

## Viking woollen square-sails and fabric cover factor

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The discovery of the five scuttled Viking ships of Roskilde Fjord in Denmark and the subsequent excavation, preservation and analysis of the remains has initiated a programme of reconstructive archaeology led by the Viking Ship Museum of Roskilde in which four of the five hulls have now been reconstructed together with their rigs and square-sails. The reconstruction of the sails has been based on fragments of heavy woollen cloth found within the roof of Trondenes church in Norway dating to the mid-13th century. This paper uses the ‘cover-factor’ modelling methods of modern textile engineering to analyse the ‘Viking’ sail fabrics and assess their strength, resilience and performance in comparison with the linen sails from the wreck of the *Vasa*.

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*Key words:* Viking square-sails, woollen sails, linen sails, cover-factor, tensile strength, extension.

### Introduction

In the second half of the 11th century the Danes of Roskilde were threatened by sea-borne attack. In the 1060s they determined to narrow and control the passage to Roskilde, by scuttling two cargo ships and a warship in the narrows of Roskilde Fjord at Skuldelev. The strategy worked. In the 1070s the blockage was reinforced with two more ships, a longship and a transport vessel. Once this danger was past the ships settled, disappeared and were forgotten.

There they remained until 1924 when fishermen recovered the keelson of what later became called Skuldelev 1. In 1956 sports divers recovered a piece of framing and, following an archaeological survey, it was determined to raise and preserve the remains. The archaeological work started in 1957 and was completed in 1962, and the initiation of conservation of the timbers revealed their excellent state of preservation. The realization that these remains preserved the entire process of shipbuilding down to the placing of the woollen luting and the insertion of each and every treenail

set in train the long process which was to lead to the reconstruction of four of the five ships and the immensely rewarding process of learning how to equip, rig, trim and sail them (Fig. 1) (Crumlin-Pedersen, 2002).<sup>[1]</sup>

### The five ships

Dendrochronology has shown that the majority of the ships were built in Scandinavian waters in the period 1030–1050. They were all clinker-built in the Nordic tradition with oak keels, stems and sternposts. The most remarkable of all the ships is wreck 2/4. This was a true longship, approximately 30 m in length, with a beam of 3.7 m and a height amidships of 1.8 m. The dendro-date for its construction is 1042 based on a close match with the Dublin curve which points to construction in south-west Ireland (Crumlin-Pedersen, 2002: 184). Unfortunately no fragments of rig or sail were discovered during the excavation and raising of the wrecks



Figure 1. *Sif Ege* and *Roar Ege* in Roskilde fiord September 2000.  
(Photo: Bill Cooke)

## Square-sails in the literature

In order to reconstruct the sails the Viking Ship Museum set about a search of the literature and the archaeological record in order to establish the basic fabric parameters to enable weaving to commence. The results of this research have been reported by Erik Anderson (Anderson, 1995). Fortunately the custom of using woollen square-sails had continued until the 20th century in Scandinavian locations and in the Faroes, and much information was accessible concerning manufacture, rigging and treatment, and the skills of the woollen sailmaker were still (just) alive.

The Vikings used square-sails woven from wool, a fact that is well attested by surviving written sources and contemporary iconography. Using these sails the Vikings became the most widely-travelled traders of their era reaching Ireland, Greenland, Iceland, Newfoundland and

the Black Sea. Nevertheless their sails have been thought to be leaky and inefficient in comparison with modern sails and incapable of beating into the wind (Larsen, 1975).

The survey of the Nordic literature carried out by Andersen demonstrated that from the Medieval Period onwards sailcloth had a considerable commercial importance in Scandinavia and lengths of sail fabric were used as a form of currency and a means of taxation. As is often the case with fabrics of considerable commercial importance in the past, the literature regarding the sale and use of sailcloth is confused in terminology and short of reliable quality descriptors. Such fabric was generally called *vadmal* (Danish), *vapmal* (Old Swedish) and *vaðmál* (Norse). There were a great many variants mentioned in written sources from different countries and local areas.

Icelandic fabrics were always 2/2 twill, a *priskept*, woven on warp-weighted looms until the

1750s. Twill (2/1) or *tuskept* began to be used in Sweden and Denmark in the 11th to 13th centuries. Gudjonsson has argued that 2/1 twill was difficult to weave on warp-weighted looms (Gudjonsson, 1985), but experiments carried-out at the Archaeological Research Centre in Lejre have demonstrated that 2/1 twill may be woven as easily as 2/2 twill (Batzer *et al.*, 1982). Further, tabby 1/1 *einskepta* was used in the Faroe Islands and Iceland and is mentioned for the first time in Icelandic written sources in 1586 (*Kulturhistorisk Leksikon*, 1956–78) and was used in the Faroes until the 20th century. The term *vaðmál* was used for tabby and twill and seems to have been applied to both fulled and non-fulled fabrics on occasion (Andersen & Andersen., 1989), although Andersen states that in the Aland islands and Sweden *vaðmál* was never used to describe sails (Andersen, 1995).

Thus those intending to reconstruct Viking sails find little direct help from the literature other than the notion that a woollen *priskept* was the construction of choice in the Early Viking Period to be replaced by a *tuskept* in the 11th and 12th centuries.

### Sail cloths: the archaeology

To add to these problems the archaeological record is sparse and in terms of attested woollen sail material limited to two remnants no more than 300 years old, together with the textile remains from the Oseberg and Gokstad ship-burials (Ingstad, 1982; Brøgger & Shetelig, 1951: 94). For sails made from hemp and flax the situation is better with the six sails from the *Vasa* which sank in 1628, and a number of similar samples in the Marine Museum at Karlskrona and the Statens Sjöhistoriska Museum in Stockholm which date to the 18th and 19th centuries (Westheden Olausson, 1988). Whilst these hemp/linen sails do not help directly with the problems of the construction of woollen sails they do offer other vital information as discussed below.

Fortunately for the project, Jon Bojer Godal heard about the discovery of textile fragments during the repair of a wooden church and his joint investigation with Erik Andersen, of 11 medieval churches along the Norwegian coast revealed that considerable quantities of woven woollen material had been used for packing between the planks of the ancient roof of Trondenes church (Godal, 1994) One of these fragments, Trondenes 06,

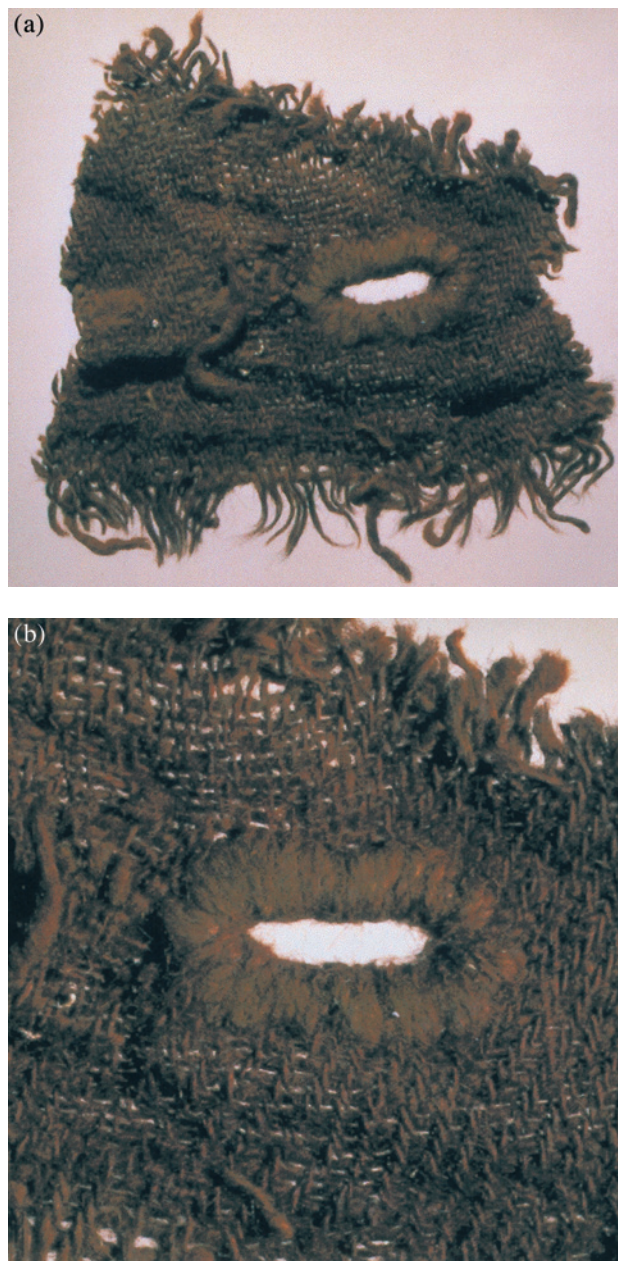


Figure 2. Sail eyelet, Trondenes 06. (Photo: Lena Hammarlund)

preserved a sewn rope sail eyelet, and thus concrete evidence of the fibre, yarn and fabric parameters used when it was made (Fig. 2). This important find was radiocarbon dated to between 1280 and 1420 and is, therefore, the earliest attested Scandinavian sail fragment. Many of the other fragments from the Trondenes church roof were of a similar quality and, whilst no other conclusive evidence of sail provenance was found, the probability is that they all represent secondary usage of damaged or worn-out sails.

The process of sail reconstruction started with the analysis of these fragments in terms of fibre type, diameter, yarn spin, and diameter and weave. The wool was from a primitive, hairy, pigmented breed prepared in such a way that the warp yarns contained a majority of long hair whilst the wefts contained a mixture of hair and shorter fibre. The warps were highly twisted and the wefts soft twisted. The fabrics were of 2/1 twill construction with an average of 8/9 z-spun warps/cm and 4/6 s-spun wefts/cm and did not show any evidence of fulling. The weight/m<sup>2</sup> is estimated at 950–1000 g, suitable for a large sail up to 130 m<sup>2</sup>. Many of the fragments were impregnated with a resinous material to the point of being stiff like leather. Of the other extant ancient sail material the *Amla* sail of c. 1712 was of a similar though lighter construction. It was approximately 300 g/m<sup>2</sup>, 11 warps/cm and 8 wefts/cm, in a 2/1 twill with a warp of mixed long hair/short fibre but with a slight predominance of long hair and weft of mixed long/short fibre. The Ormbostadt, Nordmore, sail was heavier, 750 g/m<sup>2</sup>, had mixed long/short fibre in the warp and weft, and was of 2/1 twill construction. It was heavily fullled and smörred, the smörning contributing to the weight (Andersen, 1989).

In contrast the sails of the *Vasa* were made from hemp, z-spun for both warp and weft. Six of the sails were recovered from the wreck and following conservation provided data regarding the ends/picks/cm together with the overall area of the sails (Bengtsson, 1975). The area data for the missing sails was estimated in comparison with inventories of similar ships. The *Vasa* sail parameters have been extended by Westheden Olausson who has made a comparative examination of a total of 29 attested hemp/flax sailcloth fragments (Westheden Olausson, 1988). She notes that in spite of tremendous disparities in age, two-thirds of all the sailcloth samples are almost exactly the same in terms of thread count (threads/cm) and warp and weft, namely 10/12 warps/cm and 7/8 wefts/cm woven in tabby to a typical width of 65–72 cm. The remaining one-third of the samples were finer, 11/14 warps/cm and 9/11 wefts/cm. Olausson considers the finer fabric to be for 'light wind sails'.

This information is of considerable significance as it implies that the tortuous process of trial and error inherent in the process of discovery in the pre-scientific period involving the manufacture and construction and 'testing to destruction' of many thousands of linen square-sails over several

hundreds of years yielded a 'standard' linen sail quality that was known to be serviceable.

## Sail reconstruction

The first sail reconstructions for the Viking Ship Museum started with the sails for the Skuldelev 3 replica, *Roar Ege*, using the specifications derived from the Trondenens T06 fragment as a template but with a target weight of 750 g/m<sup>2</sup> (Andersen, 1995). It was soon evident that the woollen material would have to be produced in Norway where there were still enough primitive wild Vilsau sheep to provide the correct quality and quantity of hairy wool. The manufacture was organised by Solfrid Steigen Aune. The yarn was machine spun and the fabrics were hand woven on horizontal looms. Even using these more modern methods the cost of the reconstructions were high. Andersen estimates that the cost of collecting, sorting, combing, spinning, weaving, treating and sewing the 56 m<sup>2</sup> sail for the Skuldelev 5 replica, *Helga Ask*, was 1 million Danish crowns (£2000/m<sup>2</sup>).

The fabric for the *Roar Ege* sail was half-fulled and finished at 480 g/m<sup>2</sup> that did not match the target weight of 750 g/m<sup>2</sup> and was far from the estimated 950–1000 g/m<sup>2</sup> of the archaeological template. The subsequent fabric reconstructions were carried-out by Amy Lightfoot and her staff at the Tommervik Textile Workshop, Hitra, Norway. Lightfoot and her colleagues had undertaken extensive background research into the wool-working methods of the North Atlantic seaboard, and this know-how together with the lessons learned from the *Roar Ege* reconstruction were invested in the considerable task of manufacturing sail fabric for the *Sara Kjerstine* and the *Sif Ege* (second Skuldelev 3 replica). The sail-making was carried-out by Frode Bjøru who had considerable experience from sewing sails for previous reconstruction projects. As a result of this extensive experimental process the latest sail for the Skuldelev 1 replica was planned to match Trondenens T06 as closely as possible with a design weight of 1000 g/m<sup>2</sup> for a sail of 100 m<sup>2</sup>.

This sail has now been spun, woven and made-up using horse-hair rope for the leech ropes. The finished weight of the fabric was on average 1050 g/m<sup>2</sup> and after complete smörning is likely to reach 1400–1500 g/m<sup>2</sup>. The performance of this sail is now being evaluated following the launch of the Skuldelev 1 replica, *Ottar*, in September 2000.

## Specifying sail fabric parameters

The experimental archaeology at Roskilde has demonstrated that reconstructed woollen sails perform as well as, and in certain respects better than, hemp or linen sails. In order to more fully understand the differences between wool and hemp sails the authors use data from the analysis of the *Vasa* sails together with results obtained from the testing and analysis of the yarns and fabrics of the Skuldelev 1 replica sail, (carried out at UMIST as part of the EU Raphael-funded 'Seafaring' project).

## The predictive use of cover factor

It is clearly impossible to test and analyse the mechanical properties of archaeological textile finds. It is equally impossible to ascertain the yarn weight/unit length of the yarns used to weave the fabric (count in  $\text{tex} = \text{g}/1000 \text{ m}$ ), and the majority of examinations of archaeological textiles have not measured or recorded yarn diameter. In the absence of yarn diameter measurements made on the archaeological fragments it will be necessary to estimate the yarn count or tex. Research in the modern Textile Industry has led to the development of fabric cover equations that relate threads/unit length to yarn diameter and woven structure. The basis of this predictive methodology was established by Peirce, and his equations published in 1937 are adequate for the purposes of this investigation (Pierce, 1937). The heavier *Vasa* sails had 12 warps/cm and were described as tightly woven with the weft visibly thicker than the warp. Based on the assumptions of Pierce it is possible to estimate the count of the warp threads using the following equation:

$$K = 1000 / (p \times N^{1/2}) \quad (1)$$

Where  $K$  is the 'cover-factor' (maximum value 27.93),  $p$  is the thread spacing in 1/1000 inch  $N$  is the cotton count (number of 840 yd hank lb)

This equation is inconvenient to use and to facilitate this discussion the units have been converted to threads/cm, t/cm and tex, hence:

$$K = (t/\text{cm} \times \text{tex}^{1/2}) / 9.572 \quad (2)$$

If we accept Peirce's data, and assume the specific volume of twisted cotton and hemp are similar and equal to 1.1 then we may assume the cover factor  $K$  for a very tight tabby canvas to be

18/14. With 12 warps/cm and a cover factor of 18 the tex of the *Vasa* warps can be calculated as follows:

$$18 = (12 \times \text{tex}^{1/2}) / 9.572 \\ \text{tex} = 206$$

The *Vasa* sails had 7 wefts/cm with a cover factor of 14:

$$14 = (7 \times \text{tex}^{1/2}) / 9.572 \\ \text{tex} = 366$$

Similarly it is possible to calculate the tex of the Trondenes T06 sample assuming the specific volume of a highly twisted combed hair warp is also 1.1 and the  $K$  of a tight 2/1 twill warp is 24:

$$24 = (9 \times \text{tex}^{1/2}) / 9.572 \\ \text{tex} = 651$$

For the weft a cover factor of 14 is possible with the 2/1 construction, hence:

$$14 = (4.5 \times \text{tex}^{1/2}) / 9.572 \\ \text{tex} = 887$$

The advantage of experimental textile archaeology is the existence of real fabrics for measurement and testing. The Skuldelev 1 sail fabric was woven from a 622 tex warp with 9 warps/cm and a 892 tex weft with 4.5 threads/cm. From these values the same equation is used to calculate the cover factors of the replica sail as follows. For the warp:

$$K_{\text{warp}} = (9 \times 622^{1/2}) / 9.572 \\ K_{\text{warp}} = 23.44$$

For the weft:

$$K_{\text{weft}} = (4.5 \times 892^{1/2}) / 9.572 \\ K_{\text{weft}} = 14.04$$

These values correspond closely with those suggested by Peirce for 2/1 twill and support the assumptions made above.

In considering the design parameters that are critical for sail performance a first instinct might be to assume that tensile strength would be one of the most important. The experimentation at UMIST has shown that wheel-spun flax yarns typically develop 70% of the fibre tenacity, 0.378 N/tex and that hair wool yarns develop 40% of the fibre tenacity, (largely due to breakage at

overtwisted 'thin places'), of 0.14 N/tex, 0.058 N/tex. From these results it may be assumed that hemp yarns will develop 70% of 0.47 N/tex, or 0.329 N/tex.

The *Vasa* sails would therefore have had a breaking strength in the warp of:

$$12 \times 206 \times 100 \times 0.329 \text{ N/m} \\ 81328 \text{ N/m, or } 8290 \text{ kg/m}$$

The weft strength would be:

$$7 \times 366 \times 100 \times 0.329 \text{ N/m} \\ 84289 \text{ N/m, or } 8592 \text{ kg/m}$$

The Trondenæs T06 sail warp strength would have been:

$$9 \times 651 \times 100 \times 0.058 \text{ N/m} \\ 33982 \text{ N/m, or } 3464 \text{ kg/m}$$

The weft strength would be:

$$4.5 \times 887 \times 100 \times 0.058 \\ 23150 \text{ N/m, or } 2360 \text{ kg/m}$$

It may be noted that the Skuldelev 1 replica developed a 5 cm warp strip strength of 1600 N/5 cm, or 3265 kg/m, equivalent to the Trondenæs T06 calculation.

Adding together the warp and weft strengths for each sail (to provide a first order estimate of the biaxial strength) produces a warp+weft total for the *Vasa* sail of 16,882 kg and a strength of 5824 kg for the Trondenæs sail. Therefore, the wool sail has only approximately 34% of the strength of the hemp sail. However, we now know that both these sail constructions are capable of performing well in a large sail of >100 m<sup>2</sup> and so it can be assumed that absolute tensile strength does not play a dominant role in the performance of square-sails.

In the microscopy department at UMIST the mechanisms of textile failure have been studied since 1970. From a considerable depth of experience we can say that constructed textile structures such as tents, awnings and sails rarely fail due to pure tensile failure. In a majority of instances failure under load occurs due to stress concentration and tearing. If woollen and hemp fabrics are compared in terms of their tendency to tear we can in very general terms state that hemp yarns with their low extension to break are less able to load-share through stretching and bunching. In

comparison with woollen fabrics of the same construction and weight, hemp fabrics have much lower tear strengths (Skelton, 1980).

Because sails need to withstand dynamic loading and adsorb and transmit the wind's energy, a second attempt to find comparability might consider the work of rupture of the two sail fabrics. The work of rupture for hemp fibre is 5.3 mN/tex with a breaking extension of 2.2% and for wool fibre is 26.6 mN/tex with a breaking extension of 30%. If these are scaled relative to the developed yarn strength, that is by 70% and 40% respectively, and multiplied by the sum of the warp and weft tex for each fabric, the *Vasa* sail has approximately 17% of the biaxial work of rupture of the Trondenæs sail. Even though these calculations for strength and work of rupture are very approximate the 'standard' hemp sail is of the order of three times as strong in tensile terms as the wool sail but with a capacity to adsorb dynamic bursts of energy of less than 1/5th of the wool sail. The implications of this are that in storm conditions hemp sails are much more likely to transmit damaging levels of force to the rig and because of their inability to auto-trim are much more likely to burst or tear.

In the search for comparability between the design parameters of wool and hemp sails the way in which they work needs to be considered. For most of their working lifetimes they are not functioning at the limits of tenacity, or extension, close to failure. The above calculations therefore only apply to times of crisis and their performance under conditions much closer to the ideal requires examination. When beating or reaching, square-sails adopt an airfoil configuration bowing out in response to the differential pressures in front and behind the sail. Under optimum conditions the airflow across the face of the sail is laminar and much faster than the flow across the shorter path at the rear. The extent of the velocity difference, and hence the pressure difference, or draw, depends on the sail curvature out of the wind vector plane. If the curvature becomes excessive the laminar flow breaks down and the sail starts to stall and lose power. The properties of the two sail types can be considered in the light of this. The Viking square-sail was made from vertical stands (oppsett) of fabric (warp vertical), joined with rolled seams and with a leech rope attached to all sides (Fig. 3). Because hemp fibre has a high modulus and very low stretch, (2.2% to break) and yarn spun for optimum strength has relatively low twist and thus low stretch, any significant

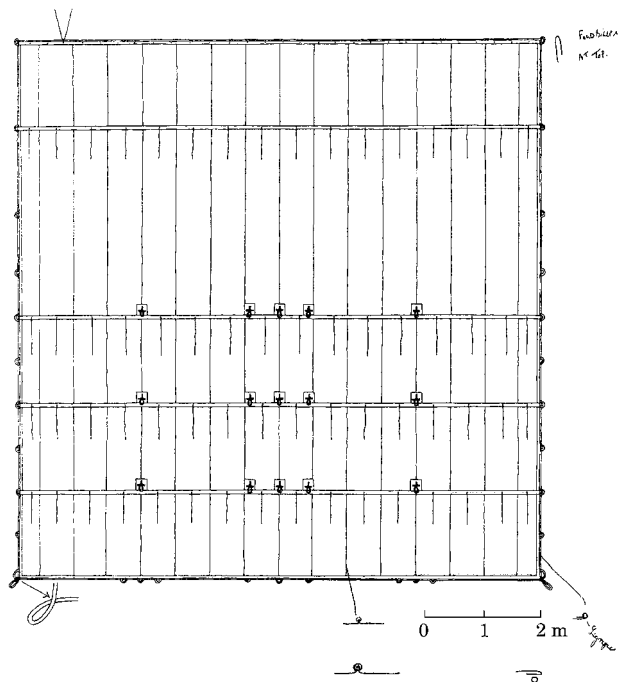


Figure 3. Schematic diagram of the *Otar* square sail. (Drawing: Viking Ship Museum)

fabric stretch must therefore come from crimp interchange. In the *Vasa* sailcloth the majority of the crimp will lie in the warp and this will provide some stretch, 5–7%, down the length of the sail and thus provide for vertical curvature. The weft has very low crimp and high modulus and there is little scope for the development of horizontal curvature in the plane of the wind direction. If such fabrics are to provide significant horizontal curvature it must be cut-into-the-sail by making the vertical stands barrel-stave shaped. It should be noted that modern low extension Kevlar sails are often bi- or tri-radially cut to provide a precise three-dimensional curvature.

A wool sail performs in a different way. Wool fibre stretches easily, (30% to break) and the high twist employed by the Viking spinners for the hairy warp yarns adds an even greater potential for stretch. Furthermore woollen fabrics can also stretch through crimp interchange. Tests at UMIST showed that modern 2/1 twill fabrics similar to Trondenes T06 when woven on a horizontal loom had warp extensions to break of as much as 52% and 59% with weft extensions of 18.6% and 21% respectively. When woven on a warp-weighted loom they were closer to square with 24% and 28% for warp and weft directions. Such fabrics provide adequate scope for develop-

ment of both vertical and horizontal curvature and do not need to be cut-to-shape. The experience with the *Roar Ege* and *Sif Ege* sails suggests that the danger with lighter wool sails in the range 500–700 g/m<sup>2</sup> is that they can be too stretchy and develop excess curvature even in moderate winds (Andersen, pers. comm.). In order to limit the stretch, the warp and weft thickness must be designed in such a way that typical average wind speeds generate the correct curvature. A built-in advantage of woollen sails is their ability, in bursts of high wind speed, to stretch beyond the optimum curvature towards the stall condition without failure. In this way they will lose power and in-a-sense self-trim.

The experience of the Vikings showed that woollen sails needed to be much thicker and heavier than hemp sails and hence the different construction details of the *Vasa* and Trondenes fabrics. In summary: the critical design parameters for hemp sails are adequate tensile strength to resist tearing together with adequate cover. The outcome of long-term ‘experimentation’ over more than 700 years was a ‘standard’ quality of 12 × 200–250 tex warps/cm and 7 × 300–350 tex wefts/cm. The critical design parameters for wool sails are totally different, namely, adequate tensile moduli to limit the stretch under load and these requirements are found in fabrics with 9 × 620 tex warps/cm and 4/6 × 850–900 tex wefts/cm. Unfortunately such wool fabrics in their loom state have a major design fault: they are too permeable to airflow to function as efficient sails.

### Air permeability and smörriing (dressing)

During sail fabric testing at UMIST in an attempt to understand the functioning of wool sails the decision was made to test air permeability. The Shirley Air Permeability Tester was used on the Skuldelev 1 replica fabric and on other similar test fabrics. Initial tests showed that the fabrics had such high permeability that the standard pressure drop of 10 mm water pressure could not be achieved at the highest flow rate. The test was modified to 2 mm water pressure before readings could be taken that were typically between 100–150 cc/sec flow rate. Fabrics with such high permeability would not function as sails because air would flow through the sail and eliminate the pressure difference between the front and rear that creates the draw. It had been suggested that half

fulling the fabrics would reduce the permeability but tests on loom-state and fulled fabrics showed that air permeability was typically only reduced by 30–35% by fulling, which was not enough to resolve the problem.

A fragment of the Nordmore sail was then tested under the same conditions and was found to have much lower air permeability, 10–20 cc/sec. The Nordmore sail had been impregnated with a resin like finish and this tied-in with comments in the literature about smörning (Andersen, 1995). Smörning involves a two-stage process of, firstly, brushing into the fabric an emulsion of water, horse fat, (from beneath the mane) and ochre. This is allowed to dry and then hot liquid beef tallow is rubbed and smoothed into the sail. This process was used twice to improve the light stretchy sail of the *Roar Ege* and was also applied to the *Sif Ege* sail (Andersen, pers. comm.). To establish the effect of smörning, the Skuldelev 1 fabric and the other test webs were tested before and after treatment and as part of this experiment the extension of a 5 cm strip at 100 N loading was also measured before and after. The air permeability tests show that smörning dramatically reduces the airflow. The sample SK1/4, (Skuldlev 1 oppsett 4) shows that a high air permeability of 111 cm/sec can be ‘tuned’ down to 4 cm/sec by the two stage process of horse fat and ochre followed by beef tallow. The results for Skuldelev 1 oppset 2 and Skuldelev 1 oppset 5, both show the effect of each of the two stages. The first application lowered the air flow from 68–85 cc/sec down to 18 cc/sec, and the beef tallow application reduced it further, to close to zero if required, dependant on the quantity of beef tallow applied. The other interesting result is that the three warp-weighted loom fabrics included in this test, AN1, AN2 and BF all give air flow values in the region of 30 cc/sec prior to smörning and this suggests that it is easier for a woman of average strength to produce a very tight fabric on a warp-weighted loom as compared with the horizontal loom fabrics which all have initial air flow values above 62 cc/sec, (62–111).

Finally the 5 cm strip testing demonstrated that smörning reduced the low load (100 N/5 cm) extension by approximately 30–40%, thus increasing the tensile modulus accordingly. Smörning can therefore be seen as an important aid in the successful use of coarse woollen sails. It enables the air permeability to be reduced to a level at which the sail will develop a good draw and it also has the effect of trimming the elasticity of the sail.

The inclusion of ochre in the mix is also of significance. It undoubtedly acts as a good filler inhibiting air flow by filling the voids in the fabric, but it also has anti-bacterial properties which help to prevent the wet sail from rotting.

## Conclusions

The experimental archaeology associated with the reconstruction of woollen sails for the reconstructed Skuldelev ships has radically altered the understanding of the functioning and efficiency of such sails. In 1975 Svend Larsen concluded his book, *Vikingsernes hav*, by stating that beating to windward cannot be done with woollen sails because they are ‘fleecy, nappy, yielding and leaky’ (Larsen, 1975). It is now known that high cover factor woollen square-sails could beat at 66° into the wind and most likely out-perform linen and hemp sails. Furthermore it has been proved conclusively that the process of smörning enables the properties of the wool sail to be improved and ‘trimmed’ during use.

In a small way the research carried out at UMIST as part of the Raphael ‘Seafaring’ project has added to the understanding derived from experimental archaeology by providing comparative quantitative data within a framework of the fibre physics and fabric mechanics essential for the evaluation of the results. It is to be hoped that this work will help to provide the foundation for a better understanding of the design and performance of woollen square-sails together with a clearer appreciation of the high level of technical skills and knowledge developed empirically by our forebears.

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