Effect of test conditions on measured loads and displacements in zero-span testing

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ABSTRACT: Single fiber mechanical properties play a critical role in determining sheet mechanical properties, but fiber mechanical properties are rarely measured because of the time-consuming nature of the tests. Zero-span strength is commonly used as a measure of fiber strength, but the results can vary with the test conditions. Modeling has shown that the load displacement curves are influenced by the thickness-to-span ratio, as there is a heterogeneous stress field in the thickness direction of the sample.

This paper presents data on the effect of grammage on the loads and displacements in zero-span tests. Clamps were designed and made for a displacement-controlled load frame. These clamps can test up to 10 plies of papers with a span length from 0 to 3 mm. For the sake of comparison, tests were made using a commercial zero-span tester, which is load controlled but limited in span length and thickness of the tested material. Both machines were found to give comparable results.

Isotropic 65 g/m^2 handsheets, 36 g/m^2 aluminum foil, and 42 g/m^2 greaseproof paper were tested as functions of sheet grammage. An intrinsic zero-span strength was defined as the y-axis intercept of a plot of zero-span strength versus grammage.

Application: This paper demonstrates that the measured zero-span strength is always less than the intrinsic zero-span strength. The results show that, for best results, the grammage of the material tested should be minimized to obtain a measured value that is as close to the intrinsic value as possible.

For well-bonded sheets, fiber strength is one of the critical factors determining paper strength [1]. Zero-span tests have long been used as a measure of the strength of the individual fibers, as it is not feasible to routinely measure the strength of single fibers. Zero-span tensile tests involve performing a tensile test with as small a gap between the jaws as possible, while short-span tensile tests involve setting the jaws at a small distance apart (usually 0.1-0.6 mm). The gap between the jaws of the tester is known as the span. Van Den Akker has shown that if the fibers are completely straight and free of defects then the zero-span strength of an isotropic sheet should be 3/8ths of the strength of a paper where all of the fibers are aligned in the stress-direction [2].

It is desirable in any form of material testing to remove as much of the sensitivity of the final test result to the test conditions as possible. For a given paper, the major test variables in the zero-span test will be the loading conditions and the clamping pressure. Most standard zero-span tests are performed using various types of Pulmac zero-span tester, for which only the clamping pressure can be readily adjusted. The existence of a plateau zero-span value with clamping pressure is easily demonstrated. The reduction in zero-span strength at low clamping pressure has been ascribed to sample slippage under the jaws, while the reduction with high clamping pressure has been ascribed to the pressure damaging the samples [3]. TAPPI T 231 "Zero-span breaking strength of pulp" calls for adjusting the pressure until the plateau zero-span strength is reached.

Zero-span strength is generally reported, as with most tensile properties, as a tensile index by correcting for the effect of grammage. One report from 1962 [4] found that the measured zero-span tensile index decreases with increasing grammage. Thus, this is an area that also needs further investigation to establish the reliability of the test.

At the start of a zero-span test the two sets of jaws are in contact with each other. As the test proceeds, an increasing jaw displacement occurs [3,5]. This displacement is not routinely measured during zero-span tests. The displacement we have measured at fracture in a zero-span test has been in the range of 20-60 μm. Despite the status of the zero-span test as an important measurement in the field of paper strength, few published studies have investigated the exact mechanisms by which load is transferred to the sample clamped between the jaws and the origin of the measured displacement. One model has been proposed by Hägglund et al [6]. The model was developed on the basis of an analytic 2-D stress analysis and from finite element analysis modeling of the stress field under the jaws.

The model, which is linear elastic, proposes that stress concentrations through the sample thickness arise due to the clamping condition, with higher stresses at the surfaces and lower stresses in the middle. The level of stress concentration largely depends on span and thickness. The numerical model predicts that, as a result of this stress concentration, the apparent modulus decreases with decreasing span, tending to zero at a span of zero. The tensile index is predicted to decrease with increasing sample thickness, because of the stress concentration.

We hope to have demonstrated in this brief introduction that the zero-span test is an important test of fiber quality, but that there still remain questions as to the absolute accuracy of the test. In the experiments in this work, we measured loads and displacements as a function of the sample grammage for several samples; the results are compared with the predictions of the model.

EXPERIMENTAL METHOD

Materials

For this study, we tested three types of materials [7]:

- Isotropic hand sheets made from a bleached and dried Scandinavian softwood kraft pulp, refined to 3000 PFI revolutions. These hand sheets are labelled K40 and are used as standard test material within SCA Graphic Research. The grammage tested was a standard 60 g/m² (ovendry), except for one series in which sheets with grammages of 30-100 g/m² were tested.
- Orthotropic greaseproof paper. This was Gourmanda Bak/Matlagnings paper manufactured by Metsä Tissue. It is silicon-treated and was tested in machine and cross directions (MD and CD).
- An aluminum foil wrap. This was Glad Aluminum folie manufactured by Mellita Toppits in Finland. It is a homogeneous material with an isotropic material response.

Material	Apparent Density	Grammage	Thickness	Friction Coefficient	
	kg/m³	g/m²	µm	Static	Kinetic
K40	747	65±0.1	87±0.1	0.32	0.2
Greaseproof	802	42±0.1	52±0.1	0.14	0.1
Aluminium foil	2141	36±0.1	17±0.1	0.32	0.2

Density, thickness, and grammage for the samples. (average ± standard deviation)

Table I lists the measured thickness, grammage, density and friction coefficients of the materials. The grammage listed is the conditioned grammage obtained when the samples were dried or conditioned in the standard atmospheric conditions of 23°C and 50% RH. Friction was measured with sample against sample according to the ASTM D 1894-87 standard method.

Equipment

A Pulmac Z-Span 2000 and an MTS 4/ML tensile tester were used for the experiments. The Pulmac tensile tester comes equipped with an x-y table, which allows 24 tests to be performed on either three disks or one large rectangular specimen. The zero- and short-span tests are carried out under force control at a rate of 22-24 N/ms. The clamping jaws have a width of 22 mm and a length of 0.8 mm. We used a pressure of 97.4 MPa (80 psi on instrument gauge) for all experiments. The force was calculated from the pressure in the pistons driving the jaws apart, using the manufacturer's calibration. The separation of the jaws was continuously measured by a Kaman KD2300 contactless displacement transducer, which was attached to the moving jaw and provided a measurement of position relative to the stationary jaw.

We converted voltage to micrometers by using a calibration curve obtained by fitting a spline curve to a set of calibrated distances between the clamps. The calibrated measuring range for the displacement sensor is roughly 1100 µm. The Pulmac instrument is also limited in the maximum force that it can apply, thus limiting the grammage that can be tested to 60-100 g/m², depending on fiber strength and orientation.

The measurements on the MTS tensile testing machine were made with a test frame equipped with clamps for zero- and short-span tensile tests fixed vertically on the machine [7]. This tensile tester can only test one 15-mm wide specimen at a time. Thus the tests are significantly slower to perform than on the Pulmac tester, which automatically tests 24 specimens each time. The zero-span geometry poses special problems in loading and aligning the samples. Taking into consideration these factors, eight specimens were tested. Of those, four specimens with the strength closest to the mean were selected for further examination. These tests were carried out under displacement control at a rate of 1 mm/min. The clamping pressure on the sample was 46 MPa.

The displacement that was measured at the crosshead is not the same as the displacement for the grip because there is a stretch of the different machine components, particularly the load cell. The stiffness of the system was measured by firmly connecting the upper and lower grip to each other. We used the slope of the measured displacement-force curve to subtract the system displacement from the total displacement to obtain the displacement due to straining the sample. The main advantage of the MTS setup over the Pulmac instrument is that displacements of up to 5000 µm can be measured compared to 1100 µm for the instrumentation attached to the Pulmac tester. In addition, the MTS system can measure much higher grammages than the Pulmac.

Estimating material parameters for finite element analysis

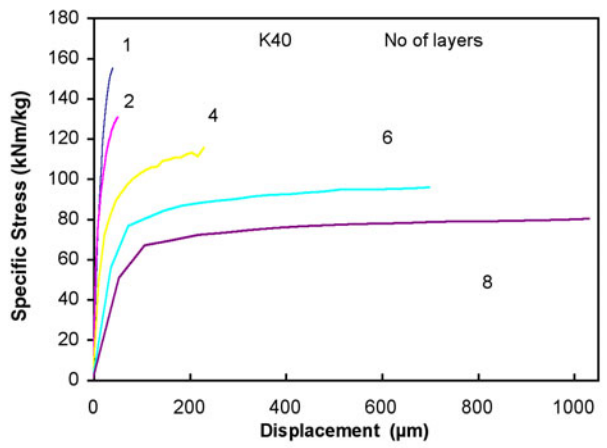
The model used has been described previously in detail [6] and is briefly summarized here. The calculations shown in this paper were for the K40 in-plane isotropic handsheets. The density of the sheets is 747 kg/m^3 and tensile stiffness index is 7.73 MNm/kg. That gives an elastic modulus of 5.77 GPa at an apparent thickness of 87 µm and a grammage of 65 g/m^2 measured at 50% relative humidity and 23°C. The transverse shear modulus and elastic modulus in the thickness direction as a function of applied pressure were estimated from the literature and scaled to the density for the K40 sheets used in this study. Westerlind et al. [8] measured ultrasonic tensile moduli on laboratory paper made on a dynamic sheet former from unbleached softwood kraft pulp. The sheets were wet-pressed to two densities and the geometric mean of the ultrasonic transverse shear moduli were extrapolated to 262 MPa, for a density of 747 kg/m^3.

The corresponding ultrasonic elastic modulus in the thickness direction was extrapolated from the same source to 220 MPa. The geometric mean of the elastic moduli in MD and CD directions was extrapolated to 7.7 GPa. An elastic modulus obtained by ultrasonic measurements is higher than that measured in a tensile tester. In Westerlind et al. [8], in-plane elastic moduli were 15% to 20% higher than corresponding elastic moduli obtained from tensile testing. For our study, we used a factor of 0.75 to scale the ultrasonically measured moduli from Westerlind's study [8] to represent moduli for the isotropic handsheets when tested in the tensile tester at lower strain rates. With this scale factor, the in-plane elastic modulus estimated from Westerlind [8] will be 5.8 GPa, which is the same as the measured elastic modulus for the handsheets. By using this scale factor, the corresponding transverse shear modulus will be 195 MPa and the elastic modulus in thickness direction will be 165 MPa. (**Table II**) These values are the moduli obtained at low applied loads in the thickness direction corresponding to the material parameters in the free span.

Stenberg [9] measured the compressive load response in the thickness direction and transverse shear response out-of-plane for paperboard using the Arcan shear test method. In that study, transverse shear moduli were found to be rather insensitive to applied load in the thickness direction. This means that the same transverse shear modulus of 195 MPa can be used for the region under the jaws. However, the loading-unloading curves in the thickness direction show that the slope of the curves steadily increases with increased applied load because of increased plastic compression. The loading curve after unloading the board at 5 MPa has a modulus of 15 MPa. The modulus of the loading curve after unloading the paperboard from a load of 40 MPa is 253 MPa. An elastic modulus of 310 MPa in the thickness direction is used in the present analysis for the region under the jaws. The value is estimated on the understanding that the region under the jaws is subjected to a pressure of 45.5 MPa and that the density is probably higher for the isotropic handsheets than for the paperboard used by Stenberg [9].

Parameter	Material Free span	Under jaw
E_x (Gpa)	5.8	5.8
υ_{xy}	0.3	0.3
υ_{yz}	0	0
G_{zx} (Mpa)	195	195
E_z (Mpa)	165	310

Elastic parameters used for simulations.



Specific stress as a function of displacement for 65 g/m^2 isotropic sheets with one to eight layers. Span is zero in the MTS tensile tester.

RESULTS

Measured and calculated loads and displacements under linear elastic loading

Figure 1 shows the specific stress as a function of displacement between the zero-span jaws for testing the various numbers of layers of K40 isotropic paper in the MTS tensile tester. All of the stress-displacement curves display an apparently linear initial region with slope that decreases quite rapidly as the number of layers increases. This reduction in slope is evidence that the nonuniform stress field through the thickness of the sample, which was posited by the model, is actually occurring.

The amount of plastic deformation after yielding increases strongly with the number of layers. The specific breaking stress also falls as the number of layers increases.

To compare the data in Fig. 1 with the predictions of the model, we must select a residual span under the jaw edges. The residual span in this context is the distance from the jaw edge until the point where the sample is held by the jaws and stress is transferred into the sample. Once the residual span is selected, the measured displacements can be converted into strains and an elastic modulus calculated. The simulation gives the apparent elastic modulus of the material as a function of the span-to-thickness ratio, so the span under the jaws is also required to estimate an elastic modulus from the model.

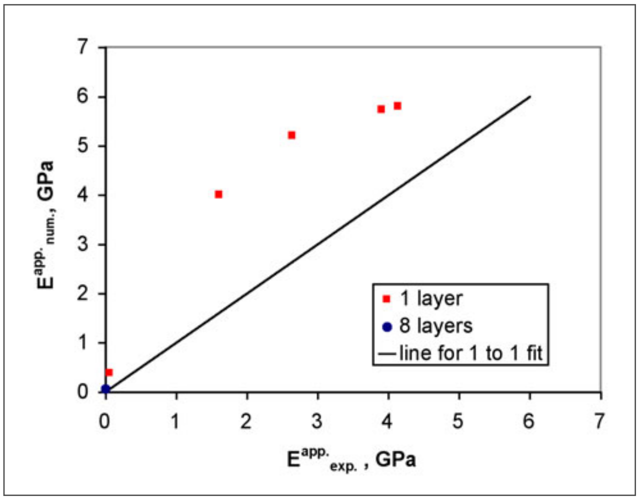
We used a residual span of 10 µm for the simulations performed for this paper. This span is probably much smaller than the actual residual span as a maximum elastic displacement of around 20 µm is observed for a zero-span test of a single layer, implying a strain of 100% if the residual span of 10 µm is assumed. This is far higher than any reasonable value for fiber strain [10,11] and a considerable length of the sample under the jaws is probably being strained to produce the measured zero-span displacement.

A large unknown residual span presents considerable difficulties in modeling as it is by no means clear how to treat the material between the jaw edge and the point where the stress is transferred into the sample. Certainly this section of material cannot be treated as if it were a free short span, given that the sample in this area will be heavily compressed and so the mechanical properties will be different. The model would also need to deal with a sample that had been compressed without any stress having been transferred into the sample. Given these difficulties and the uncertainty as to how large the span should be, we decided not to attempt further simulations with higher residual spans.

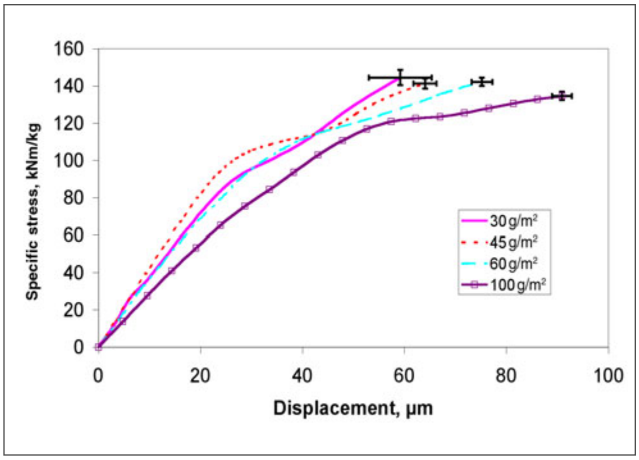
Figure 2 compares the elastic constant predicted by the model and the experimental values. The different data points for one layer were generated by including various short spans in addition to the residual span under the jaw. A comparison point is also included for eight layers tested at zero span (a nominal residual span of 10 µm). For all data, the measured elastic modulus is always less than the calculated modulus, which is partly due to the small residual span used for the calculations. The highest elastic moduli are for the largest short span between the jaws.

The data show a common trend, in that the apparent elastic modulus is very small for the zero-span tests and increases with the short span between the jaws. This is ascribed to the nonuniform stress field suggested by the finite element analysis (FEA) model. Given that the model is linear-elastic, it cannot be used to predict the zero- or short-span breaking strength, because fracture takes place after considerable plastic deformation. Indeed, the model predicts that the displacement at break will be reduced as the thickness of the paper is increased, when in fact the opposite occurs experimentally.

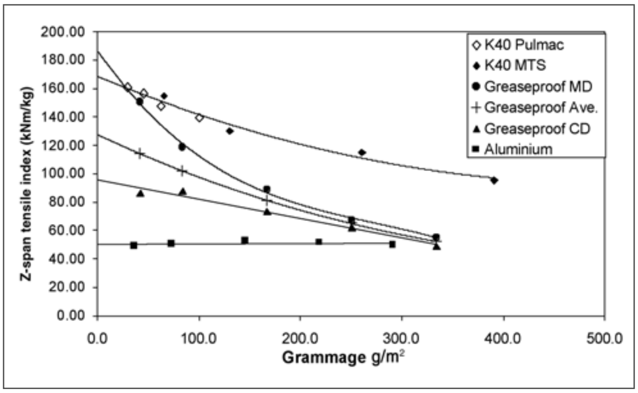
The data in Fig. 1 and the modeling summarized in Fig. 2 are, however, good evidence for the existence of the nonuniform stress field through the thickness of the sample, which is posited by the model. The existence of such a stress field then has important practical implications for whether the



Numerical apparent elastic modulus as a function of experimental modulus (measured on the MTS tensile tester) for different span lengths for one layer (squares) and for a 10 µm span for eight layers (circle) for isotropic sheets (K40). The total span (free span plus assumed span under jaw of 10 µm) varied from 10 µm to 2 mm in the finite element analysis (FEA) analysis.



Effect of grammage of K40 isotropic handsheets on measured stress-displacement curves from zero-span testing on the Pulmac instrument. The 95% confidence intervals are given for the end-points of the measurement.



Zero-span tensile index as a function of sample grammage for K40 isotropic handsheets, greaseproof paper tested in machine and cross directions (MD and CD), the aluminum sheets and the geometric mean for the greaseproof paper.

zero-span tensile strength can be used as an intrinsic material parameter. This is discussed in the next section.

Zero-span strength measurements

Figure 3 shows the effect of grammage for testing the K40 material on the Pulmac instrument. As the grammage increases, the breaking stress decreases slightly and the displacement at break increases considerably. This arises because the breaking stress is almost constant. Therefore the breaking load increases almost linearly with grammage. Grammage has a much larger effect on the measured displacement than it does on the measured breaking stress.

The zero-span tensile indices at fracture were plotted against grammage for all materials tested. **Figure 4** shows the results. All the data were collected on the MTS machine except for one of the two sets of K40 data, which were collected with the Pulmac instrument. The data from the MTS machine were collected by testing multiple plies, while the data from the Pulmac were tested by measuring sheets formed at different grammages. The points from the Pulmac and MTS instruments are indicated with the open and closed diamonds, respectively. Both instruments give comparable results for the K40 tests, with both data sets collapsing onto a single curve. This limited data here also suggest that using multiple plies has had the same effect as if the sheets tested had been formed at the higher grammage.

Figure 3 also shows the trend lines fitted to each set of data. Each trend line has been forecast back to a grammage of zero. This is because our model predicts that the stress distribution through the thickness of the sheet will be perfectly uniform only when the sample is infinitely thin (zero grammage). The y-axis intercepts of the fitted curves may be thought of as the intrinsic zero-span strength of the material. From the data in Fig. 3, a single-ply test underestimates the intrinsic zero-span strength by 9% for the K40 sheets, 20% for the 41 g/m² greaseproof sheets tested in the MD direction, and 10% for testing the greaseproof in the CD direction. The greaseproof data is also interesting because the MD and CD data show quite different trends, with a cubic polynomial required to adequately represent the MD data, while a simple linear function was used for the CD data. The MD zero-span strength is much more sensitive to grammage than the CD for this sample.

The difference in grammage sensitivity between MD and CD cannot be due to thickness effects. We hypothesize that the differences between the testing in the two directions is due to stress-transfer effects. The load in a zero-span test will be largely taken up by those fibers aligned near the stress direction. There are fewer such fibers in the CD direction and to load these fibers greater stress transfer through the sheet thickness may be necessary, as most fibers in contact with the jaws will be aligned away from the direction of the applied load. Any increase in stress transfer through the thickness will reduce the sensitivity of the test result to grammage. Such load-transfer effects are not considered in the model.

The results for the K40 and the aluminum sheets also support this hypothesis that stress transfer between the fibers could affect the sensitivity of the result to the sheet grammage. The aluminum sheets have no fibers and therefore no requirement for transferring stress between fibers. They would be expected to have the smallest sensitivity of the measured results on the grammage. In fact, the data show no change at all with grammage. The K40 isotropic handsheets would be expected to show results intermediate between the tests in MD and CD. This is observed as the zero-span tensile index decreases linearly with grammage for higher grammages, but hooks upward for grammages below 100 g/m². Interestingly, when the geometric mean (equivalent to handsheet result), Z_i, of the greaseproof paper was calculated from $Z_i = \sqrt{Z_{MD} Z_{CD}}$, the results showed a similar trend to the K40 data. The geometric mean tested at 41 g/m² was 11% lower than the intrinsic zero-span strength determined from the y-axis intercept.

CONCLUSIONS

Two separate instruments were used to measure zero- and short-span strengths and displacements as a function of sample grammage. The results were comparable between the instruments. An intrinsic zero-span strength was defined as the intercept of a graph of zero-span strength versus sample grammage. We found the intrinsic zero-span strength to be a useful innovation for interpreting and explaining the results from zero- and short-span tensile tests.

The following conclusions about the zero-span as a measure of intrinsic fiber strength can be drawn:

- The measured zero-span strength will always be less than the intrinsic zero-span strength of the material because of stress gradients through the thickness of the sample. The ratio of measured/intrinsic strength falls as the grammage increases.

- The sample grammage should be set as low as possible, or extrapolation as a function of grammage used, if we wish to measure the intrinsic zero-span strength.
- Zero-span strength comparisons should never be made between samples of different grammages, but will provide a reliable relative measure of fiber strength between different samples of the same grammage.
- The measured/intrinsic strength ratio was highly sensitive to grammage when testing in the MD direction, but much less sensitive when testing in the CD direction. The sensitivity to grammage can be reduced, in comparison to testing in the MD direction, if the geometric mean is used.

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INSIGHTS FROM THE AUTHORS

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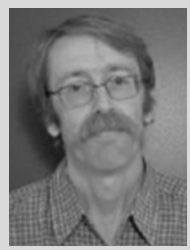

Gradin

This work is part of an on-going project to use zero- and short-span testing to obtain information on fiber mechanical properties. The research combined an FEA model of stress transfer under the jaw with experimental measurements on the effect of grammage on loads and displacements during the zero-span test. This had never before been done. The FEA model helps us address how stress is transferred into the sample from the jaw surfaces.

One of the most challenging aspects of the study was to express the results of the modeling in a way that could be readily compared with the experimental result. We found, among other things, that the zero-span index decreases as the sheet grammage increases due to an inhomogeneous stress field under the zero-span tester jaw.

The results from this study suggest that mills should consider minimizing the sheet grammage tested in the zero-span test, to obtain a result that better represents the true strength of the fibers.

Our next step is to continue work to better understand stress is transferred to the fibers in the test so that the results of the test can be directly used to calculate single fiber properties.

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