.3.2 MASS SPECTROMETRY

Digested samples were analysed by LC-MS/MS using an UltiMate® 3000 Rapid Separation LC (RSLC, Dionex Corporation, Sunnyvale, CA) coupled to a LTQ Velos Pro (Thermo Fisher Scientific, Waltham, MA) mass spectrometer.

Peptide mixtures were separated using a gradient elution from 92% A (0.1% FA in water) and 8% B (0.1% FA in acetonitrile) to 33% B, in 44 minutes at 300 nL min^{-1}, using a 75 mm x 250 µm, i.d. 1.7 mM, Ethylene bridged hybrid (BEH) C18 analytical

column (Waters). Peptides were selected for fragmentation automatically by data dependent analysis. Data produced were searched using Mascot (Matrix Science UK), against the Uniprot database with taxonomy of *ovis* selected. Data were validated and visualised using Scaffold (Proteome Software, Portland, OR).

4.3 Results and Discussion

SDS-PAGE

4.3.1 Virgin wool

Virgin wool was extracted with 10 different buffers as described in section 4.2.2. One- and two-dimensional SDS-PAGE analysis was performed and the results presented here.

4.3.1.1 1-DE gels

1-DE gel: Buffer B (Varying Urea concentration)

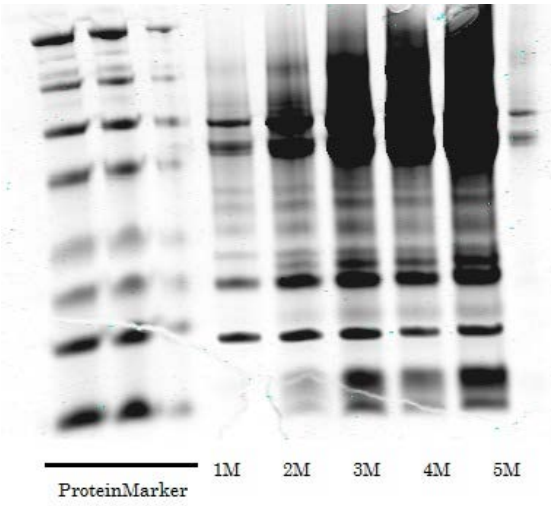


Figure 4.5 1-DE gel of Virgin wool obtained using 1-5 M Urea and 50mM DTT

The virgin wool at varying urea concentration gel showed that the best concentration for KAP enrichment was 1M urea, although 2M urea was also acceptable, Figure 4.5. Concentrations of above 3M urea showed a sharp increase in the quantity of IFP extracted as indicated by the large dark upper bands. The clarity of the bands was sharp, indicating that the proteins have separated successfully and are likely to be intact and not degraded; which was as expected in the virgin wool.

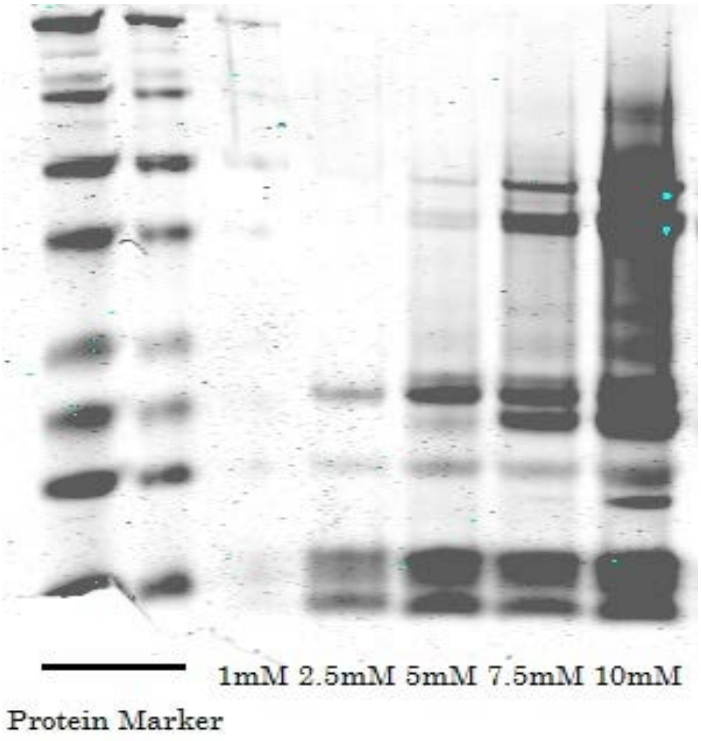


FIGURE 4.6 1-DE GEL OF VIRGIN WOOL OBTAINED USING 1-10MM DTT

The virgin wool at varying concentrations of DTT gel was similar to the urea gels above, however the level of protein extraction was less, Figure 4.6. The optimum buffer for this gel system was 2.5mM DTT, although 5mM DTT was also acceptable but the bands were less sharp.

4.3.1.2 2-DE GELS

The primary purpose of developing virgin wool 2-DE gels was to provide a baseline for comparison with the artificially aged samples. The original objective was to perform 2-D SDS-PAGE on virgin, artificially aged and historic wools and compare the 2-D maps to identify protein spots which had "moved" and therefore undergone some modification or change. The following 2-D maps (Figures 4.7 and 4.8) for the virgin wools would be the baseline as the wool represents the original undamaged "fresh" wool of a new tapestry.

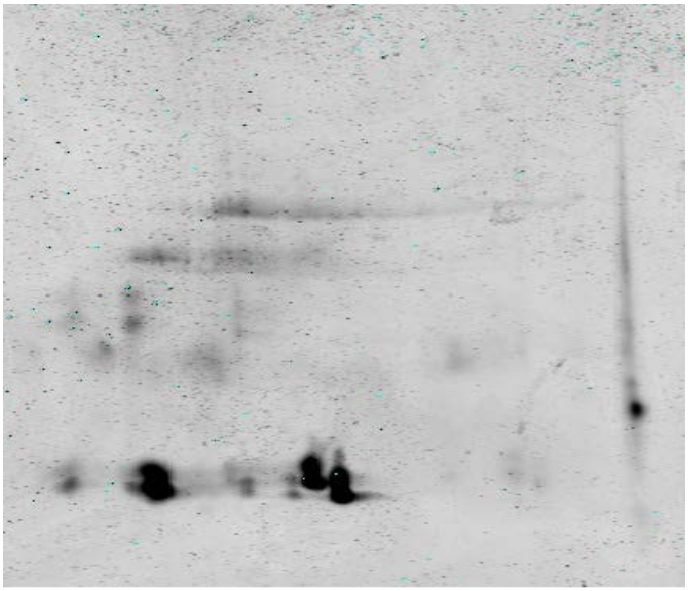


FIGURE 4.7 VIRGIN WOOL, PH 4-7, 40MG LOAD, 2-DE GEL

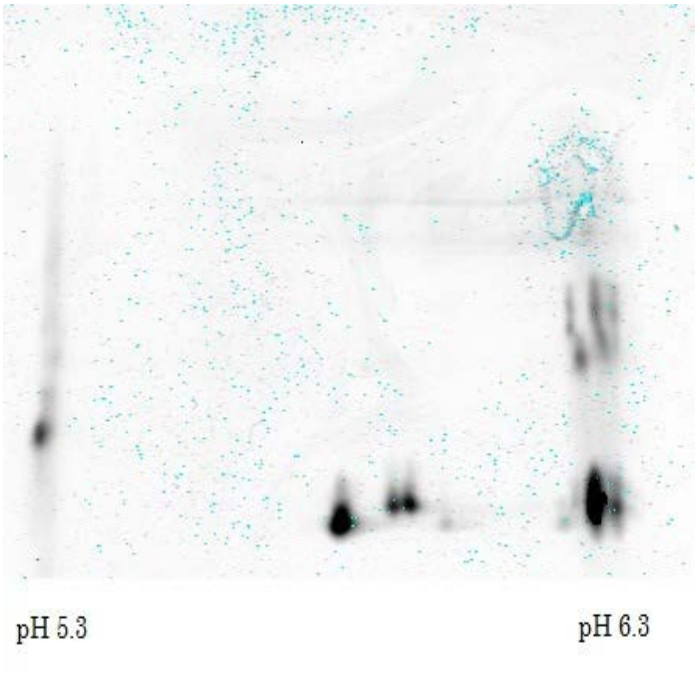


FIGURE 4.8 VIRGIN WOOL, PH 5.3-6.3, 50MG LOAD 2-DE GEL

4.3.2 LIGHT AGEING

Below are presented the results for the light-aged wool gel top analyses.

4.3.2.1. LIGHT AGED WOOL 1-DE GELS

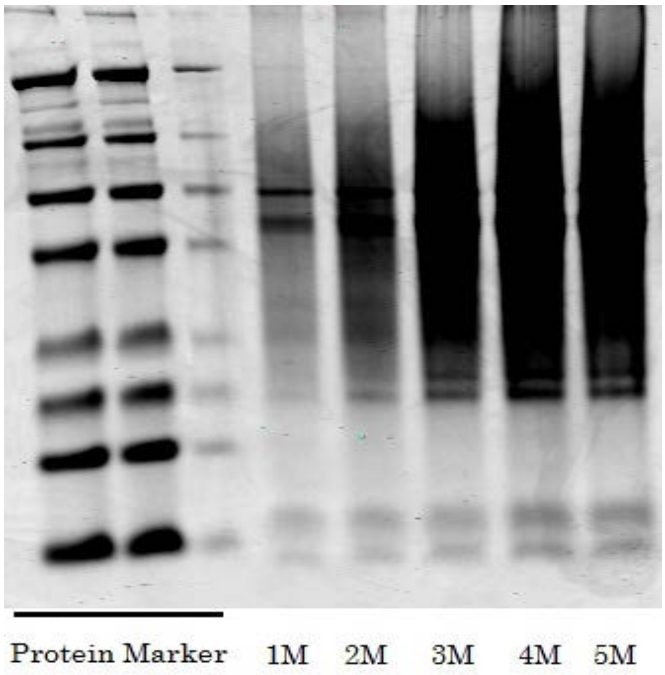


FIGURE 4.9 LIGHT-AGED WOOL, UREA 1-5M, 1-DE GEL

The light-aged 1-D gel with varying urea concentration (Figure 4.9) still showed some sharp bands in 1M and 2M urea however the 3-5M urea extraction showed significant smearing of the protein indicating protein deterioration had occurred (discussed further in section 4.3.5).

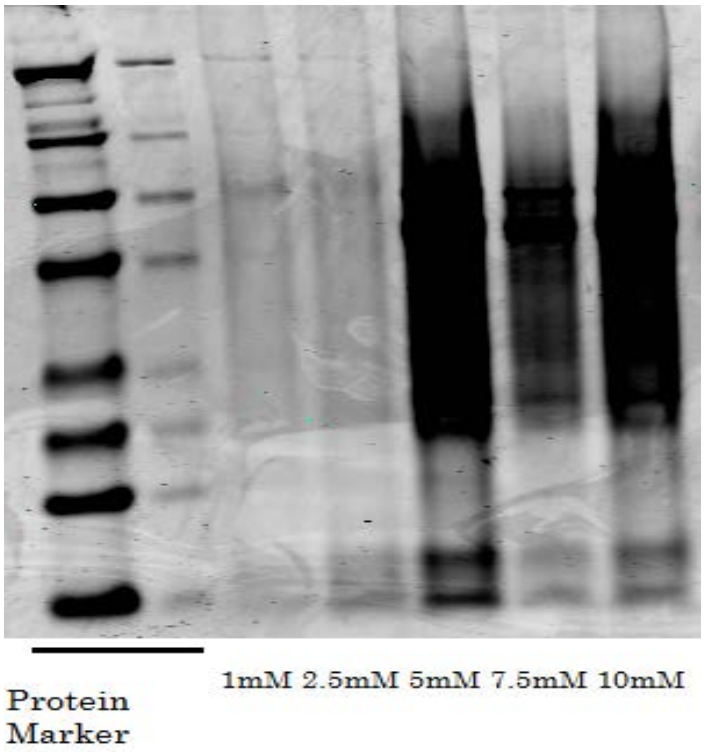


FIGURE 4.10 LIGHT-AGED WOOL, 1-10MM DTT, 1-DE GEL

The light-aged wool 1-D with varying DTT gel showed variation across the concentrations (Figure 4.10). 5mM DTT and above showed significant IFP presence and smearing, however the 1mM and 2.5mM DTT extraction showed very faint bands. Therefore 2.5mM was chosen as the extraction buffer, but the load was increased for use in the 2-DE protein maps.

4.3.2.2 LIGHT AGED WOOL 2-DE GELS

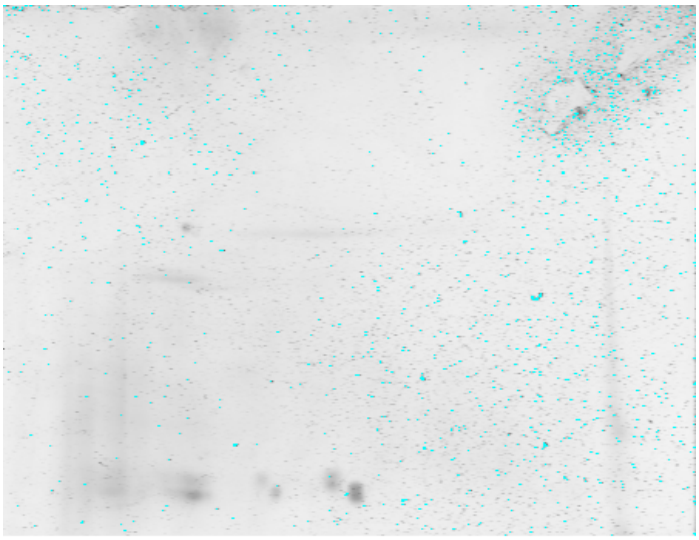


FIGURE 4.11 LIGHT-AGED WOOL, PH 4-7, 80MG LOAD, 2-DE GEL

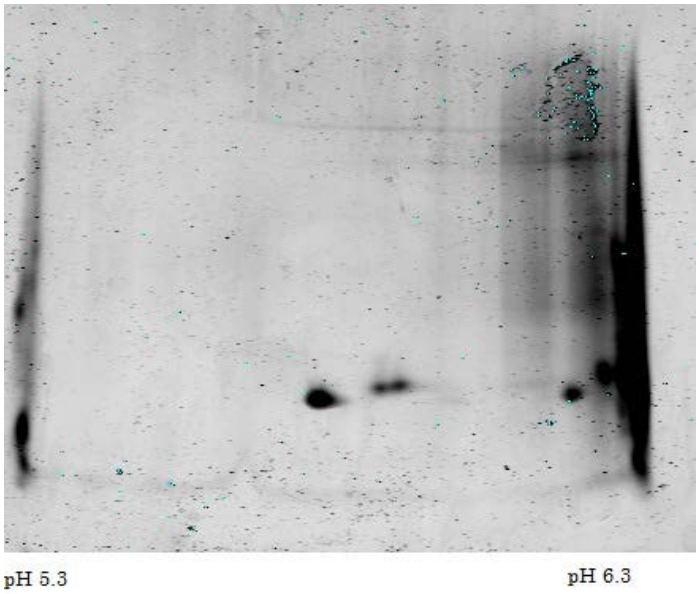


FIGURE 4.12 LIGHT-AGED WOOL, PH 5.3-6.3, 80MG LOAD, 2-DE GEL

The 2-DE gels for light-aged wool (Figures 4.11 and 4.12) demonstrated that although the protein spots were similar to those seen in the virgin wool gels,

double the load of protein was needed to achieve acceptable visualisation and there was smearing in the pH 5.3-6.3 gel (although some spots were still very clear). The necessity of a greater load of protein was possibly indicative of the solubility of the protein. This will be discussed in greater detail in section 4.3.5.

4.3.3 Relative Humidity and Thermal Ageing

Below are presented the results for the relative humidity and thermal ageing gel top analyses.

4.3.3.1 RH/T aged 1-DE gels

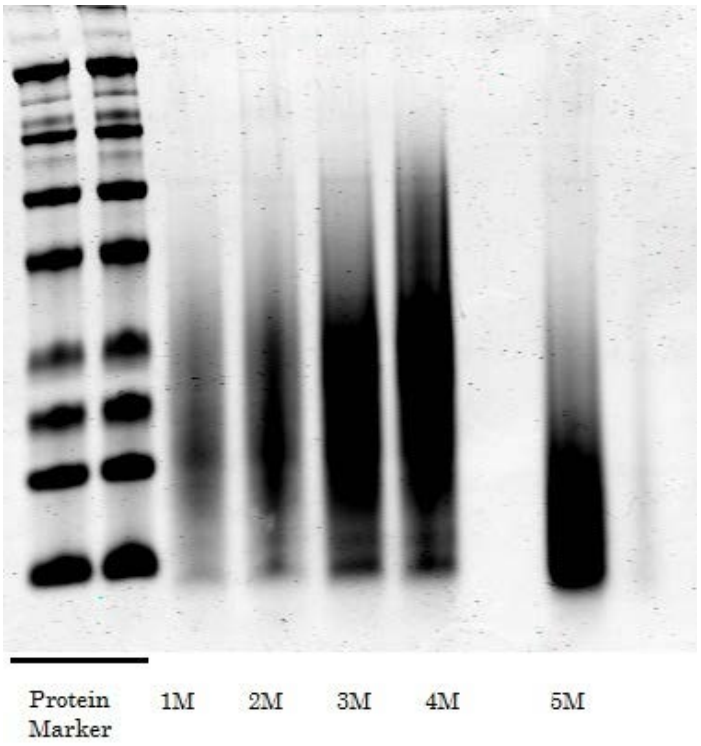


Figure 4.13 RH aged wool, Urea 1-5M, 1-DE gel

Analysis of the gels of the Relative humidity and thermal aged wool indicated significant deterioration of the protein, with protein smearing clearly visible across

all concentrations of buffer (Figure 4.13). This was the first indication that Relative humidity and thermal ageing caused serious damage to the protein structure of wool. No particular concentration can be identified as better for KAP enrichment than another so 2M urea was chosen as this was the most appropriate with all other samples, and produces a clear dark smear towards the bottom of the band as opposed to throughout the band.

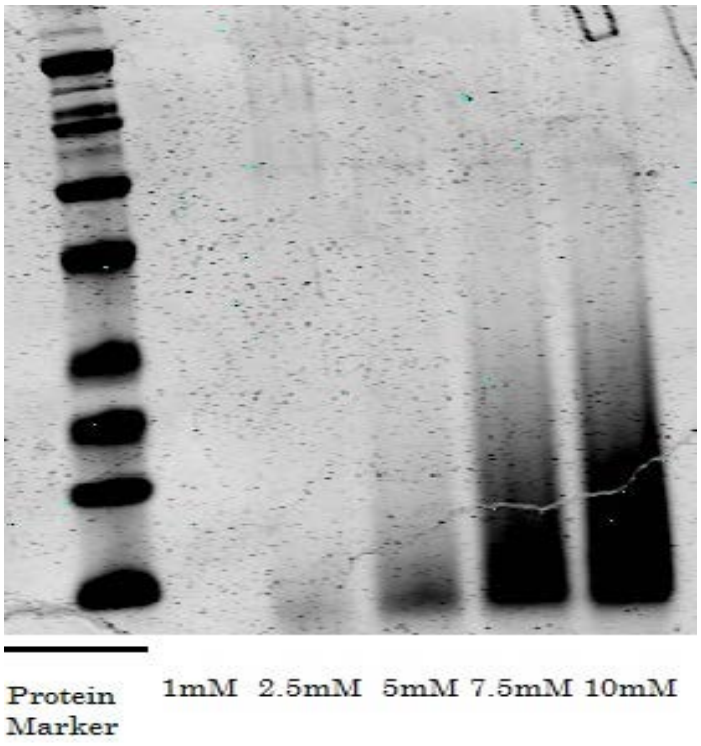


FIGURE 4.14 RH-AGED WOOL, 1-10MM DTT 1-DE GEL

The Relative humidity and thermal aged wool 1-D varying DTT gel, Figure 4.14 indicated deterioration of protein once again. The 1mM DTT treatment gel was completely blank, 2.5mM and 5mM DTT had faint indications of a low MW protein smear and 7.5mM and 10mM showed a larger quantity of deteriorated protein.

4.3.3.2 RH/T AGED 2-DE GELS

A variety of 2-D gels were developed from the relative humidity and thermal aged wools. However, despite experimenting with different buffers and increasing loads, all gels remained blank, even on repeat trials. This indicated problems with extracting and solubilising the protein – an extension of the smearing seen in the previous 1-D gels. However, after even separating in another dimension as well, the result was still that no protein was visualised. Although disappointing that no comparison can be made with the virgin wool samples, this result is significant in itself as it was an initial indicator that solubility of protein could be a primary marker in the degradation of the wool fibre.

4.3.4 HISTORIC SAMPLES

The historic samples were separated into warp and weft yarn samples to investigate if the level of deterioration in both was the similar. Samples were prepared in the same way as the virgin and artificially aged wools.

4.3.4.1. HISTORIC SAMPLES 1-DE GELS

WARP

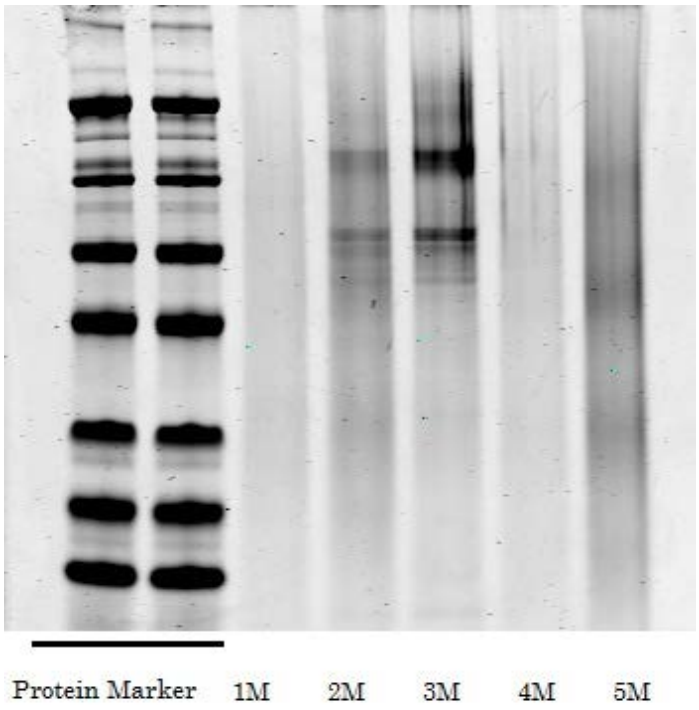


FIGURE 4.15 HISTORIC WARP WOOL, 1-5M UREA, 1- DE GEL

The historic warp variable urea concentrations 1-D gel, Figure 4.15, indicated that the only concentrations to produce any bands were the 2M and 3M urea samples, although the bands which are clarified are IFP in nature. However, the best concentration with clear bands and minimum smearing was the 2M urea condition so that this concentration was chosen for further experiments.

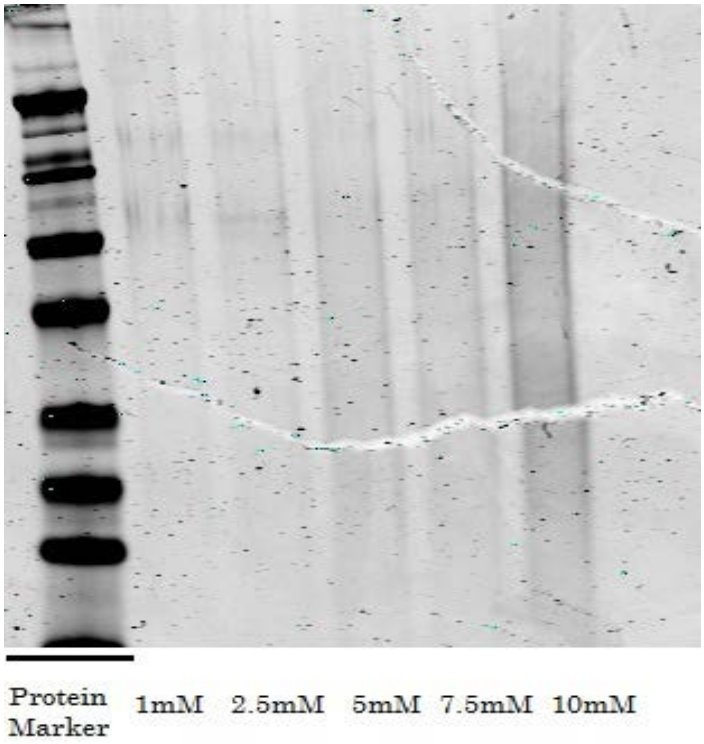


FIGURE 4.16 HISTORIC WARP WOOL, 1-10MM DTT, 1-DE GEL

The historic warp variable DTT concentration 1-D gel (Figure 4.16) showed that across all concentrations the extraction was not successful in extracting proteins, with a few bands visible and still smeared, Figure 4.15.

WEFT

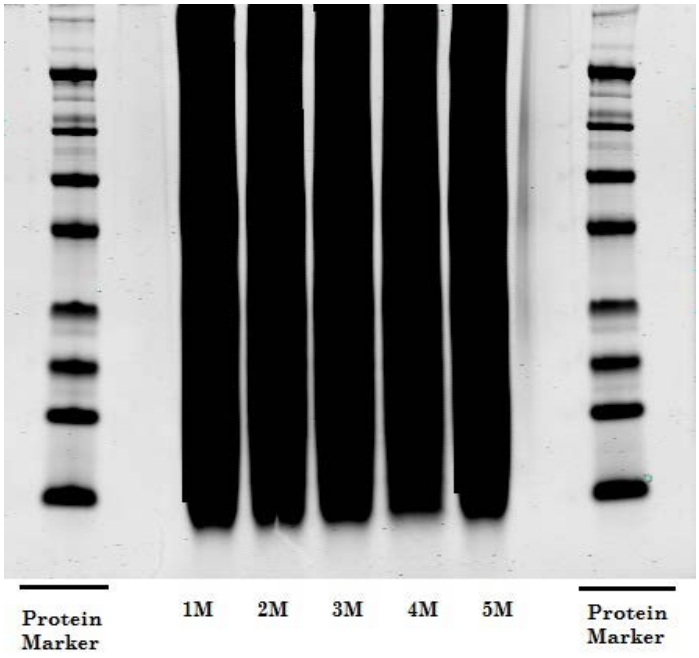


FIGURE 4.17 HISTORIC WEFT WOOL, 1-5M UREA, 1- DE GEL

The variable urea concentration 1-DE gel for historic weft showed extensive deterioration of protein, Figure 4.17. The darkness of the bands indicates that protein has been successfully extracted but is significantly degraded across all concentrations and is smeared both up and down the band.

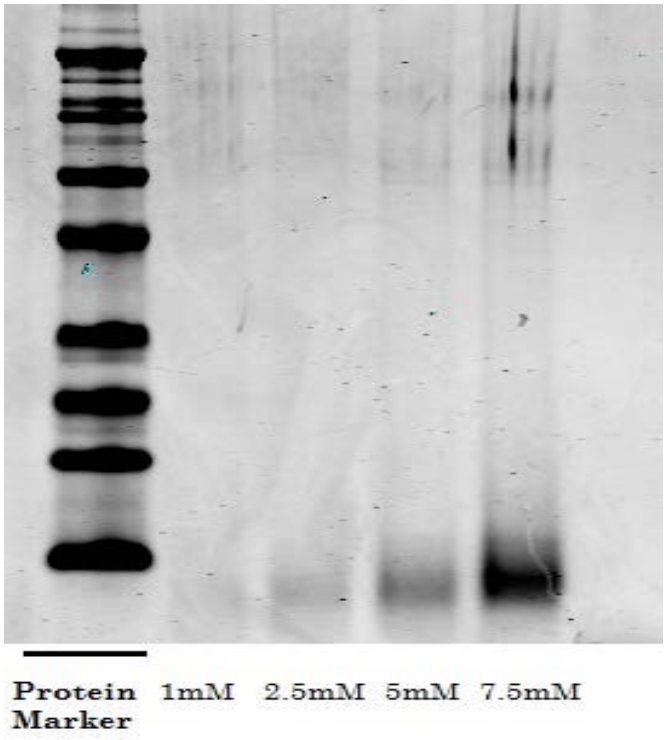


FIGURE 4.18 HISTORIC WEFT WOOL, 1-7.5MM DTT, 1-DE GEL

Similar to the historic warp, the historic weft sample analysis also shows minimum extraction using varying concentrations of DTT, Figure 4.18.

Overall, although extensively deteriorated, the only extraction which showed protein clearly is the historic weft urea extraction so it was this buffer condition (2M for consistency) which was chosen for further work.

4.3.4.2. HISTORIC SAMPLES 2-DE GELS

WEFT

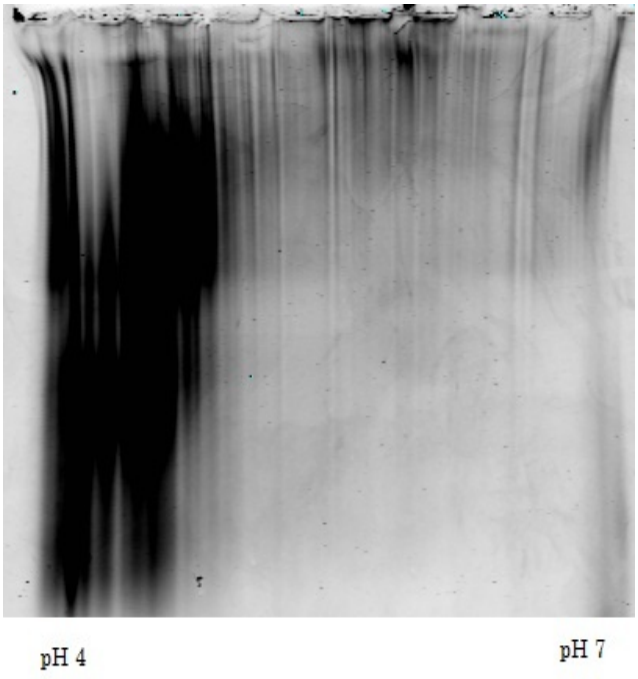


FIGURE 4.19 HISTORIC WEFT WOOL, PH 4-7, AND 2-DE GEL

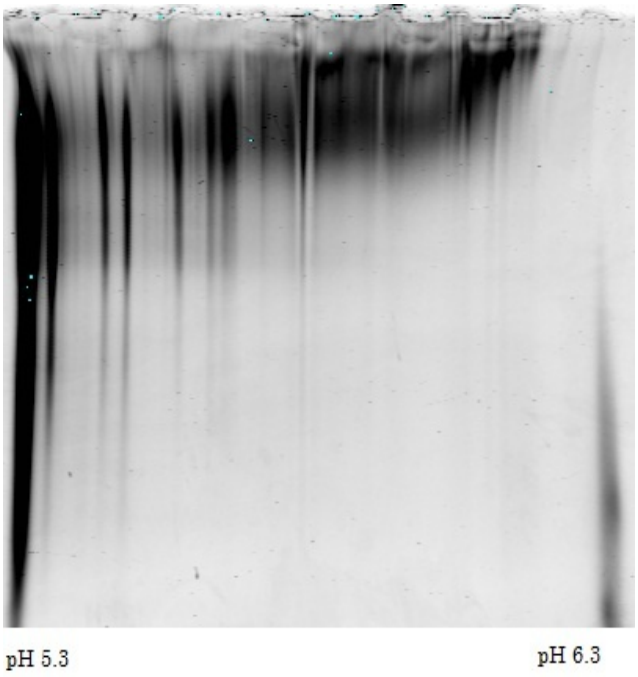


FIGURE 4.20 HISTORIC WEFT WOOL, PH 5.3-6.3 2-DE GEL

Both the 2-D gels for historic weft (as warp was not sufficiently soluble/extractable to undertake further analysis) indicate severe protein degradation, Figures 4.19 and 4.20. The gels were repeated to ensure that the smearing was a result of the sample condition rather than an experimental error. The severity of the smearing compared to the other samples is of significance as it can be used as an indicator of severe degradation; with virgin wool 2-D gels at the other extreme.

4.3.5 Ageing comparison

After performing gel electrophoresis on all samples it was clear that the original experimental plan of comparing protein spot movements and identifying modifications would not be possible. The samples were far more chemically degraded than originally expected, and the extractability of proteins was more of an indicator. With this discovery, more experiments were carried out to determine the cause of the solubility/extractability issues and whether a comparison could be made between the different ageing regimes and the historic samples. Gel-top analysis was carried out as described below.

4.3.5.1 Gel-top analysis

Four gel-top analyses were performed: 2 virgin wool samples (experimenting with different concentrations of reducing agent), Relative humidity and thermal aged wool and historic wool.

In order to investigate the issue of protein insolubility, it was decided to assess the effect of varying the concentration of reducing agent (TCEP rather than DTT due to

its greater longevity) and to establish whether different proteins were released at different concentrations. An initial range of 0-200mM was evaluated in the preliminary study and then a focused range of 5-45mM was assessed; however, a clear pattern was not discerned from the data. Nevertheless when the data from different wool samples were compared, a few trends were clear as summarised in Table 4.4.

Sample	**Total proteins: keratins**	**Low MW: high MW proteins**
Virgin (0-200mM)	0.26	0.37
Virgin (0-50mM)	0.35	0.32
RH Ageing	0.44	0.19
Historic	0.57	0.14

TABLE 4.4 PROTEOMIC ANALYSIS OF DIFFERENT WOOL SAMPLES

From Table 4.4, it is apparent that with increasing ageing, two effects can be observed:

The fraction of keratins identified to total proteins identified increased with increasing “age”;

The fraction of low MW keratins: high MW proteins (low MW was less than 40 kDa) decreases with increasing “age”.

The possible explanation for these observed effects is that with increasing age, and increasing deterioration of the wool fibre, the main protein chain swells during reduction and the smaller MW proteins are trapped inside and are not solubilised. Therefore the greater the deterioration, the greater the damage to the main chain which results in a less soluble fibre. The most likely reason for a decrease in solubility is the change to the disulphide cross-links both within the protein chains, intrachenic, and between the protein chains, interchenic. There are a number of different oxidation states of the disulphide cross-link and the way in which they are formed could indicate the true mechanism of damage. In addition perthiocysteine was reported to be formed in light aged wool and possibly increased lanthionine formation may reduce protein extraction and solubility (Jones and Speakman, 1960).

The different oxidation states and products of disulphide cross-links are shown below.

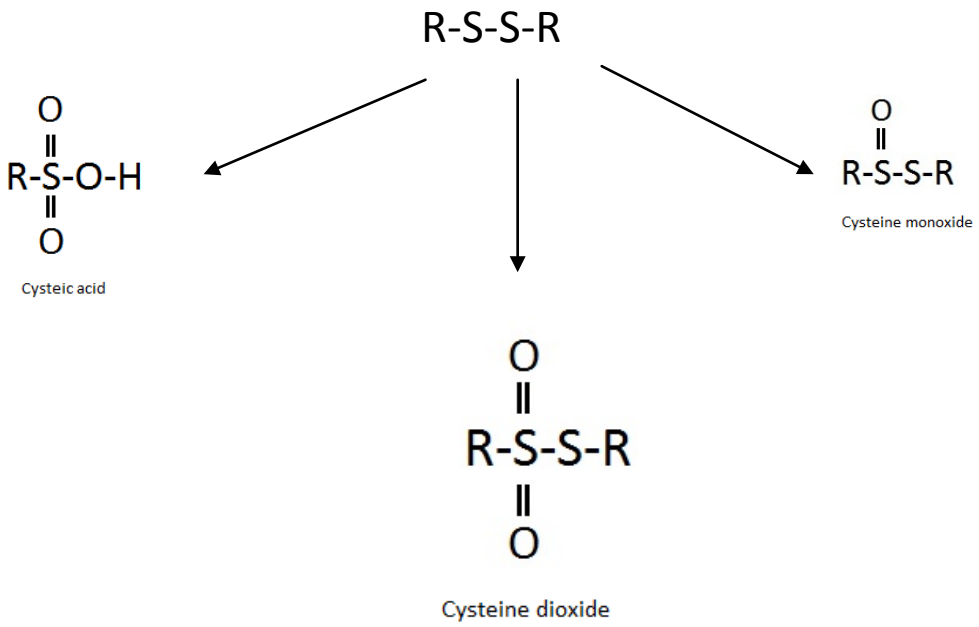


FIGURE 4.21 COMMON OXIDATION STATES OF THE DISULPHIDE BOND (ADAPTED FROM MACLAREN AND MILLIGAN, 1981)

When cystine (R-S-S-R) is exposed to an excess of an oxidising agent the most stable and common product is cysteic acid (R-SO_3-H). However, if the oxidation process is not as controlled, or there is less oxidant available then various intermediate products can be formed including cysteine monoxide (R-SO.S-R) and cysteine dioxide (R-SO_2.S-R). Additional products (not shown on the above diagram) include the Bunte salt (R-S-SO_3-H) and cysteine sulphinic acid (R-S-O_2-H). However, in an oxidative environment, the sulfinic product is less stable and disulphide bond cleavage is preferred. Although these products are termed "intermediate" products they are stable; their naming originates from the fact that they will often

hydrolyse to become cysteic acid or return to cystine when further oxidants or reductants are introduced into the reaction environment (MacLaren and Milligan, 1981, Alexander et al., 1963).

Therefore, at any one time (possibly more in the case of a tapestry sample) the cystine links may be in a number of different oxidation states. By using infra-red spectroscopy or XPS one should be able to identify and quantify which of the different states are present at the surface and within the fibre bulk. If certain oxidation states related to more or less a quantifiable change in mechanical strength a definitive scale could be developed. This is one area where future work should be continued to investigate how the different ageing processes may produce different oxidation states of cystine in wool and relate and transform this information into a technique for using non-destructive scientific analysis to identify an object on a chemical scale of “damage”.

EPR

The following section presents the results for the analysis using Electron Paramagnetic Resonance (EPR).

4.4 EPR RESULTS FOR ALL SAMPLES

Below are presented the results of electron paramagnetic resonance (EPR) for all samples analysed.

4.4.1 VIRGIN WOOL AND ARTIFICIALLY AGED UV/OZONISED SAMPLES

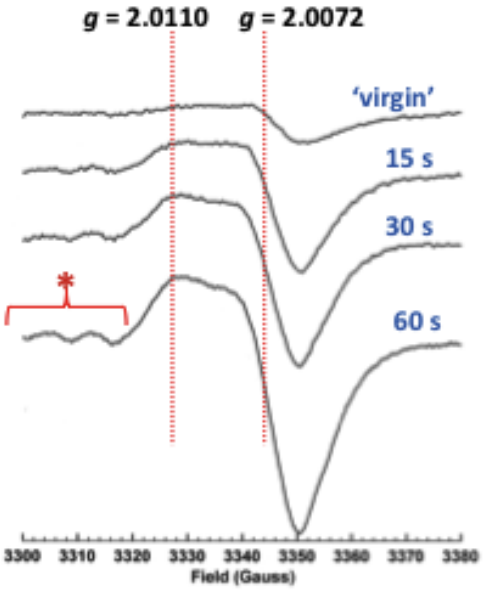


FIGURE 4.22 EPR SPECTRA FOR VIRGIN WOOL AND UV/OZONISED WOOL (15, 30 AND 60S EXPOSURE)

Figure 4.22 shows the EPR spectra for both virgin wool and artificially aged UV/ozonised wool at increasing exposure times; (15s, 30s and 60s exposure).

All samples showed the presence of organic free radicals, with the dominant species being the thiyl peak, to the left of the g = 2.0072 line in Figure 4.22 at g = 2.0110. This peak is likely to be the result of the cysteine formation in the wool fibre and therefore the radical is more specifically cysteinyl (RS•). The radical is formed through the deprotonation of a thiol group (R-SH).

Another feature we can see from these spectra is the gradual formation of a thioperoxy radical with increasing UV/ozone exposure. This feature is highlighted with an asterisk in Figure 4.22. A thioperoxy radical (RSOO•) is the formed through the combination of a thiol group and oxygen and is an important observation.

4.4.2. Artificially aged samples

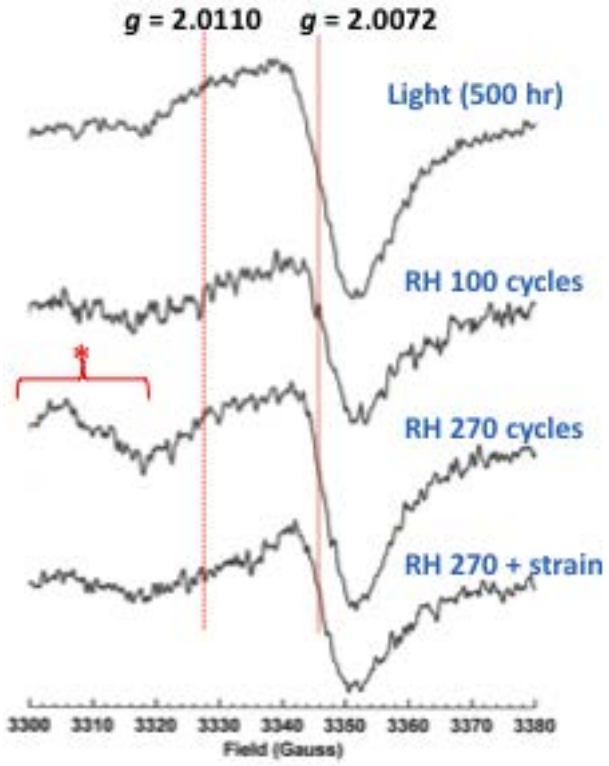


Figure 4.23 EPR spectra for artificially aged samples

Figure 4.23 presents the spectra for all artificially aged samples tested. In comparison to the virgin wool and UV/ozonised sample spectra these spectra have more noise and are not as smooth. This difference in spectral intensity is due the very high intensity of the 184 and 250nm uv radiation in the uv/ozoniser; however the radical responses are still clearly visible in the less aggressive and more realistic ageing regimes. The thiyl peaks were present in all samples, and the amount of thiyl radical increased with the increasing number of Relative humidity and thermal cycles.

Thioperoxy radicals are present in all Relative humidity and thermal aged samples but not in the light aged samples, implying that the formation of thioperoxy radicals is due to chemical changes occurring during relative humidity and thermal ageing only. This highlights the different chemical changes occurring in the distinct ageing mechanisms which in turn may provide insight into the damage introduced into historic textiles through the different agents of decay.

4.4.3 Historic samples

A significant observation in the analysis of historic samples 5 and 8 was the presence of a large free radical signal in their spectra, Figure 4.24. However, the radical species do not match those of the thiyl or thioperoxy peaks observed in both the virgin, uv/ozonised and artificially aged samples.

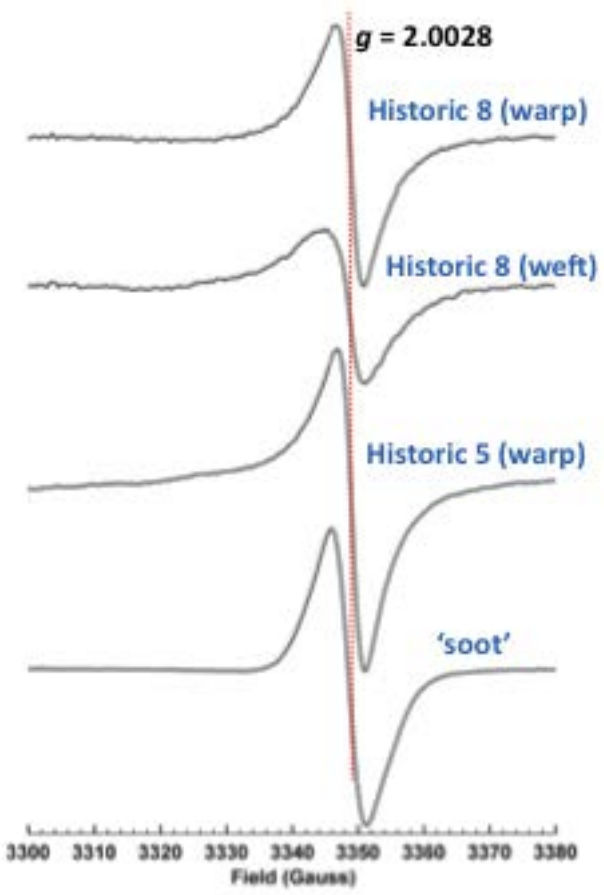


FIGURE 4.24 EPR SPECTRA OF HISTORIC SAMPLES AND SOOT

This radical intensity was similar to those of a carbon-based radical, and this was confirmed by comparing the spectra to that of a standard EPR soot calibration sample. The overlaying and intensity of the carbon-based peak in the historic samples results in the thiyl peak being masked and therefore the amount of thiyl radicals in historic samples cannot be resolved.

However, the discovery of the carbon-based radical peaks, and the size of these peaks is of interest. The presence of these carbon-based radicals implies that the past exposure of these textiles to wood fires, candle smoke, tobacco smoke and industrial pollution maybe more important than previously thought.

Section 4.5 discusses the investigation of “clean” and “dirty” samples to ascertain if there is a difference in the radical peaks – potentially highlighting the efficiency of the conservation cleaning methods in removing these carbon-based “soot” radicals.

Table 4.5 presents the relative radical concentrations for each sample with the relative concentrations of the various radicals present per unit fibre mass determined by deconvolution of the overlapping contributions to the spectra together with numerical integration to determine the area under each spectrum (proportional to radical concentration). Therefore for the first time we can make direct quantitative comparison between the samples.

Wool Sample	Relative [-S●]	Relative [-SOO●]	Relative [C●]
Virgin	1	Not detected	Not detected
UV/Ozonised 15s	3.76	0.43	Not detected
UV/Ozonised 30s	4.65	0.65	Not detected
UV/Ozonised 60s	6.82	1.02	Not detected
Light (500 hr)	1.5	0.14	Not detected
H/H (100 cycles)	0.93	0.38	Not detected
H/H (270 cycles)	1.35	0.72	Not detected
H/H (270 cycles) + Strain	0.9	0.34	Not detected
Historic 8 (warp)	Less than 0.1	Not detected	1.05
Historic 8 (weft)	Less than 0.1	Not detected	0.67
Historic 5 (warp)	Less than 0.1	Not detected	1.24

TABLE 4.5 RELATIVE INTENSITIES OF TYPES OF RADICAL FOUND IN DIFFERENT WOOL SAMPLES

4.5 Effect of wet cleaning on soot and free radical concentrations

The discovery that soot radicals could be present in historic tapestry samples prompted further investigation to determine whether wet cleaning methods had an effect on the removal of these carbon-based radicals.

In tapestry conservation, a large part of a conservation treatment can be the cleaning of the historic textile. The inherent fragility, age and size of a tapestry are just some of the factors that need to be taken into consideration when determining a cleaning treatment.

Tapestries often are exposed to high levels of soiling during their lifetimes – they are usually on display in rooms which may have had open fires, candlelight together with other forms of pollution coupled to the dust levels created by a large volume of people and animal traffic. This build up of dirt on the surface of a tapestry can cause long-term damage by increasing the acidity of the textile and causing chemical changes in the fibres – often resulting in the textile becoming brittle and friable.

Additionally, the dirt on the surface of any work of art can obscure the design and reduce the aesthetic quality of the object – therefore reducing its impact and value for the observer and owner.

Wet cleaning is an essential part of all conservation treatments and there are a number of different approaches which can depend on; size, fragility, material, dye fastness, structural stability and time. The wet cleaning of a tapestry requires a lot

of space, time, people and equipment and is usually only undertaken perhaps once or twice a century (for each tapestry).

4.5.1 Wet cleaning methodologies

Two wet cleaning methods are described below as samples from both methods were investigated in this study.

Hampton Court Wet Clean method

The Hampton Court Palace tapestry wet clean method has been developed by the Textile Conservation team in-house over many years. The procedure involves the tapestry being laid out flat on a purpose-built grid in a separate "wash-house" in the grounds at Hampton Court Palace. This grid is large enough to wash any tapestries from the Royal Collection. The wash table has specialised water input and drainage systems which allow a continuous water flow (in the form of a spray) and drainage throughout the process. The water used has already been softened and de-ionized and then mixed with a detergent (Synperonic) developed especially for this purpose.

Initially, the tapestry is lowered into a water bath until it is floating on top of a thin layer of water. To ensure thorough soil removal, mechanical action is required. This is achieved by sponging the tapestry directly or through a fine netting if the tapestry is particularly fragile. A moving gantry transports conservators up the length of the tapestry to apply the sponges to obtain maximum penetration of the water and detergent for cleaning. After this stage has finished, the grid is raised

above the water bath. The tapestry is then rinsed with de-ionized water (without detergent) repeatedly until there is no detergent left in the drained water.

The pH and amount of detergent are continuously monitored throughout the process to ensure no soapy residue remains in the tapestry.

Finally, the tapestry is blotted with towels and left to dry overnight (usually 12-24 hours) in a high air-exchange rate environment.

FIGURE 4.25 TAPESTRY WET CLEANING SYSTEM AT HAMPTON COURT PALACE. PHOTOGRAPH © HISTORIC ROYAL PALACES[3]

MANUFACTURE DE WIT WET CLEAN METHOD

The wet cleaning method used at the Manufacture De Wit is different from that at Hampton Court Palace in a number of ways. The main reasons that tapestries are sometimes chosen from the Royal Collection to be cleaned at the De Wit facility is that they are too fragile or, more commonly, they have fugitive dyes and therefore the in-house method of immersion wet cleaning is not always suitable.

[3] http://conservation100.hrp.org.uk/about/ accessed 2013-05-15

The system created at the Manufacture De Wit uses an innovative combination of a suction table and aerosol spraying.

Tapestries are laid flat on a suction table (5m x 9m) within a sealed glass chamber. Above the tapestries (at a height of 1.75m) a range of 45 aerosol sprays are arranged. During the cleaning process, the tapestry is continuously held in place through the vacuum suction whilst the chamber is filled with the spray containing water vapour and a non-ionic detergent. This detergent solution is applied by three conservators whilst simultaneously sponging the tapestry. This process continues for as long as necessary – depending on the level of soiling. After this cleaning has finished, the vacuum continues to hold the tapestry in place whilst towels are used to blot dry the tapestry. The whole process from start to finish takes around 8 hours.

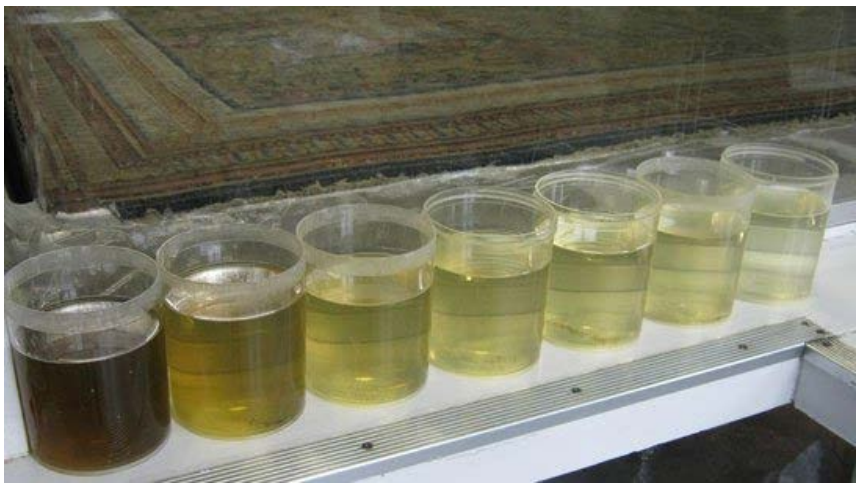


FIGURE 4.26 SUCCESSIVE DIRTY TO CLEAN WASH WATER SAMPLES FROM A DE WIT CLEANING OF THE SHELDON TAPESTRY MAP OF WARWICKSHIRE ©BRITISH MUSEUM 2012[4]

[4] http://blog.britishmuseum.org/2012/07/26/tale-of-a-tapestry/ 2013-05-15

4.5.2 Wet cleaning results

Sixteen samples were taken from two separate tapestries before and after their wet cleaning treatments. One tapestry (The History of Alexander the Great: Alexander and Hephaestion visiting the tent of the wife of Darius RC 1079.2) was wet cleaned at Hampton Court Palace using their standard wet cleaning procedure and the other (The Virtues Challenge the Vices as Christ Begins his Ministry: 'The Anglesey Panel' HRP 3003478) was sent to Belgium to be cleaned at the Manufacture De Wit using their slightly different wet cleaning method. When the samples were taken there was no indication of whether the samples would contain any soot and the carbon-based radicals.

Ten samples were taken from the De Wit tapestry and six from the Hampton Court tapestry. Samples were removed before cleaning and the location of the sample recorded. Then, after cleaning, another sample was removed from the same location and, where possible, the same yarn.

Samples were taken from the various locations on the tapestries so that a range of different dyes and chemistries could be observed in an attempt to minimise the effect of different dyes on the investigation into soot removal. The samples were not analysed to identify which specific dyes were present.

Of these sixteen samples, seven were identified as being suitable for EPR analysis and this decision was made based on the measurable mass of the samples. Some of the samples were too small to weigh accurately and also to handle for mounting into tubes for analysis. Therefore four De Wit samples and three Hampton Court

samples were identified for analysis. This made a total of 14 analyses (each sample has a before and after wet cleaning).

Analysis was carried out under the same conditions described in section 4.4, and the results presented below.

4.5.2.1 De Wit Samples

Figures 4.27-4.30 show the results of EPR analysis for eight samples: Samples 1, 2, 5 and 9 for both "before" wet cleaning (“B” spectra) and "after" wet cleaning (“A” spectra). Sample lines have been normalized with respect to their individual sample masses. “B” spectra lines have been displaced vertically so that a comparison can be more clearly made between the two spectral lines.

Samples 1 and 5 showed a small decrease in the radical signal level brought about by cleaning. This difference was not perceptible in samples 2 and 9.

The radicals in these samples appeared to be centered about a g value of 2.004 which suggests that they arise from polyphenolic compounds (e.g. quinines, tannates) derived from the associated dyes rather than the protein structure itself. This result is reassuring in that if the washing was significantly removing the dye the appearance and colour of the cleaned tapestry would be adversely affected.

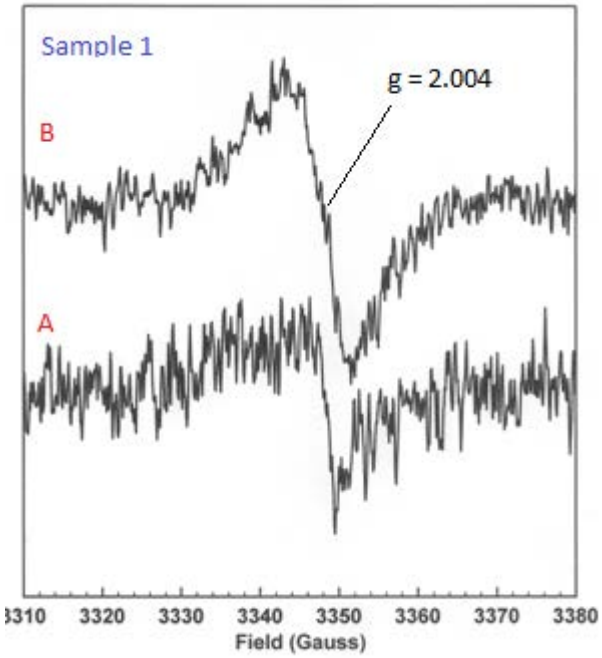


FIGURE 4.27 DE WIT TAPESTRY SAMPLE 1 EPR SPECTRA FOR "BEFORE" AND "AFTER" WET CLEANING TREATMENT

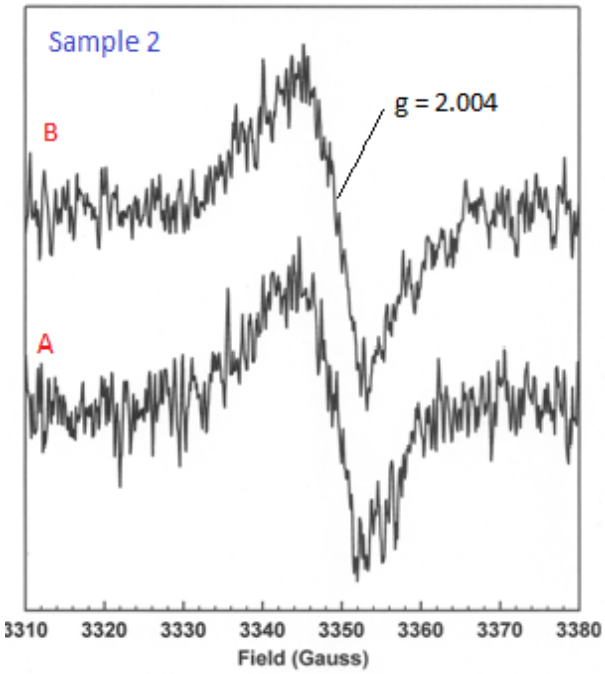


FIGURE 4.28 DE WIT TAPESTRY SAMPLE 2 EPR SPECTRA FOR "BEFORE" AND "AFTER" WET CLEANING TREATMENT

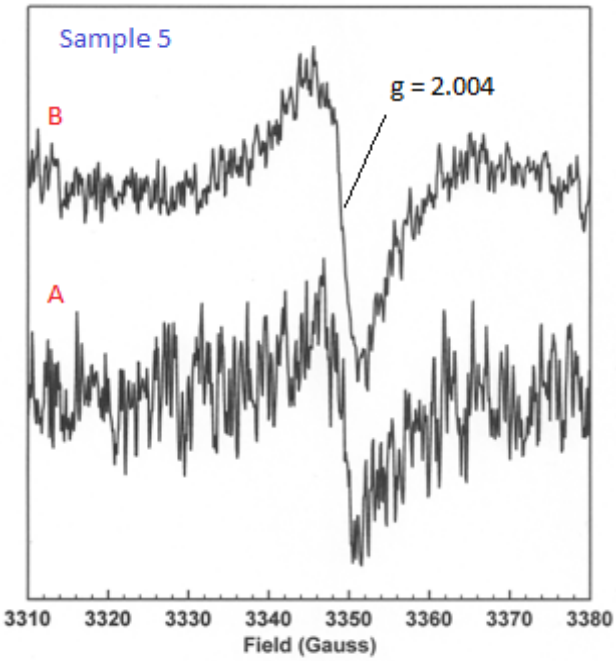


FIGURE 4.29 DE WIT TAPESTRY SAMPLE 5 EPR SPECTRA FOR "BEFORE" AND "AFTER" WET CLEANING TREATMENT

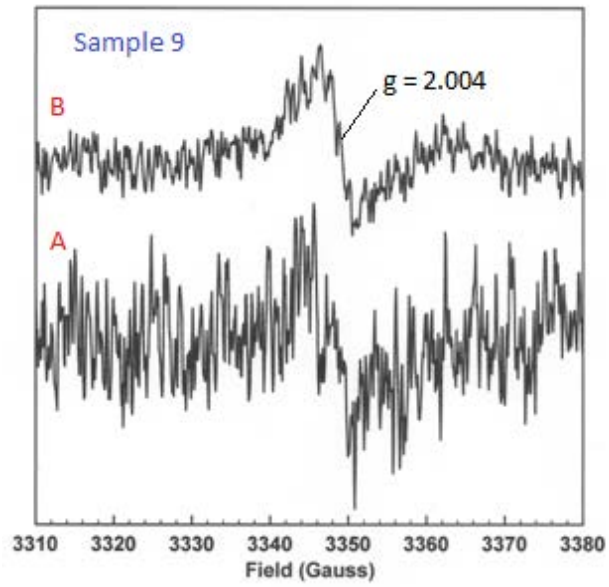


FIGURE 4.30 DE WIT TAPESTRY SAMPLE 9 EPR SPECTRA FOR "BEFORE" AND "AFTER" WET CLEANING TREATMENT

These samples do not show the clear “soot” signal that was observed in the historic samples analysed previously. This difference is likely to be to be due to the fact that the reference samples have been stored for a long time and were unlikely to have been cleaned to a great extent beforehand. The samples from the “Anglesey Panel” will have been part of the textile conservation studio’s work plan over the last 100 years and therefore are likely to have been previously cleaned and stored more appropriately. Nevertheless the presence and influence on historic artefacts should not be overlooked and should be investigated further.

4.5.2.2 Hampton Court Samples

Figures 4.31-4.33 present the six spectra related to the Hampton Court tapestry after wet cleaning. The only sample which demonstrates a clear reduction in radical concentration is sample 2, where a difference in peak to trough size is discernible between the before and after spectra. Similar to the De Wit samples, the radicals are centered around g = 2.004 suggesting their assignment to the associated dyes rather than cysteine radicals produced through protein changes in the structure of the wool fibre.

These phenolic types of radical detected are known to be quite stable with low reactivity and are not likely to give rise to damage within the textile. This also means that they are unlikely to be removed by any cleaning treatment and would possibly only be completely removed through the removal of the dye itself from the fibre – not an option for a historic object whose integrity includes the colour of the different yarns to form the pattern or image.

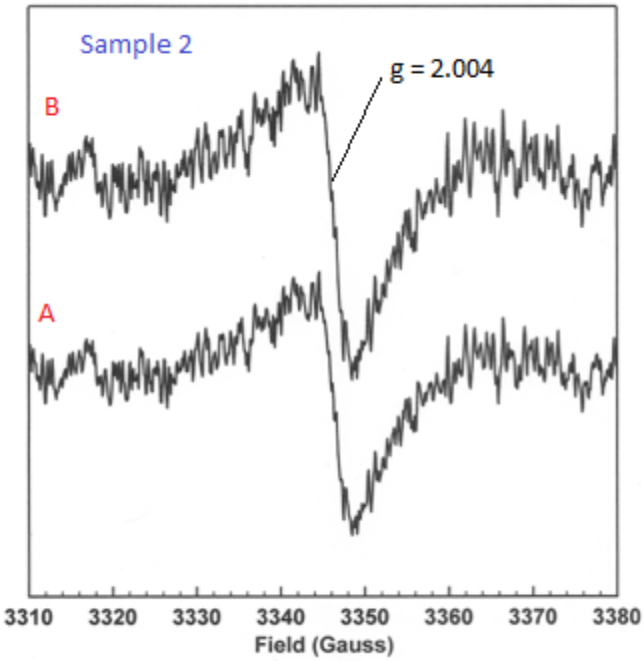


FIGURE 4.31 HAMPTON COURT TAPESTRY SAMPLE 2 EPR SPECTRA FOR "BEFORE" AND "AFTER" WET CLEANING TREATMENT

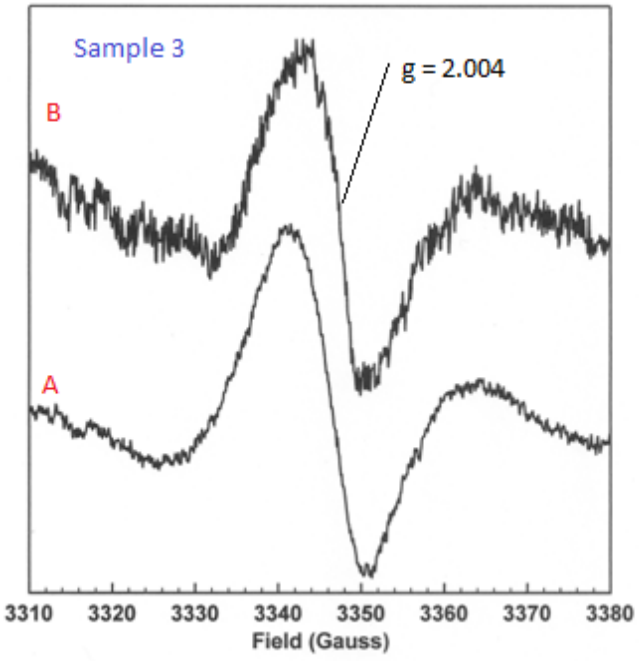


FIGURE 4.32 HAMPTON COURT TAPESTRY SAMPLE 3 EPR SPECTRA FOR "BEFORE" AND "AFTER" WET CLEANING TREATMENT

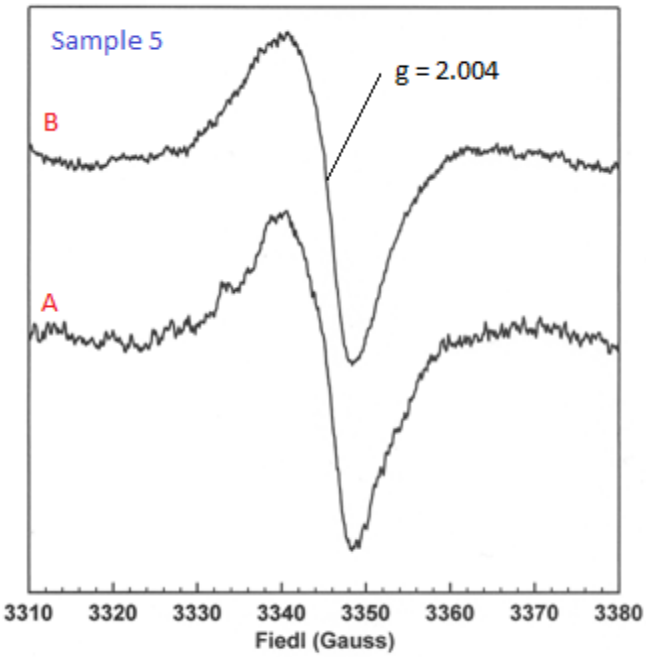


FIGURE 4.33 HAMPTON COURT TAPESTRY SAMPLE 5 EPR SPECTRA FOR "BEFORE" AND "AFTER" WET CLEANING TREATMENT

The high levels of cysteine radical observed through the simulated ageing and uv/ozonization experiments suggest that perhaps these are not seen in historic samples which are dominated by either dye chemistry or dirt (reference samples).

At this stage of research it is difficult to draw conclusions from these analyses relating to the protein chemistry as the more complex spectra obtained through the analysis of historic samples can mask the protein chemistry occurring beneath them. A larger range of historic samples would be needed to examined in order to fully understand the differences between artificially aged samples and historic samples.

For future work, further characterization of samples to identify the presence of specific dyes would increase the understanding of the EPR spectra and potentially which phenolic radicals are related to which dye-type.

Additionally, the important question has been raised by these results of whether the carbon radicals which are present in the reference samples and the phenolic radicals present in these “wet cleaning” samples present any danger to the future preservation of the textile and their overall chemical stability.

4.6 Wool yellowing

The yellowing of wool samples was observed after both light ageing and Relative humidity and thermal ageing although yellowing is usually associated with photo-degradation (Davidson, 1996, Millington, 2006a, Millington, 2006b, Smith, 1995). The yellowing of wool samples as an effect of the Heat/Humidity (H/H) ageing confirms that the yellowing is not just an effect of photo-degradation as this process can occur in the dark – raising questions on the mechanism of the “dark” reaction.

Spectrophotometric measurements were taken over a spectral range of 400 to 700 nm with a spectral resolution of 10 nm. Measurements were taken using a D65 illuminant on a Spectraflash 600 with specular reflectance excluded and UV included. The machine was calibrated using a white standard and black trap. An average was calculated from 5 measurements and 3 locations on the fabric to ensure a high degree of accuracy. The fabric thickness was 5 mm.

Figure 4.33 and Table 4.6 present the spectrophotometer results for virgin, light aged and Relative humidity and thermal aged samples. Figure 4.33 is the reflectance data in the visible region for all 3 samples and Table 4.6 presents the *Δb** values.

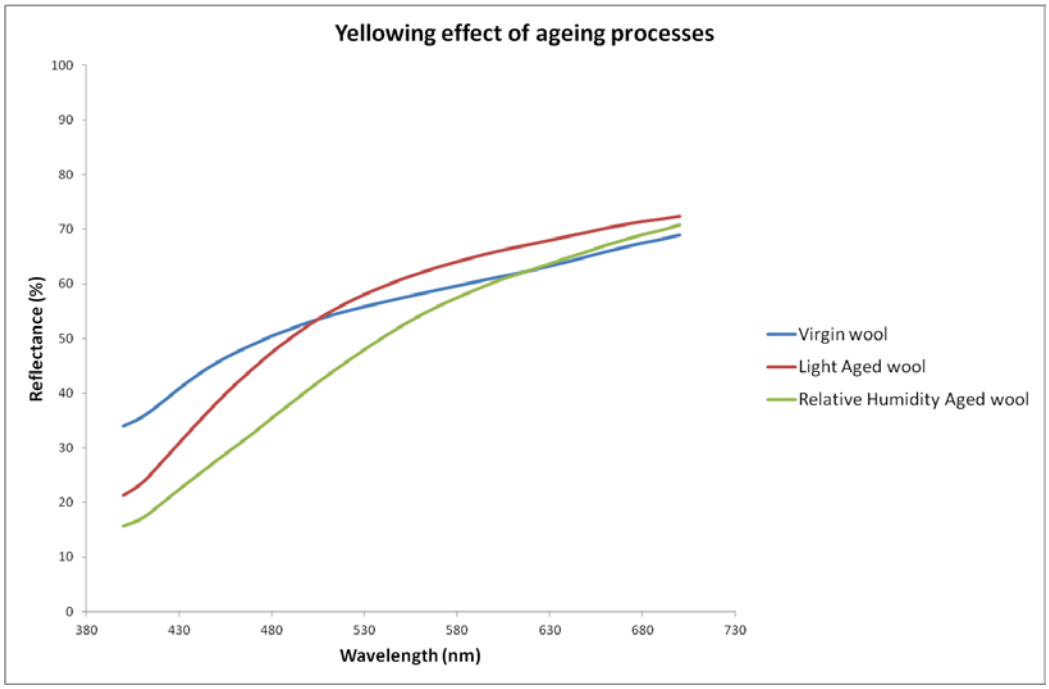


FIGURE 4.34 REFLECTANCE CURVES FOR VIRGIN, LIGHT AGED AND RELATIVE HUMIDITY AND THERMAL AGED WOOL

	Background	Virgin	Light aged front	Light aged reverse	H/H Aged
*Δb**	-1.5	-1.1	10.5	-0.3	16.5

TABLE 4.6 ΔB* VALUES FOR TAPESTRY SAMPLES

The CIE *L*a*b** colour scale allows colour to be standardised and for different colours to be compared and quantified. The *L** scale relates to lightness (black and white) from 0 (black) to 100 (pure white). The a* and *b** scales do not have assigned numerical limits but relate to a degree of red and green (*a**) and blue and yellow (*b**), respectively. Positive values of *a** relate to red colours, negative values of a* present green. Positive *b** values are yellow, negative *b** values are blue.

In this case, we are interested in the *b** values as it is a yellowing of the fabric. The *Δb** values can indicate the relative "yellowing" effect between samples. In Table 4.6, the *Δb** difference between virgin wool and light aged wool is 11.6 (-1.1 to 10.5) showing a significant yellowing of the wool. The reverse of the light aged fabric, as it was not exposed to the light source has not yellowed by any significant amount. The Relative humidity and thermal aged samples have a difference of *Δb** 17.6 (-1.1 to 16.5), which is surprisingly even more yellow than the light aged samples.

While these preliminary results indicate that the samples in the "dark" reaction are equally, if not more, yellowed than purely light aged fabrics further materials ageing studies need to be undertaken to fully characterise the relative yellowing effects. Possible future research in this area is discussed in the final chapter: Future Work.

5.0 Conservation Strategies

In section 1.5, the methods of tapestry conservation were discussed. Understanding the historical and current methods of tapestry support methods is important in order to focus the research to be relevant for current practice. In order to develop the digital model for tapestries and conservation supports it was important to survey the current methods.

5.1 Questionnaire

In order to ascertain which methods textile conservators use to support large-scale textiles, a questionnaire was prepared. The survey posed 21 questions on a variety of issues including materials, techniques, stitching, treatment criteria and history of technique.

The questionnaire was the main focus of the first half of the first year of this project: it supported some of the original research questions (see section 1.2.1). However, as the research questions evolved to investigate the chemical degradation rather than the conservation methods used the survey's relevance decreased as part of this study so it is not included as part the main body of this thesis.

A copy of the questionnaire as well as a detailed analysis of the answers can be found in Appendices 1 and 2 respectively.

5.2 Finite Element Analysis

5.2.1 Introduction

Little work has been undertaken to investigate the nature of the mechanical properties of tapestries and other large-scale textiles. However, preliminary investigations carried out at Historic Royal Palaces, UK, by Howell et al., 1997, were a foundation for this research project. In Howell's work, tests were carried out on tapestry samples and calculations undertaken to estimate the forces on individual yarns. 3D modelling of the fabric was undertaken and showed that under the loads involved the fabric cross-section changed from a circular arc towards a straight line (Bilson et al., 1997). This project has formed a strong base onto which further projects, including this one, were founded. However, their computer model was at the yarn-scale and this project aims to produce a computer model for a tapestry-scale scenario.

The conclusions were that their model was too simple to accurately represent the complex system of a tapestry, and that although individual yarns had small loads of little concern, the overall effect of long-term degradation (especially of large areas of silk), the different moduli of the fibres and some original hanging methods resulted in larger forces on individual weft yarns.

A study conducted to test conservation stitching methods and develop a test methodology for tapestry samples was also undertaken at the Textile Conservation Studios at Hampton Court Palace. In this study, samples were made from replica

material and different conservation stitching methods applied to the back of the samples through a linen scrim support fabric. The different types of sample duplicated different stitching support methods used at HRP. The samples were then tensile tested at a load comparable to that experienced by the tapestry whilst hanging, and the deformation was recorded using calibrated images. The results from this project indicated that physical loss greatly affects the strength of the sample, and that conservation stitching does strengthen areas of loss by reducing deformation under load; however, further work was needed as due to the variability in textile samples some of the results were too variable to draw conclusions (Asai, 2007, Asai et al., 2008). This work is an important contribution to the overall conservation strategy especially when combined with the results of the questionnaire presented in section 5.1. However, although experimental work was undertaken the work does not contain any mechanical modelling which is where the work presented in this study will further the research understanding.

The University of Southampton carried out a "parallel" project to MODHT investigating the mechanical properties (specifically strain) of tapestries and explored how these can be monitored. The project aimed to develop a non-destructive method for measuring and monitoring damage in tapestries during hanging; both with and without support fabrics. The project was completed in 2009 and the main outcome was the development of a method which successfully integrated a number of separate engineering techniques forming a "hybrid" method using: optical fibres; digital image correlation and 3D photogrammetry. This hybrid method was used to monitor the physical properties of large hanging textiles, with a focus on strain deformation (Dulieu-Barton et al., 2005, Dulieu-

Barton et al., 2007, Lennard et al., 2008, Sahin et al., 2006, Williams et al., 2009, Ye et al., 2009).

The MODHT project focused on the chemistry of fibres and degradation methods and the effect on individual fibre/yarn strength. This project confirmed that scientific tools can be successfully used in association with conservator experience as an effective condition assessment (Quye et al., 2009).

5.2.2 Mechanical modelling of plain woven textiles

The mechanics of modelling plain weave fabrics originates in Pierce's classic model, which introduces a simple geometric model for a plain woven cloth cross-section. From this work, later models have been developed which are the basis of the most recent modelling work.

Pierce's model assumes that the yarns are circular in cross-section, the bending resistance is negligible (which means the yarns are straight except where they cross) and there are no internal forces – i.e. it is an exclusively geometric model (Pierce, 1937).

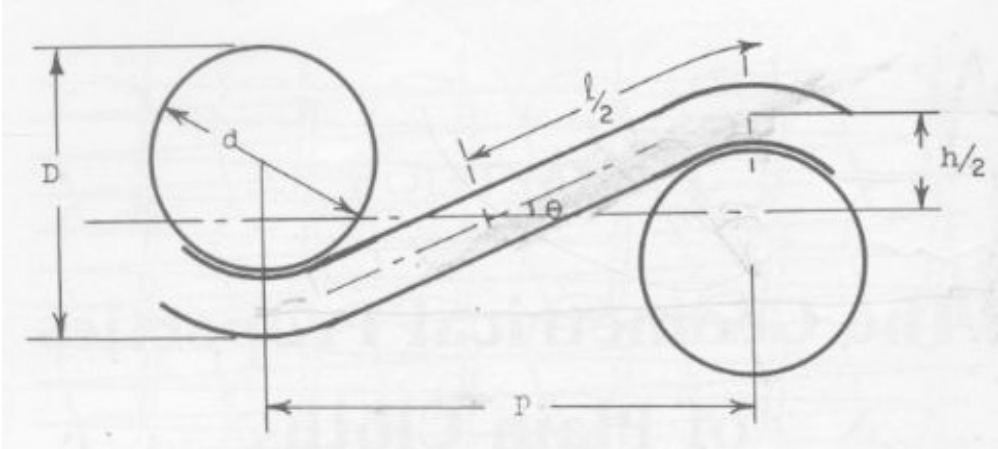


FIGURE 5.4: PIERCE'S MODEL (HEARLE, 1969, P.324)

Where d_1– warp diameter, p_1 – warp spacing, θ_1 – maximum angle of the thread axis to plane of cloth, l_1 – length of thread axis between planes containing the axes of consecutive cross threads, h_1 – maximum displacement of the thread axis, normal to the plane of the cloth, c_1 – crimp (fraction not percentage). Note - The suffix "1" denotes the geometric relation for the warp yarn however, "2" can be inserted instead for the values of the weft yarn.

From Figure 1, 7 equations can be derived for 11 variables.

$$c_1 = \frac{l_1}{p_2} - 1 \qquad \text{Equation 1a}$$

$$c_2 = \frac{l_2}{p_1} - 1 \qquad \text{Equation 1b}$$

$$p_1 = (l_2 - D\theta_2)\cos\theta_2 + D\sin\theta_2 \qquad \text{Equation 2a}$$

$$p_2 = (l_1 - D\theta_1)\cos\theta_1 + D\sin\theta_1 \qquad \text{Equation 2b}$$

$$h_1 = (l_1 - D\theta_1)\sin\theta_1 + D(1 - \cos\theta_1) \qquad \text{Equation 3a}$$

$$h_2 = (l_2 - D\theta_2)\sin\theta_2 + D(1 - \cos\theta_2) \qquad \text{Equation 3b}$$

$$D = h_1 + h_2$$ Equation 4

This model has been adapted for different structures and changed assumptions over time. Few yarns are actually circular in diameter, especially when woven into a fabric. Experimental work has shown that the likelihood of yarns not flattening during weaving is small (Taylor, 1963). Updates on this model include an elliptical cross-section (Pierce) and a "racetrack" shape (Kemp, 1958). The other limitation of the Pierce model is that forces are ignored in the assumptions and therefore there is no mechanical contribution to the calculations. However, it is generally acknowledged that the Pierce model can be applied to open structures and used as a basis for further modelling.

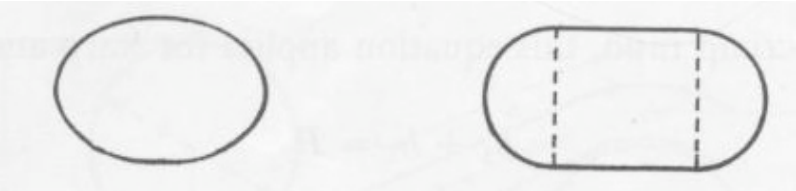


FIGURE 5.5: POSSIBLE YARN CROSS-SECTIONS - ELLIPTICAL (L) AND RACE-TRACK (R).

The appropriate model can be chosen when a sample of the fabric cross-section is examined under optical or electron microscopy. This should enable the shape of the cross-section to be determined and the corresponding closest model to be selected. A sample of replica tapestry material used by textile conservators at Hampton Court was examined under a microscope and digital macro-photography analysis undertaken. The image obtained showed the cross-section of the weave clearly however for the replica samples made for this project the samples were mounted and examined more accurately. It should be noted that this weave is not as dense as the replica samples woven in this study.

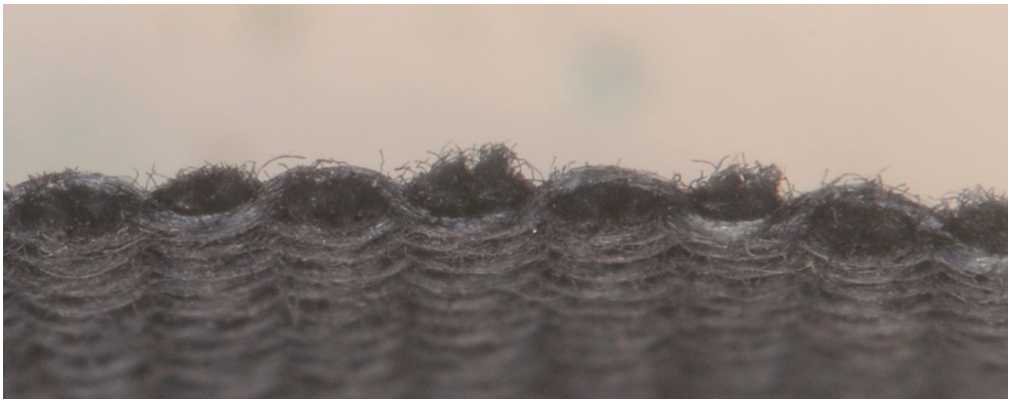


FIGURE 5.6: DIGITAL MACRO-PHOTOGRAPH OF COMMERCIAL TAPESTRY REPLICA FABRIC (TRACY DEWEY, UNIVERSITY OF BRISTOL)

5.2.3 METHODS

For creating the digital model, it was decided that a macro-model would be created to provide an estimation of an entire tapestry considering the macro-stresses which would be introduced by features of the structure such as slits and material differences.

The decision to follow this research path instead of creating a multi-scale model including information about the fabric structure at the micro-model (information in section 5.2.2) can be justified for the following reasons:

For an object as large as a tapestry, the number of finite elements that would be created if the model included fabric structure would be too large and beyond the resources of this study. If pursued this would take the modelling into a different scale from the computing point of view and it would potentially need to involve parallel computing – a costly and complicated process (Margetts, 2010);

As noted in Bilson et al.'s research (Bilson et al., 1997), the purpose of modelling a tapestry in this way is to understand the larger stresses taking place. We are not as interested in the smaller stresses, for instance those frictional stresses introduced in the weave structure between yarns. These extra calculations and considerations would add to the complexity of the model and greatly increase the running time of the model;

To a simple approximation, those potential smaller stresses mentioned in b) will be included in the macro-model because their effect on mechanical behaviour is included in the results for ***fabric*** tensile testing.

The model was created in the commercial FEA program ABAQUS 6.10 (Dassualt Systemes, 2004-2011) as this is the standard system used at the University of Manchester across all computing, engineering and material science departments.

The software is suitable for pre-processing of data (in this case, building up a tapestry system from "scratch" rather than importing an X-ray scan, for example), processing and visualization of results (the running and computing of model) and post-processing (the adapting of the results for application and publication). Many software programs are not designed to complete all three parts of the process – some only do pre-processing and so this software is well suited to this research project.

A number of separate finite modelling methods were considered before deciding on the most suitable for this project. These avenues included investigating methods which are used in: the modelling of draping fabrics (Sharma and Sutcliffe, 2004, Chen et al., 2001, Sze and Liu, 2007); multi-scale modelling (Ivanov and

Tabiei, 2001, Nilakantan et al., 2010, Tserpes et al., 2010) and more simplified models, which often employed both Pierce's and Kawabata's work on the basic modelling of plain weave textiles (Jeon et al., 2003, Kollegal and Sridharan, 2000, Leaf and Anandjiwala, 1985, Tan et al., 1997, Kageyama et al., 1988, Kawabata et al., 1973).

However, many of these were not suitable for this project; although the draping of fabrics was attractive as tapestries and other hanging textiles often do not hang in a straight line but have undulations (Figure 5.7a and 5.7b) and this feature would be beneficial to include in the digital model.

FIGURE 5.7A UNDULATIONS OF A HANGING TAPESTRY – SIDE VIEW

FIGURE 5.7B UNDULATIONS OF A HANGING TAPESTRY – VIEW FROM BELOW

Unfortunately, many of the existing fabric draping models are interested in the draping of a fabric in contact with a solid shape such as a human body or, more simply, a sphere. This does not relate to the situation of the natural drape which occurs in hanging textiles such as tapestries and curtains.

The multi-scale models, although effective, were discarded for the reasons already stated in this section mainly due to model complexity and computing power readily available.

Therefore ideas were formed from basic principles of computer modelling and mechanics and with guidance from the FEA publications obtained from NAFEMS[5]

[5] http://www.nafems.org/publications/

(Baguley and Hose, 1997, Hellen, 2007) as well as the Abaqus user manual (Abaqus et al., 2001, Simulia, 2009).

5.3.2.1 Creating a model in Abaqus

There are various stages in creating a finite element model and the following procedure sets out the method used in this project to produce a FEA model within Abaqus.

Before any processing of the model began in Abaqus, Table 5.1 was consulted. This table outlines the correct units as Abaqus itself does not use units – the values inputted must match the rest of any data. For instance, if the length was inputted in mm and mass in kg then the gravitational acceleration should be 9.807. However, if dimensions are in mm but mass in tonnes then the gravitational input should be 9807. Using a formatting protocol system like Table 5.1 is essential to maintain order of magnitude within a model as Abaqus assumes correct input of information and no units are ever entered, only numerical values.

mass unit	t	kg	kg	t	lb
length unit	mm	m	mm	m	in
time unit	sec	sec	*	sec	ψ
gravitational acceleration	9807	9.807	9.807	9.807	386
force unit	N	N	N	kN	$pound_f$
pressure and modulus of elasticity unit	MPa	Pa	MPa	$kN\ m^{-2}$	psi
density unit	$t\ mm^{-3}$	$kg\ m^{-3}$	$kg\ mm^{-3}$	$t\ m^{-3}$	$lb\ in^{-3}$
modulus of elasticity in steel	200000	2.0E+11	200000	200	3.0E+07
modulus of elasticity of concrete	3.0E+04	3.0E+10	3.0E+04	3.0E+01	4.5E+06
modulus of elasticity of polythene	800	8.0E+08	800	0.8	120000
density of steel	7.86E-09	7860	7.860E-06	7.860	0.284
density of concrete	2.380E-09	2380	2.380E-06	2.380E-06	0.086
density of polythene	9.0E-10	900	9.0E-07	9.000E-07	0.025

* Although the units in these columns are frequently used satisfactorily for static analysis, the unit of time is $\sqrt{0.001}$ sec ~ 0.0316 sec, which is not suitable for dynamic analysis. Weight can be modelled by an acceleration with the familiar numerical value of 9.807, but it is really 9.807 mm $(0.0316\ sec)^{-2}$

ψ This is similar except that the time unit is $\sqrt{1/386}$ sec.

***TABLE 5.1 CONSISTENT UNITS FOR STRUCTURAL ANALYSIS* ((BAGULEY AND HOSE, 1997)**

The steps taken to produce a model within Abaqus are outlined below:

PRE-PROCESSING

1) **Create the geometry of the model within Abaqus** (Figure 5.8)

Create a "part" by choosing an element type (e.g. shell) and specify general size (e.g. 10mm, 10m or a mile);

Sketch out the 2-D shape using the toolbar (e.g. square, rectangle, circle etc.);

Apply the specific dimensions and angles to the shape;

Apply the correct constraints to the geometrical shape – e.g. resting on the floor, hanging from the corners;

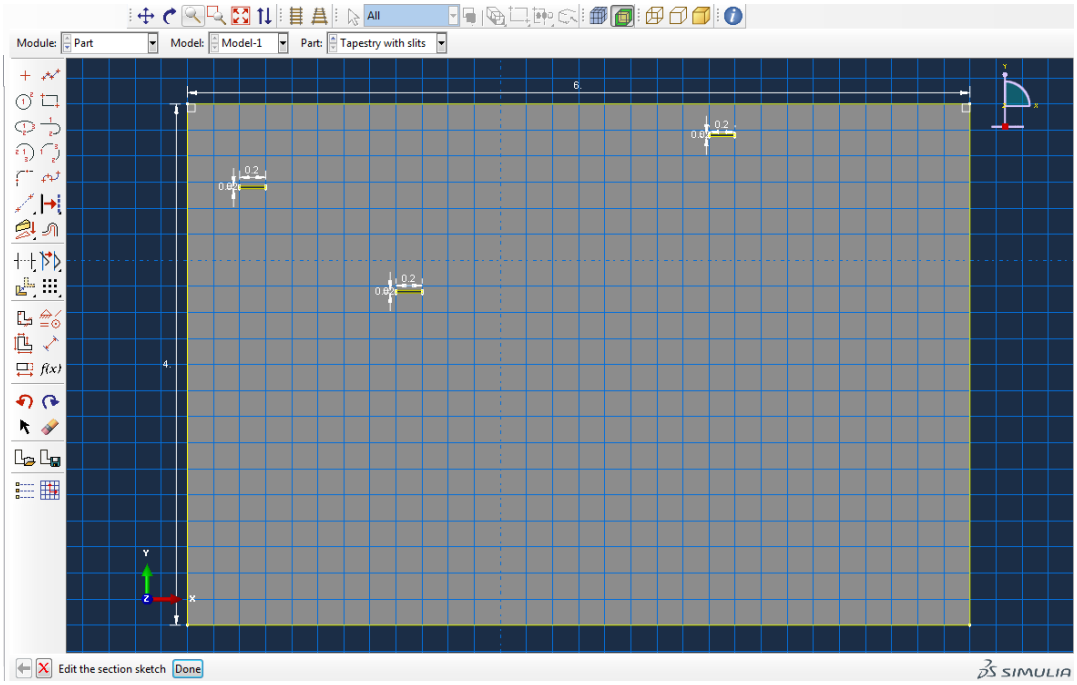


FIGURE 5.8 STAGE 1: CREATING A "PART" IN ABAQUS

2) **Create Material Profile**

a) Describe the material being created (e.g. wool, un-aged);

b) Input properties relevant to model (e.g. density, stiffness);

Define and Assign Section Properties

Select portions of original "part" to be assigned to a "section";

Assign properties to different "sections" (e.g. material);

For Shell elements, this is where the thickness of the shell is defined (i.e. the thickness of a tapestry);

Create and Define Assembly

All models only contain one assembly, but this assembly can contain a number of different parts and sections. For example modelling an airplane will contain a large number of different parts however the final model will only have one assembly – all the parts together);

This is where if there are any parts which join together (e.g. support strategies for tapestries) their joining mechanisms are defined and modelled;

Create an "instance" – assigning a time period to different events (in this case, only one instance as nothing is time dependent);

Create Steps

Create an initial step (before load is applied);

Create load steps plus any other analysis steps necessary (e.g. Repetitive loading or different loads);

Apply boundary conditions and loads

Decide on loading type (e.g. body load, point load etc.);

Decide on boundary conditions (e.g. constraints);

Mesh the model (Figure 5.9)

Assign element type (e.g. TRI3);

Seed parts – adjust element size to refine the mesh (this part is often repeated to test effectiveness of mesh size – if there are not enough "seeds" in the mesh it will not be accurate however if there are thousands then the model takes a long time to process with little change in result);

Mesh the parts;

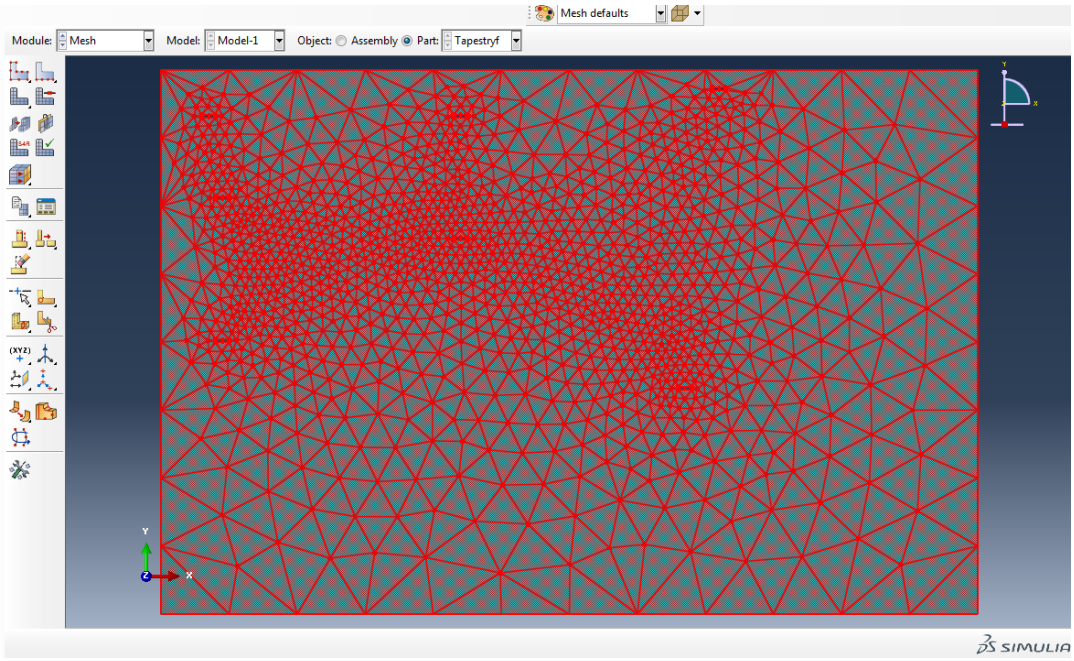


FIGURE 5.9 STAGE 7: CREATING A MESH IN ABAQUS

The mesh which has been shown in Figure 5.9 is a mesh in the process of being optimized. Looking at this mesh, it is clear that the element sizes vary greatly from the edges (large) to the areas of stress concentration (around the slits). This is not an ideal situation, although it is optimal to have more elements around an area of stress concentration (to better model the properties of this area) when there are large discrepancies in the element size it can introduce further inaccuracies with the final model (Baguley and Hose, 1997).

PROCESSING

Create a "job" and submit for analysis

By creating a "job" the same model type can be run a number of different times – for example by changing the mesh to observe the effects on the final result- without needing to re-do the whole model;

Run analysis

Once the job is submitted the model runs and checks for any errors. If there are errors, they need to be fixed before visualizing the results;

This part of the process can be very quick for a small, simple model (less than a minute) however for complex models sometimes they need to be left overnight to run (up to 12 hours);

POST-PROCESSING

Switch to "visualisation" mode and view results (Figure 5.10)

Opening the results window allows visualisation of the results;

In this mode, the results can be adapted for any parameter of interest (e.g. strain, stress, S22, S23 etc.);

Here the numerical settings can be changed to produce images and graphs in any form.

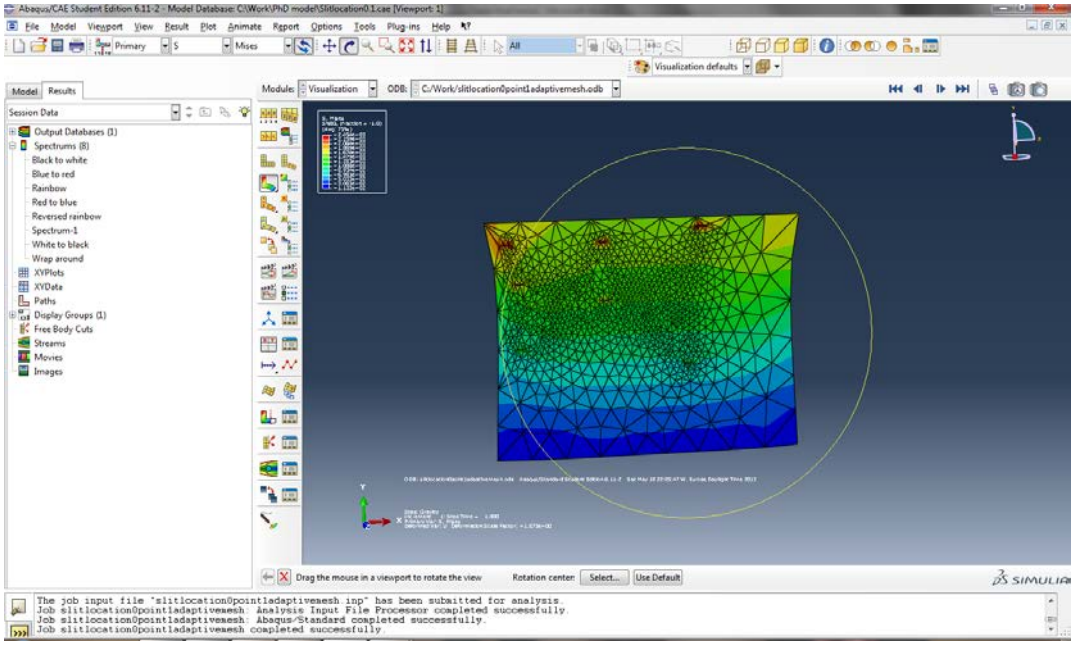


FIGURE 5.10: STAGE 10: VISUALISATION MODE FOR VIEWING RESULTS AND EDITING FOR PUBLICATION

5.2.3.2 FINITE ELEMENT METHOD FOR TAPESTRY PROJECT

The final model was created using the shell element STRI3; a 3-node triangular facet thin shell element with 6 degrees of freedom at each node and is ideal for flat geometries (where initial curvature is ignored).

A static elastic analysis was used with gravitational loading. This type of analysis was used as the majority of loading should be well within the elastic limit of behaviour of the fabric. Gravitational loading was used (which is applied as a "body-force") as the primary force of interest was the tapestry's own weight which originates from gravity.

Material profiles were created for both wool/wool and silk/wool fabric. The fabrics were defined as isotropic (just the values for the weft (hanging) direction were

entered – future expansion on model would include orthotropic values for weft and warp), with the Young's Modulus inputted directly from data collected from tensile testing (section 3.2.1) and Poisson's ratio from the literature (Postle et al., 1988, Alsawaf, 1985). Table 5.2 summarises the values inputted into the model.

	Wool/wool, un-aged	**Silk/wool, un-aged**	**Historic**
Poisson's ratio, ν	0.4	0.4	0.4
Stiffness, E	10500	25000	22900
Density, ρ	500	320	625
Fail strength, UTS	33800	47800	5000

TABLE 5.2 MATERIAL VALUES ENTERED INTO FINITE ELEMENT MODEL

The densities for the different material profiles shown in Table 5.2 were calculated in slightly different ways. For the un-aged fabrics, an estimation of density was derived from two sources: firstly the replica fabric itself. A section of fabric was weighed and measured and the density approximated using:

Density = mass/volume

$\rho = m/V$

For the historic fabric, the information gathered early in the project on actual tapestries and their associated weights (Figure 2.1) was consulted and for the area of the tapestry size modelled ($24m^2$) the associated mass (~58 kg) was used. A conservative overestimation of 75 kg gave a density of 625 kg/m^3 (using a tapestry

thickness of 5mm). The reason for this overestimation was to model the "worst-case" scenario. If a tapestry has a large amount of metal threads and a thick weave it is not unlikely that it could weigh this top estimate.

5.2.4 Model of plain wool hanging tapestry

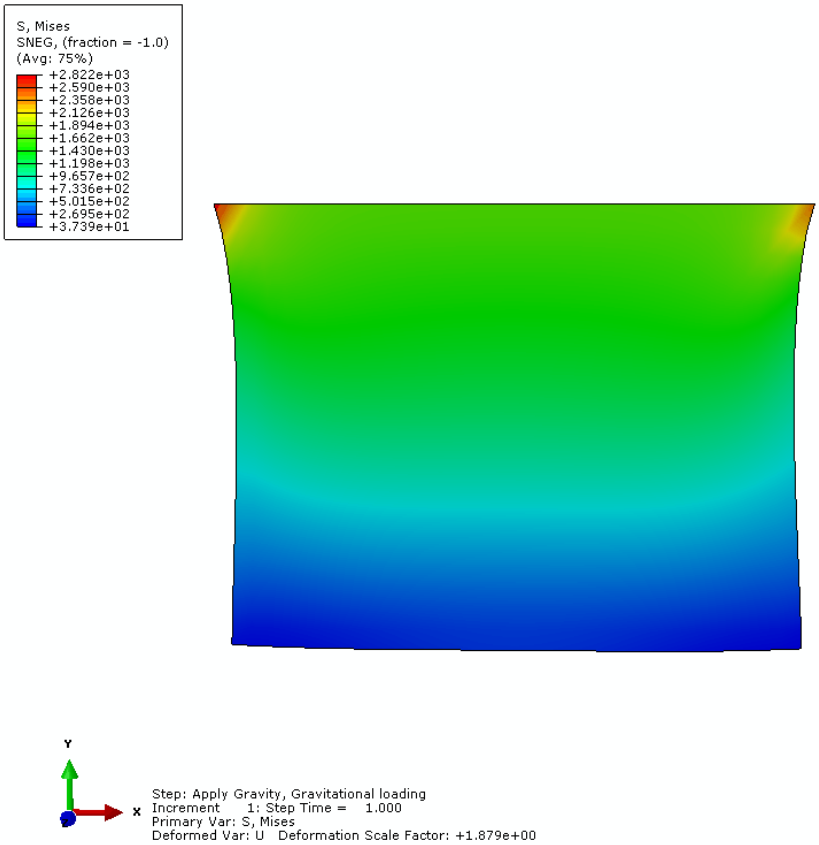


Figure 5.11 FEA model of a plain wool hanging tapestry with no slits

The preliminary model represents a hanging tapestry of 6 m width and 4 m height. The tapestry was constrained along the top edge, to mimic homogenous hanging with Velcro along the top, and hangs under its own weight (a gravitational load applied to the entire model). Figure 5.11 shows the S22 stress distribution for a hanging tapestry with no slits. The S22 stress is the stress in the vertical, hanging

direction in N/m. Figure 5.11 shows that the stress concentrations are in the top corners (the areas more yellow/red), and the stress experienced by the tapestry decreases with increasing vertical distance.

Effectively, the upper third of the tapestry experiences most of the stress whereas the bottom of the tapestry experiences little or no stress**.**

This corresponds to common degradation patterns observed in tapestry conservation practice. Commonly, the top third contains a large amount of silk as silk is often used to represent areas of sky in an image. Therefore the common disintegration of silk areas was not surprising as on tapestry top is usually more prone to light damage and it also experiences the majority of the stress force.

5.2.5 Model of plain wool hanging tapestry with slits

The effect of slits on the stress distribution of wool/wool tapestry is illustrated in Figure 5.12, where the slits are all of identical size and introduced prior to the load being applied (10 cm long and 2 cm high).

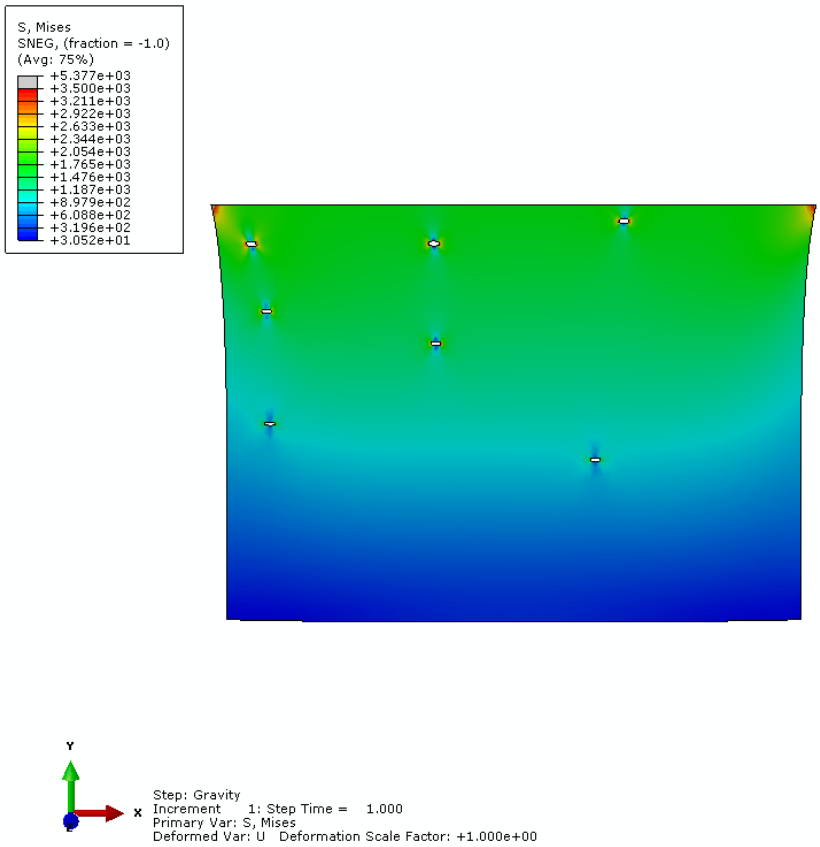


FIGURE 5.12 FEA MODEL OF PLAIN WOOL HANGING TAPESTRY WITH SLITS

One of the primary reasons remedial conservation is commonly undertaken is to sew up slits in tapestries and it can be seen that the slits introduce regions of stress concentration around their edges. Additionally, the maximum stress created by having slits in a tapestry was greater than when the slits were not present (comparison to Figure 5.11).

Although the magnitude of the stress still lies within the elastic region of behaviour of the fabric, areas of stress concentration will accelerate deterioration as proven experimentally in an ageing study carried out as part of this project by ageing fabric under strain (2.6.3). It is also an area of weakness which is more likely to fail if the applied force is increased or deterioration of the fabric progresses. The models

presented in Figures 5.11 and 5.12 are for un-aged fabric and more advanced deterioration would be seen if the material values were changed to represent aged or historic fabric (see section 5.2.7).

5.2.6 Model of mixed material hanging tapestry with slits

Figure 5.13 presents the effect of mixed materials in the composition of a tapestry. When compared to Figures 5.11 and 5.12 it can be seen that there is a slight distortion in the stress distribution at the bottom of the top third of the tapestry. This is likely to be an effect of the difference in elastic moduli between wool and silk (Daniel and Ishai, 2005, Hibbeler, 2008).

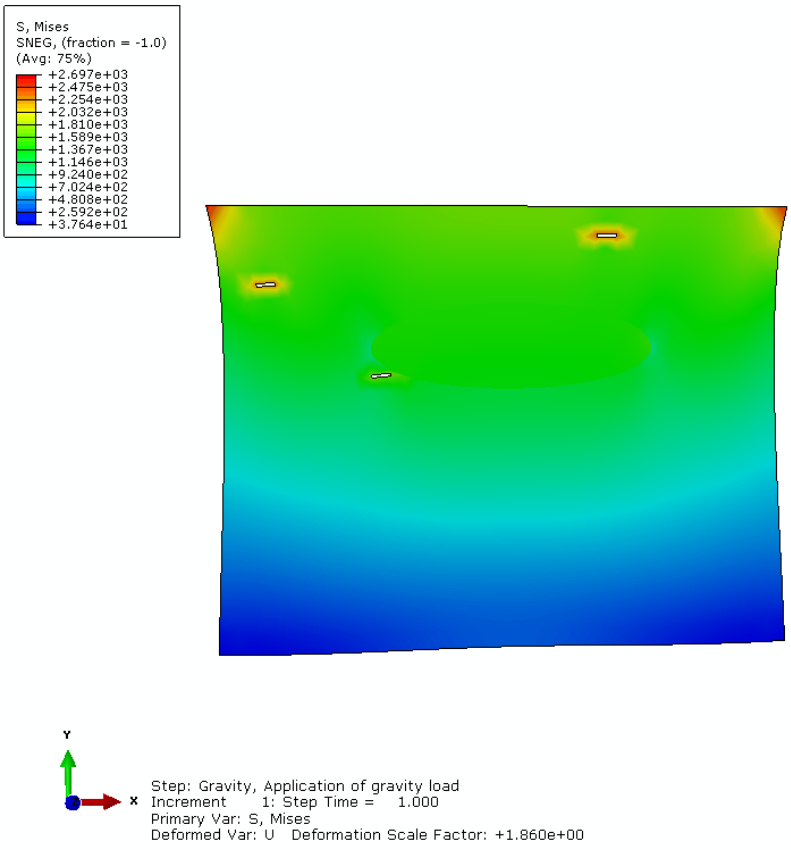


Figure 5.13 FEA model of wool and silk hanging tapestry with slits

Figure 5.14 highlights where the wool and silk areas of the tapestry are located and the ellipse in the middle of the tapestry has silk properties whereas the rest of the tapestry is wool.

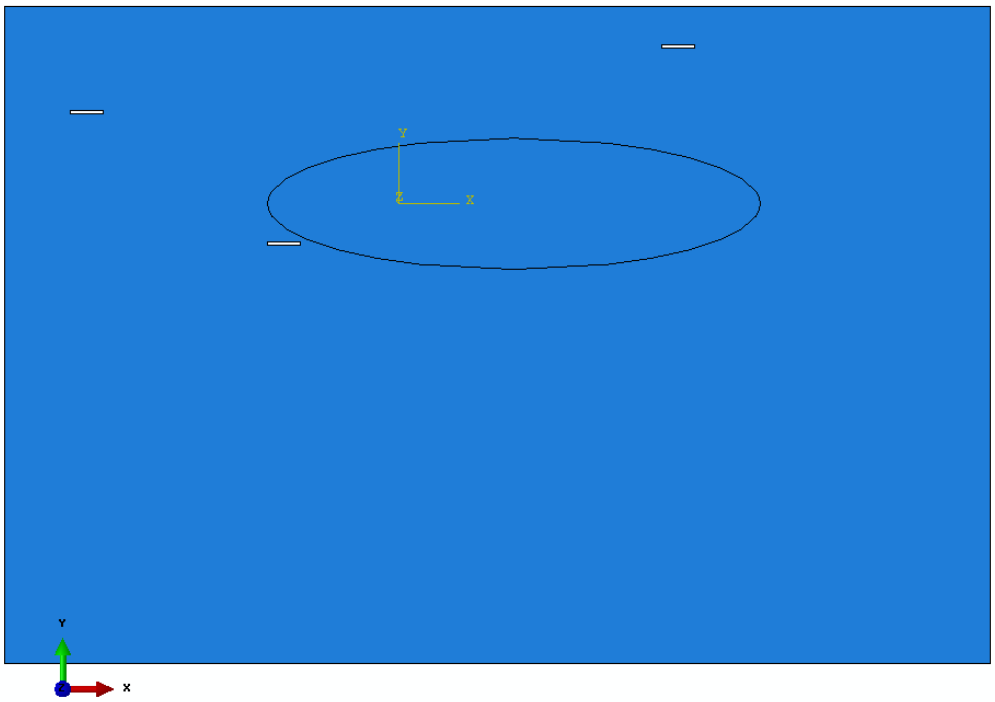


FIGURE 5.14 "PART" DIAGRAM FROM ABAQUS SHOWING WOOL AND SILK AREAS OF A TAPESTRY WITH SLITS

5.2.7 MODEL OF HISTORIC MATERIAL HANGING TAPESTRY WITH SLITS

The effect of changing the material properties to reflect the deteriorated state of historic wool is shown in Figure 5.15. The primary difference in the material properties is the fail stress of the fabric, which is only 13% of the fail strength of the wool/wool un-aged fabric.

The main difference which can be observed from this figure when compared with the un-aged figures (5.11-5.13) is that the slits have opened more widely, implying that the relative force has a greater effect on the inherent structural faults.

It should be noted that it is likely that extensive further characterization of the historic fabric should be undertaken to obtain a more accurate representation of a historic tapestry in the finite element model. For example, an identical Poisson's ratio was used to represent historic fabric whereas in reality it is highly unlikely that this would be the same in un-aged and historic samples. Additionally, the model demonstrates how the tapestry would behave under these set conditions however observations in real-time show that the density of many tapestry weave structures stabilise movement and although the slits do open up when on open display conservation efforts either recent or in the past have sewn up slits.

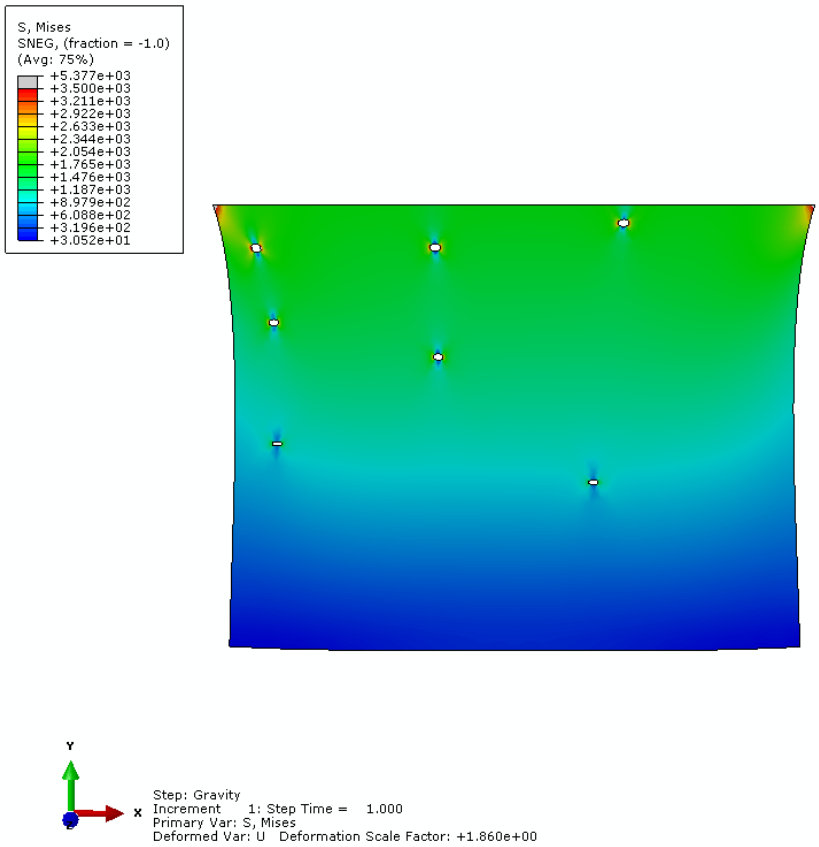


FIGURE 5.15 FEA MODEL OF HISTORIC WOOL HANGING TAPESTRY WITH SLITS

5.2.8 WEAKNESSES OF FEA MODEL

This FEA model is a "ground-breaking" preliminary development and has highlighted the need for a more detailed investigation where a range of factors are incorporated. There are a number of issues which should be dealt with in this kind of model which have not been developed here:

The basic analysis of a tapestry as a rectangular plate/shell could be improved by a more complex structure. One option could be using a laser scan "point cloud" of data to produce a more accurate representation of a tapestry 3D shape (Figure 5.16)

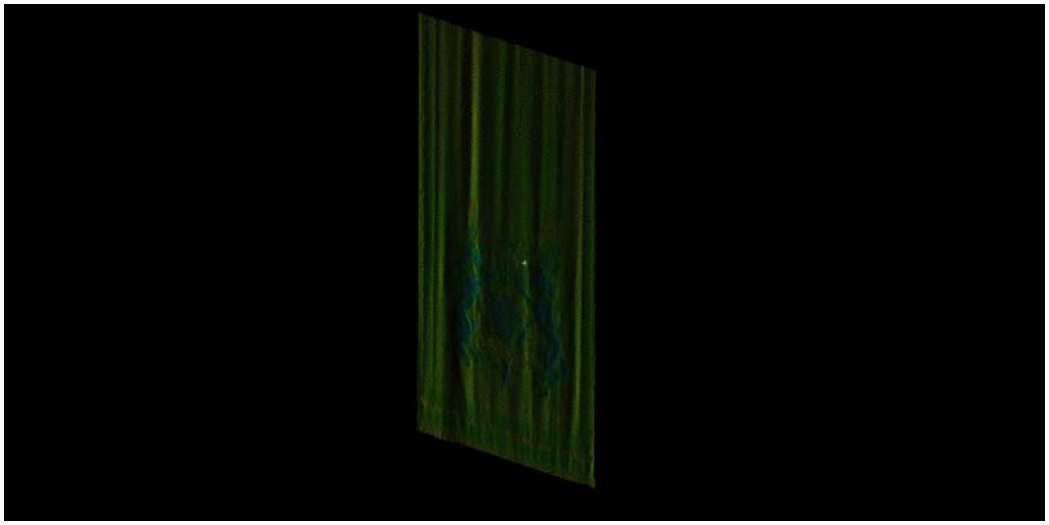


FIGURE 5.16 3D LASER SCAN OF A STIRLING CASTLE TAPESTRY – IMAGE © HISTORIC SCOTLAND 2012

The concept of modelling "drape" to account for the undulations in a tapestry could be significant and would most readily be introduced into the system using a real-life scan of an object;

The models presented here are all "macro-scale" – i.e. on the scale of a tapestry. There have been a number of studies dedicated to textile modelling on the micro-scale and yarn-scale. If these studies could be combined so that a tapestry could be modelled on a number of different scales with the same model (multi-level modelling (Nilakantan et al., 2010)) it may offer greater levels of analysis and therefore increase the understanding of their structural analysis;

Further characterisation of the fabric would increase the accuracy of the material profiles. For instance, although Kawabata studies were carried out on un-aged and artificially aged fabrics there was not sufficient time and resources to process this information to make it relevant to input into the model.

To increase accuracy an ideal scenario would be to test the model experimentally. This could be achieved by modelling the effect on a smaller tapestry (e.g. 1m x 1m) and measuring the change in strain and, where possible, stress and comparing that to the predicted dimensional changes from the model. This way the model can be verified beyond doubt;

A feature of this study has been the need to fully understand the physiochemical factors involved in the ageing process in the tapestries. This study has for the first time established that “dark” reactions as well as light degradation are important in the ageing process. Therefore in lacking this fundamental information at the start of the project it has been apparent that the models that can be produced through using such programming software are only as good as the information which is inputted by the user. Therefore it is likely that such models could be vastly improved in terms of reducing errors and improving accuracy by the additional input of all the degradation pathways;

Lastly a vital aspect of the modelling study is the necessity for a significant amount of time and practice in FEA development, which combined together with all the other analyses involved in this project, was not possible in this ambitious study. Nevertheless significant progress has been made and provides the platform for further focused studies.

6.0 CONCLUSIONS

This research project fulfilled the purpose of encouraging and establishing interdisciplinary research within Science and Heritage. Diverse fields of study were incorporated into the study in order to develop the project and establish a fundamental database. Techniques centred on biochemistry, computer science, engineering modelling, heritage science, textile science, materials science and chemistry were all beneficially used.

The conclusions of this research can be summarised as the following:

- working from strong foundations set by previous projects investigations have been carried out at all levels of degradation in tapestries. The understanding of degradation mechanisms and behaviour from protein structure through to a complete tapestry has been increased;

- a novel ageing protocol was designed to investigate the effect of ageing under strain. Additionally, a number of different ageing techniques were used on replica tapestry samples in an attempt to quantify how different types of ageing contribute to overall damage of tapestries. It was discovered that ageing under strain does increase the amount of damage experienced by the textile in both wool/wool and silk/wool samples, predominantly by decreasing their extensibility and decreasing their ultimate tensile strength;

- the integration of testing of historic and model samples at the fabric level concurred with previous investigations on a fibre level that artificially aged samples are not as damaged as historic samples, by a scale of at least 2;

- the implications of the ageing study undertaken in this project suggest that samples being produced for scientific study to replicate historic damage should have more than one type of ageing applied to them in the process of their production in order to more accurately reproduce the level of ageing experienced by authentic historic textile samples;

- ageing of wool/wool and silk/wool samples undertaken in a dark chamber using relative humidity and thermal cycling produced yellowed samples. This suggests that the discolouration of wool, in particular, is not always related to photoyellowing, the most commonly reported phenomenon;

- the unexpected observation of carbon radicals – "soot" radicals – on some historic samples analysed by EPR suggests that further research is necessary to better understand these radicals and the possibility that they could cause damage to historic textiles and potentially be analysed to provide further information about the history of the textiles;

- finite Element Analysis was performed out to model a hanging tapestry structure and the effects of fabric modification. It was found that the slits in the structure created points of stress concentration and also that where two areas of different materials met (wool and silk) a distortion in the stress distribution was caused;

- a world-wide questionnaire was completed to survey textile conservation techniques relating to tapestry support systems. The technical data received from this project inputted into decisions and data for the FEA and beyond whereas the more “moral” questions and answers along with the rest of the data will hopefully be published in the conservation field to benefit the wider conservation community.

7.0 FUTURE WORK

As a result of the interdisciplinary nature of this project, a wide range of potential further research has been created. These are summarised below:

- a more thorough investigation of the link between a change in the elastic modulus (stiffness) of silk/wool fabrics and ageing mechanism could be undertaken. This could establish a more concrete reasoning for why RH-T ageing produced a decrease in stiffness but when the sample was aged under strain the stiffness increased;
- an expansion of the finite element model would provide an excellent tool for conservators and conservation scientists. The full possible developments of the model can be seen in section 5.2.8;
- an investigation to study the "dark" reaction of wool yellowing would provide vital information not just in the heritage field but also the wider field of textile and fashion. The potential importance of a colour change which can affect aesthetic as well as mechanical strength is significant. Further research into the colour chemistry of the fibres and what specific chemical mechanism is causing this type of damage would be an important contribution to the field;
- the discoveries during this project performing proteomic analysis indicate that there is potential to develop this research further. Most useful to the conservation field would be the establishment on a chemical "scale" of

damage as discussed in section 4.3.5.1. The extension of this scale to include a technique for non-destructive portable analysis could provide an invaluable new method in the conservation of historic textiles;

- the observation of “soot” and phenolic radicals on some historic samples suggest that the EPR technique could be a helpful technique in heritage to analyse historic textiles. In general, the “dirt” that is removed from textiles is not studied and is removed as part of a conservation treatment. However, the possibility that this “dirt” could inform us on the history and composition of the object should be considered. The fact that some types of dirt appear to have radicals present should be investigated further, in particular how are these radicals created, how do they affect the textile and finally should they be removed, and if so, how?

APPENDIX 1

SAMPLE QUESTIONNAIRE

Tapestry Support Techniques

Questionnaire

Personal Details

Name

Current place of work

General Questions

How many tapestries are conserved at your studio per year?

A support fabric is often applied to tapestries using a variety of methods. This is usually to add additional support in weakened areas of the tapestry whether

through natural material deterioration, insect damage or strain. What would you say are the main reasons you would apply a support fabric?

Type of support

In general, which is the most common type of support method that you use?

Full support

Patch support

Strap support (if so, at what distance?)

None

Other (please specify)

What factors will affect the decision as to the type of support fabric method used?

Please rate 1 to 5 (**1** being **not very** important and **5** being **very** important).

Extent of damage

Time

Cost

Material availability

Facilities available

Other (please specify)

If you receive a tapestry for conservation which is structurally in good condition would you still apply a support fabric (perhaps as a long-term/preventive treatment for instance)?

Fabrics

What material do you use as support fabric?

Linen

Cotton

Other (please specify)

Do you use the same fabric for all types and conditions of tapestry? If no, please explain. (E.g. you may use different fineness of support fabric weave depending on the fineness of the tapestry weave)

What are your reasons for using this type of fabric?

It allows the tapestry to change dimensions with the environmental conditions as it responds faster/at a similar rate to the tapestry;

It restricts the movement of the tapestry as the fabric does not respond to changes in the environmental conditions;

Other (please specify).

Fabric preparation

Do you wash the fabric before application? If yes, then please specify your procedure including temperature, number of washes, detergent used if any and type of water.

Amount of fabric

When applying a structural support, do you apply an excess of support fabric to allow ease? If so, how much?

How do you test this? (e.g. do you carry out hanging tests?)

Stitching methods

How do you stitch the support fabric to the back of the tapestry? (E.g. stabilizing lines of running stitch in the weft direction, over 1 warp on the front and 5 on the back, at distances of 15 cm apart).

If there is an area of moderate weakness, what stitching methods do you use to strengthen the area, if any? (e.g. open couching of continuous running stitch, over 1 warp on front and 3 on the back, 1.5cm apart in weft direction).

If there is an area of severe weakness, what stitching methods do you use to strengthen the area, if any? (e.g. close couching of continuous running stitch, over 1 warp on front, 1 or 2 on the back, less than 1 cm apart).

Please feel free to describe your stitching methods in more detail below.

Materials for stitching

For general stitching of support fabric to the reverse of a tapestry, what type of thread do you use?

For stitching of silk areas, what type of thread do you use?

For stitching of wool areas, what type of thread do you use?

What factors contribute to the decision to use a particular thread? (please rate 1-5: **1** being **not very** important **5** being **very** important).

Aesthetics;

Mechanical strength of thread;

Ageing properties of thread;

Cost;

Availability;

Other (please specify).

History

Is the current method that you use today always been the method used in your place of work? If no, please explain how the method(s) have evolved.

What would you say are the main reasons that the current method is used?

Tradition;

Based on current research;

Material availability;

Cost;

Dictated by owner/curator;

Restrictions due to resources e.g. time, conservators and space;

Other (please specify).

APPENDIX 2

ANALYSIS OF QUESTIONNAIRE

The questionnaire was sent out to 116 textile conservators across the world, and 60 responses were received, of which 28 were completed questionnaires. The remaining replies predominantly expressed a lack of experience and knowledge in large textiles such as tapestries and therefore felt unable to successfully complete the questionnaire.

8 items on the questionnaire related to the principles behind conservation methods, the reasons why conservators choose the methods and materials that they use.

12 items in the survey were technical questions about materials, stitching methods and the support techniques. These were to ascertain the precise methods and materials used by respondents.

A copy of the full questionnaire can be found in the Appendix.

RESULTS AND DISCUSSIONS

1. *How many tapestries are conserved at your studio per year?*

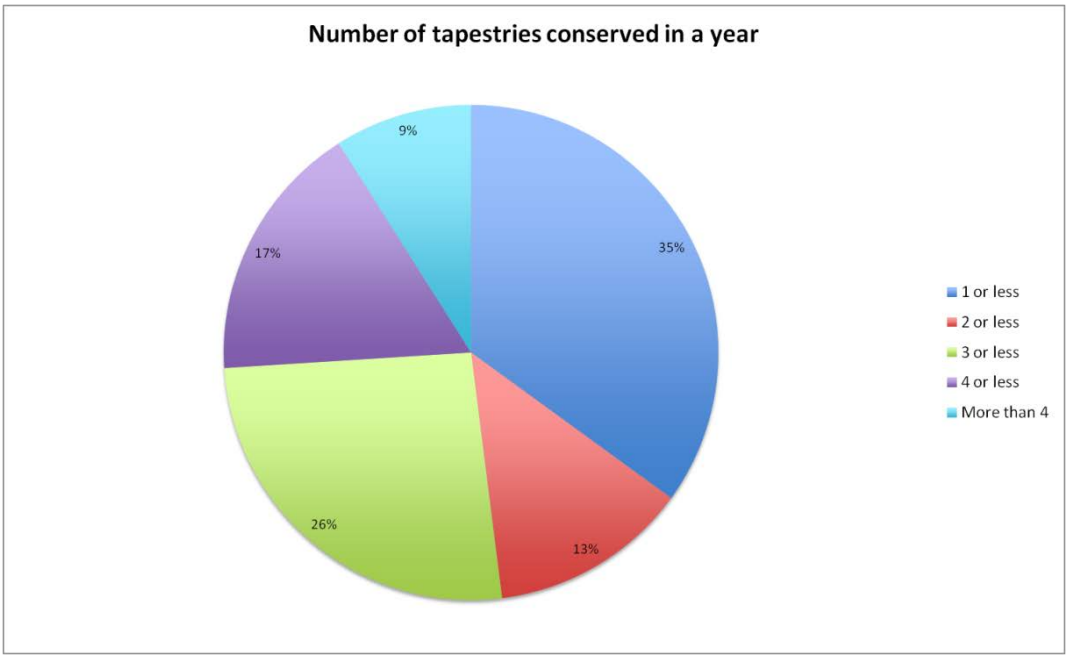


FIGURE 5.1: NUMBER OF TAPESTRIES CONSERVED IN A YEAR

This question was to develop an understanding of how many tapestries the respondents were conserving every year. Some of those who replied were specialists in tapestries so would only conserve tapestries all year round whereas other studios may have many additional objects to consider as part of a work programme.

2. *What are the main reasons for applying a support system?*

There were many different answers to this question however most followed similar themes and these are summarised below:

Strengthening areas of weakness due to material deterioration (through a variety of causes);

Distribution of load;

Support for display;

Preventive strengthening for the future when tapestry cannot support its own weight;

Facilitate safe handling.

The above comments are in order of frequency: every answer contained the first statement of stabilising areas of weakness – primarily for display purposes but sometimes to account for future loss and deterioration.

3. *In general, which is the most common type of support method that you use?*

a) Full support	40 %
b) Patch support	10 %
c) Full and Patch depending on condition	40 %
c) Strap support	10 %

An equal number of respondents use full support or a combination of full and patch support (depending on condition). It was made clear by the majority of respondents that treatments depended on the condition of the object. Not many could afford the time or costs involved to apply a full support if the condition of the object did not warrant such a treatment (see question 5). Despite the world-wide nature of the questionnaire, only 10% of respondents use a strap support even though it was reported (Breeze, 2001) that the strap system is the primary system in use in the USA. However, this is probably a reflection of the relatively low number of responses received from the USA compared to those from Europe and the UK.

4. *What factors will affect the decision as to the type of support fabric method used? Please rate 1 to 5 (**1** being **not very** important and **5** being **very** important)*

Extent of damage

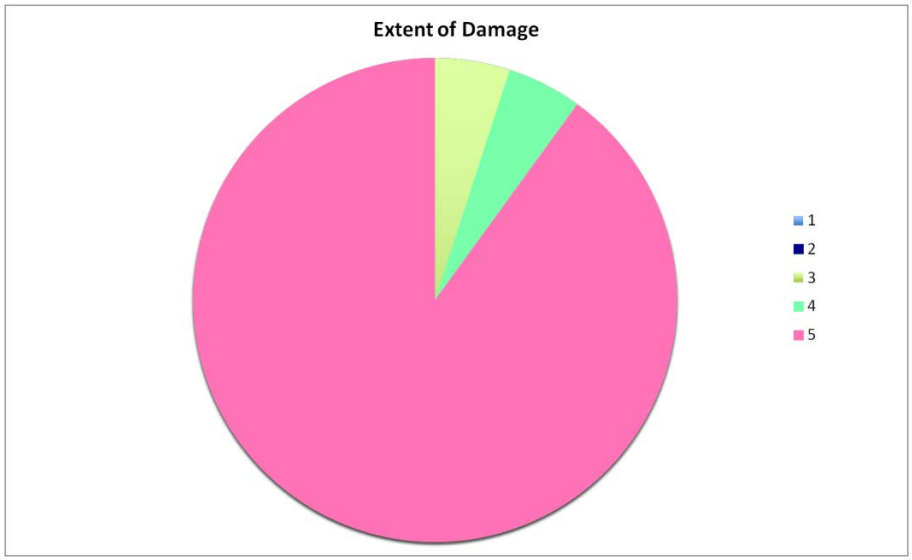
Time

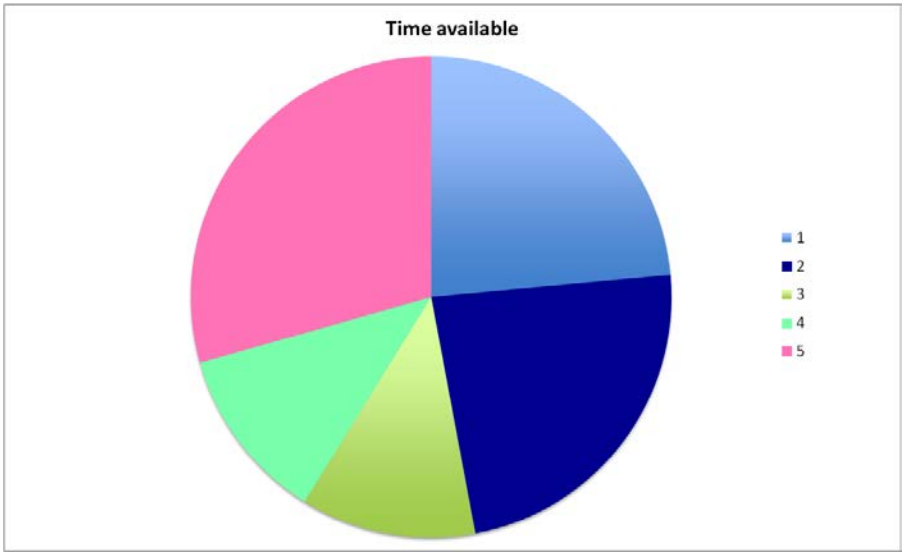
Cost

Material availability

Facilities available

Other (please specify)


Extent of Damage
1
2
3
4
5


Time available
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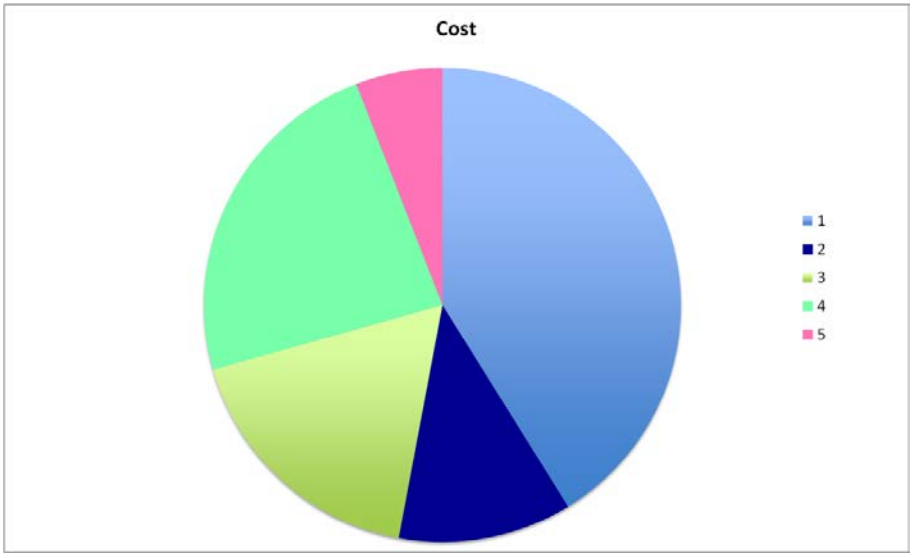
Cost
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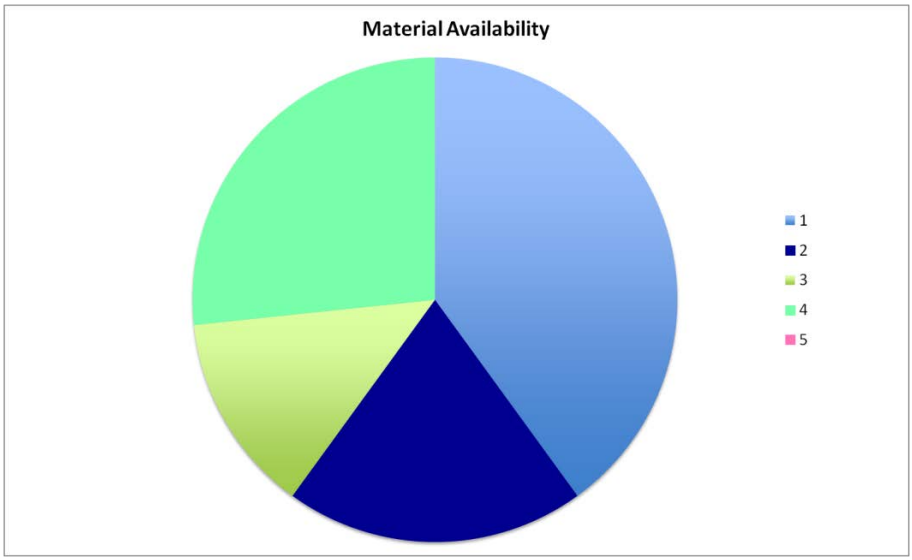


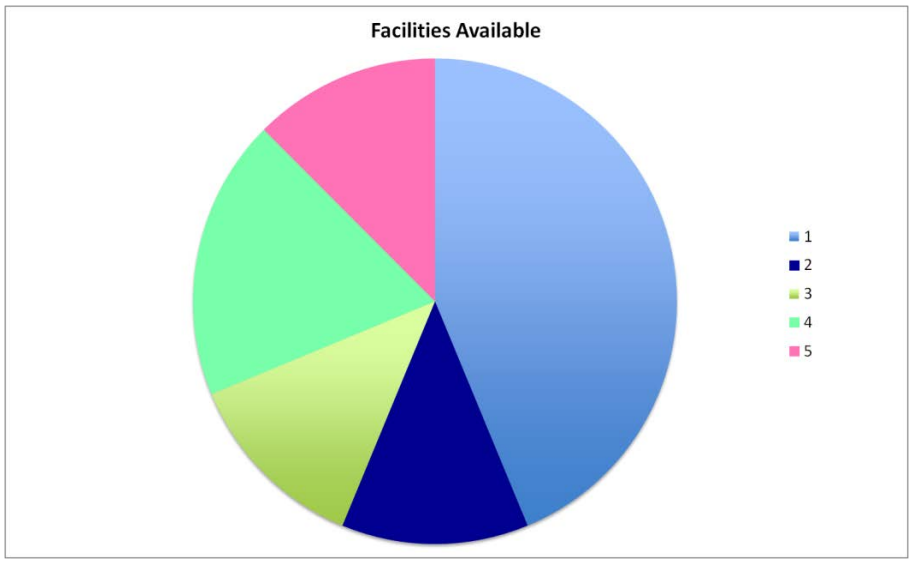


FIGURE 5.2: PIE CHARTS REPRESENTING THE RELATIVE IMPORTANCE OF DIFFERENT FACTORS WHEN CHOOSING SUPPORT FABRIC

The answers to this question reflect the driving force behind conservators' decision as regards support methods. It was clear once again that the most important factor was the extent of damage (1) and time (2). The least important considerations were material availability, facilities available for conservation and cost. However, one possible reason for this was that most conservators were restricted as to objects that they can treat before taking on a project. For instance, if a studio does

not have the space and equipment necessary to conserve a tapestry they are unlikely to include tapestries in their list of possible projects which they can undertake. Therefore, the respondents who completed the questionnaire were likely to already have facilities and sourced materials to carry out tapestry/large scale textile conservation.

If you receive a tapestry for conservation which is structurally in good condition, would you still apply a support fabric (perhaps as a long-term/preventive treatment for instance)?

Yes: 30 %

No: 60 %

Patch: 10 %

The majority (60%) of respondents would not consider applying support to a tapestry if the present condition did not warrant such treatment. This is most likely to be linked to time and cost of unnecessary treatment as most conservators are working on a limited budget for either an institution or a private client. Some respondents did state that if there was money available they would carry out preventative structural support for any future deterioration.

What material do you use as support fabric?

Linen 55%

Cotton 30 %

Both 15%

Other 1 respondent - Polypropylene

The majority (55%) of respondents use linen as a support fabric, and 30 % use cotton. The rest (15%) who use "both" often stated that they used different material for the patches than the primary support material. For instance, one respondent used cotton patches and linen "full" support whereas another used linen patches and cotton straps.

Do you use the same fabric for all types and conditions of tapestry?

Yes	25 %
No	0 %
Depends on tapestry weave	75 %

Most conservators (75 %) will choose a fabric which closely resembles the tapestry weave in terms of fineness (warp count), and the rest state that they use the same fabric for all types of tapestry.

8. *What are your reasons for using this type of fabric?*

It allows the tapestry to change dimensions with the environmental conditions as it responds faster/at a similar rate to the tapestry

60%

It restricts the movement of the tapestry as the fabric does not respond to changes in the environmental conditions

30%

Other

tradition (4%)

not sure (6%)

The widely held view appears to be that the support fabric should allow the tapestry to move with changing environmental conditions; indeed it should move with the tapestry. However, there does seem to be a substantial amount of respondents who disagree with this opinion and think that the tapestry should be restricted in movement. It should be noted that there appeared to be some confusion as to the properties of linen and cotton as some thought that linen would restrict the movement of a tapestry and others that it would respond in a similar way to a tapestry. This may have had an effect on the relative proportions to this answer.

Do you wash your fabric?

These answers were quite complicated and this question was mainly asked out of interest for the conservators at HCP, and also to ascertain if there was a clear standard. There is certainly no clear standard; however, all but one respondent do wash their fabric. One clear pattern was seen in country of practice – this is likely to be related to the detergents available, water quality and local traditions.

When applying a structural support, do you apply an excess of support fabric to allow ease? If so, how much?

1 cm per 25 cm	20 %
1.5 cm per 20 cm	10 %
2 cm per 20 cm	10 %

No 50 %

Half the respondents indicated that they did not apply any excess fabric. However, at a later stage in the questionnaire when examining stitching methods in detail many of these respondents made it clear that they had accounted for the extra fabric needed for stitching, but gave no information as to how much. As a result, it is not clear what proportion of the 50 % of the respondents who stated that they did **not** allow excess, **do** in fact measure the fabric exactly to fit the object size.

Do you test this? If so, how?

No 50 %

Hanging 28 %

Experience 22 %

Many respondents who answered "no" stated that they relied on their training standards and current research by other institutions.

How do you stitch the support fabric to the back of the tapestry?

Running Stitch: 84 %

Herringbone stitch: 16 %

Distance apart:

8-10 cm 21 %

15 cm 43 %

20 cm 36 %

Length of stitch:

1.5 – 2 cm	64 %
20 cm	27 %
45 cm	9 %

Direction:

Weft	100%

If there is an area of moderate weakness, what stitching methods do you use to strengthen the area, if any?

Couching stitching (running stitch):	95%
Herringbone stitch:	5 %

Distance apart:

1.5 cm	80 %
2-3 cm	20 %

Over 1 warp under 1 warp:	20 %
Over 1 warp under 3 warps:	60 %
Over 1 warp under 5 warps:	20 %

If there is an area of severe weakness, what stitching methods do you use to strengthen the area, if any?

Couching stitching (running stitch): 95 %

Herringbone stitch: 5 %

Distance apart:

0.5 cm: 85 %

1.5 cm: 15 %

Over 1 warp under 1 warp: 47 %

Over 1 warp under 2 warps: 53 %

16. For general stitching of support fabric to the reverse of a tapestry, what type of thread do you use?

Polyester: 30 %

Cotton: 30 %

Cotton/polyester: 13 %

Silk: 27 %

17. *For stitching of silk areas, what type of thread do you use?*

Polyester: 5 %

Cotton: 41 %

Cotton/polyester: 5 %

Silk:	41 %
Polyester & silk (2 strands):	8 %

18. For stitching of wool areas, what type of thread do you use?

Polyester:	14 %
Cotton:	28 %
Cotton/polyester:	4 %
Silk:	8 %
Wool:	33 %
Polyester & wool (2 strands):	13 %

It is clear from the answers to the stitching methods and materials section of the questionnaire that there was no clear universal trend for stitching patterns or materials. Certainly the original practice of using "like-for-like" when stitching was not still adhered to unanimously – only around a third of conservators would replace silk with silk and wool with wool. New methods have clearly been developed over time to account for the changes in attitudes towards conservation and experience in working with weak fibres and the differences between modern and historic dyes on the strength and fading of yarns.

*19. What factors contribute to the decision to use a particular thread? (Please rate 1-5: **1** being **not very** important, **5** being **very** important)*

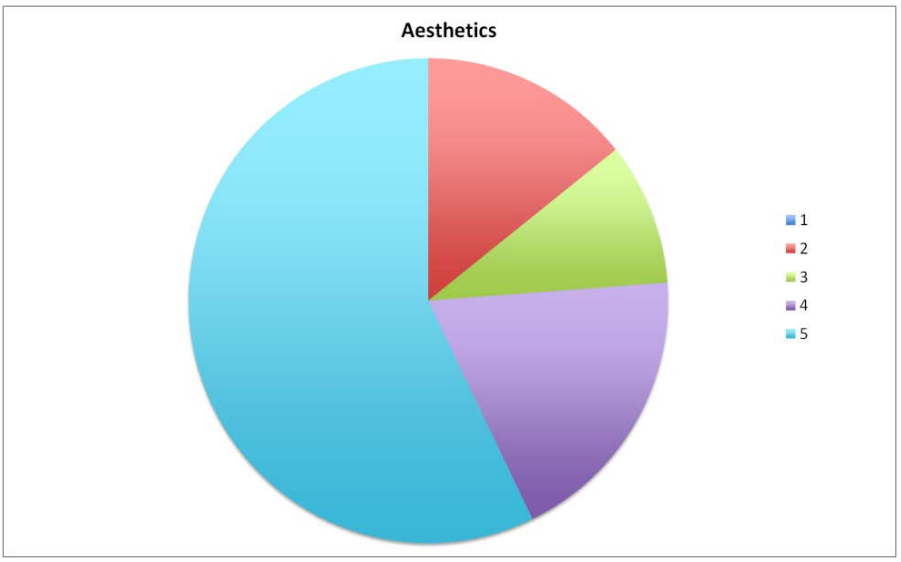
Aesthetics

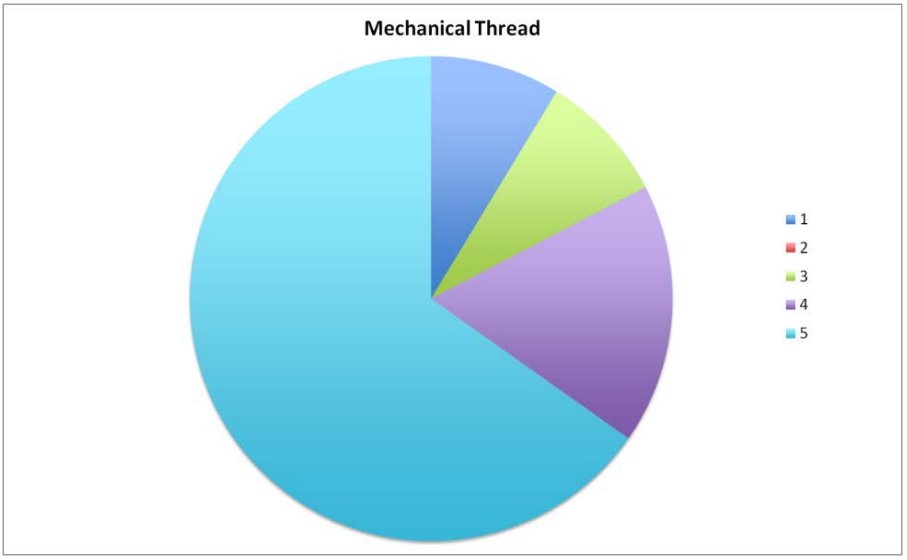
Mechanical strength of thread

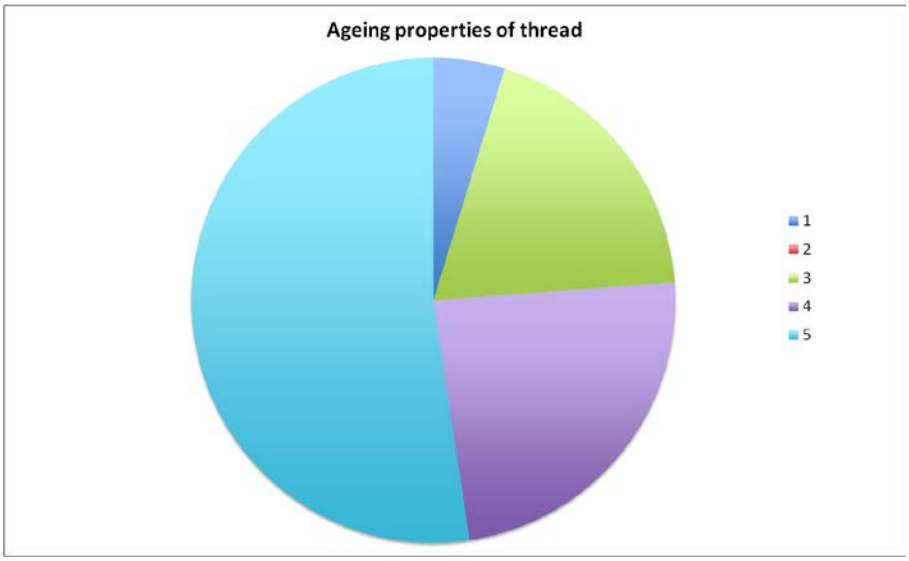
Ageing properties of thread

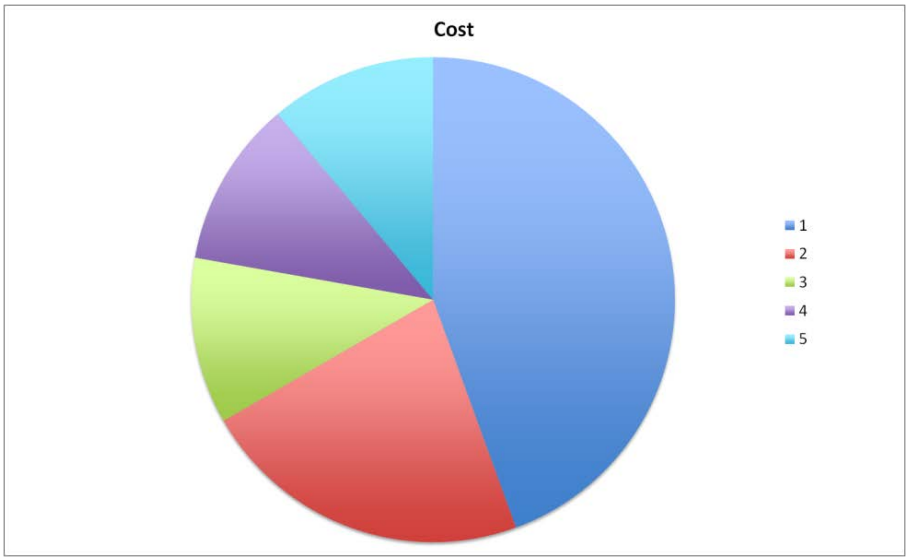
Cost

Availability









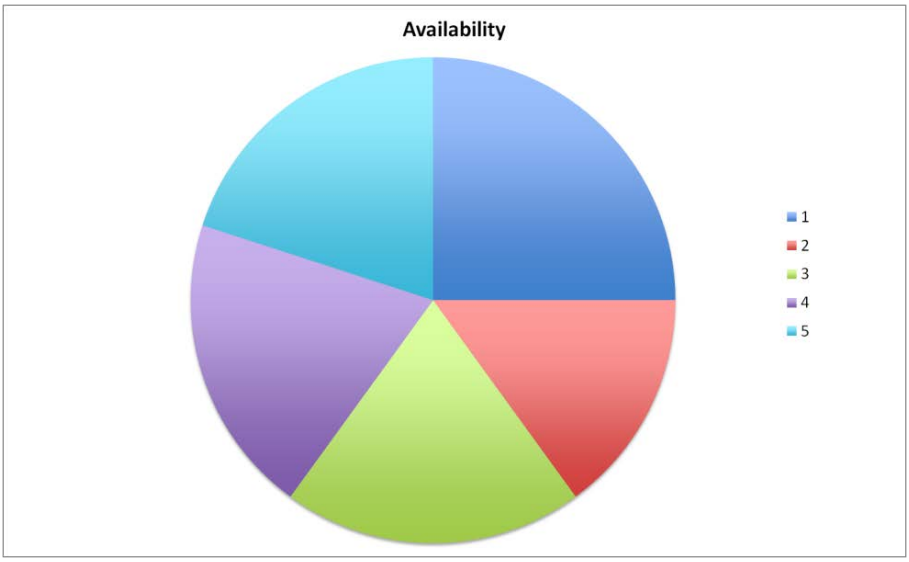


FIGURE 5.3: PIE CHARTS REPRESENTING THE RELATIVE IMPORTANCE OF DIFFERENT FACTORS WHEN CHOOSING STITCHING THREAD

The above figures show the respective importance of aesthetics, mechanical properties of thread, ageing properties of thread, cost and availability. The light blue indicates the strongest importance and it can be seen from this that the properties (both mechanical and ageing) as well as the aesthetic qualities of the thread are judged to be the most important.

20. *Is the current method that you use today always been the method used in your place of work?*

Yes: 50 %

No: 50 %

This half-half proportion shows that half the studios/individuals have developed their methods through experience, trial and error and current research. Half still use the traditional methods that the studio is associated with or the original training they received.

21. *What would you say are the main reasons that the current method is used?*

Tradition	30%
Based on current research	30%
Material availability	16%
Cost	12%
Dictated by owner/curator	3%
Restrictions due to resources e.g. time, conservators and space	9%

This seems to indicate again that tradition and current research both play their part in the current methods which are chosen. Equal proportions of respondents use the traditional methods, proved through experience, whereas half are willing to change their methods based on the current research.

Questionnaire Conclusions

This survey provides a valuable insight into current textile conservation practice across the world. It attempted to discover not only differences in technical methodology but also the reasoning behind making difficult conservation decisions.

As with many conservation studies, the end result is that every conservation treatment is object-specific and all conservation decisions are tailored to suit the object in question. It is this fundamental reality that makes any endeavour to "standardise" or create a "universal" rule a challenge within this field.

However, many important factors can be concluded from this questionnaire.

Firstly, conservators concur on the reasons for conserving an object: the primary factor is to strengthen and stabilise areas of loss or degradation. Other factors include providing support for display and safe handling.

Despite an increasing movement towards preventive conservation in many institutions and museums, not many conservators will apply any support to a "sound" tapestry – that is provide support for an object which is currently in good condition as a safeguard measure for future degradation and damage. This type of treatment is still "interventive" in that it involves actively stitching the object and therefore the ideal of "minimal intervention" overrides the need to slow down the

degradation of the object in this way. The minimising of degradation is managed through good environmental control and storage.

On this topic, the reasons for choosing a particular conservation treatment over another is mainly due to the extent of damage with time and cost being important as well (presumably based upon the client budget and time-scale). Interestingly, material availability and resources available were not as important which suggests that conservators are willing to source appropriate materials and equipment even if it is not immediately available to them indicating once more the importance of the object.

The answers to type of support and material for support fabric are likely to be skewed towards European trends as fewer replies were received from the Americas which according to research (Breeze, 2001) would have made strapping (method) and cotton (material) more significant.

However, both linen and cotton are clearly both used in different treatments and the importance of providing clear information on the different properties of these materials is paramount. The potential confusion of their properties could be important when determining whether a material should respond with an object to environmental changes or not and therefore restrain the object from dimensional changes.

Finally it is interesting to note that conservators appear to be split in whether they follow current research or remain in "traditional" practices. It is clear that the leading conservation institutions that actively carry out research and provide training are responsible for updating practice as many look to them for guidance

and change in practice. Although many smaller independent studios do carry out their own research, not all feel confident enough to carry this through to updating their methods without the backing of further expertise and equipment.

The number of responses and feedback throughout the project indicates a high level of interest and encouragement for collaboration between private individuals and larger institutions.

The results of this questionnaire will be made available online so that they are publically available for conservators and other heritage professionals within the field.

BIBLIOGRAPHY

ABAQUS, HIBBITT, K. & SORENSEN (2001) *ABAQUS/CAE: user's manual: version 6.2,* Pawtucket, Pawtucket: Hibbitt, Karlsson and Sorensen.

ALEXANDER, P., HUDSON, R. & EARLAND, C. (1963) *Wool: Its chemistry and physics,* London, Chapman & Hall Ltd.

ALSAWAF, F. B. (1985) A study in the mechanical properties of fabrics. *Department of Textiles.* Manchester, UMIST.

ASAI, K. (2007) Less is More? A Study of the mechanical effects of tapestry conservation methodologies. Historic Royal Palaces.

ASAI, K., BIGGS, E., EWER, P. & HALLETT, K. (2008) Tapestry conservation traditions: an analysis of support techniques for large hanging textiles. *15th Triennial Meeting of ICOM-CC.* New Delhi, ICOM.

ATKINS, P. W. & DE PAULA, J. (2002) *Atkins' Physical Chemistry*, Oxford University Press.

BAGULEY, D. & HOSE, D. R. (1997) *How to Model with Finite Elements,* Glasgow, NAFEMS.

BALLARD, M. Hanging Out: Strength, Elongation, and Relative Humidity: Some Physical Properties of Textile Fibers. *ICOM.*

BILSON, T., HOWELL, D. & COOKE, B. (1997) Mechanical Aspects of Lining "Loose Hung" Textiles. *Fabric of an Exhibition: An Interdisciplinary Approach.* CCI.

BOLLAG, D. M., ROZYCKI, M. D. & EDELSTEIN, S. J. (1996) *Protein methods*, Wiley-Liss.

BREEZE, C. M. (2001) The evolution of American tapestry conservation. *The Textile Specialty Group postprints of papers delivered at the Textile Subgroup Session: American Institute for Conservation annual meeting***,** 75-88.

BREWER, J. S., GAIRDNER, J. & BRODIE, R. H. (1861-3) *Letters and Papers, Foreign and Domestic of the Reign of Henry VIII*, Longman, Roberts and Green.

CAMPBELL, T. P. (2002) *Tapestry in the Renaissance: Art and Magnificence,* New York, Metropolitan Museum of Art Press.

CANDEE, H. C. (1935) *The Tapestry Book,* New York, The Tudor Publishing Co.

CARR, C. M., EVANS, J. C. & ROBERTS, M. W. (1987) An X-Ray photoelectron and electron spin resonance study of wool treated with aqueous solutions of Chromium and Copper ions. *Textile Research Journal,* 57**,** 109-113.

CHAPMAN, B. M. (1969) A Review of the Mechanical Properties of Keratin Fibres. *Journal of the Textile Institute,* 60.

CHEN, S. F., HU, J. L. & TENG, J. G. (2001) A finite-volume method for contact drape simulation of woven fabrics and garments. *Finite Elements in Analysis and Design,* 37**,** 513-531.

CLERENS, S., CORNELLISON, C. D., DEB-CHOUDHURY, S., THOMAS, A., PLOWMAN, J. E. & DYER, J. M. Developing the wool proteome. *Journal of Proteomics,* 73**,** 1722-1731.

COOK, J. G. (1993) *Handbook of Textile Fibres: Natural Fibres,* Durham, Merrow.

COOK, J. R. & FLEISCHFRESSER, B. E. (1986) Hygral expansion of wool yarns. *Journal of the Textile Institute,* 77**,** 146-150.

CORBMAN, B. P. (1983) *Textiles: Fiber to Fabric,* New York, McGraw-Hil.

DANIEL, I. M. & ISHAI, O. (2005) *Engineering Mechanics of Composite Materials*, OUP USA.

DAVIDSON, R. S. (1996) The photodegradation of some naturally occurring polymers. *Journal of Photochemistry and Photobiology B: Biology,* 33**,** 3-25.

DULIEU-BARTON, J. M., DOKOS, L., EASTOP, D., LENNARD, F., CHAMBERS, A. R. & SAHIN, M. (2005) Deformation and strain measurement techniques for the inspection of damage in works of art. *Reviews in Conservation,* 6**,** 63-73.

DULIEU-BARTON, J. M., SAHIN, M., LENNARD, F., EASTOP, D. & CHAMBERS, A. R. (2007) Assessing the feasibility of monitoring the condition of historic tapestries using engineering techniques. *Key Engineering Materials,* 347**,** 187-192.

DYER, J. M., PLOWMAN, J. E., KRSINIC, G. L., DEB-CHOUDHURY, S., KOEHN, H., MILLINGTON, K. R. & CLERENS, S. (2009) Proteomic evaluation and location of UVB-induced photo-oxidation in wool. *Journal of Photochemistry and Photobiology B: Biology,* 98**,** 118-127.

FEUGHELMAN, M. (1997a) *Mechanical Properties and Structure of Alpha-Keratin Fibres*, University of New South Wales Press.

FEUGHELMAN, M. (1997b) *Mechanical properties and structure of alpha-keratin fibres: Wool, human hair and related fibres,* Sydney, University of New South Wales Press.

FEUGHELMAN, M. (2002) Natural Protein Fibers. *Journal of Applied Polymer Science,* 83.

FIETTE, A. (1997) Tapestry Restoration: An historical and technical survey. *The Conservator,* 21**,** 28-36.

GIBB, I. (2010) Personal Communication.

GRAAFF, J. H. H. D. & BOERSMA, F. (1997) Tapestry Conservation: Support Methods and Fabrics for Tapestries. Amsterdam, Netherlands Institute for Cultural Heritage (ICN).

GRAAFF, J. H. H. D. & BOERSMA, F. (1998) Tapestry Conservation: Support Methods and Fabrics for Tapestries. Amsterdam, Netherlands Institute for Cultural Heritage (ICN).

HACKE, A.-M. (2006) Investigation into the Nature and Ageing of Tapestry Materials. *School of Materials Science.* Manchester, University of Manchester.

HACKE, A.-M., CARR, C. M., HOWELL, D. & BROWN, A. (2003) Investigation into the nature of metal threads in a Renaissance tapestry and the cleaning of tarnished silver by UV/Ozone (UVO) treatment. *Journal of Materials Science,* 38**,** 3307-3314.

HALLETT, K. & HOWELL, D. (2005) Size exclusion chromatography of silk: inferring the tensile strength and assessing the condition of historic tapestries. *14th Triennial Meeting of ICOM-CC.* The Hague, ICOM.

HAMES, B. D. (1998) *Gel electrophoresis of proteins: a practical approach*, Oxford University Press.

HEARLE, J. W. S. (2000) A critical review of the structural mechanics of wool and hair fibres. *International Journal of Biological Macromolecules,* 27**,** 123-138.

HELLEN, T. (2007) *How to - Use Beam, Plate and Shell Elements,* Glasgow, NAFEMS.

HIBBELER, R. C. (2008) *Mechanics of materials*, Prentice Hall.

HOWELL, D. (1996) Some mechanical effects of inappropriate humidity on textiles. *11th Triennial meeting of ICOM-CC.* Edinburgh, ICOM.

HOWELL, D. (2005) Prioritising interventive treatments for textile materials. IN JANAWAY, R. C. & WYETH, P. (Eds.) *Scientific Analysis of Ancient And Historic Textiles: Informing Preservation, Display and Interpretation: Postprints*

Archetype Publications.

HUNTER, G. L. (1925) *The Practical Book of Tapestries,* London, J B Lippincott.

IVANOV, I. & TABIEI, A. (2001) Three-dimensional computational micro-mechanical model for woven fabric composites. *Composite Structures,* 54**,** 489-496.

JEON, S. B., CHUN, S. Y. & HONG, C. J. (2003) Structural and Mechanical Properties of Woven Fabrics Employing Peirce's Model. *Textile Research Journal,* 73.

JONES, B. W. & SPEAKMAN, P. T. (1960) The Relation between the Number of Lanthionine Crosslinks and the Urea-Bisulfite Solubility of Alkali-Treated Wool. *Journal of Applied Polymer Science,* 3**,** 43-46.

JOSEPH, M. L. (1977) *Introductory textile science*, Holt, Rinehart and Winston.

KAGEYAMA, M., KAWABATA, S. & NIWA, M. (1988) The validity of a "Linearizing Method" for predicting the biaxial-extension properties of fabrics. *Journal of the Textile Institute***,** 543-567.

KAWABATA, S., NIWA, M. & KAWAI, H. (1973) 3 - The finite-deformation theory of plain-weave fabrics Part 1: The biaxial-deformation theory. *Journal of the Textile Institute,* 64**,** 21-46.

KEMP, A. (1958) An extension of Peirce's cloth geometry to the treatment of non-circular threads. *Journal of the Textile Institute,* 49**,** 44-8.

KING, A. L. (2011) Influence of Trace-Metals on the colour and photostability of wool. Melbourne, Deakin University.

KOEHN, H., CLERENS, S., DEB-CHOUDHURY, S., MORTON, J. D., DYER, J. M. & PLOWMAN, J. E. The Proteome of the Wool Cuticle. *Journal of Proteome Research,* 9**,** 2920-2928.

KOLLEGAL, M. G. & SRIDHARAN, S. (2000) A Simplified model for plain woven fabrics. *Journal of Composite Materials,* 34.

KORENBERG, C. (2007) The effect of ultraviolet-filtered light on the mechanical strength of fabrics. *The British Museum Technical Research Bulletin,* 1**,** 23-27.

KREPLAK, L., DOUCET, J., DUMAS, P. & BRIKI, F. (2004) New Aspects of the α-Helix to β-Sheet Transition in Stretched Hard α-Keratin Fibers. *Biophysical Journal,* 87**,** 640-647.

LANDI, S. (2006) A description and evaluation of a conservation system for tapestries. IN LENNARD, F. & HAYWARD, M. (Eds.) *Tapestry Conservation: Principles and Practice.* London, Butterworth-Heinemann

LEAF, G. A. V. & ANANDJIWALA, R. D. (1985) A Generalized Model of Plain Woven Fabric. *Textile Research Journal,* 55**,** 92-99.

LENNARD, F. (2007) Preserving Image and Structure: Tapestry conservation in Europe and the USA. *Reviews in Conservation,* 7**,** 43-53.

LENNARD, F. & HAYWARD, M. (2006) *Tapestry Conservation: Principles and Practice,* London, Butterworth-Heinemann.

LENNARD, F. J., EASTOP, D. E., DULIEU-BARTON, J. M., YE, C. C., KHENNOUF, D., CHAMBERS, A. R. & WILLIAMS, H. (2008) Progress in strain monitoring of tapestries. *ICOM 15th Triennial Meeting.* New Delhi, India, ICOM.

LUXFORD, N. (2009) Reducing the Risk of Open Display: Optimising the Preventive Conservation of Historic Silks. *School of Art.* Southampton, Southampton, Textile Conservation Centre.

MACLAREN, J. A. & MILLIGAN, B. (1981) *Wool Science: the chemical reactivity of the wool fibre*, Science Press.

MARGETTS, L. (2010) Consultation on finite element analysis of historic tapestries. IN DUFFUS, P. (Ed.). Manchester.

MILLINGTON, K. R. (2006a) Photoyellowing of wool. Part 1: Factors affecting photoyellowing and experimental techniques. *Coloration Technology,* 122**,** 169-186.

MILLINGTON, K. R. (2006b) Photoyellowing of wool. Part 2: Photoyellowing mechanisms and methods of prevention†. *Coloration Technology,* 122**,** 301-316.

MILLINGTON, K. R. & CHURCH, J. S. (1997) The photodegradation of wool keratin II. Proposed mechanisms involving cystine. *Journal of Photochemistry and Photobiology B: Biology,* 39**,** 204-212.

MORTON, W. E. & HEARLE, J. W. S. (1993) *Physical properties of textile fibres,* Manchester, The Textile Institute.

MUNOZ-VINAS, S. (2004) *Contemporary Theory of Conservation*, Butterworth-Heinemann.

NICHOLLS, C. H. (Ed.) (1980) *Developments in Polymer Photochemistry,* London, Applied Science Publishers.

NILAKANTAN, G., KEEFE, M., BOGETTI, T. A., ADKINSON, R. & JR, J. W. G. (2010) On the finite element analysis of woven fabric impact using multiscale modeling techniques. *International Journal of Solids and Structures,* 47**,** 2300-2315.

OKAMOTO, S. & KIKUCHI, M. (1958) The decomposition of silk fibroin by sunlight. V, On the discrystallization of the crystalline parts of silk by light. *Journal of Sericultural Science of Japan,* 27**,** 367-373.

PIERCE, F. T. (1937) The Geometry of Cloth Structure. *Journal of the Textile Institute,* 28**,** 45-96.

PLOWMAN, J. E. (2003) Proteomic database of wool components. *Journal of Chromatography B,* 787**,** 63-76.

POSTLE, R., CARNABY, G. A. & JONG, S. D. (1988) *The mechanics of wool structure,* London, Ellis Horwood.

PRICE, N. & NAIRN, J. (2009) *Exploring Proteins: A student's guide to experimental skills and methods*, Oxford University Press, USA.

QUYE, A., HALLETT, K. & CARRETERO, C. H. (2009) *Wroughte in gold and silk: Preserving the art of historic tapestries,* Edinburgh, NMS Enterprises Ltd.

RIPPON, J. A. (1992) The Structure of Wool. IN LEWIS, D. M. (Ed.) *Wool dyeing.* Leeds, Society of Dyers and Colourists.

SAHIN, M., CHAMBERS, A. R., DOKOS, L., DULIEU-BARTON, J. M., EARL, J., EASTOP, D. E. & LENNARD, F. J. (2006) Mechanical testing and its role in the condition assessment of tapestries. IN LENNARD, F. J. & HAYWARD, M. (Eds.) *Tapestry Conservation: Principles and Practice.* Oxford, Elsevier.

SHAO, J., CARR, C. M. & HAWKYARD, C. J. (1997) Investigation into the effect of UV/Ozone treatments on the dyeability and printability of wool. *Journal of the Society of Dyers and Colourists,* 113**,** 126-130.

SHARMA, S. B. & SUTCLIFFE, M. P. F. (2004) A simplified finite element model for draping of woven material. *Composites Part A,* 35**,** 637-643.

SHILOH, M., HUNTER, L. & SMUTS, S. (1982) The effect of fibre properties and weave crimp on the hygral expansion of woven wool fabrics. *Journal of the Textile Institute,* 73**,** 238 - 245.

SIMMONDS, D. H. (1955) The amino acid composition of keratins II. The amino acid composition of a keratin derivative extracted from wool with alkaline Thioglycollate solution. *Australian Journal of Biological Science,* 8.

SIMULIA, D. S. (2009) Abaqus/CAE User's Manual Version 6.9. *http://abaqusdoc.ucalgary.ca/v6.9/books/usi/default.htm.* Dassault Systèmes Simulia.

SMITH, G. J. (1995) New Trends in Photobiology (Invited Review) Photodegradation of keratin and other structural proteins. *Journal of Photochemistry and Photobiology B: Biology,* 27**,** 187-198.

SMITH, G. J., MILLER, I. J. & DANIELS, V. (2005) Phototendering of wool sensitized by naturally occurring polyphenolic dyes. *Journal of Photochemistry and Photobiology A: Chemistry,* 169**,** 147-152.

SPEAKMAN, J. B. (1941) The chemistry of wool and related fibres. *Journal of the Textile Institute,* 32**,** 83-108.

SZE, K. Y. & LIU, X. H. (2007) Fabric drape simulation by solid-shell finite element method. *Finite Elements in Analysis and Design,* 43**,** 819-838.

TAN, P., TONG, L. & STEVEN, G. P. (1997) Modelling for predicting the mechanical properties of textile composites - A review. *Composites Part A,* 28**,** 903-922.

TAYLOR, H. M. (1963) An Experimental and theoretical investigation of biaxial stress-strain relations in a plain-weave cloth. *Journal of the Textile Institute,* 54**,** 323-347.

TIMÁR-BALÁZSY, Á. & EASTOP, D. (1998) *Chemical Principles of Textile Conservation,* Oxford, Butterworth-Heinemann.

TSERPES, K. I., LABEAS, G. & PANTELAKIS, S. (2010) Multi-scale modelling of the mechanical response of plain weave composites and cellular solids. *Theoretical and Applied Fracture Mechanics,* 54**,** 172-179.

VASARI, G. (1568) *Delle vite de'più eccellenti pittori, scultori et architettori,* Florence.

VERLET, P., FLORISOONE, M., HOFFMEISTER, A. & TABARD, F. (1978) *The Book of Tapestry: History and technique,* London, Octopus Books.

VIG, J. R. (1985) UV/Ozone cleaning: a review. *Journal of Vacuum and Science Technology A,* 3**,** 1027-1034.

WILLIAMS, H. R., DULIEU-BARTON, J. M., CHAMBERS, A. R., LENNARD, F. J. & EASTOP, D. E. (2009) Application of digital image correlation to tapestry and textile condition assessment. *AIC Textile Specialty Group.* Los Angeles.

WORTMANN, F. J. & ZAHN, H. (1994) The Stress / Strain Curve of alpha-Keratin Fibers and the Structure of the Intermediate Filament. *Textile Research Journal,* 64**,** 737-743.

YE, C. C., DULIEU-BARTON, J. M., J, W. D., C, Z., G-D, P., CHAMBERS, A. R., LENNARD, F. J. & EASTOP, D. E. (2009) Applications of polymer optical fibre grating sensors to condition monitoring of textiles. IN JONES, J., CULSHAW, B., ECKE, W., LOPEZ-HIGUERA, J. M. & WILLSCH, R. (Eds.) *20th International Conference on Optical Fibre Sensors.* SPIE.

YSSELSTEYN, G. T. V. (1969) *Tapestry: The most expensive industry of the XVth and XVIth centuries,* Brussels, Van Goor Zonen.