STUDIA UBB PHYSICA, Vol. 64 (LXIV), 1-2, 2019, pp. 41-53
(RECOMMENDED CITATION)
doi:10.24193/subbphys.2019.05

LOW-COST, LOAD CELL AND MICROCONTROLLER BASED BENDING STIFFNESS TESTER

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ABSTRACT. Paper and paperboard have many applications, from writing, printing and householding to packaging. Bending stiffness is probably the most important mechanical property of paper and paperboard, it provides rigidity in some industrial processes like printing or folding. The present work describes the design and implementation of a low-cost bending stiffness tester proposed as a graduation project for Engineering Physics students. The performances of the device were successfully tested on both certified and real-life paper products.

Keywords: *bending stiffness, paper products, strain gauge, load cell, stiffness tester*

INTRODUCTION

Bending stiffness is very important for the paperboard-based packaging industry, therefore various methods and devices were proposed to measure such a characteristic. The topic is a complex one, from both theoretical and experimental point of views and giving an excellent inter- and multidisciplinary subject for Engineering Physics undergraduate students.

This work describes the implementation of a low-cost bending stiffness tester proposed as a graduation project for Engineering Physics specialization, at Babeș-Bolyai University, Faculty of Physics [1]. The paper is organized as follows: in the first section the general properties of paper and paperboard are briefly presented, with emphasis on stiffness and measuring principles, the design, implementation and calibration processes are described in the subsequent sections and finally, the measurement results made on some commercially available paperboard-based food packages are also presented.

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THE BENDING STIFFNESS OF PAPER PRODUCTS AND ITS MEASUREMENT

Paper and paperboard have many applications, from writing, printing and householding to packaging. Paper is a relatively thin material (usually less than 0.3 mm) produced by filtration of a cellulose pulp (suspension) followed by pressing and drying, meanwhile paperboard is thicker (usually over 0.30 mm), has a more complex structural construction and consequently a better foldability and rigidity [2, 3].

Due to characteristics of the processing technologies and the fact that cellulose fibers are much longer than thick, the fibers become oriented more or less in the plane of the paper. Therefore, paper becomes a layered structure, but with a certain anisotropy. The preferred orientation of the cellulose fibers is called machine direction (MD) because it is determined by the hydrodynamic forces present in the papermaking process. The in-plane direction perpendicular to this preferred direction is called the cross machine (CD) direction, meanwhile the off plane perpendicular direction is called the thickness direction (ZD) [4].

The resistance of an object to a mechanical action is called stiffness. If this action tends to bend the object, we call the response bending stiffness. According to the most generally accepted methods of stiffness measurements, bending stiffness is the measure of the force which has to be applied in order to bend a piece of material through a given distance or angle. Bending stiffness is probably the most important mechanical property of paper and paperboard, it provides rigidity in some industrial processes like printing or folding. A certain level of bending stiffness of the paperboard is required in converting, packaging, transportation, storing and handling of paperboard-made packaging products. The soft, less rigid paper products used in householding (tissues and towels) have low bending stiffness, a high stiffness is required for newspaper in order to avoid falling together or bending under its own weight. Paper-based food packages, boxes and sacks requires high stiffness to reduces the tendency of buckling when their content presses against walls.

In paper industry, bending stiffness (S_b, measured in mN·m units) is defined as the moment of the resistance, per unit width that a paper or board present against bending within the limits of elastic deformation [4] or as the bending moment, per unit width of a rectangular test paper divided by the curvature [5]:

$$S_b = \frac{EI}{b} \tag{1}$$

$$S_b = \frac{M}{bc} \tag{2}$$

where E is the Young modulus of the paper, I is the second moment of area (moment of inertia) of the cross/sectioned area about an axis through the center of that area, perpendicular to the direction of bending, b is the width of the cross section area considered, M is the bending moment (force x its arm), c is the curvature (inverted value of the bending radius)

There are several well proven techniques for measuring bending stiffness: namely resonance, two-point, three-point and four-point method. All these methods are well documented and described in literature [3-8] and there are several standardized, commercially available bending stiffness measuring devices [9-14]. All of them were designed for industrial use, consequently their market price is relatively high.

The resonance method (Fig. 1a) is based on the determination of the length at which a paper strip will come into forced resonance. The strip of paper or paperboard is held vertically in a clamp vibrating at a fixed frequency. The free length of strip projecting above the clamp will undergo forced vibration. This free length is adjusted for resonance condition (visually recognizable as maximum vibrational amplitude of the free end). The free length of the strip at which resonance occur, is measured. It is called resonance length and is related to bending stiffness (S_b, in mN·m) by the following relationship:

$$S_b = 3.19 \cdot 10^{-12} \cdot l^4 \cdot w \cdot f \tag{3}$$

where w is the grammage or paper density (in g/m^2), f is the vibration frequency (in Hz) and l is the resonance length (in mm).

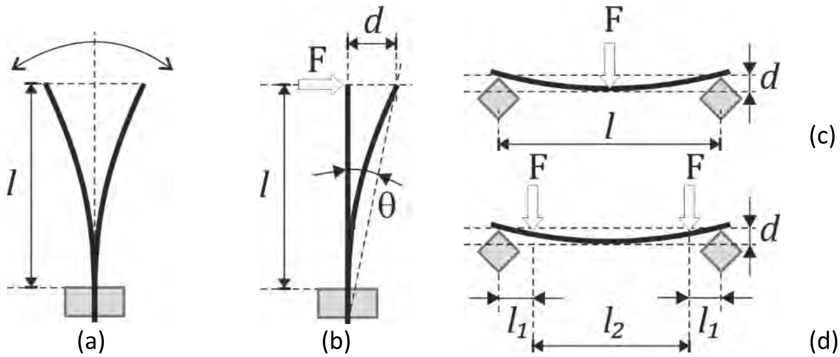


Fig. 1 Bending stiffness determination by: (a) resonance method, (b) two-point method, (c) three-point method, (d) four-point method

The stiffness of lightweight or thin materials is measured by applying a force (*F*) to the free end of a fixed size piece of the material having length (*l*), which is clamped at the other end, and deflecting the free end through a fixed distance (*d*) or angle (θ). This is the two-point method (Fig.1b). For heavyweight or thick materials, the two-point method could cause crushing, even at low-bending angles, which results in anomalously low stiffness values. For these materials, the three-point (Fig.1c) or the four-point (Fig.1d) methods are preferred.

The bending stiffness (S_b, in mN·m) is given by the following relationships:

two-point method: $$S_b = \frac{60Fl^2}{b\theta\pi} \quad (4) \quad \text{and} \quad S_b = \frac{Fl^3}{3db} \quad (5)$$

three-point method: $$S_b = \frac{Fl^3}{48db} \quad (6)$$

four-point method: $$S_b = \frac{Fl_1\, l_2^2}{3db} \quad (7)$$

where F is the bending force (in N), l is the test length or bending length (in mm), b is the test width (in mm), d is the deflection (in mm) and θ is the angular deflection (in degrees), l_1 (in mm) is the distance between the outer support and its nearer inner support and l_2 (in mm) is the distance between the inner supports.

Regardless of the applied technique, due to the anisotropic structure of the paper, bending stiffness has to be determined in both MD and CD directions. The MD stiffness value is always higher than the CD value. Stiffness ratio (i.e. MD stiffness/CD stiffness) is a very commonly used indicator of the anisotropy of the paper product (rarely, the geometric means stiffness, i.e. the square root of the product of the two stiffnesses is used).

FORCE MEASUREMENT

The values of the quantities used in the above-mentioned methods (angle, length, dimensions, deflection) are given by international standards and excepting the resonance method, all techniques require force measurement.

A very convenient force measurement method uses strain gauges. A strain gauge (Fig. 2) is a passive transducer whose relative electrical resistance varies in proportion to the amount of strain in the device [15]. Usually, it consists of a very fine wire or metallic foil arranged in a grid pattern bonded on a thin supporting foil (carrier).

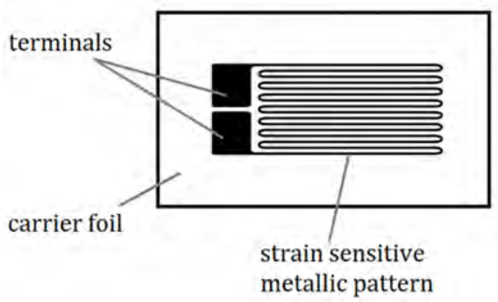


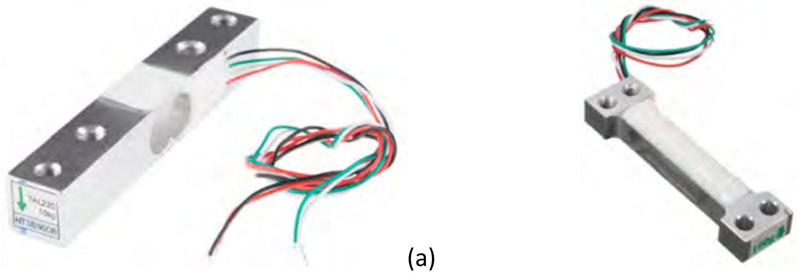
Fig. 2 Metallic strain gauge

Although, the first investigations about the changes of resistance caused by the strain in wires were made in the 1850's [16], the strain gauges were invented almost same time only in the late 1930's and patented in mid-1940's, the by E.E. Simmons [17] and A.C. Ruge [18]. Simmons was investigating the stress–strain behavior of metals under shock loads, while Ruge investigated the influence of earthquakes on mechanical structures.

Strain gauges are available commercially with nominal resistance values from 30 to 3000 Ω, with 120, 350 and 1000 Ω being the most common values [19].

There are several disadvantages in the use of stand-alone strain gauges: difficulty in manipulation, the relative change in resistance cannot be measured directly, low sensitivity, influence of temperature variations and thermal expansion, etc.

In order to avoid those disadvantages, load cells were developed. A load cell is a force sensing module, a transducer taking as input a force and converting it at the output into an electrical signal (voltage). It is consisting of a specially designed aluminum structure, having four strain gauges mounted in precise locations on the structure. The strain gauges form a full Wheatstone bridge in a special arrangement: without externally applied force the bridge is balanced, when the two opposite positioned gauges are in compression, the other two will be in tension, thus the unwanted influences of the temperature and thermal expansion are eliminated. The load cells are active transducers, they need a supply voltage to work properly. One of the most common shape for a load cell is the double bending sheer beam (Fig. 3 a and b) [19, 20].



(a) (b)

Fig. 3 Load cells: (a) beam (max. 10 kg), (b) mini (max. 100 g)

Although the electrical signal output is directly proportional to the product between the supply voltage and the relative change in resistance, it is still very small and requires specialized amplification and analog-to-digital conversion (Fig. 4) in order to be used in measurement systems based on computer or microcontrollers [21].

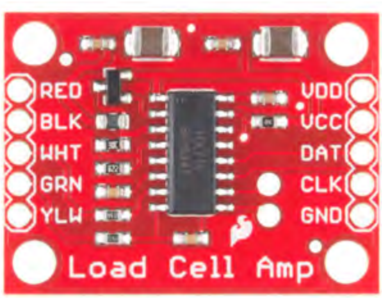


Fig. 4 The HX711 load cell amplifier

STIFFNESS TESTER DESIGN AND IMPLEMENTATION

Besides reliability, low-cost and the stand-alone status were the most important requirement for the bending stiffness tester designed and implemented as graduation thesis. Keeping in sight the values of bending stiffnesses for common papers and paperboards, a 100 g mini load cell and the two-point method were selected.

The schematic of the electronic circuitry (wiring, device driving, data acquisition, processing and display) is presented in Fig. 5 [22].

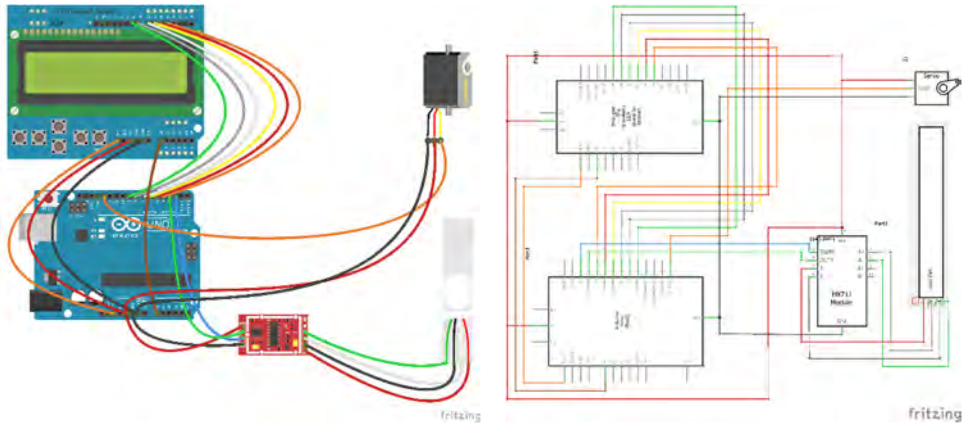


Fig. 5 Electronic circuitry

For driving, data acquisition and processing an Arduino Uno [23] microcontroller was selected. It drives the HX711 load cell amplifier and the Tower Pro MG90S type micro servo motor [24], which is used in the bending process of the paper samples. A LCD-S-1602-BLUE type display [25] was used to ensure that the measurement results can be displayed computer independently. The mechanical design was performed using Autodesk Inventor Professional software package [26]. The tester has only one moving component, the deflector disk which ensures the bending. It was made out from brass using CNC machining technology (Lang Impala 200LNC). All other pieces were obtained via PLA based 3D printing technology (DIY Cartesian FDM). As regarded the rectangular paper test piece, it was dimensioned according to the TAPPI T 489 om-08 standard [27]: 38.1 $\pm$ 0.3 mm in width and 70 $\pm$ 1 mm in length. This piece is immobilized in the sample holder at one of its free ends. At 50 mm from this point, the deflector will ensure a 15^{o} deflection in both directions. The force is measured by the load cell, the bending moment is calculated in both directions (force arm is 50 mm), the average is displayed in mNm units. The ready to use stiffness tester, with its most important parts, is presented in Fig. 6.

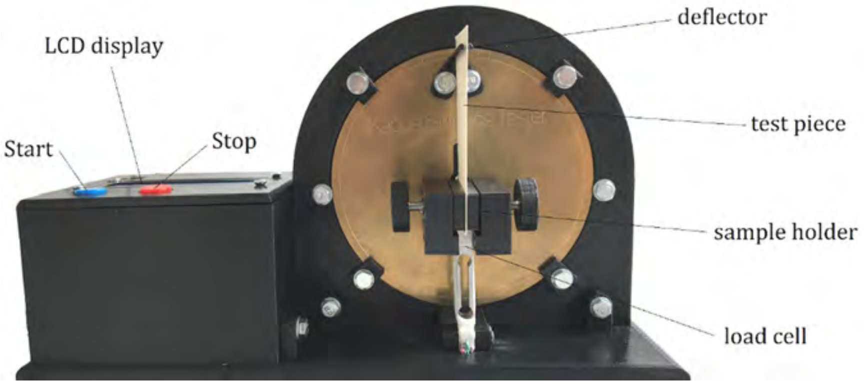


Fig. 6 The assembled bending stiffness tester assembled

CALIBRATION

The bending stiffness tester was calibrated in order to be able to display the bending moment in mNm units.

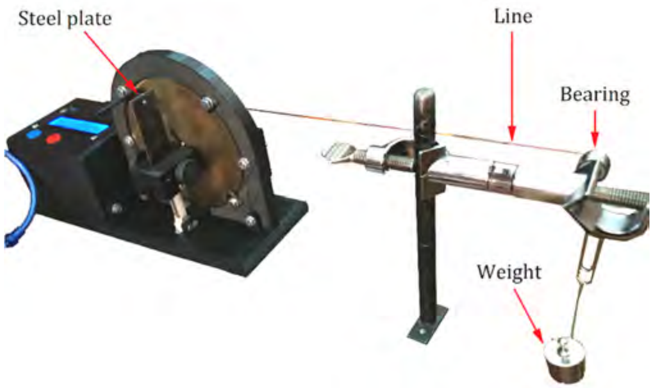


Fig. 7 Set-up for calibration

The calibration process is carried out by matching the measured force with a well-known value given by some analytical balance weights: a steel plate of the size of test pieces was inserted in the holder, the weights (0 g, 1 g, 2 g, 5 g, 10 g, 20 g, 50 g) were attached on it to ensure controlled value of force via line and bearing (Fig.7), bending moment was calculated by means of product between force and arm (l = 5 cm). The relationship between the measured load cell response and calculated bending moment is depicted in Fig.8. One can observe that there is an almost perfect linearity (r^2 = 0.99992) between them, the equation of the fit being:

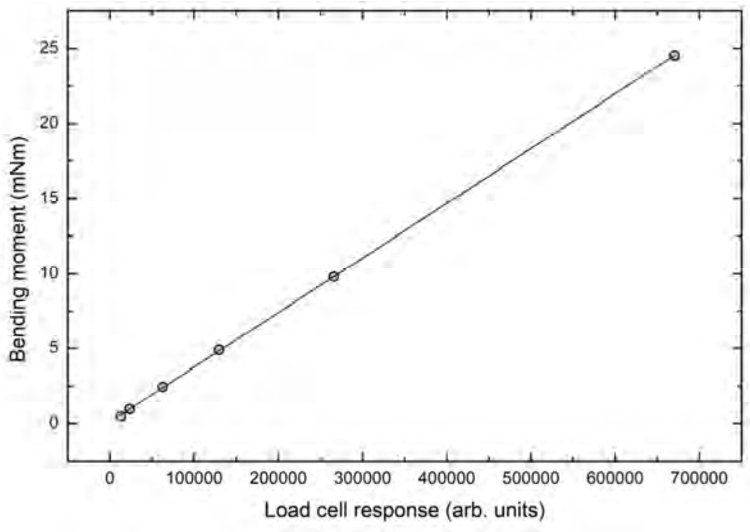


Fig. 8 Calibration curve

According to relationship (4), in the case of the two-point method, the bending stiffness is directly proportional to the bending moment. Subsequently, the Arduino code was implemented accordingly to this linear relationship and in any further measuring situation, the bending stiffness is displayed directly (in mNm units) on the LCD of the tester.

EXPERIMENTAL DETERMINATIONS

The reliability of the system was tested using some fully coated bleached paperboard with white back from Carta Solida [28]. The bending stiffnesses given by the manufacturer and those measured with our tester are presented and compared in Table 1.

As one can see the measured bending stiffnesses are in good agreement with the data given by vendor, the maximum relative error being around 7 %. Experimentally determined data have lower values due to different environmental testing conditions (temperature, humidity), but are well within the tolerance given by vendor (Fig. 9). Tests were performed also on some common, everyday life, commercially available products (Fig. 10), too.

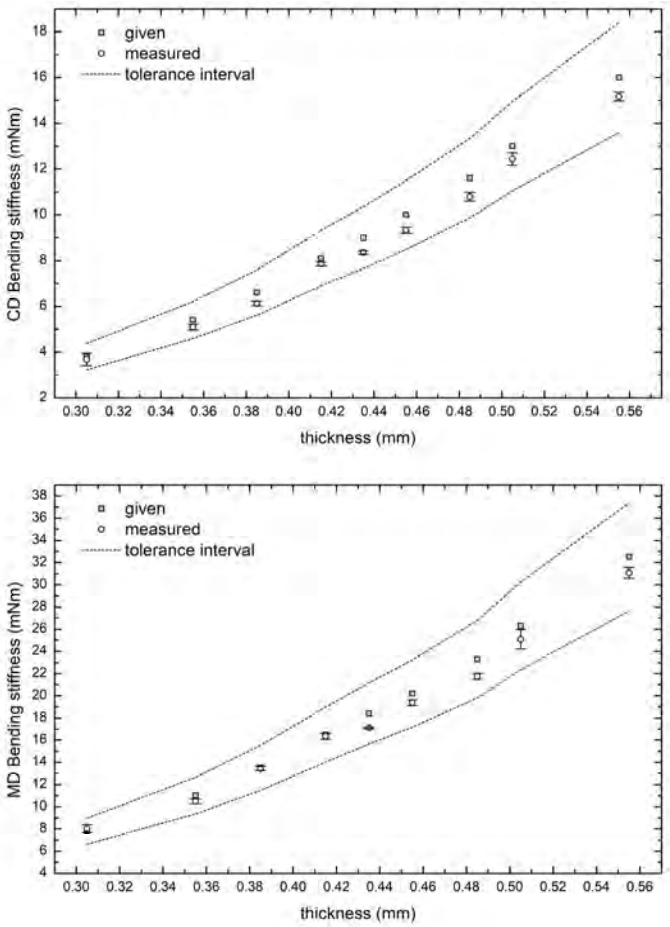


Fig. 9 Comparison between experimentally determined bending stiffnesses and vendors data as function of thickness and machine direction

Fig. 10 Common tested products

Table 1. Bending stiffness measurements
on certified Carta Solida products

Grammage / Thickness / Orientation (1)			Bending stiffness (mN·m)		RE (4)
			Given (2)	Experimental (3)	
200	0.305	CD	3.80	3.684 / 0.266	- 3.16
200	0.305	MD	7.80	8.034 / 0.357	+ 2.95
225	0.355	CD	5.40	5.088 / 0.119	- 5.74
225	0.355	MD	11.00	10.485 / 0.237	- 4.64
235	0.385	CD	6.60	6.13 / 0.105	- 7.12
235	0.385	MD	13.50	13.446 / 0.190	- 0.37
250	0.415	CD	8.10	7.863 / 0.092	- 2.96
250	0.415	MD	16.50	16.337 / 0.260	- 0.97
260	0.435	CD	9.00	8.355 / 0.080	- 7.11
260	0.435	MD	18.40	17.108 / 0.063	- 7.01
270	0.455	CD	10.00	9.33 / 0.134	- 6.70
270	0.455	MD	20.20	19.373 / 0.266	- 4.11
285	0.485	CD	11.60	10.793 / 0.190	- 6.98
285	0.485	MD	23.30	21.749 / 0.276	- 6.65
295	0.505	CD	13.00	12.436 / 0.274	- 4.31
295	0.505	MD	26.30	25.094 / 0.883	- 4.60
320	0.555	CD	16.00	15.168 / 0.195	- 5.19
320	0.555	MD	32.50	31.068 / 0.498	- 4.40

(1) Grammage in g/m^2, Thickness in mm, Orientation: CD cross machine / MD machine; (2) Testing method: Taber 15 (ISO 2493), Tolerance: ± 15 %; (3) Average / Standard deviation of 10 measurements; (4) Relative error in % (Given – Experimental)/ Given

The test pieces for the common materials were prepared and the measurements were performed according to the methodology described above. The results are presented in Table 2.

Table 2. Bending stiffness measurements on common products

Product	Fiber orientation	Bending stiffness (mN·m) *
pasta box	CD	10.31 / 0.10
	MD	23.21 / 0.11
milk box	CD	9.23 / 0.11
	MD	18.90 / 0.14
wine gift bag	CD	14.74 / 0.12
	MD	28.57 / 0.16
ID badge paper	CD	2.09 / 0.02
	MD	2.93 / 0.02
PET	none	6.80 / 0.04

* Average / Standard deviation of ten measurements

CONCLUSIONS

We have proposed a low-cost bending stiffness tester as a graduation project for Engineering Physics. The student designed and implemented a microcontroller driven device, the over-cost being around 100 EURO. The device was calibrated and measurements were performed on both commercially available certified paper products and some everyday life paper-based products.

The results obtained are in good agreement with literature. The project was an important diagnostic tool for the students' performances and skills, and it was successfully presented at the final graduation exam.

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