

Assessing the physical state of the fore topsail of HMS *Victory*

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ABSTRACT Marine textiles form a vital part of our cultural heritage. Some extant sails and surviving sail fragments in museum collections are hundreds of years old. The *Victory* sail, from the early 19th century, was not only subject to the ravages of the marine environment during its working life but has since suffered further deterioration during storage and display. To determine the optimum protocol for future conservation, display and storage, it was essential to determine its current physical state.

The physical properties of sailcloth are influenced by a number of factors, many of which relate to its complex hierarchical structure. The *Victory* sail is composed of linen, a bast fibre comprised of cells reinforced with fibrillar microcrystalline cellulose within hemicellulose and pectin matrices. Lignin serves to cement aggregates of these 'ultimate' cells together. At the higher levels of the hierarchy, fibre bundles are spun together as yarns, which in turn form the weave structure of the cloth.

To assess the current state of these fibres, physical properties of yarns from the *Victory* sail and appropriate surrogate materials were determined. Additional destructive tests on surrogates suggested a good correlation between the characteristics of individual yarns and of the bulk sailcloth. As a result it was possible to suggest loading limits for the *Victory* sail. Further non-destructive slippage tests performed directly on the sail also proved crucial to informing decisions on appropriate arrangements for display.

Examination by electron microscopy revealed a variety of features that correlated with the mechanical data: defects and defibrillation were apparent in the more highly degraded specimens, as were surface debris and evidence of mould growth. When ruptured fibres were investigated, it was found that fractures appeared to propagate in a manner that could be linked to the degree of deterioration.

Keywords: linen, deterioration, tenacity, cellulose, artificial ageing, slippage

Introduction

The Victory sail

The fore topsail of HMS *Victory*, Nelson's flagship at the Battle of Trafalgar on 21 October 1805, is an artifact of particular historic importance. The sail was extensively damaged during the battle by musket and cannon fire, and by a mast that tore a long gash through the fabric as it collapsed (Fig. 1). The sail's origin can be traced back to Baxter Brothers Linen and Jute Manufacturers of Dundee; it was in use by 1803 and was probably employed at sea for roughly 18 months prior to the battle. Not only does it represent a link to one of the most important naval battles in British history, it is also believed to be the only surviving sail from the period and the largest marine textile artifact in existence.

The sail itself is 80 ft (24 m) wide at the foot, 55 ft (17 m) in height and weighs approximately 360 kg. It is constructed from bolts of linen cloth (each roughly 2 ft wide), running from head to foot, and is reinforced with similar material running across the width of the sail; the edge is strengthened with hemp rope. The sailcloth is of a plain weave (that is, a simple weave in which the warp and weft yarns interlace alternately),

woven with paired warps (10.8 warp pairs/cm or 21.6 individual warps/cm); the warps run along the length of the bolts of cloth, the weft yarns (8.3/cm) run across.

In order to assess the state of this sail and suggest appropriate approaches to conservation, an understanding of the

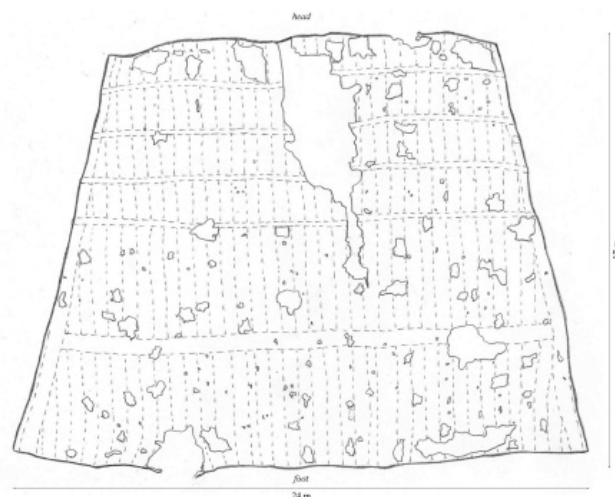


Figure 1 Diagram of the fore topsail of HMS *Victory*, with the component bolts of cloth indicated by dashed lines.

microstructure, chemistry and degradation mechanisms of linen was essential. It was also important to consider the known history of the sail – the mechanical stresses and exposure to the marine environment during its use, the damage it suffered during the battle, and the more subtle deterioration (including inevitable but limited mould growth) over the subsequent two centuries of storage and occasional display.

To assess the state of the sail, mechanical testing techniques were employed. With the data from these experiments it was possible both to determine the current condition of the cloth and to suggest an appropriate protocol for display and storage.

Linen

Linen, or flax, is a bast (stem) fibre derived from certain varieties of *Linum usitatissimum* (Catling and Grayson 1998; Marshall 1992). It is the first plant known to have been used for the production of fibres dating back several thousand years BC. Linen fibres have good mechanical properties including a relatively high strength and low extensibility; these factors, combined with the increase in fibre strength observed on wetting, mean that linen is a good choice for the production of sailcloth.

All plant fibres share a similar composition and structure. The fibres are cellular in nature being composed predominantly of cellulosic cell walls around a hollow lumen. In the case of flax fibres, bundles of these cells (ultimates) are cemented together by the lignaceous middle lamella. The cell walls of flax, as with all plant fibres, are largely composed of polysaccharides – principally cellulose (62.1%), along with hemicelluloses (16.7%) and pectin (1.8%) – and a smaller proportion of lignin (2.0%), proteins, pigments, waxes and minerals (Hearle and Peters 1963; Lewin and Pearce 1998; Marshall 1992; Tímár-Balászy and Eastop 1998; Daniels 1999). Cellulose itself is composed of 1,4- β -(D-glucose) units, though the repeat unit is usually considered as cellobiose, a glucose dimer.

Typically, for undegraded linen cellulose, the degree of polymerisation is of the order of 10,000 cellobiose units. The polymer is linear, facilitating strong intermolecular attraction between adjacent cellulose chains, which results from hydrogen bonding involving the hydroxyl groups. This intermolecular association leads to a high degree of crystallinity (typically about 70% for flax), which results in the suitability of cellulose as a structural material in plants and also lends it a high degree of chemical resistivity.

The fibres possess a fairly complex hierarchical microstructure in which regions of well-ordered crystalline cellulose are interspersed with areas of random crystallinity, lacking long-range ordering, and amorphous regions, in which the ordering of the polymer breaks down completely; among these components, additional matrix species such as hemicelluloses, pectins and lignin are also found. At the molecular level, the cellulose chains are organised into parallel – and hence crystalline – bundles (of the order of 100 or so), which associate to form micelles or elementary fibrils (typically 5–6 nm in diameter). In turn, aggregates of roughly 15 of these micelles, embedded within the amorphous intermicellar space, form microfibrils (generally 75–90 nm in diameter). Bundles of

microfibrils, set within the amorphous interfibrillar space, form macrofibrils (also referred to simply as fibrils, typically 0.5 μm in diameter). Macrofibrils are found within lamellae in the cell walls. The intermicellar and interfibrillar matrices, as well as the intercellular middle lamella, are composed of the non-crystalline components mentioned above – amorphous cellulose, hemicelluloses, pectin and lignin. The cell walls are organised in layers; the secondary wall is thicker than the primary (typically several microns, as opposed to several tenths of a micron), possesses a greater degree of crystallinity, and makes the dominant contribution to the physical properties of the fibre. In these cell walls, the microfibrils are wound with an angle and sense characteristic of the fibre species, for example, the secondary cell wall is S wound at $\sim 6.5^\circ$ for flax, or Z wound at $\sim 7.5^\circ$ for hemp.

Degradation of linen

Linen is subject to deterioration by a variety of mechanisms. Those believed to be applicable to the current state of the *Victory* sail are outlined below.

Cellulosic materials are susceptible to a range of degradation processes including those associated with chemical attack, photolysis, microbial and fungal metabolism, and thermal degradation. As cellulose comprises the major structural component of the fibres, its degradation may dictate the altered performance with ageing. In general, the deterioration of the material is due to oxidative processes or hydrolysis, leading to the scission of the cellulose polymer.

Moisture plays an important role in the stability of the fibres; cellulose is most stable within a relative humidity (RH) range of 45–6% (Lewin and Pearce 1998; Marshall 1992; Tímár-Balászy and Eastop 1998). Water is readily absorbed through the pre-existing network of pores where it will act as a plasticiser, particularly in the amorphous regions, and may disrupt hydrogen bonds. High humidities and excess water may cause swelling, leading to a deterioration in mechanical properties as well as rendering the fibres more prone to biological and chemical attack due to the opening of the polymer structure. Desiccation and shrinkage may occur at low humidities, resulting in the formation of additional hydrogen bonds and loss of flexibility; in more extreme conditions, condensation reactions between adjacent hydroxyl groups can occur, leading to cross-linking and a further rigidity. Dissolved salt will affect the way in which the fibres absorb water due to the presence of the hydrated ions, and on subsequent drying the crystallisation of salt within the material will lead to microstructural disruption.

Free radical thermal oxidation reactions may result in both cross-linking and chain scission, as well as discoloration (Lewin and Pearce 1998; Marshall 1992; Tímár-Balászy and Eastop 1998; Selli *et al.* 1998; Yatagai and Zeronian 1994). These reactions occur slowly at normal temperatures but are accelerated by the presence of pre-existing free radicals such as those arising from photoreactions. Lignin and, to a lesser extent, hemicelluloses are both more susceptible to thermal damage than is cellulose.

Cellulose is susceptible to attack by acids (e.g. those present as atmospheric pollutants or the products of oxidative

degradation via the mechanism of acid hydrolysis). This occurs rapidly and randomly throughout the chain, particularly in the amorphous regions, leading to the scission of the glycosidic ether bond and the formation of hydrocellulose fragments. The resulting material is highly crystalline, rigid and mechanically weak (Lewin and Pearce 1998; Marshall 1992; Tímár-Balászy and Eastop 1998; Feller *et al.* 1986).

Linen fibres are susceptible to damage by light, especially radiation in the ultraviolet (UV) region. On exposure, cellulose undergoes various photodegradative reactions including direct photolysis, photochemical and radical oxidation and photosensitised degradation (Lewin and Pearce 1998; Marshall 1992; Tímár-Balászy and Eastop 1998; Selli *et al.* 1998; Yatagai and Zeronian 1994; Dufour *et al.* 2000). These processes are accelerated by the presence of moisture and catalysts such as trace metals. Extensive photodegradation will lead to depolymerisation and the formation of a variety of small, water-soluble acidic species, which tend to be yellow or brown in colour, thus leading to discoloration. As a consequence of their solubility, they can readily be washed out of degraded fabrics, but this also risks further weakening the fabric itself.

Finally, cellulose is also susceptible to damage by a range of microorganisms, which break the polymer down to yield metabolites (Matthews 1947; Lewin and Pearce 1998; Marshall 1992; Tímár-Balászy and Eastop 1998; Selli *et al.* 1998; Yatagai and Zeronian 1994); by-products of these reactions, such as hydrogen peroxide and organic acids, may cause additional damage to the polymer. As with other forms of attack, microbial attack will preferentially occur when there is improved access to the polymer chain, specifically in the amorphous regions and in areas of pre-existing damage such as photodegradation or swelling. Hemicelluloses and pectins are also the targets of biological degradation, but lignin appears to exhibit some resistance.

Investigations on the sail

Various analyses were carried out on the sail in order to determine its current state, to suggest appropriate display and storage conditions, and to predict its likely future. The limited number of samples that could be taken from the *Victory* sail itself meant that surrogate materials were also employed; these were chosen to mimic various aspects of the *Victory* sail in order to more fully understand its behaviour. Surrogates included modern linen sailcloth from Banks sails, a sail from the *Standart* (a modern reproduction of the flagship of Peter the Great of Russia) that had been used at sea for a similar period to the *Victory* sail, and finally a range of sections of modern sailcloth subjected to accelerated ageing regimes; all of these materials were of a similar composition and weave structure.

The investigations employed a variety of methods. Mechanical testing was used to determine the tenacities of the component yarns and investigate the manner in which these values varied across the sail. Slippage tests gave an indication of the extent to which the movement of fibrillar elements within fibres, of fibres within yarns and of yarns within the bulk fabric affected both the overall strength of the material and the extent to which it could be loaded before permanent deformations were observed. Finally electron microscopy enabled the fibres to be closely examined in order to assess whether observed mor-

phological features could be linked to the measured physical properties.

Experimental method

Sampling and surrogates

Yarn samples, of approximate length 5–10 cm, were taken from the *Victory* sail (from areas of pre-existing damage so as to minimise the intervention). One of the sampling positions was chosen in an area where mould growth had been observed in order to assess the effect of this factor. Permission was also obtained to remove a single piece of sailcloth, approximately 4 × 3 cm in size, hanging by a thread.

Artificially aged surrogates were prepared from sections of the modern Banks sailcloth. These samples were aged using a series of steps outlined below and specimens were retained after each stage. These ageing methods were chosen to mimic the known history of the *Victory* sail: use at sea (1); exposure to sunlight (2); almost two centuries of storage (3) and, most recently, limited exposure to light again during display (4):

- 1 Immersion in heated brine (35% NaCl, 70 °C, 1 hour), rinsing and drying (at room temperature), a cycle repeated 24 times.
- 2 Exposure to high intensity simulated sunlight using a Philips 300 W 57265F/28 sunlamp for one week (120 klux, UV 200 W/m², at a temperature of approximately 40 °C), equivalent to one year's exposure to sunlight.
- 3 Heating in sealed vessels (100% RH, 70 °C) for seven weeks.
- 4 Exposure to high intensity simulated sunlight, as above, for a further week.

Similar yarn samples, as well as larger fabric sections, were taken from these surrogates as well as the Banks sailcloth and the *Standart* sail. The length of each specimen was recorded (tensioning the yarns slightly to remove the crimp imposed by the weave structure), as well as the mass, after which it was stored at a controlled humidity of approximately 60%.

Mechanical testing

Yarn samples from the *Victory* sail and the surrogates were subjected to mechanical testing; a gauge length of 2.5 cm was employed. Sections of yarn of approximate length 3.5–4 cm were taken and the ends set between pairs of acetate squares using LR White (medium grade) resin, leaving the central 2.5 cm of the sample free. All the samples were woven with a 'paired warp'; where warp yarns were tested, a single warp from the pair was taken.

To complement the 'dry' tests, wet mechanical tests were also performed on yarns from the *Victory* sail, the *Standart* sail and the Banks sailcloth, to assess the manner in which the properties of the fabrics altered on wetting. This was achieved by immersion of the samples in distilled water for approximately 30 minutes before testing.

A number of tests were subsequently carried out on sections of sailcloth. The single piece of sailcloth from the *Victory* was sufficient in size to allow a gauge length of 2.5 cm (in the direction of the warp) and a width of 1.5 cm. Samples from the *Standart* sail and Banks sailcloth of the same dimensions were also tested. In addition, to determine the effect of the length of the sample on the data, pieces of *Standart* sail of gauge lengths 10 cm and 45 cm were assessed.

The samples were loaded on an Instron 4301 mechanical tester equipped with either a 100 N (for yarns) or a 5 kN load cell (for fabric samples). The choice of load cell determines the force resolution of the experiment, being approximately $\frac{1}{250}$ (i.e. 0.4%) of the maximum load. For yarns, an extension rate of 10 mm/min and a data capture of 20 points/min were used. For fabrics, the respective values were 10 mm/min and 10 points/min. These tests were carried out under ambient conditions (approximately 23 °C and 55% RH).

Where available, multiple samples were tested to yield more accurate results. In the case of the yarns from the *Victory* sail, four samples from each sampling location were assessed; ideally a greater number of samples would have been used, but the size of these specimens was limited. For the *Standart* and Banks samples, where a greater quantity of material was available, six samples were tested.

Slippage tests

Slippage tests were performed on the bulk *Victory* sail and on sections of the *Standart* sail using a rig developed by Colin Appleyard of Hood Sailmakers. This device consists of an angled board with a wide (21 cm) set of fixing pins at the top and a narrower (10 cm) set attached to a movable beam at the base; these pins allow a 30–40 cm section of sailcloth to be firmly affixed to the apparatus, after which it is secured by wooden battens. Weights can be attached to a cord and pulley system, which, due to the minimal friction between the base and the cloth, enables the material to be subjected to the equivalent of vertical loading. Measuring the batten-to-batten distance allows the extension of the sailcloth to be monitored. Although this test is not strictly non-destructive, as it is likely to result in a permanent deformation of the fabric, it was considered that the benefit in terms of the critical data provided by the test outweighed any concerns over the albeit relatively minor distortion that might occur. In any case, this would be limited to a small region of the cloth and would not noticeably disfigure the sail given its already generally uneven nature.

Nonetheless, the slippage tests were restricted to just four locations on the *Victory* sail. Initially a 1 kg weight was applied and the extension measured after 15 minutes. Further weights were then applied in 1 kg steps and the extension similarly recorded. After loading to the maximum required weight, the extension was monitored for up to three weeks. The weights were then removed and the cloth allowed to relax under ambient conditions for a week or more. After this period, the extension was re-measured, and again after reloading with 1 kg for 15 minutes.

To determine a suitable range of weights for these tests, the loading to which the sail might be subjected was estimated. At the head, the sail is approximately 16 m wide. Hung vertically,

with the head of the sail bearing the full load across its width, a 10 cm span would be expected to carry a load of roughly:

$$360 \text{ kg} \times (10 \text{ cm} / 1600 \text{ cm}) = 2.3 \text{ kg}$$

Due to the significant loss of material at the head, however, the majority of the weight would be carried by roughly one-third of the full width, increasing the load per decimetre to 6.8 kg. Therefore loads between 2 and 8 kg were employed. The details of loading weights and times are presented in Table 1.

Table 1 Loading regimes for the *Victory* sail slippage tests.

	Site			
	1	2	3	4
Maximum load/kg	8	5	4	2
Loading duration/days	5	7	5	21
Relaxation period/days	9	7	9	10

Electron microscopy

After mechanical testing, small sections (~ 1–2 mm) of the yarns from the *Victory* sail and the surrogates were mounted on aluminium stubs, gold coated and then examined using a Philips XL30 ESEM under high vacuum conditions with an accelerating voltage of 20 kV. Secondary electron micrographs of regions of interest were recorded.

Results and conclusions

Breaking load and tenacity

The yarn breaking loads, along with the sample lengths and weights, were used to calculate tenacities, a measure of the strength of material per unit linear density, as:

$$t = \frac{F_B \times l}{10 \times m}$$

where: t = tenacity (cN tex^{-1}); F_B = breaking force (N); l = yarn length (m); m = yarn mass (g); and linear density (tex) = m (g)/1000 l (m).

Average tenacities determined for the *Victory* sail and the various surrogates are presented in Table 2, along with wet

Table 2 Calculated average tenacities (cN.tex^{-1}) for warp yarn samples from the *Victory* sail and surrogate materials.

Sample	Standard test		Wet test	
	Tenacity	Std. dev.	Tenacity	Std. dev.
<i>Victory</i> sail	5.1	2.5	2.4	0.6
<i>Standart</i> sail	3.0	0.6	1.0	0.2
Banks sailcloth	17.6	2.1	19.2	0.7
Artificially aged (1)	14.4	1.6	–	–
Artificially aged (2)	6.9	0.9	–	–
Artificially aged (3)	5.1	0.4	–	–
Artificially aged (4)	3.4	0.2	–	–

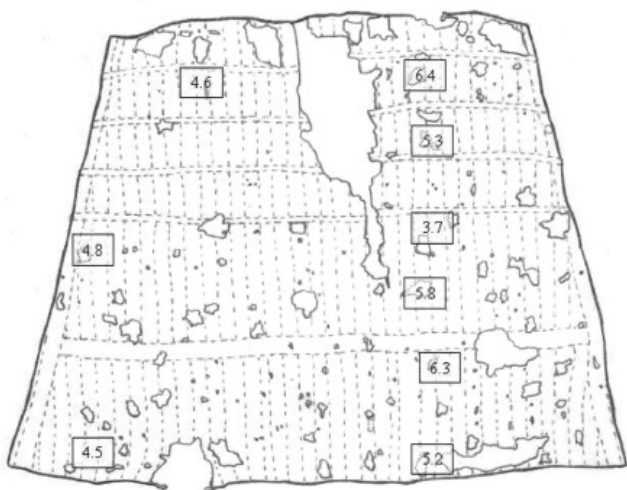


Figure 2 Diagram of the fore topsail of HMS *Victory*, with tenacities (cN.tex^{-1}) at selected sampling positions across the sail.

tenacities where appropriate. Tenacities measured for various sampling positions on the *Victory* sail are shown schematically in Figure 2.

It can be seen that the values for the *Victory* sail yarns are all quite close, and that they do not appear to vary in a systematic manner across the sail. Similarly, the value for the samples taken from the area that had suffered surface mould growth is within the range of the data from the other warp yarns, suggesting that the mould has caused little significant microstructural damage to the fabric.

On the basis of the tabulated data, it is apparent that the *Victory* and *Standart* sails have deteriorated to a similar extent. Their yarn tenacity values are significantly lower than those for the new Banks sailcloth. This conclusion is supported by the wet tenacities, which show that while the Banks sailcloth increases in strength on wetting (as would be expected for new linen), both the *Victory* and *Standart* sails lose strength under these conditions. Additionally it can be seen that the latter two stages of the artificial ageing regime yield materials with similar mechanical properties to the *Victory* sail itself, with photo-ageing at stages 2 and 4 having the most dramatic effect on the linen.

Sailcloth pieces

Breaking loads in the warp direction for the 1.5 cm wide sailcloth sections, including the piece from the *Victory* sail, were measured, giving the results presented in Table 3 (a). To determine the correlation between the properties of individual yarns, and the bulk properties of the fabric as a whole, the average breaking loads per yarn from the individual yarn tests and from the sailcloth piece tests were determined from the breaking strengths and the warp counts (Table 3 (b)). For the *Victory* sail sample, the warp yarns used for comparison were taken from the piece adjacent to the section used for the fabric testing and were of relatively poor quality. Nonetheless, it can be seen that there is a good correlation between the breaking load of individual yarns and that of the sailcloth pieces, an important consideration when attempting to extrapolate data derived from yarns to the fabric as a whole.

It should be noted that the breaking strength of the *Victory* sail piece is significantly lower than the values typically observed for the other samples taken from the sail, around just 10% of the average value. This suggests that in addition to the general deterioration of the fabric, there may be particular areas, probably around the holes, in which the sailcloth has been weakened to an even greater extent.

Sample length

When assessing the mechanical strength of the material, the sample length is also an important factor. In addition to failure caused by the rupture of individual fibres, failure is also possible due to fibres slipping past each other. For short samples, fibre fracture and slippage of the ultimate cells (approx. 3–5 cm in length) are important. Slippage of the fibres themselves needs to be borne in mind as well once the length of the yarn sample approaches that of the staple, i.e. the length of the fibres, which is generally 10–20 cm for the tow (the short, coarser fibres used for canvas). If fabric pieces are used which are short with respect to the fibre length, it is unlikely that a significant number of fibre ends will be found in the sample, and so this failure mechanism will not be observed. In order to obtain a more accurate indication of the strength of the material it is necessary to use a sample of sufficient length so that both the rupture and slippage mechanisms will take effect.

Given the typical staple length for flax fibres, it was assumed that the data derived from 45 cm long sections would be representative of the sailcloth as a whole. It was only possible to perform this test on samples taken from the *Standart* sail as sufficiently large pieces of the other two specimens were not available. The results are presented in Table 4, and from these data it can be seen that the slippage mechanism is an important aspect of failure: changing from a 2.5 cm to a 45 cm gauge length leads to the breaking strength dropping to approximately 82% of its original value.

Slippage tests

Beyond the elastic limit, the extension observed in a fabric can be categorised as either primary or secondary creep. The

Table 3 Derived mechanical properties for sailcloth sections (derived from both yarn and cloth tests).

Source	(a) Physical properties of sailcloth sections			(b) Average breaking load per yarn/N	
	Breaking load/N	Std. dev.	Warps/cm	Yarn	Cloth
<i>Victory</i> sail	24	—	21.6	0.4	0.7
<i>Standart</i> sail	147	56	23.0	4.5	4.3
Banks sailcloth	831	47	19.8	27.7	28.0

Table 4 Breaking loads for sections of *Standart* sail of various gauge lengths.

<i>Standart</i> sail test specimen lengths	2.5 cm	10 cm	45 cm
Average breaking load / (N/cm width)	89.1	78.8	73.2
Average breaking load / (N/warp)	4.5	4.0	3.7

former is reversible whereas the latter is irrecoverable. Initially an applied load will serve simply to decrimp a woven cloth, tightening the weave and straightening the warp yarns. After decrimping, subsequent extension may be reversible or irrecoverable. Ultimate cell and fibre slippage will give a permanent extension. Intra-fibre cellulose polymer chain straightening is likely to be elastic but polymer chain slippage will eventually result in lasting deformation. For the *Victory* sail yarns, the recoverable extension due to decrimping, and perhaps elastic stretch and primary creep of the cellulose polymer, is about 4%.

Load versus extension plots for the slippage tests are shown in Figure 3. At site 1, a sharp increase in elongation was observed on loading over 6 kg. A small extra creep took place over the following four days and after relaxation a permanent extension of a few per cent remained. At site 2, with a 5 kg total load, there was still a residual extension after the relaxation period. An equilibrium appeared to have been reached after the initial loading, but creep began after the load had been maintained for three days. Site 3, with a loading of 4 kg, exhibited decrimping throughout the loading period. This load was removed when the extension appeared to reach the limit required for the tightening of the weave and the cloth subsequently relaxed almost completely. The lowest load (of 2 kg) was applied to site 4, and the initial extension was similar to those observed for the other sites; after elongation was observed for four days, it remained constant over the next

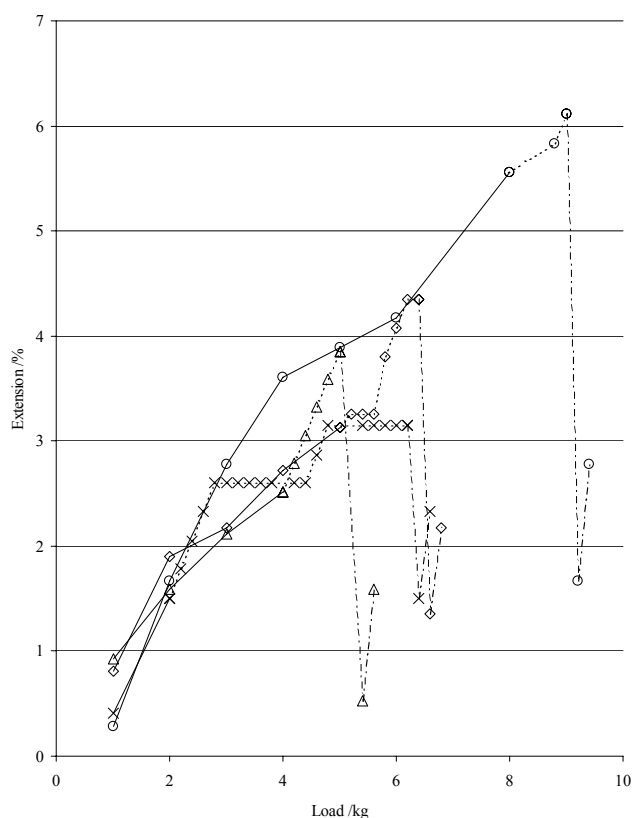


Figure 3 Load versus extension plots for the four slippage tests (1: ○; 2: ◇; 3: △; 4: ×). A solid line indicates the extension during initial loading, a dashed line the extension during the period of maximum loading (one day is equivalent to a 0.2 increment on the abscissa), and a dotted-dashed line denotes relaxation. In each case the penultimate point was recorded with no load and the final point with a 1 kg load after relaxation.

eight days. There was then further extension, although this stabilised again, but a permanent residual elongation resulted.

From these data it can be seen that permanent deformation can arise in two ways. It will occur rapidly if the material is subjected to a large, short-term loading, as might be expected. It will also happen, however, if the cloth is subjected to a much smaller load for prolonged periods.

Conclusions for mechanical studies

Noting that a good correlation can be drawn between the breaking strengths of individual yarn and the bulk fabric, and taking into account the average warp count for the *Victory* sail and the calculated contribution from the slippage failure mechanism, the weight that the sailcloth might bear (not taking into account the areas of loss and bulk damage) can be calculated:

- Breaking load, F_B : 8.5 N/warp \equiv 0.87 kg/warp
- Warp density: 21.6 warps/cm
- Slippage factor: 82%

The estimated breaking load for the sail is approximately 154 kg/10 cm. This compares to a value of 565 kg/10 cm for the Banks sailcloth, assuming that the samples tested are representative.

The fact that some specific areas of the sail, probably around holes, exhibit significantly poorer mechanical properties than the bulk (as highlighted by the results from the piece of *Victory* sailcloth tested), suggests that to minimise the risk the limit should be further lowered, to around 15 kg/10 cm. This suggests an adequate safety margin, since, from the above calculations, the load expected to be borne by the head, if the sail is hung vertically, is only 2.3 kg/10 cm.

The limit may be set even lower, however, if it is felt appropriate to restrict the extension. While pristine linen will withstand an extension of 2–5% before permanent deformation, such irrecoverable damage may occur at shorter extensions for the *Victory* sailcloth, given its degraded nature. Limiting the extension will further reduce the maximum load that may be applied to the sail.

The results of the sailcloth slippage tests further highlight the fact that even if subjected to a relatively low load (for example, 2 kg/10 cm), creep will still occur over time. The implication is that a permanent deformation will result even if the sail is fully supported across the head with the weight evenly distributed.

We conclude that undue and prolonged stress should be avoided when handling the sail during its conservation and that for its display the sail should ideally be positioned at a shallow angle, on a suitable support, so that the effective loading of the cloth is substantially reduced.

Electron micrographs

Typical electron micrographs are presented in Figure 4.

The deterioration of the *Victory*, *Standart* and surrogate samples was apparent through fractures in the fibres (Fig. 4 a and b), regions of defibrillation and extensive debris on the

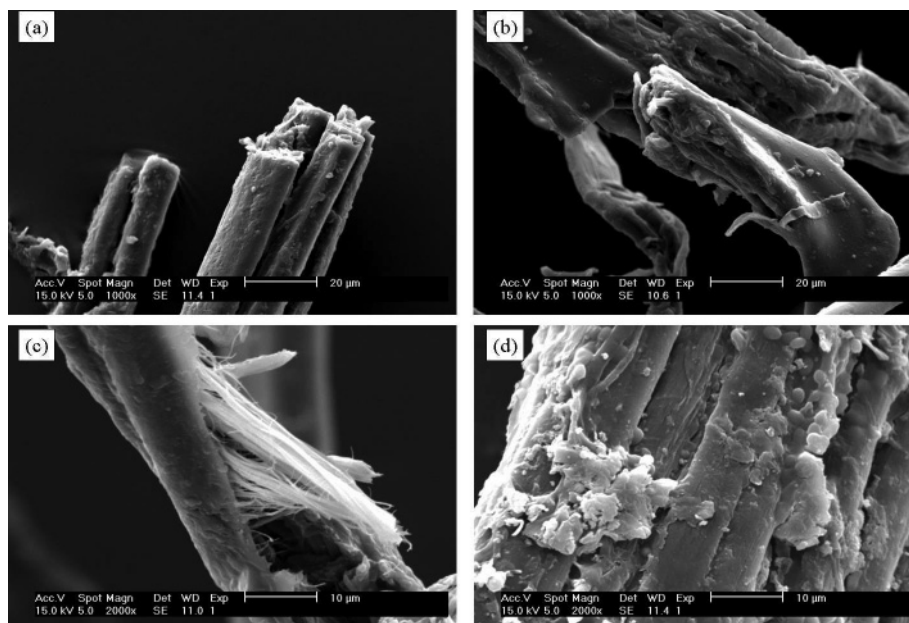


Figure 4 Electron micrographs of various sailcloth samples: (a) smooth fracture surface of *Victory* sail yarns; (b) fibrillar surface of Banks sailcloth yarn; (c) defibrillation of *Victory* sail yarn; (d) mould growth on *Victory* sail yarns

fibre surfaces (see Fig. 4c). In addition, in the sample taken from one of the regions of the *Victory* sail, mould growth was evident (Fig. 4d). These features were not observed with the modern, unaged material.

When the fracture surfaces resulting from the mechanical testing were examined, it was clear that the nature of the surface reflected the state of deterioration of the material. With new materials (i.e. the Banks sailcloth) fractures showed extensive evidence of the fibrillar nature of the fibres (Fig. 4b for example). With more heavily degraded materials, however – such as the *Victory* sail itself, the *Standart* sail and the artificially aged surrogate materials – these surfaces became progressively smoother and of a less obviously fibrillar character (Fig. 4a). This was taken to suggest that in the degraded materials the accumulation of faults within the sample results in brittle fractures readily propagating across the width of the fibre, whereas in the less heavily deteriorated specimens, this propagation cannot so easily occur and instead the fracture results from a series of discrete failures of the individual fibrillar elements at points of weakness.

These observations confirm the conclusions drawn from the mechanical testing and demonstrate that a limited indication of the state of degradation of these types of material can be derived from microscopic examination. These data do not, however, provide sufficient information to obtain accurate quantitative conclusions as to the physical state of the artifact with the currently available methodology; for this the more thorough approaches detailed above are required.

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