LANDTECHNIK 70(4), 2015, 84–96
DOI:10.15150/lt.2015.2663

LANDTECHNIK
AGRICULTURAL ENGINEERING

Determination of the properties of cereal stalks when being bent and cut with the aid of a universal test bench

Andrej Batos, Maximilian Ruepp, Andreas Jahr, Burkhard Corves

A universal test bench was designed to measure the properties of stalk-type materials when being bent and cut. The measured values obtained with this test bench serve for the setup of simulation models to virtually represent agricultural cutting processes. In this study wheat stalks were investigated. The cutting tests were carried out for two cutting velocities and two cutting angles. The mean values obtained from 50 measurements are compared with one another. The moisture content of the samples ranged between 5.5 and 7.1%. The bending stresses were 1.09 N/mm² for the first, 0.99 N/mm² for the second and 1.07 N/mm² for the third internode. With the cutting tests the highest stress (4.44 N/mm²) occurred while cutting the second internode (50 mm/s, 40°). The lowest stress (2.20 N/mm²) was found while cutting the third internode (150 mm/s, 60°). Apart from one exception, the cross-section-related cutting energy (12.18–19.85 mJ/mm²) was always higher with the larger cutting angle. The mean variation coefficients lay between 5 and 32%.

Key words
Universal test bench, measurement, bending properties, cutting properties, stalk-type materials

A statistic of the United Nations on the development of the world's population forecasts that it will increase to approx. 10.85 billion people by the year 2100 (Statista 2014). Since the amount of land suitable for agricultural cultivation is limited, increasing the level of production on the areas available represents the sole solution here. For this reason increases in the efficiency of agricultural machines are necessary. In order to achieve these objectives, the manufacturers of agricultural machines are making increasing use of commercially available simulation software. These can contribute to accelerate the development of new machines and at the same time to reduce development costs. To be able to represent harvesting processes with the aid of simulation models in an as close-to-reality manner as possible, it is in particular necessary for the properties of the particular crop being harvested to be known precisely.

A challenge in this respect is the fact that there are no standardized measurement methods available for determining the mechanical properties of stalk-type materials in agriculture. As a result the measured values obtained from the numerous studies carried out so far can be compared with one another only to a very limited extent. For this reason presented here is a relatively simply constructed universal test bench with which – amongst other things – bending and cutting tests can be carried out on cereal stalks (Figure 1).

Wheat plays a decisive role in the world-wide production of food. In Germany with 51.8% of the area under cultivation, wheat is by far the most produced cereal type (BMELV 2013). For this reason

received 2 February 2015 | accepted 30 March| published 2 July 2015

wheat stalks were selected as test samples in this study. They were taken from a field in the vicinity of Düsseldorf (North Rhine-Westphalia).

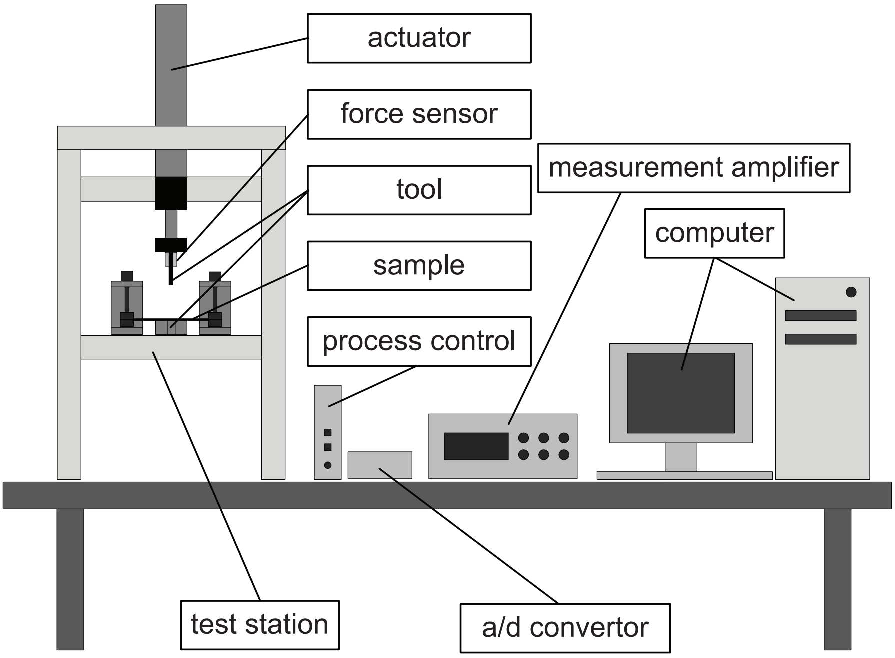

Figure 1: Schematic of the universal test bench

Test samples and methods

The universal test bench represented schematically in Figure 1 was used in the tests. The test bench was developed and designed by the authors for the measuring of agricultural products. It consists primarily of an actuator on which a force sensor and a device, which can be exchanged rapidly for loading the sample, are mounted. Bending, cutting, shearing and pulling tests can be carried out with the test bench by fitting the appropriate device. Used in the case described here were a bending punch and a blade that moves through a stationary mounted matrix. The dimensions of the blade are shown in Figure 2 d. The path covered by the tool is measured with a laser sensor (micro-epsilon optoNCDT 1300-50). Used for measuring the force was a sensor, the nominal load of which is 20 N (Burster type 8523-20). The recording and evaluating of the measurements were carried out with Matlab.

In order to achieve usable results, the plants used for the tests were removed prior to harvesting of the crop from the field individually and not by machine. Thus the use of damaged samples was avoided. In addition it appeared wise to check the harvested plants for damage (Figure 2 c) and to defoliate them prior to the tests. The defoliating facilitated the handling of the samples during test preparation. In addition this prevents parts of the plants becoming entangled in the test bench and distorting the measurement. Since the mechanical properties of plants change with time, there is as a rule only a very limited period of time for carrying out the tests. The length of this period of time depends on the nature of the test sample and primarily also on the changes of its moisture content, this in turn depending on the storage conditions. If execution of the tests takes too long and if the moisture content changes significantly during this time, the results obtained can no longer be compared with one another. For this reason samples were used in this study, the moisture content of which had been caused to fall to a largely stable level through storage which was as dry as possible. For this reason a relatively long period of time was made available for carrying out the tests. To lower the moisture content the samples harvested on 9.8.2013 were first of all stored for some 20 days in the form of bundles (diameter approx. 15 to 20 cm) open at room temperature. After this the samples were stored loose in cardboard boxes. The bending tests were carried out between 2.12.2013 and 6.12.2013, the cutting tests between 15.1.2014 and 4.2.2014. In a similar manner to that used by Tavakoli et al. (2009) the measurements were carried out using the first, second and third internodes (Figure 2 a).

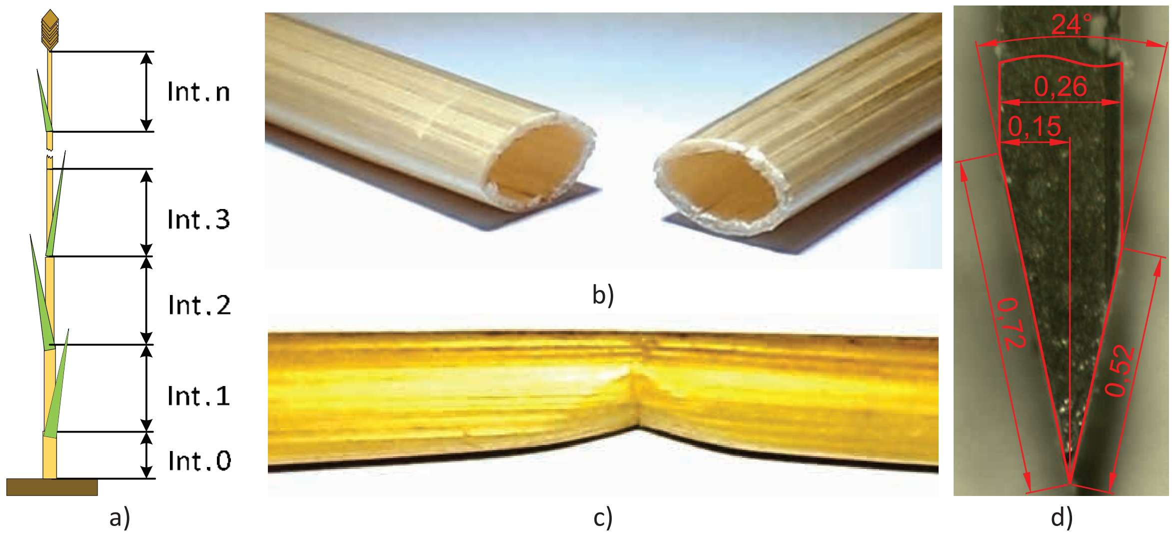

Figure 2: Structure of a wheat stalk
a) Internodes, b) Cross-section, c) Kink point, d) Blade geometry (longitudinal dimensions in mm)

To determine the moisture content the samples were dried directly after the tests in an electric oven at 105 °C for 24 h. This temperature and this drying time are the same as those used by Chandio et al. (2013) and Chattopadhyay et al. (1999) for the drying of wheat or, respectively, stalk. The moisture content f was determined in accordance with Equation 1 from the difference in weight of the sample prior to (m_E) and following (m_S) the drying process.

$$f = 100\% - \frac{m_E \cdot 100\%}{m_S} \quad \text{(Eq. 1)}$$

The mean moisture content of the first internode was 5.5 %. The second and third internodes of the plants showed mean moisture contents of 6.3 % and 7.1 % respectively.

The bending and cutting tests presented here were carried out with the aid of the universal test bench represented schematically in Figure 1 as developed specially for the studying of stalk-type materials. In comparison with most of the other test benches known from other studies the universal test bench is characterized by the variety of different ways in which it can be employed. Thus – without a great deal of conversion work being necessary – numerous properties of different stalk-type materials as well as different blades can be investigated. In addition its construction is relatively simple so that further test bench units can be manufactured and calibrated without great expense.

The bending test is based on the principle of a beam supported loosely at both ends and with a point load acting in the middle (Figure 3 a). This principle is the same as that used by Casada et al. (1969) and McClelland and Spielrein (1957) whereas Curtis and Hendrick (1969) and Prince et al. (1965) used the principle of a beam clamped firmly at one end for their bending tests. The bending punch, with which the transverse force was applied to the cereal stalk, has in this case a round cross-section with a diameter of 12 mm and was moved with a velocity of 0.75 mm/s. The objective is the determination of a stress. Instead of determining the stress as bending stress by dividing the bending torque by the moment of resistance as usually done, here it is calculated as shear stress by dividing the transverse force by the cross sectional area. The cross-sectional area A of the cereal stalk results after pressing together the sample from the product of the sample width B and the sample thickness D (Equation 2).

$$A = B \cdot D \qquad \text{(Eq. 2)}$$

In this way the measuring of the sample diameter – something that is often subject to error because samples often have not an ideally round shape (Figure 2 b) – is replaced by a simpler variant. Here the sample width and thickness are always measured with a vernier calliper after the test. With the transverse force F_Q and the cross-sectional area A as measured it is possible to calculate the stress σ_Q (Equation 3).

$$\sigma_Q = \frac{F_Q}{A} \qquad \text{(Eq. 3)}$$

For carrying out the cutting tests the samples were placed on a matrix and clamped firmly at each end (Figure 3 b). Here care had to be taken that the sample did not experience any pretensioning. To prevent a sample tearing at the clamping points, a short metal rod was inserted into the sample at both ends. The diameter of the metal rod inserted to prevent the end of the sample being crushed together by the clamping device is approximately the same as the diameter of the sample.

The matrix has a narrow gap through which the blade moves in the cutting test. The matrix acts on the sample like a counter bracket so that it is comparable with a blunt counter blade. The matrix prevents the sample being bent. Preliminary tests are carried out to show that the sample is not pushed away to the side.

It is to be assumed that tensile forces act on the sample to a certain extent during the test. These forces are caused by the angled position of the blade. The tensile forces only act to prevent lateral movement of the stalk if a low degree of friction between the matrix and the sample is assumed. However the results are distorted by these forces not more than by the bending of the sample if it had not been clamped. Although locating of a sample without clamping is more similar to a cut without a counter blade, it requires a high cutting velocity so that inertial forces act as counter forces. In the case of the low cutting velocities selected in this study, the sample would only be pressed away and not cut. In addition tensile forces generated by inertial forces can be present in the case of cutting with a counter blade and a fast rotating blade and a relevantly long cereal stalk. Moreover there are also tensile forces when plants are cut close to the soil. For this reason it is assumed that clamping at both ends is permissible.

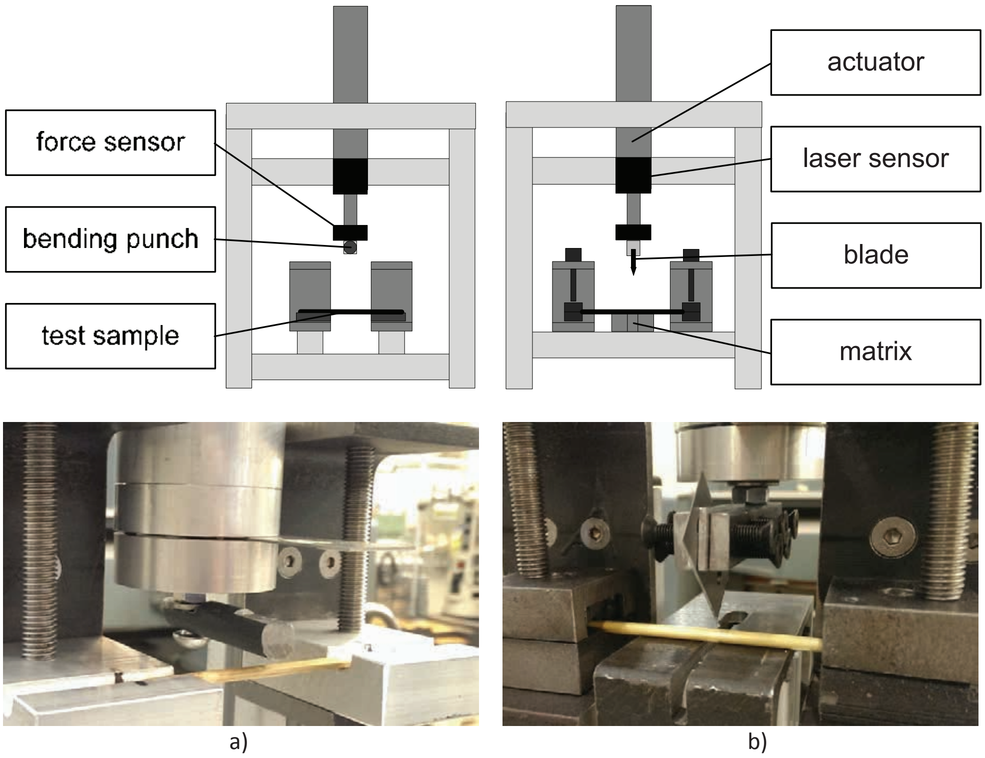

Figure 3: Structure of the universal test bench for the bending (a) and cutting tests (b)

The angle between the cutting edge of the blade and the horizontal plane on which the cereal stalk is lying can be set in an infinitely variable manner. Accordingly, the cutting velocity ratio, i.e. the ratio of the velocities tangential (drawing component $\dot{x}_t$) and normal (pressing component $\dot{x}_n$) to the cutting edge of the blade (Equation 4) (Stroppel 1939), can be freely set.

$$Speed\ \ of\ \ the\ cut = \frac{\dot{x}_t}{\dot{x}_n} \tag{Eq. 4}$$

The cutting tests were carried out at two cutting angles (40° and 60°) and two blade velocities (50 mm/s and 150 mm/s). The different cutting angles permitted to investigate cuts that were primarily pressing (40°) and primarily drawing (60°). The selection of a cutting angle of 40° ensures that the pressing cutting force component and thereby the cutting force do not reach values that are too high. Since at an angle of 45° the pressing and drawing components are equally large, it might be thought that an angle of 50° would be best for the primarily drawing cut. However the angle of 60° selected here ensures that there is a significant difference in the course of the cutting forces. A cutting velocity of 50 mm/s was selected for the lower of the two velocities investigated since if the cutting velocity is too low there is the risk that the samples will be compressed rather than cut. The higher cutting velocity was selected as 150 mm/s in order to be able to determine in addition in a clear manner the influence of the cutting velocity on the cutting energy.

The objective of the cutting tests was to determine the shear stress and the arising cutting energy. In a similar manner to the calculation of the stress arising from the transverse force, the shear stress τ_S results from the division of the cutting force F_C and the cross-sectional area A (Equation 5, A in accordance with Equation 2).

$$\tau_S = \frac{F_C}{A} \quad \text{(Eq. 5)}$$

The cutting energy E_C is calculated by multiplying the cutting force F_C with the path travelled by the blade s_C (Equation 6).

$$E_C = \int F_C \cdot ds_C \quad \text{(Eq. 6)}$$

The determination of the cutting energy according to Equation 6 was carried out by numeric integration using the trapezoidal method. Since cereal stalks have different dimensions, considered below will be the quotient of the cutting energy and the cross-section of the cereal stalk instead of just the cutting energy.

In order to ensure the correct functioning of the universal test bench, preliminary tests were carried out prior to each test series. Since cereal stalks are natural products, the properties of which vary considerably from plant to plant, normal commercially available drinking straws of plastic were used for these preliminary tests. In many respects these are similar to cereal stalks. However they are manufactured in large quantities under controlled conditions so that their properties are fundamentally the same and also constant with respect to time. Nevertheless, due to the lack of standardization, it is advisable to use drinking straws from the same batch. The measuring procedures used in the preliminary tests and the subsequent tests were exactly the same, the only difference being the samples used. With the measuring device the results of the preliminary tests showed very low variation coefficients, namely 0.57 % with the bending test, 0.86 % with the cutting test and 2.6 % with the cross-section-related cutting energy. The reason for the higher variation coefficient of the cross-section-related cutting energy is that here measurement errors may appear in both the measurement of the force and the measurement of the path. In addition inaccuracies appear as a result of the numeric integration of the discrete measured values with the aid of the trapezoidal method. This error source could theoretically only be excluded if the sampling rate was infinitely high. Summarizing it can be established that the measuring precision of the universal test bench is completely adequate for the purpose in hand.

All the tests were carried out for 50 samples in each case. Thus 50 bending tests and 200 cutting tests (2 cutting angles and 2 blade velocities) were conducted. Since each test was carried out on three internodes of the cereal stalk, a total of 750 tests was necessary.

Results and discussion

Figure 4 shows the non-smoothed force-path curves for the three internodes of one wheat stalk recorded within the framework of the bending tests. The curves recorded with the other samples showed a similar course. It can be clearly seen that the bending plots shown in Figure 4 are almost identical for all three internodes. In the case of the first internode the maximum of the transverse force shows a slightly increased value. The shift with respect to time is to be explained by the fact that the measurement and the actuator were each started manually and therefore were not synchronized.

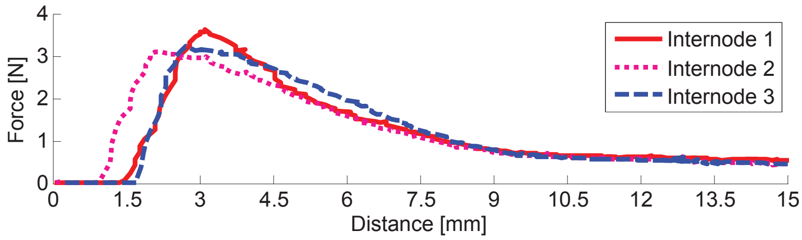

Figure 4: Results of the bending tests for three internodes of sample No. 31
($\dot{x}_B$ = 0,75 mm/s, *sampling rate* = 10 1/s, A_1 = 4,32 mm², $F_{B1,max}$ = 3,63 N, A_2 = 3,21 mm², $F_{B2,max}$ = 3,11 N, A_3 = 3,69 mm², $F_{B3,max}$ = 3,24 N)

A rapid increase in force is followed by an only sub-proportional increase in force, this being due to the change in cross-section. The change in cross-section results from the compressing of the initially ideally round cross-section of the wheat stalk to an approximately rectangular shape. By this point in time the cereal stalk has already been irreversibly deformed. After the maximum shear load has been reached, the force sinks towards zero. A residual force remains since the kinked wheat stalk is pushed through the bracket. Table 1 shows the values determined.

Table 1: Results of the bending tests (mean values from 50 tests)

Internode	A [mm²]	$F_{Q,max}$ [N]	σ_Q [N/mm²]	V_Q [%]	m [10^{-6} kg]
1	4.36	4.87	1.09	22	107.2
2	4.04	4.50	0.99	18	87.4
3	3.68	3.90	1.07	15	82.0

V_Q = variation coefficient of the stress with the bending tests
m = mass of the internode

The mean values show that the shear loads able to be withstood by the plant also decrease with the reduction of the cross-sectional area of the stalk from the first or lowest to the third or highest internode (Figure 2 a) whereby the cross-sectional area follows proportionally the weight of the internode in question. The maximum mean stress is 1.09 N/mm² (Equation 3). This is achieved with the first internode and is almost identical with that achieved with the third internode of 1.07 N/mm². For the second internode the mean stress as determined was 0.99 N/mm². The notably high variation coefficients ranging from 15 to 22 % are due primarily to the different cross-sectional shapes of the samples. Thus it was notable in the determination of the cross-sectional areas that the shape of the cross-section varied frequently above all for the first or lowest internode. For this reason the highest variation coefficient is found in the first internode. The lowest variation coefficient is found in the third internode, this having always an almost ideal round shape. Comparisons with other studies are difficult as a result of the different methods of determining the stress employed. For their bending tests on rice stalks Tavakoli et al. (2010) state variation coefficients of 18 to 25 % or, as the case may be, 8 to 17 %. Accordingly these values lie at least in a similar range to the values determined in this study.

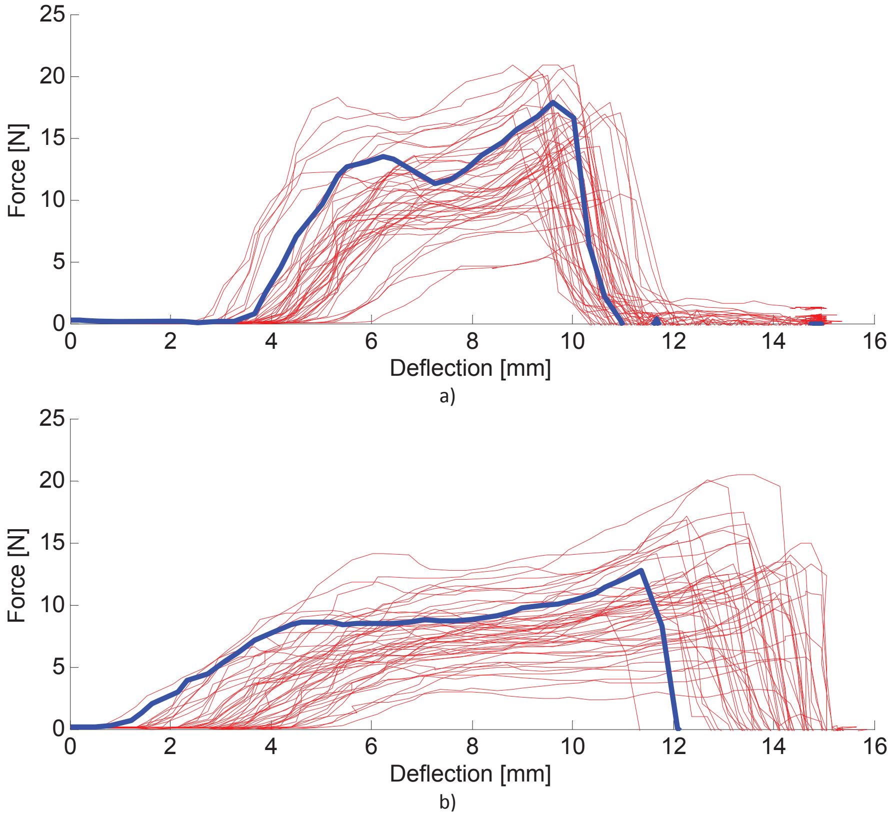

Figure 5: Results of all cutting tests for the first internode with in each case one curve highlighted as example (sampling rate = 250 1/s)
a) Cutting velocity: 50 mm/s, cutting angle: 40° (sample No. 26),
b) Cutting velocity: 50 mm/s, cutting angle: 60° (sample No. 7)

Represented in Figure 5 are the results of the cutting tests carried out on all the samples for the first internode with cutting angles of 40° (Figure 5 a) and 60° (Figure 5 b). The scatter of the values as measured can be clearly seen. For purposes of clarification a curve with a characteristic form of one sample is highlighted in each figure. The calculation and representation of a curve, which reproduces the mean value of all measurements, is not directly possible. The reason for this is that the samples had different diameters so that the length of the path travelled by the blade during the cutting process is always different.

For the different cutting angles different courses resulted. Thus the force increase with an angle of 40° is significantly steeper than with one of 60° (Figure 5). The higher cutting velocity ratios (Stroppel 1939) can be recognized in particular by the fact that at a cutting angle of 40° the blade has to travel a significantly shorter path to separate the sample.

Examination of the two force peaks reveals a further difference, namely that the force peak at a cutting angle of 40° is significantly more apparent. This can be explained by the fact that the surface being cut changes during the cutting process. Thus, at a cutting angle of 40° the cutting force falls first of all after reaching its preliminary maximum value because the surface being cut is becoming smaller (Figure 6). Thereafter it increases again as the frictional force and the size of the surface being cut increase. At a cutting angle of 60° the influence of the frictional forces arising as the blade slides through the sample is significantly greater. In addition higher tensile forces act in the sample acting against the movement of the blade. For this reason the cutting force hardly decreases at all after reaching its first maximum.

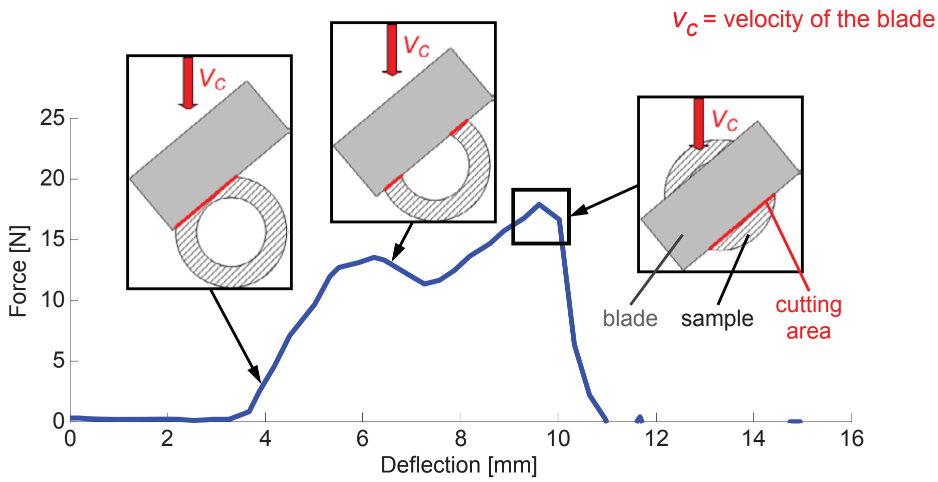

Figure 6: Clarification of the cutting-force-path curves shown in Figure 5

The mean values of all the results of the cutting tests are reproduced in Table 2. With one exception with the first internode, the lowest values for the stresses were found with a cutting angle of 60°. In the case of the first internode the lowest stress of 2.79 N/mm² was achieved with a cutting velocity of 50 mm/s. With the second and third internodes the lowest values were 2.35 N/mm² and 2.20 N/mm² respectively. These were achieved with a cutting velocity of 150 mm/s. The variation coefficients range between 5 and 15 %. As with the bending tests, the variation coefficients were highest with the first internode and lowest with the third internode. Here again the values for the variation coefficients are within the usual range for the testing of natural products. Thus, for example, the shear stresses measured on cotton stalks by Amer Eissa et al. (2008) showed variation coefficients between 6 and 13 %. The greatest variation coefficients were found in the upper part of the plants. With some of the results on shear tests on rice stalks presented by Tavakoli et al. (2010) the variation coefficients range between 18 and 25 %.

Table 2: Results of the cutting tests

Int.	$\dot{x}_C$ [mm/s]	α [1°]	A[1)] [mm²]	$F_{C,max}$[1)] [N]	$\tau_{S,max}$[1)] [N/mm²]	V_C[1)] [%]	E_C/A[1)] [mJ/mm²]	V_{CE}[1)] [%]
1	50	40	3.62	14.89	4.17	13	16.68	19
1	150	40	4.13	13.08	3.19	15	14.06	20
1	50	60	4.21	11.91	2.79	14	17.96	18
1	150	60	4.18	13.56	3.25	10	19.85	19
2	50	40	3.63	16.05	4.44	7	13.37	32
2	150	40	3.97	12.30	3.12	6	14.52	14
2	50	60	3.67	10.27	2.81	9	18.60	14
2	150	60	4.17	9.73	2.35	8	15.56	11
3	50	40	3.53	11.84	3.53	7	12.46	26
3	150	40	4.17	12.40	2.98	5	13.24	17
3	50	60	4.27	11.97	2.80	7	16.02	19
3	150	60	3.74	8.19	2.20	5	12.18	13

1) mean values from 50 tests.
V_C = variation coefficient of the stress with the cutting test
V_{CE} = variation coefficient of the cutting energy related to the cross-section

Without exception the greatest stresses appear at an angle of 40° and a cutting velocity of 50 mm/s. They amounted to 4.17 N/mm², 4.44 N/mm² and 3.53 N/mm² for the first, second and third internodes respectively. The shear stresses determined by O'Dogherty et al. (1995) on wheat stalks range between 4.91 and 7.26 N/mm². Kronbergs (2000) states a value of 8.47 N/mm² and Kushwaha et al. (1983) state values of between 7 and 11 N/mm². On the other hand Prasad and Gupta (1975) obtained values in the range of only 2 to 3.3 N/mm² for maize stalks, whereby however the moisture content was around 74 %.

The maximum cross-section-related cutting energy amounted to 19.85 mJ/mm² for the first internode, 18.60 mJ/mm² for the second internode and 16.02 mJ/mm² for the third internode. In contrast to the stresses, the cross-section-related cutting energy fell from the first to the third internode of the wheat stalk whereby the highest values were obtained in each case at a cutting angle of 60°. An exception occurred with the third internode. Moreover these maximum values occurred – except for the first internode - at a blade velocity of 50 mm/s. A completely different picture can be recognized for a cutting angle of 40°. Here – except for the first internode – the cross-section-related cutting energy is greater at a cutting velocity of 150 mm/s. The variation coefficient varies between 11 and 32 %. The values reported in other studies for the cross-section-related cutting energy found on similar plants are clearly higher. Thus Prasad and Gupta (1975) state a maximum value of 21 mJ/mm² for their measurements on maize stalks. The investigations carried out by McRandal and McNulty (1980) on ryegrass showed a value of 23 mJ/mm². The moisture content is in both cases relatively high.

Summary of the results

- With the bending tests the mean stresses range between 0.99 N/mm² and 1.09 N/mm². The highest values appear for the first internodes of the plants. The lowest values were found for the second internodes. The mean value of the stresses determined at the third internodes range between these values at 1.07 N/mm². The variation coefficients range between 15 % for the third and 22 % for the first internode. The variation coefficient for the first internode is the largest since this differs most from the ideal round shape.
- The stresses determined in the cutting tests range between 2.79 and 4.17 N/mm², 2.35 and 4.44 N/mm² and 2.20 and 3.53 N/mm² for the first, second and third internodes respectively. For the variation coefficients the values vary between 5 and 15 % whereby the highest stresses were found at a cutting angle of 40° and a blade velocity of 50 mm/s. Apart from the exception of the first internode, the lowest stresses were found at a blade setting of 60°. The mean values of all the stresses measured were 3.35 N/mm², 3.18 N/mm² and 2.88 N/mm² for the first, second and third internodes respectively. Accordingly the stress decreases from the lower to the upper part of the wheat stalk.
- Changing the cutting angle and thereby the cutting velocities ratio (Stroppel 1939) had a decisive influence on the measured force-path curve. Thus with a cutting angle of 40° the curve shows two marked peaks for the cutting forces whereas these peaks are much less marked at a cutting angle of 60°. The main cause for this difference is the greater friction at the larger cutting angle. In addition it has to be noted that the blade has to travel a longer distance in order to separate the sample at a cutting angle of 60°.
- The cross-section-related cutting energies range between 14.06 and 19.85 mJ/mm², 13.37 and 18.60 mJ/mm² and 12.18 and 16,02 mJ/mm² for the first, second and third internodes respectively. Apart from one exception with the third internode, the cross-section-related cutting energies found were higher at a cutting angle of 60° than at a cutting angle of 40°. The mean values of the individual values amount to 17.14 mJ/mm², 15.51 mJ/mm² and 13.48 mJ/mm² for the first, second and third internodes respectively. Accordingly the results show that the cross-section-related cutting energy required decreases from the lower to the upper part of a wheat stalk. The variation coefficients range between 11 and 32 %. Responsible for these high values are in particular also the inaccuracies that result from the use of the numeric integration method, this being needed to calculate the cutting energy from the values measured.

Conclusions

The standardization of measuring methods for determining the properties of stalk-type materials makes sense with respect to the comparability of measurements. The universal test bench presented here represents an initial proposal in this respect. The availability of standardized measuring methods represent a fundamental requirement for the creation of databases which contain material parameters and can, for example, be used for simulations. Alternatively the specification of a reference sample could make sense. Suggested here are plastic drinking straws since they are available in large quantities, are cost-favourable and can be manufactured with defined material properties. In future studies the values determined with the reference sample could be stated in comparison with the measurement results obtained. In this way the measurement results could then be better compared with one another.

The transferring of the measurement results obtained in this study into agricultural practice will be carried out first indirectly with the aid of simulations. In this way the measurement results will initially be put into simulation models which depict the universal test bench virtually. The objective is the preparation of a validated cereal stalk model for multi-body simulation. This model will then be used for the simulation and optimization of harvesting processes as arise in, for example, forage harvesters. In addition the measurement results presented here may be of use in the development of agricultural machines.

References

Amer Eissa, A. H.; Gomaa, A. H.; Baimoy, M. H.; Ibrahim, A. A. (2008): Physical and mechanical characteristics for some agricultural residues. Misr J. Ag. Eng. 25(1), pp. 121–146

Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (2013): Ernte 2013 – Mengen und Preise. S. 25, http://berichte.bmelv-statistik.de/EQB-6001012-2013.pdf, Zugriff am 16.2.2014

Casada, J. H.; Walker, J. N.; Smith, E. M. (1969): A Method of Predicting Flexural Behavior of Intact Tobacco Stalks. Transactions of the ASABE 12(3), pp. 292–294

Chandio, F. A.; Changying, J.; Tagar, A. A.; Mari, I. A.; Guangzhao, T.; Cuong, D. M. (2013): Comparison of mechanical properties of wheat and rice straw influenced by loading rates. African Journal of Biotechnology 12(10), pp. 1068–1077, http://www.academicjournals.org/journal/AJB/article-full-text-pdf/E9ACFD322463, Zugriff am 25.7.2013

Chattopadhyay, P.S.; Pandey, K. P. (1999): Mechanical Properties of Sorghum Stalk in Relation to Quasi-static Deformation. Journal of Agricultural Engineering Research 73, pp. 199-206

Curtis, L. M.; Hendrick, J. G. (1969): A Study of Bending-Strength Properties of Cotton Stalks. Transactions of the ASABE 12(1), pp. 39–40

Kronbergs, E. (2000): Mechanical strength testing of stalk materials and compacting energy evaluation. Industrial Crops and Products 11, pp. 211–216

Kushwaha, R.L.; Vaishnav A.S.; Zoerb, G.C. (1983): Shear strength of wheat straw. Canadian Agricultural Engineering 25(2), pp. 163–166

McClelland, J.H.; Spielrein, R.E. (1957): An Investigation of the Ultimate Bending Strength of some Common Pasture Plants. Journal of agricultural engineering research 2, pp. 288–292

McRandal, D.M.; McNulty, P.B. (1980): Mechanical and Physical Properties of Grasses. Transactions of the ASABE 23(4), pp. 816–821

O'Dogherty, M.J.; Huber, J.A.; Dyson, J.; Marshall, C.J. (1995): A Study of the Physical and Mechanical Properties of Wheat Straw. Journal of Agricultural Engineering Research 62, pp. 133–142

Prasad, J.; Gupta, C.P. (1975): Mechanical Properties of Maize Stalk as Related to Harvesting. Journal of Agricultural Engineering Research 20, pp. 79–87

Prince, R.P.; Wolf, D.D.; Bartok, J.W. (1965): The Physical Property Measurements of Forage Stalks. Bulletin/Storrs Agricultural Experiment Station, No. 388, University of Connecticut, pp. 1–27

Statista (2014): Prognose zur Entwicklung der Weltbevölkerung. http://de.statista.com/statistik/daten/studie/1717/umfrage/prognose-zur-entwicklung-der-weltbevoelkerung/, Zugriff am 12.2.2014

Stroppel, T. (1939): Was weiß man heute vom Schneiden? In: RKTL-Schriften 91, 5. Konstrukteur-Kursus, Berlin, Beuth-Vertrieb GmbH, S. 78–97

Tavakoli, H.; Mohtasebi, S.S.; Jafari, A. (2009): Physical and mechanical properties of wheat straw as influenced by moisture content. International Agrophysics 23, pp. 175–181

Tavakoli, M.; Tavakoli, H.; Azizi M.H.; Haghayegh, G.H. (2010): Comparison of Mechanical Properties Between Two Varieties of Rice Straw. Advance Journal of Food Science and Technology 2(1), pp. 50–54

Authors

MScEng Andrej Batos is a scientific employee, **BEng Maximilian Ruepp** is a student assistant and **Prof. Dr.-Ing. Andreas Jahr** is the executive managing director of the scientific staff of the Institute for Product Development and Innovation (FMDauto), in each case at the University for Applied Sciences, Düsseldorf, Josef-Gockeln-Str. 9, 40474 Düsseldorf, e-mail: andrej.batos@fh-duesseldorf.de.

Prof. Dr.-Ing. Burkhard Corves is director of the scientific staff in the Department of Mechanism Theory and Dynamics of Machines (IGM) of the RWTH Aachen University, Aachen, Kackertstr. 16–18, 52072 Aachen.

Acknowledgement

Supported by the Federal Ministry of Education and Research on the basis of a decision by the German Bundestag within the FHprofUnt funding line and the Fachhochschule Düssseldorf – University of Applied Sciences. The project was carried out in co-operation with the companies Krone and RLE. The samples were made available by Mr. Huber, a farmer from Düsseldorf.