14. Bundle Strength

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Learning objectives

By the end of this topic, you should have:

- an appreciation of the difference between bundle tenacity, staple strength and intrinsic fibre strength
- an understanding of the measurement methods for bundle strength and their limitations
- an appreciation of the key factors that affect bundle strength
- an understanding of the impact of lowered fibre strength (bundle and staple) on processing

Key terms and concepts

Single fibre vs. bundle tenacity, extension at break, intrinsic fibre strength, load/extension curves

Introduction to the topic

This topic examines what is meant when we refer to the strength of a top. The average tenacity is usually expressed in terms of bundle strength. The measurement of bundle tenacity and intrinsic fibre strength are examined in terms of the methods and how they depend on and relate to the strength properties of individual fibres, to staple strength, and to variations within and between fibres. The test methods and instruments for measuring bundle strength are briefly examined with particular emphasis on Sirolan Tensor. Finally, the potential causes and implications of differences in fibre strength are examined in terms of their effects on yarn properties and spinning performance.

14.1 Tenacity vs. Strength and Bundles vs. Staples

Wool metrology is the measurement of the properties of wool. We need to measure the properties in order to establish whether a given lot of wool will be suitable for a particular end-use and to be able to predict how it will perform in processing. This will establish whether it meets the customer's needs and enable it to be correctly valued. Strength is potentially important because weaker fibres can be expected to break more in processing, giving a shorter top and more wastes. The yarns might then be weaker and suffer more ends-down in spinning, break more in weaving or knitting and even detrimentally affect fabric performance.

The instruments that measure strength hold a group of prepared fibres (e.g. a staple or bundle) between jaws then extend the jaws at a fixed speed or rate of loading, while monitoring the force, until all the fibres are broken. The mass of fibres is then measured. The procedure is repeated for many staples or bundles.

Staple strength (SS), a property of greasy wool, is used with other fibre properties to estimate the likely mean fibre length and wastes in topmaking. As discussed in an earlier topic, and below, SS is technically a tenacity in which the peak force at break is normalised by the mean linear density of the staple. So it is an attempt to quantify the mean material strength of greasy wool. Bundle strength is a property of tops (or slubbings or rovings) and is used to assess whether the fibres have been damaged to an extent that would affect spinning and yarn performance. Again it is a tenacity and an attempt to quantify the mean material strength of top. The peak force at break is divided by the mean linear density of the bundle of fibres held by the jaws. The main differences are that the staple test grabs the ends of the staple and weighs the broken halves whereas the bundle test grips a short length (typically 3.2mm between the jaws)
of partly straightened fibres, cuts off fibres extending beyond the jaws, and weighs the length held by the jaws.

Staple strength and bundle strength are both measures of the mean strength of individual fibres. However, the peak force will be affected by the extent to which fibres share the load as well as the extent to which the mean linear density at the point of break is correctly measured. The usefulness of each measure not only depends on its ability to accurately and precisely measure average material strength but also the extent which this property can be used to predict performance in processing. A key issue is the way in which variation along and between fibres affects the total load that can be borne by the staple or bundle.

**Load/Extension Curves**

The effects of fibre length variation and fibre thickness variation on the way in which groups of fibres share the load needs careful consideration. This is best done by considering the nature of the load/extension curve of a single fibre and then to work out how such curves can be summed when fibres are different. The typical stress-strain curve of a fairly uniform single wool fibre is shown in Figure 14.1. There is a steep Hookean region that occurs in the first few percent extension, followed by an almost flat Yield region out to about 30% extension, then a Post-Yield region out to failure. The slope of the yield region appears to be higher in air (above the glass-transition temperature) than in water, and this slope is increased and the slope of the Hookean region and apparent extension to break decreased by non-uniformity in the cross-sectional area of the fibre (Collins & Chaikin 1969; Feughelman & Robinson 1967). For a given total extension, thinner sections will be more, and thicker section less, extended.

The long, nearly flat, yield region distinguishes animal fibres, like wool, from cotton and most synthetics. Relative to such fibres, wool has a very high extension to break but a low peak force at break (see, for example, Morton & Hearle 1965). Moreover, because wool is a glassy polymer whose glass-transition (softening) temperature depends on moisture content the stress-strain curve is quite sensitive to ambient conditions.

For a bundle of straight, non-interacting, fibres all extended by the same amount, the combined stress-strain curve will be the average of the single fibre curves out to the extension at which the first fibres start to break. If the fibres do not all have the same straightened length between the jaws then the initial slope will be lessened but the peak force will hardly be changed, provided all fibres are extended into their yield regions before any fibres start to fail.

![Figure 14.1 Idealised stress-strain curve for a single fibre.](image-url)

The net effect is for the load/extension curve of a bundle of fibres to have the general form shown in Figure 14.2.

After a short extension most fibres are in the Hookean region (steep) then, as some fibres or parts of fibres reach the Yield region the curve takes a lesser slope until some fibres begin to fail. Soon loss of strength due to fibre breakage exceeds the increased load taken up by the remaining fibres and the curve peaks and turns down until all fibres are eventually broken. The maximum load (breaking load) is referred to as the peak force at break and is shown together
with the extension at break. The total area under the curve is the work-to-break and should correspond to the sum of the work needed to break all fibres.

Any repeatable test of fibre strength must specify the test conditions of temperature and humidity and speed of testing because, as a glassy polymer, wool behaves differently (the shape of the load/extension curve changes) under different conditions, particularly as a function of water content. The faster wool is tested the more brittle it becomes (higher load, lower extension). The wetter the wool the more plastic (lower load, higher extension) it becomes, while both load and extension decrease at higher temperatures (Yang and Schütz 1998).

Figure 14.2 Realistic stress-strain curve for a bundle of fibres.

### Tenacity of Bundles

The definition of tenacity is the peak force at break divided by the cross-sectional area at the point of break. For a single fibre you can, in principle, measure the diameter or cross-section of the broken ends (if they have not been permanently distorted by the breakage process). In the bundle and staple tests the cross-section is estimated using the weight and length of the group of fibres. However, variation in cross-sectional area along fibres and the presence of less than full-length fibres means that the estimated total cross-section is always larger than the actual total minimum cross-section and the measured tenacity is always less than the true tenacity or underlying material strength. The peak force at break is also an underestimate of the total force (the sum of all the single fibre peak loads) that would be measured if all fibres broke simultaneously, i.e. all reached their peak loads. Calculation of the effect of bundles, i.e. variations within and between fibres, on tenacity requires some modelling of fibre bundles.

### Models for Collective Effects in Fibre Bundles

Fibre length variation between the jaws affects the extent to which the individual fibre contributions can be added. Differences in fibre length between the jaws mean that the loads will be taken up at different times affecting the degree of overlap. However, the extent of overlap will depend not only on the variation in lengths but also the variation between fibres including variation in their extension at break. The load/extension curves of fibres which have a low extension at break (short, marked thin places) will overlap less than fibres which are just as thin but have twice the length of thin place and hence twice the extension at break.

For staples, the range of fibre lengths can be expected to be correlated with the between-fibre diameter distribution because of the strong correlation between length and diameter within a staple (Ford 1990) and a weak correlation has been observed (Peterson, Gherardi & Doyle 1998 and Schlink, Brown & Longree 2000). For bundles, the range of fibre lengths will depend on the extent to which all fibres are straightened (de-crimped) and parallel.
For straightened fibres is bundle testing the fibre lengths are fairly similar. For staples the range of fibre lengths is much larger. This can be seen by pulling on the two ends of a staple. It will be observed that some fibres take up the load while the crimp wave of the majority of fibres is still clearly visible. For bundle testing, if the fibres do not all have the same straightened length between the jaws then the initial slope will be lessened but the peak force will hardly be changed, provided all fibres are extended into their yield regions before any fibres start to fail. This is shown in Figure 15.3 (taken from Huson and Sambell 1998) where the contributions of a large number of single fibre curves was summed. The curves A, B, C, D correspond to increasing coefficients of variation in the length of fibres between the jaws.

![Simulated stress-strain curve from summing fibres](image)

Figure 15.3  Simulated stress-strain curve from summing fibres (tested at an effective gauge of 5mm) but with varying spreads in length between the jaws. Source: Huson and Sambell (1998).

A more complex analysis of bundle effects has been made (Lamb 2004a). If fibres vary in their cross-sectional area then the thin section of a fibre will be extended in proportion to its diameter squared and so, when a load is applied, will reach the yield region before other parts of the fibre. If the slope of the yield region was zero then only this region would be further extended until the post-yield region was reached. The small slopes of the yield and post-yield regions relative to the Hookean region mean that fibre sections which are significantly thinner will fail before most parts of the fibre have been extended out of the Hookean region. Thus the extension at break for the whole fibre will be much less than the extension of the thinnest region.

The effect of a marked thin place is that most parts of the fibre will only be strained by a few percent when the thinnest section fails at something over 30-40% extension. Thus a single fibre extension at break of 5% may mean that the failure region was initially no more than about one tenth of the length of the fibre, i.e. one tenth of the fibre extended by 40% and nine-tenths extended by 1%. In a bundle of fibres that take up the load at different times, due to differences in straightened length between the jaws, the single fibre extension at break can strongly influence staple strength. If the extension to break is small relative to the spread in lengths then many fibres will break before others begin to share the load.

The above discussion applies to both staples and bundles of fibres. For bundles of fibres from top samples the fibres are more straightened than for staples while they are likely to be slightly more variable in properties. For bundles the test length is much shorter (and the fibre segments should come from a wide range of positions along staples) so variations in diameter along-fibre are much less important. The signature that all fibres have reached the yield region is that there is a second stage in the load-extension curve of approximately constant slope as in curve A of Figure 15.3. For fibre bundles tested at a short gauge the variation in strain (extension) at break appears to be much higher than the variation in fibre lengths between the jaws (since the fibres have already been straightened in preparation of the top and are also pre-tensioned). In this case the peak force is not significantly reduced by the spread in lengths and so bundle tenacity should be a good measure of single fibre tenacity. For staple testing the gauge length is much longer and fibres are substantially crimped so that the variation in length of fibres between the jaws is likely to be much larger than for fibres in a bundle tenacity test. Moreover, the minimum diameter for every fibre will be between the jaws. It is therefore likely that not all
fibres will share the load before some fibres start to break. For fibres of constant material strength, the peak force will be determined by the mean and range of minimum cross-sectional areas, together with the single fibre elongations and spread in fibre lengths (both of which affect load sharing). The peak force is then divided by the mean cross-sectional area, calculated from the mass of fibre divided by the length, to give the tenacity.

**Intrinsic Fibre Strength**

The strength of a single fibre is dependent on variations in the cross-sectional area of the fibre and on the variation in the intrinsic strength of the fibre material. The intrinsic fibre strength (IFS) is the tenacity of a single fibre obtained by measuring the force to break the fibre divided by the cross-sectional area at the point of break. This is laborious and suffers from the difficulty of getting an accurate measure of the cross-section of the point of break which may be irregular and may have been distorted by the breakage process. IFS is a measure of the inherent tenacity of the wool complex at its weakest points. There may be other places along the fibre where the tenacity is different.

An instrument named the Single Fibre Analyser (SIFAN) (Peterson et al. 1998) enables a relatively fast simultaneous measurement of the diameter profile and the breaking force of single fibres and hence an estimate of IFS. The instrument can also measure the diameter profile along the pre-tensioned wool fibre after rotation through 90º if desired before extending the fibre to break while recording the load/extension curve. While diameter can be recorded every 40 µm along the fibre, the profile of each fibre is eventually reduced to 50 data points by averaging a sequential number of raw data measurements. The minimum of the 50 data points is then used to calculate the minimum cross-sectional area of the fibre. It is implicitly assumed that fibres break in the region of the minimum diameter.

### 14.2 Measurement Instruments for Bundle Tenacity

The existing test method (IWTO-32-82(E)) for Determination of the Bundle Strength of Wool Fibres is somewhat dated as it was approved in 1979. It is based on the use of a mechanical instrument called the Stelometer or the use of a special accessory to clamp the fibre bundle for testing on any normal strength tester such as an Instron. The Stelometer uses a pendulum arm to apply a steadily increasing load while “normal” strength testers move the jaws apart at a constant rate and measure the required force. The two types of instrument are thus characterised as constant rate of load or constant rate of extension. The apparent strength of wool depends on the test speed so, for comparable results, the time taken to break the fibres should be similar for the two cases.

Each fibre bundle is prepared between a pair of jaws using special accessories and the jaws are then loaded into the strength tester. It is important that fibres are not allowed to slip while being broken and historically this was achieved by using leather-coated Pressley clamps which are closed using a torque spanner. More recently the leather has been replaced by special paper. The fibres are clamped on one side before being straightened and parallelised by combing and then pre-tensioned by a fixed amount using a manually activated gripper and a pre-tension lever. The length of fibre being tested can be varied by placing spacers between the pairs of jaws, but the standard spacings are 3.2, 5 and 10mm.

The test procedure involves "squaring" the top, which then allows groups of fibres to be withdrawn with their ends approximately aligned. A number of such draws are overlaid and the bed of fibres is then cut to a length of 45mm and a subset of these fibres is picked up from the opposite end to which they were aligned and loaded into the clamps. The combing will then remove most fibres that did not reach to 45mm. After combing, pre-tensioning and clamping the ends of the fibres protruding from the outsides of the jaws are trimmed using a razor blade. The clamps are loaded onto the tester and the force to break is measured. The fibres are then scraped off the jaws and weighed. At least 10 tests must be performed and the spread in results (CV) must be less than 3% or more tests performed. A single set of measurements, one wool lot, takes at least an hour.
Testing must be carried out at standard conditions of temperature and humidity (20 ± 2 °C and 65 ± 2% r.h.) and the sample must have been kept at these conditions for at least 24 hours before testing and equilibrium of the wool must be reached from the dry side.

Early on in the development of predictions for yarn tenacity (Sirolan Yarnspec) it was found that, even for undyed top, a measurement of bundle tenacity could significantly improve the prediction of yarn tenacity. However, relative to the time taken to measure other fibre properties (D, CV_D and H) the measurement of bundle tenacity was extremely slow and of poor accuracy. This stimulated the development of an improved instrument (Sirolan Tensor) that used know-how from the design of jaws for the Atlas staple strength tester.

**Sirolan Tensor**

The instrument uses a load cell to measure force and an LVDT to measure position while the jaws are moved apart at constant speed. The biggest improvements relate to the improved jaws, the incorporation of the jaws and fibre preparation onto the machine rather than using separate accessories, a special pre-tensioning method and the interfacing of the weighing device, calculations and data storage under the control of user-friendly software. The instrument is shown in Figure 14.4.

![CSIRO Sirolan-Tensor wool strength tester](source: CSIRO Textile and Fibre Technology)

The software asks for the sample to be weighed after breaking is complete and then automatically calculates the tenacity and other parameters. The jaws use compressed air and special rubber to clamp the fibres extremely strongly and reproducibly. Two additional clamps are provided. One allows short fibre that would not span the main jaws to be combed out from the fibre beard. The other provides a slipping pre-tension to the beard prior to clamping.

The slipping pre-tension is a unique development that contributes significantly to reduced operator dependence and improved accuracy. The pre-tension jaw slides over the fibre beard thereby straightening fibres and removing crimp while actually providing very little final tension. The normal pre-tension method appears to straighten fibres but, because it allows no relative movement, it just causes some fibres to be more highly tensioned, i.e. stretched, and does not alter the untensioned length of fibres held between the jaws. With the old method a significant dependence of bundle tenacity on crimp is observed, because crimp induces a range of lengths in the fibres held between the jaws. It can be shown that the effect is not a real correlation between strength and crimp (curvature) because a similar effect is observed when the same wool top is allowed to recover different amounts of the greasy wool curvature by relaxation. The new pre-tensioning significantly reduces the effect although it does not completely eliminate it. The effect also leads to a problem because of the requirement that the wool be conditioned from the dry side. The rapid temperature change due to oven-drying of a wool sample causes partial crimp recovery, even when the sample is held in a twisted state. This means that the curvature tends back towards that of the greasy wool, which is significantly higher than that found in tensioned top. The result is that measured BT decreases a variable amount with oven drying and reconditioning.
The rate of extension is user selectable but the normal rate is 20mm/min, which for a 3.2mm gauge is much faster than the recommended rate of 100%/min in IWTO-32-82(E). The new method is also less dependent on the weight of the bundle tested so that the allowed weight corresponds to 500 ± 100 tex compared with the previous 350 ± 50 tex. The wider weight range makes it easier for the operator and the reduced errors in testing mean that sufficient accuracy appears possible with 5 samples, instead of 10, tested per wool lot. Preparing the bundle in situ is also quicker so that overall the total test time is reduced by a factor of 3 to 4, i.e. to 15 to 20 mins. This is still slower than desirable and compares poorly with the speed of strength testing in the HVI (High Volume Instrument) method used in cotton testing.

Studies over a wide range of temperature and humidity (Yang and Schütz 1998) have allowed correction algorithms to be incorporated into the software that convert measurements at fixed conditions other than the standard 20 ± 2 °C and 65 ± 2% r.h. (e.g. 27 ± 2 °C in tropical countries) back to standard conditions. The revised method based on Sirolan Tensor has not yet become an official IWTO standard but this is more to do with the difficulty of commercialising a new machine that has only a limited market. The instrument has also been used in studies of the strength of woollen slubbings, alpaca fibres, flax and synthetic fibres.

The instrument has also been used to show a flaw in the existing method when there is significant along-fibre variation in diameter. When the top is squared half the fibres in the sample have their tips approximately aligned and half their bases. If there has not been a large amount of fibre breakage in processing and the profiles of different staples are similar (as occurs with wools shorn at a similar time from one geographical area) then the thinnest part of fibres may be significantly aligned. The measured bundle tenacity will then depend on the position of the weak section relative to the jaws. Decreases of 10% in BT along the bundle have been observed when the aligned ends of similar such bundles were placed at sequential positions relative to the jaws.

14.3 Compare Staple Strength, Bundle Strength & Intrinsic Fibre Strength

We have three measures of fibre strength. Before examining their relationship to processing performance we will compare and contrast them and explore how differences arise. Staple strength (SS) and bundle strength are both measures of the mean tenacity of individual fibres. However, the peak force will be affected by the extent to which fibres share the load as well as the extent to which the mean linear density of the points of break is correctly measured. Variation along and between fibres affects the total load that can be borne by the staple or bundle. The variation can be in the material strength (IFS), in cross-sectional area (diameter profile) and straightened length.

The ATLAS measurement of SS uses the measured length of a staple to position jaws to grab each end. It determines the force required to break a staple at its weakest point, which is usually the region of minimum total cross-sectional area. The peak force at break is normalised by the average linear density, determined from the weight of the staple corrected for the measured length and yield. Staple strength thus has units of tenacity (N/ktex) but the mean linear density rather than the minimum is used. The peak force results from the combined behaviour of a large number of individual fibres. Any variation in thickness along the fibre reduces the total load that can be supported and variation between fibres in thickness and length means that they can extend at different times and rates and so not share the load equally or not break at the same time, which reduces the peak force. Thus staple strength is a measure of the average strength of the weakest places in single fibres modified by their collective behaviour and normalised by the average linear density.

The Tensor measurement of bundle tenacity (BT) is normally carried out on top. It uses a much shorter gauge than staple testing, the fibres have been straightened (much of the crimp removed) both by processing to top and by the combing and slipping pre-tension used in the instrument, and the fibres have been somewhat randomised by processing. The blending and shuffling in processing mean that the sample between the jaws should be representative of the mean along fibre strength, whereas staple strength is strongly determined by the weakest places along the whole fibre and the similarity between fibres within the staple. If all fibres were
straight, parallel, independent and broke at the same time the peak force would be the sum of the single fibre peak forces. If the fibres were also of constant cross-section then a measurement of the mass of the known length would give the correct linear density and full IFS.

**Variation in Length**

Since greasy wool fibres are crimped their average length is longer than the measured staple length. The mean fibre length of fibres in a staple has been found to be, on average, 1.17 times the staple length, but has been observed to vary from just over one to 1.35. A more recent review claims the average ratio of fibre length to staple length to be in the range from 1.18 to 1.43 (Murray 1996). Moreover, all fibres within a staple do not have the same straightened length and the individual fibre length and diameter are correlated. The crimp cannot be removed just by pulling the ends; the fibres do not all take up the load simultaneously. Staples can also contain shed fibres – when the fibre follicle has shut down – which do not contribute to the load bearing.

The carding, gilling and combing steps of topmaking remove much but not all of the crimp in individual fibres. In bundle testing it is desirable to remove any remaining crimp and also any fibres that do not span the full length from outside of one jaw to the other. The straightening and parallelisation must be more accurate the shorter the gauge. The straightened fibres need to all be carrying the same, preferably very small, load. It is not just a matter of gripping and pulling the ends because the already straightened fibres will take up more of the stress and so break sooner anyway. The Sirolan Tensor tries to achieve this with a slipping pre-tension but it is still observed that the measured bundle tenacity depends weakly on the measured fibre curvature. This is not due to a correlation between curvature and strength because it is still observed with the same wool top where different curvatures are obtained by allowing the fibres to relax (i.e. recover some of their original crimp) before testing.

**Variation in Diameter Profile**

Variation in diameter, and hence cross-section, along and between fibres can lead to an underestimate of the actual total linear density of fibres being broken, as well as altering the extent of load sharing between fibres, and so affect SS and BT. Researchers therefore developed methods of determining mean fibre diameter along the length of staples. Diameter also varies between fibres so there can be coefficients of variation both along staples and between fibres across staples. The latter does not affect the measurement of linear density and would not affect the load sharing if all fibres had the same load/extension curves.

**Variation in Material Strength**

Measurement of the material strength (IFS) of single fibres is slow and error prone. Fortunately, it has been shown (Gourdie et al. 1992) that most fibres are cleaved in smooth plane fractures normal to the long axis of the fibre, so that a reasonable estimate of the cross-section can be made. Any error in the measurement of diameter will affect the calculation of IFS so, even if all fibres had identical IFS, any such error will introduce a bias such that the thinnest places will appear to have higher IFS. In a study using SIFAN (Peterson & Lamb 2005) repeat measurements of IFS after selection of fleeces into groups of extreme IFS reduced the apparent difference in mean IFS from a factor of 2 to just 13%. This indicated that there were large differences between fibres or between staples or large measurement errors. Therefore, a number of fibres were divided into three and the middle section (containing the thinnest place) and the last third were measured for IFS. A negligible relationship between the IFS of the middle and the last third section of the same fibre was found. Taken together with other studies it appears that there can be large variations in IFS both within and between fibres.

**Relative Contributions of Variation in Diameter, Length and Material Strength**

An overview of work, compiled by Adams and Kelly (2000), includes a joint paper by a number of the different workers in this area (Schlink et al. 2000). The general conclusion from the above studies is that variations in along-fibre diameter (profile) and variations between fibres significantly influence staple strength but no relationship between intrinsic strength and staple strength has been found in Merino sheep. It was also concluded that intrinsic strength and fibre
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shredding are not usually important contributors to variation between animals or flocks in staple strength of their wool.

14.4 Impact of fibre strength in processing

The test of the measures of strength is in their relevance to any effect on processing performance or quality in topmaking, spinning and through to fabric. The first point to note is that we would expect the single fibre breaking load, rather than the material strength (IFS), to be more relevant to the level of fibre breakage in processing. Thus coarse fibres of the same IFS as fine fibres can bear higher loads and should be expected to break less.

Topmaking

An extensive review of published literature on the effect of fibre properties in processing was carried out in 1980 (Hunter 1980). It was pointed out that fibre strength is largely a function of the fibre diameter or more particularly the minimum diameter or cross-sectional area, and that the published work showed there is little variation in the intrinsic strength of untreated wool within the Merino breed of sheep. Higher staple strengths were said to generally result in less breakage during carding, combing, drawing and spinning, producing longer and squarer tops and less noil.

Rottenbury et al. (1981) concluded that the strength of single wool fibres is a major determinant of wool processing efficiency. Stronger fibres will resist breaking during carding and combing, or allow for yarns with fewer fibres in the yarn cross-section. A recent review (Lamb 2004) concluded that staple strength has a relationship to breakage and losses in topmaking that is more pronounced at low staple strength, but the size of the effects actually due to SS appear to be smaller than those suggested by the TEAM-2 (Trials Evaluating Additional Measurements 1988) regression coefficients. Further, the effects attributed to SS in the TEAM formulae arises in part from correlations with other fibre attributes and from the method of determining top fibre length using the Almeter. It was hypothesised that breakage in processing would be more likely to relate to single fibre strength than to staple strength.

A recent attempt to determine the impact of differences in intrinsic fibre strength on processing (Peterson & Lamb 2005) found no clear effect but the differences in IFS were small. Four batches of raw wool differing in intrinsic fibre strength (IFS) were processed to top and yarn. Two pairs of lots, differing in IFS by 11% and 13% but closely matched for TEAM predicted hauteur, were processed to top, measured for bundle tenacity, and then spun to the same yarn tex. For the first matched pair the high IFS lot processed more poorly, being 4.6 mm shorter relative to the expected hauteur than the low IFS lot. For the second matched pair the high IFS lot processed 0.5 mm longer than expected relative to the low IFS lot. The bundle tenacities of the resultant tops were similar for all four lots.

So we have the situation that we expect fibre strength to have a significant impact on topmaking whereas SS sometimes only appears to have a moderate effect on breakage in processing to top, that this relationship may not be constant, and that some of the effects can be attributed to variation in diameter. On the other hand, material strength (IFS) and SS are, at best, weakly related and IFS variation is either small or does not have a significant effect on breakage in topmaking. In hindsight these observations can be understood as arising from assumptions that include what we mean by “strength”. Staple strength is a measure of the tenacity of the weakest place along a whole staple. It may indicate how easily a staple of given average linear density may be broken but can easily be a poor indicator of the load that individual fibres can support. For undamaged wools, IFS also has only a weak relationship with the breaking load of individual fibres. Our understanding of how breakage arises in processing is also limited. It is likely to depend as much on the degree of entanglement introduced by scouring as on the strength of fibres.

While single fibre strength may be the more relevant property, its measurement is slow and tedious whereas staple strength measurement is routine, is available for most Australian wools sold at auction, and does have some relationship to the achievable fibre length and losses in topmaking. There is a significant increase in price paid as staple strength increases, particularly for superfine wools. A recent analysis claims an increase in price of 20 to 40 cents/kg for each
unit (N/ktex) increase in SS of 17μm wool (Lamb & Curtis 2004). Interestingly, higher prices are paid when both SS is high and CV_D low.

**Impact of Staple Strength on Bundle Strength**

The next questions are whether SS and IFS affect the bundle strength (BT) of the top and whether they or BT affect performance beyond topmaking. The author’s experience with overseas spinners is that it is commonly assumed that low staple strength (SS) necessarily means a low strength top and poor spinning performance.

Only a very weak correlation has been observed between staple strength and bundle strength for single sale lots of wool (Yang 1994) and for sire group batches of fleeces. The latter data from 71 lots (Lamb, Purvis & Robinson 2000) is shown (Figure 14.5). A small correction has been applied to the data to take into account the measured curvatures of the tops as it has an effect on the measured bundle tenacity. With or without this correction there is negligible correlation between bundle tenacity and staple tenacity in this set of wools (■) from hoggets reared together. For these relatively sound wools (■) from hoggets reared under good conditions the average fibre strength of untreated tops shows relatively little variation (CV=3%) and no significant dependence on staple strength. Results for six batches of low staple strength wool (○) from WA are also given in Figure 14.5, and show a downward trend of about 7% for a halving in SS (from 30 to 15 N/ktex).

![Figure 14.5 Bundle tenacity of tops – Armidale sire groups (■), Katanning batches (○). Source: Lamb (2004).](image)

Note that the bundle tenacity is much larger than the staple strength because the linear density used to calculate SS is the average for the whole staple, not the total of the thinnest cross-sectional areas of every fibre. Thus, in the reasonably sound wools examined, which have not been damaged by a chemical treatment or by microbial action, the average fibre material strength (BT) of top is hardly related to staple strength. For the time-being we postpone the relationship between IFS of greasy staples and BT.

**Spinning**

**Impact of SS**

Yarn tenacity measurements are typically carried out on a single 0.5m length of yarn which is extended at a constant rate until broken. The mean breaking load is converted to a tenacity using the measured average linear density of a number of 100m segments of yarn. The breaking load of any individual test is primarily determined by the thinnest section of yarn within the 0.5m length together and the extent to which the fibres are bound by the twist (with longer fibres being more strongly bound). On average, in a fine yarn (mean 35 fibres in the cross-section) there will be a thin place of half the mean cross-section approximately every metre of yarn length so the apparent yarn strength is strongly dependent on yarn irregularity and a large number of yarn segments must be tested to obtain an accurate result for the mean yarn tenacity.

In most worsted yarns the fibres are tightly bound by twist (with a full turn of twist every 1 to 3mm) and so should be expected to share their load over distances comparable to the gauge used in bundle testing. Hence, yarn tenacity should not be strongly affected by staple strength except via differences in hauteur (top length), but be affected by the extent that SS reflects a small residual variation in material strength (IFS), and via any correlated increases in yarn unevenness (variations in thickness) through increased CV_D and reduced hauteur. Yarn
strength increases as yarn evenness improves because the number and severity of thin places decreases.

In the review mentioned earlier (Hunter 1980), it was claimed that it can be expected that yarn and fabric strength will be proportional to fibre strength and that this had been confirmed experimentally. However, the references contain a mixture of staple and fibre strength studies. Any claimed effects of SS can, in fact, be attributed to differences in mean fibre length and yarn evenness with no additional effect of staple strength. On the other hand, there is extensive data that yarn tenacity is proportional to fibre bundle tenacity and that accurate measurement of bundle strength can improve the prediction of yarn strength and spinning performance (Lamb & Yang 1995b; Yang et al. 1995). The small range of tenacities observed in undamaged wools means that the impact on yarn tenacity is seen more clearly when the bundle tenacity is reduced by damage in dyeing.

A few more recent studies have looked at the effect of staple strength on spinning. One experiment (Robinson et al. 1995) compared the processing of sound (36 N/ktx) and tender (24 N/ktx) batches of similar wool. Tops matched for hauteur were achieved by using different card loadings and comb settings for the two wools. The bundle tenacity of the tender wool was then found to be 4% lower but the spinning performance and yarn tenacity were the same within errors, while the yarn elongation was down 2% and the fabric strength averaged 5% lower. The wools from a topmaking trial using batches varying in both staple strength and position of break (Rottenbury et al. 1986) were taken through to yarn (Plate, Robinson & Rottenbury 1987). The breakage through to the spinning frame (prior to twist insertion) was measured and found not to be related to SS. End-breaks in spinning were observed to vary linearly with hauteur and not with SS except via hauteur. There was little variation in yarn tenacity with hauteur or SS except for one yarn from the shortest wool.

The processing trials mentioned earlier (Smith, Lamb & Purvis 2005) were used to examine the effects of staple strength (approximately 25 versus 50N/ktx) on yarn properties and spinning performance. These were consistent with there being no effect of SS on bundle tenacity and no additional effect of SS on downstream performance beyond those expected from the correlated differences in CV_D and the small differences in hauteur.

Impact of IFS

In a trial examining the impact of differences in intrinsic fibre strength on processing (Peterson & Lamb 2005) the spinning performance and yarn properties were as expected and showed no dependence on IFS. However, the re-measured differences in IFS of the greasy wool were only 12% and it was also found that the IFS of two adjacent sections of the same full length fibre had a negligible relationship. It seems that the current measurement of IFS may be of limited accuracy but, more importantly, the weakest place along the whole fibre may not reflect the average tenacity of sequential short segments.

Impact of BT

If BT is a good measure of average material strength then, in the limit that all fibres share the load equally (during the testing of both BT and yarn tenacity) then a doubling of BT should lead to a doubling of yarn tenacity. This has been confirmed in trials using the same wool damaged to varying degrees by dyeing (Yang, Blenan & Lamb 1995; de Jong & Smith 1988). It has also been confirmed indirectly on undyed tops (Yang et al. 1995) where adjusting the predicted tenacity in direct proportion to the measured BT significantly improved the prediction of yarn tenacity.

The load-extension curve of a uniform section of yarn is fairly similar to the load-extension curve seen in bundle testing. There is a steep Hookean region followed by a longer Yield region. However, the large variation in thickness along most yarn segments means that much of the extension can be concentrated into one short thin place while the total yarn extension is small. Thus the variability of yarn extension (normally referred to as yarn elongation) is much higher than the variability of tenacity and a small reduction in tenacity can correspond to a large reduction in apparent extensibility. This “extensibility” or elongation at break should not be confused with the straightening extension of crimped fibres. Some people assume that more highly crimped wools will give yarns with higher elongation. Fibres are essentially straightened,
all the crimp is removed, during spinning and the evenness of the yarn will be the prime
determinant of yarn extension at break. Because higher crimp wools tend to give slightly
shorter fibre length in top and slightly less even yarn, the yarn elongation (at break) tends to
decrease as crimp increases. However, the yarn will contract more (increase in bulk) if steam
relaxed when not under tension. This apparent difference in bulk disappears under very low
tensioning of the relaxed yarns.

A drop in yarn strength is expected to lead to a deterioration in spinning performance. Typically,
a reduction of 10% in bundle tenacity is observed to lead to an increase of 50 to 100% in ends-
down in spinning, when spinning near the spinning limit. There is some evidence that a severe
dyeing has a bigger effect than expected from the change in bundle tenacity and this could be
because it also changes the shape of the load-extension curve.

Studies comparing matched fabrics produced from yarns dyed in commercial mills have shown
very good agreement between differences in yarn tenacity and fabric wet burst strength,
although there is again a suggestion that the differences in bundle tenacity underestimate the
extent of damage.

The bundle tenacity measurements of blends of wool with cotton or synthetics must be treated
with caution. In bundle testing the fibres do not interact so that, for example, all the low
extension synthetic fibres might be broken before any of the wool fibres approach their breaking
extension. In the yarn, the proportion of the different strength fibres will also vary so that a
prediction of yarn tenacity will be more difficult.

14.5 Variations in Bundle Strength
Yang et al. (1995) reported a spread in measured bundle tenacity of sale lots of 10% in CV. However,
much of this can be attributed to differences in mean diameter and SS and, possibly,
curvature. In sire groupings of sound wool from sheep reared together and SS>30 N/ktex
(Figure 15.7) the observed variation was only 3% in CV. Both lots of data are also consistent
with a 6 to 7% drop in bundle tenacity for a drop in SS from 30 to 15 N/ktex. Mean bundle
tenacity was found to increase by 8% for a 5μm increase in mean diameter. This is a general
observation made by a number of researchers but may arise from the negative correlation
between diameter and curvature. It has also been observed that BT increases with hauteur,
which may arise because stronger wools give longer tops.

There is much evidence for photodegradation of keratin exposed to UV light and of tip damage
of wool fibres that leads to “tippy” dyeing. However, there appears to be little evidence, apart
from damage to the very tip, that weathering will significantly reduce fibre bundle tenacity. Dunn
and Weatherall (1992) observed only a 1% difference in the BT of the tip and root halves of
fibres taken from the midback region of sheep reared outdoors.

Huson and Turner (2000) found that transgenic wools where either of similar strength or
significantly weaker than normal wools. They observed some differences in intrinsic strength,
measured in water, with bloodline but none of these differences persisted into intrinsic strength
measured in air or into bundle tenacity.

In summary, it appears that undyed tops made from sale lots of normal sound wool of similar
diameter have very similar bundle tenacity (Yang et al. 1996). Consequently, consignments
which comprise many sale lots could be expected to also have very similar tenacity. Low SS
lots will give rise to tops of slightly lower BT but the decrease is small. This does not rule out
the possibility of tops with low BT made from rotten (microbially) damaged wool or from damage
during processing.

Ways of Reducing Bundle Strength
Wool can be damaged by high temperatures and the damage increases with increasing
moisture, at extremes of pH and with time. Hence, the most common cause of reduced bundle
tenacity is damage from dyeing when the wool may be held at or above the boil for more than
an hour. However, it is also possible for undyed wool top to have been damaged in processing.
Scouring at high pH (e.g. if NaOH is used) will cause damage as well as drying at high
temperature after scouring. Some wools may also be carbonised (acid treatment followed by
baking and crushing) without the recipient knowing and it has also been reported that occasionally wools will be bleached to improve their whiteness. It is also possible to damage yarns during steaming but yellowing of the wool and differences in dye uptake are also likely to be more obvious consequences.

**Effect of Top Dyeing**

Dyeing of wool top is the major cause of reduced bundle tenacity. Prolonged aqueous dyeing of wool, at or above boiling, can induce marked damage to wool fibres as evidenced by significant drops in fibre bundle tenacity and extension and yarn tenacity and elongation (Gore, Lee & Rogers 1990; Rippon, Harrigan & Tilson 1995; Yang, Schültz & Lamb. 1997). In fact, in trials with commercial mills in both India and China, damage in dyeing was identified as the major cause of underperformance in yarn properties and spinning performance. Damage can be significantly reduced by either using chemicals that allow faster dyeing or lower temperature dyeing (Rippon, Harrigan & Tilson 1995) or by additives that protect the fibre against damage (Cookson et al. 1995).

**Readings**

The following readings are available on web learning management systems


2. IWTO-32-82(E), Test method for Determination of the Bundle Strength of Wool Fibres, International Wool Textile Organisation test method. (This reading does not need to be studied in detail but will give the reader an appreciation of the detail and explicit nature required for a test method.)

**Summary**

Bundle tenacity (BT) is a measure of the average strength of fibres measured using a short gauge (typically 3.2mm). It is normally made on cleaned and processed wool such as top in which the fibres have been mostly straightened and disentangled. In practice, it has been found that undyed tops from sound wool vary little in BT for a given fibre diameter and, contrary to some expectations, lower staple strength does not imply low BT except at very low SS where a halving in SS has resulted in an observed 7% drop in BT. Theory and experiment predict that yarn tenacity should vary in direct proportion to bundle tenacity and, when using tops made from a wide range of sale lots, it has been found that an accurate measurement of BT can improve the agreement between measured and predicted values of yarn tenacity and elongation. On the other hand, BT can be significantly reduced by chemical action such as occurs in dyeing (heat, moisture, time). The major reason for measuring BT in tops is therefore to assess the extent of damage from dyeing or as an assurance against wool that has been unexpectedly damaged (e.g. from poor scouring, microbial action, bleaching etc.) or of unusually low SS. Harsh dyeing conditions can lead to drops in BT exceeding 10% and greatly increase the breaks (ends-down) in spinning and downstream processing.

Bundle, staple, and intrinsic fibre strength are all measures of the load that can be supported by fibres normalised by their linear density (cross-sectional area). Intrinsic fibre strength requires an accurate measure of the cross-section at the point of break and so is error-prone and laborious, and it appears that the IFS may vary along the fibre. As yet, large and consistent differences in IFS between sheep, that lead to differences in BT of the resultant tops, have not been established (except for transgenic wools or where there has been a deficiency in trace elements). Staple strength is strongly affected by the variation in diameter along fibres and the unequal sharing of the load between fibres, particularly due to differences between fibres such as in straightened length. Consequently, SS is not a good guide to the average strength of the fibre material and is only very weakly correlated with BT. Bundle tenacity is slightly affected by the extent to which fibres are straight and parallel and the method of a slipping pre-tension appears promising as a means of reducing the residual dependence on fibre curvature. All current methods used for wool involve a manual preparation of the sample between parallel
jaws which are then moved apart while the peak force to break is measured. The need to measure at least 5 to 10 samples means that the methods take at least 15 mins (Tensor) or 1 hour (IWTO-32-82(E)).

References


CSIRO Textile and Fibre Technology, Sirolan Tensor, technical brochure.


Lamb, P.R. 2000, ‘The impact of CV(D) and crimp or curvature on processing performance,’ *Proc. of IWTO*, Technical and Standards Committee meeting, Report CTFO2, Christchurch.


### Glossary of terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td>Elongation (yarn)</td>
<td>the % by which a yarn is extended at the time of the peak force at break</td>
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<td>Extension at break</td>
<td>the distance or % by which fibres or staples are extended at the peak force</td>
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<td>Gauge</td>
<td>the distance between the inside of the pair of jaws gripping the bundle of fibres</td>
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<td>Glass-transition temperature</td>
<td>the temperature above which a polymer like wool starts to flow like hot glass rather than be brittle like cold glass</td>
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<td>Hookean region</td>
<td>the start of the stress-strain curve when the fibres behave like ideal springs and will fully recover when the force is removed</td>
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<td>IFS</td>
<td>the inherent or intrinsic fibre strength (tenacity) of the fibre</td>
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<td>Load/extension curve</td>
<td>the stress-strain curve or change in length (extension) with change in applied force</td>
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<td>Peak force at break</td>
<td>the largest force encountered during breaking when the increase in the load carried by some fibres just matches the decrease in load as other fibres begin to fail</td>
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<td>Photodegradation</td>
<td>damage to the chemical bonds (particularly disulphide bonds) by the ultra-violet component of (sun)light</td>
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<td>Relaxation (wool)</td>
<td>the tendency of wool fibres to return to their previous state when taken above their glass transition temperature</td>
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