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TESTING MACHINE FOR ASSESSING THE MECHANICAL PROPERTIES OF BIOLOGICAL MATERIALS

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K e y w o r d s: testing machine, biological materials, Young modulus, Poisson's ratio.

A b s t r a c t

The paper describes the construction and the principle of operation of a testing machine for assessing the mechanical properties of biological materials. The described measuring system enables the application of two methods for determining the Young's modulus and the Poisson's ratio. The first of them is a method that employs the Fourier analysis, designed for testing dry materials. The other one, called the "brocade" method, enables testing specimens with a high moisture content. In combination with the two proposed methods for analysis of changes that occur under tension, the described testing machine is an interesting and viable alternative to expensive devices, which are not always more precise.

BADANIA MASZYNY WYTRZYMAŁOŚCIOWEJ DO MATERIAŁÓW BIOLOGICZNYCH

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S ł o w a k l u c z o w e: maszyna wytrzymałościowa, materiał biologiczny, moduł Younga, współczynnik Poissona.

S t r e s z c z e n i e

Przedstawiono budowę i zasadę działania maszyny wytrzymałościowej przeznaczonej do badania właściwości mechanicznych materiałów biologicznych. Opisany układ pomiarowy umożliwia zastosowanie dwóch metod określania modułu Younga i współczynnika Poissona. Metoda wykorzystująca analizę Fouriera jest przeznaczona do badania materiałów suchych. Metoda „brokatowa" umożliwia badanie próbek o dużej wilgotności. Opisana maszyna wytrzymałościowa, w połączeniu z dwoma zaproponowanymi metodami analizy zachodzących zmian podczas rozciągania, stanowi ciekawą i bardzo przydatną alternatywę dla drogich i nie zawsze precyzyjniejszych urządzeń.

Introduction and Aim of the Study

The mechanical properties of biological materials are usually tested with the use of devices designed for testing metallurgical materials. Their adaptation for testing and measuring biological materials is difficult, while the installation of additional equipment (e.g. CCD cameras) is often impossible. In addition, these devices are very expensive, since they provide a wide range of acting forces, even up to 600 kN. They usually enable acquiring information on strain in the direction of the acting force, whereas the acquired result is usually distorted by boundary effects in the area of the fastening clamps of the tested specimen.

The application of strong forces is not necessary while testing biological materials, such as seed coats. Forces of the order of a few hundred N are generally sufficient. However, it is important to be able to determine strain in directions other than that of the acting force. Making the measurements independent of the boundary effects is also of primary importance.

This paper presents a measuring system designed by the author of this paper and constructed at the Department of Physics, Agricultural University in Lublin, which can be used for testing the mechanical properties of biological materials, with particular emphasis on the seed coats of pulses. This system fulfils the requirements mentioned above and was tested using bean (*Phaseolus* L.) seed coats as experimental material.

During combine harvesting seeds are subjected to high mechanical load (PICKETT 1973, SINGH LINVILL 1977, DOBRZYŃSKI 1998, DOBRZAŃSKI, RYBCZYŃSKI 1995), since there appear significant crippling stresses. Seed coats may also undergo damage during the seed drying process (HENDERSON, PABIS 1962, PABIS et al. 1998). In order to find the causes of damage, it is necessary to determine the physical properties of seed coats, in particular the values of the Young modulus and the Poisson's ratio. The mechanisms causing seed damage must be known in order to reduce seed material losses as well as to improve the quality and market value of seeds.

The described measuring system enables the application of two methods for determining the Young's modulus and the Poisson's ratio. The first of them is a method that employs the Fourier analysis, which is based on applying a pattern of lines to the tested material (DUPRE et al. 1993). The diffraction image of the grid covering the tested material is observed during the test (BELL 1959). The spatial frequency of grid lines is observed during the experiment, as are determined the changes in these frequencies under various values of the acting force. The registered changes in the pattern of lines of the grid are directly related to strain of the tested material. This method was applied to test the mechanical properties of various materials (Douglas et al. 1965, Sharpe 1968, Pryor, North 1971, Boone 1971).

The distribution of stress in the tested material may be automatically calculated using optoelectronic devices (Pickett 1973, Singh, Linvill 1997). This method is again gaining wide interest due to the significant increase in CCD camera resolution (Dupre et al. 1993, Breque et al. 2001, Moulder et al. 1986, Bremand et al. 1992, Auvergne et al. 2000/2001). However, applying lines (most often in the form of a square grid) is related to the necessity to place the tested specimen in a vacuum chamber, permitting deposition by the cathode sputtering method. The tested material must first be subjected to drying. Therefore, this method may be successfully employed in testing the seed coats of dry seeds (Gładyszewska, Chocyk 2004), but cannot be used for moist materials e.g. for testing fresh seeds. A new measuring method was proposed for this reason, which does not require the modification of the described system and may be applied to dry materials as well as those characterized by high moisture levels. This method is called "brocade", due to the application of randomly distributed points (markers) on the tested material. The method is described in detail in (Gladyszewska et al. 2006).

The objective of this study was to propose a construction solution for a testing machine for assessing the mechanical properties of biological materials, enabling the determination of the Young modulus E and the Poisson's ratio n.

Experimental Design

Figure 1 presents a measuring stand which includes the described testing machine. The stand top (*15*) may be leveled thanks to a leveling and dampening system (*16*). Special rubber pads separate the stand from the floor and dampen mechanical vibrations. This ensures image stability for the tested specimen (*17*), acquired on the CCD camera element (*12*) equipped with a microscope lens (*11*). The specimen is placed in the machine's clamps (*8*, *9*). One of the clamps (*9*) is connected to an extensometer (*10*), while the other (*8*) is a movable clamp. This clamp is connected to the gear (*5*) with a string (*6*) passing through a bearing roll (*7*), which establishes the acting direction of tensile force. The gear is composed of two coaxially installed wheels with a radius of R_1 = 0.15 m and R_2 = 0.05 m. This provides a transmission ratio of 3:1 or 1:3 if the string clamps are reversed. The 1:1 ratio may be obtained by placing the string clamps on the same gear wheel. The gear wheels are connected through a steel string (*4*)

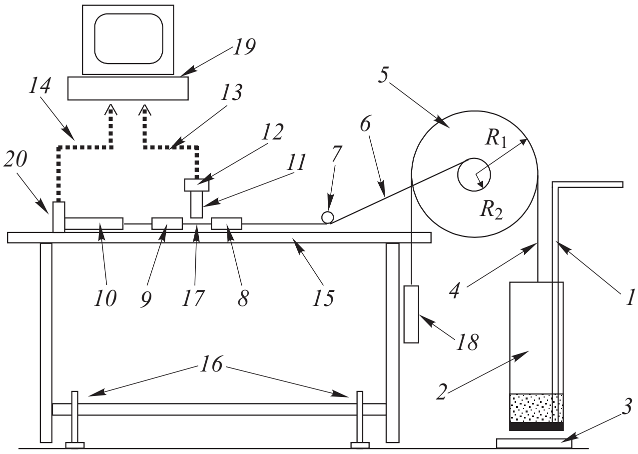

Fig. 1. Testing machine scheme. *1* – tube delivering water to the tank, *2* – tank with water, *3* – impact absorbing layer, *4* – string, *5* – gear, *6* – string, *7* – bearing roll, *8* – movable fastening clamp, *9* – fixed fastening clamp, *10* – extensometer, *11* – microscope lens, *12* – CCD camera, *13* – video cable, *14* – USB cable, *15* – stand top, *16* – leveling and dampening system, *17* – tested specimen, *18* – balancing weight, *19* – computer, *20* – analog-to-digital converter

to a tank (2) with a capacity of 8 liters, which can be filled with water delivered at a given flow rate set by the person performing the measurement, using a tube (*1*) (mechanically isolated from the tank not to introduce disturbances into the system). Since the tested specimen is ruptured during the test, the tank is secured by a combined layer of sponge, rubber and styroplast (*3*), located a few centimeters under the tank, absorbing its movement following the specimen rupture. In order to establish the initial zero force, the machine is “reset” prior to commencing the experiment by a respectively applied weight (*18*) balancing the weight of the tank. As the strength test begins, the specimen image from the camera (*12*) is transferred to the computer memory (*19*) along with information on the actual value of tensile force corresponding to the given image. The signal from the extensometer (*14*) is transferred to the computer through an analog-to-digital converter (*20*), while the image is transferred through (*13*) the video card entry. This allows to later correlate the tensile force value with the specimen strain.

The tested specimen is installed in the clamps as shown in Figure 2. A grid of lines (the method based on the Fourier analysis) or randomly sputtered markers (the “brocade” method) are applied on its surface. The direction of *F* force ensures specimen tension exactly on its horizontal plane. The markers applied to the specimen do not affect its mechanical properties. The applied line system is only 50-100 nm thick, while the randomly sputtered markers (e.g. graphite dust) do not adhere to one another, therefore the natural mechanical properties of the

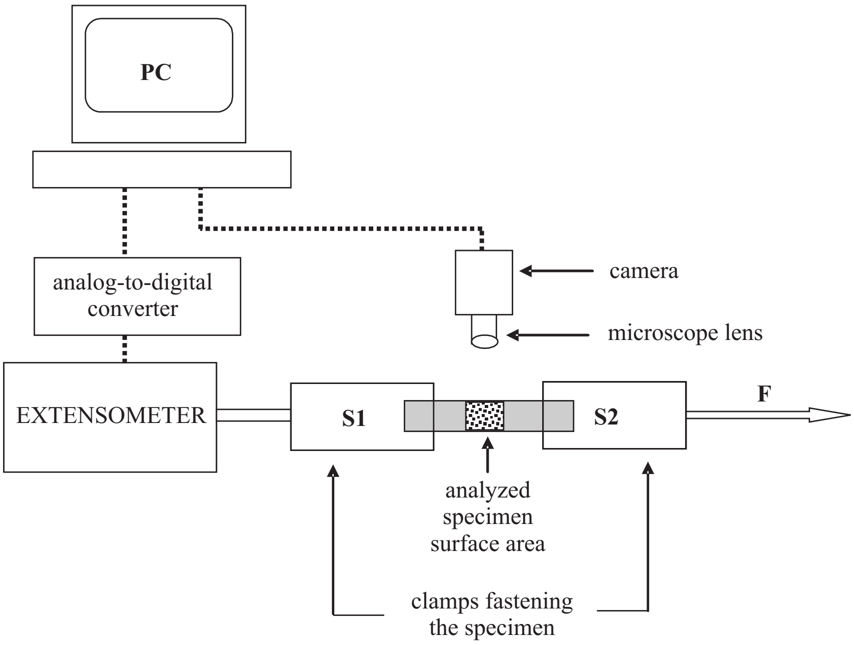

Fig. 2. Scheme of specimen's fastening in clamps

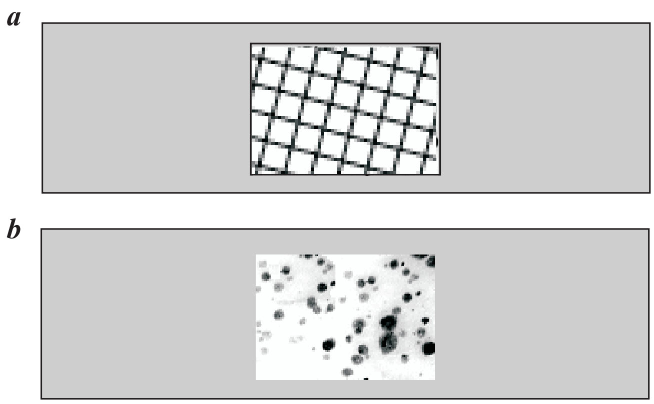

Fig. 3. Markers applied to the tested material in the Fourier distribution method (*a*) and the "brocade" method (*b*)

specimen are maintained in both methods. In order to provide a good image of the specimen under strain, the markers cover up to 30% of its surface area (Fig. 3).

The signal transferred from the extensometer through the analog-to-digital converter must be first calibrated in order to assign specific values expressed in (N) force units to the strain. Laboratory weights were used for this purpose. As a result, the force acting on the extensometer was increased, maintaining very

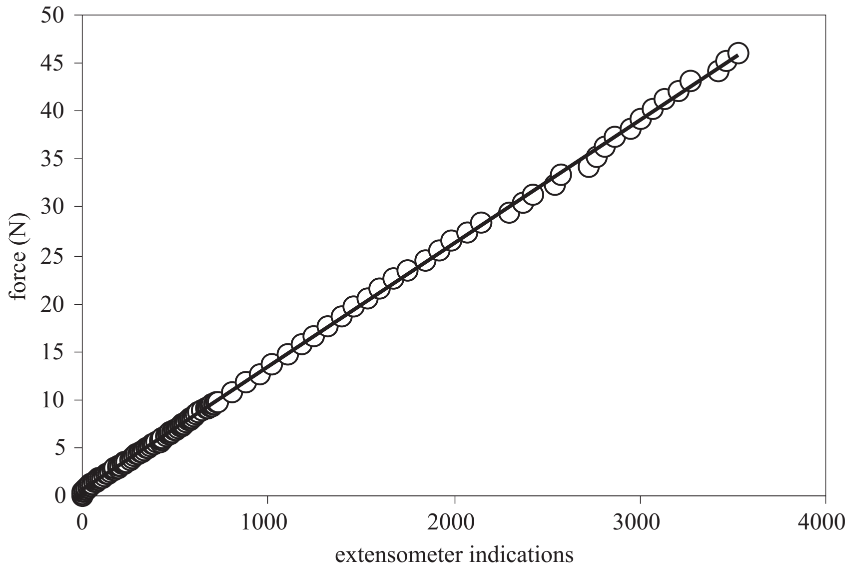

Fig. 4. Extensometer calibration chart

high calibration precision. Figure 4 presents a calibration chart generated for acting forces ranging from 0 to 45 N. Inscribing straight-lines into the measuring points by the least squares method made it possible to determine the formula for calculating the exact value of force upon the given extensometer value:

$$F(\mathrm{N}) = 0.01286 \cdot t + 0.51367 \tag{1}$$

where t is the signal from the extensometer, F is the actual value of tensile force expressed in newtons and applied at the given moment to the tested specimen.

Measuring Methods

The described testing machine allows to perform tests on biological materials by two methods: a method based on the Fourier analysis and the "brocade" method. Both methods are described in detail in previous papers (GŁADYSZEWSKA, CHOCYK 2004, GŁADYSZEWSKA et al. 2006). Since the main objective of this study was to present the construction and the principle of operation of the testing machine alone, the description of the methods used for the analysis of results was limited to a minimum.

It should be noted that it is relatively easy to determine strain in the case of a square grid of markers when the direction of tensile force corresponds to the direction of lines. This is illustrated in Figure 5a. By comparing changes of the

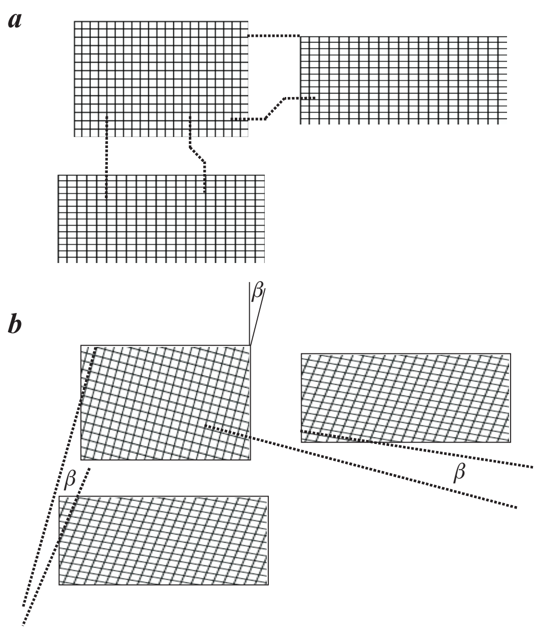

Fig. 5. Schematic representation of square grid strains, when the direction of marker lines coincides with the direction of the applied tensile force (*a*) as well as when the marker lines are deviated from the *x* and *y* axis by angle γ (*b*) prior to testing

grid constant in the direction of tension (let us assume this is direction *x*) as well as in the perpendicular direction to the direction of tension (direction *y*), we can easily determine strains (ε_x and ε_y) within the grid. By knowing the cross-section dimensions of the tested specimen (width *c* and thickness *d*), the stress σ may be determined as:

$$\sigma = \frac{F}{S} \tag{2}$$

where *F* is the value of acting force, while $S = c \cdot d$ is the specimen cross-sectional area. After conducting the test, based on acquired dependencies, the desired Young modulus *E* and Poisson's ratio n values may be determined:

$$E = \frac{\sigma}{\varepsilon_x} \tag{3}$$

$$\nu = -\frac{\varepsilon_y}{\varepsilon_x} \tag{4}$$

Formulas (3) and (4) are also applied when the grid lines of markers are not parallel or perpendicular to the direction of acting force, or when they are randomly distributed on the specimen surface. However, as presented in Figure 5b, theses cases lead to twisting grid lines by angles α, β, which must be taken into account in the analysis since it makes it difficult to directly relate the values of strains ε_x and ε_y to stress σ. The Fourier analysis enables to observe the spatial frequencies of grid lines as well as to determine changes in these frequencies at various values of acting forces. The registered changes in the pattern of lines of the grid are directly related to strain of the tested material. Examples of real

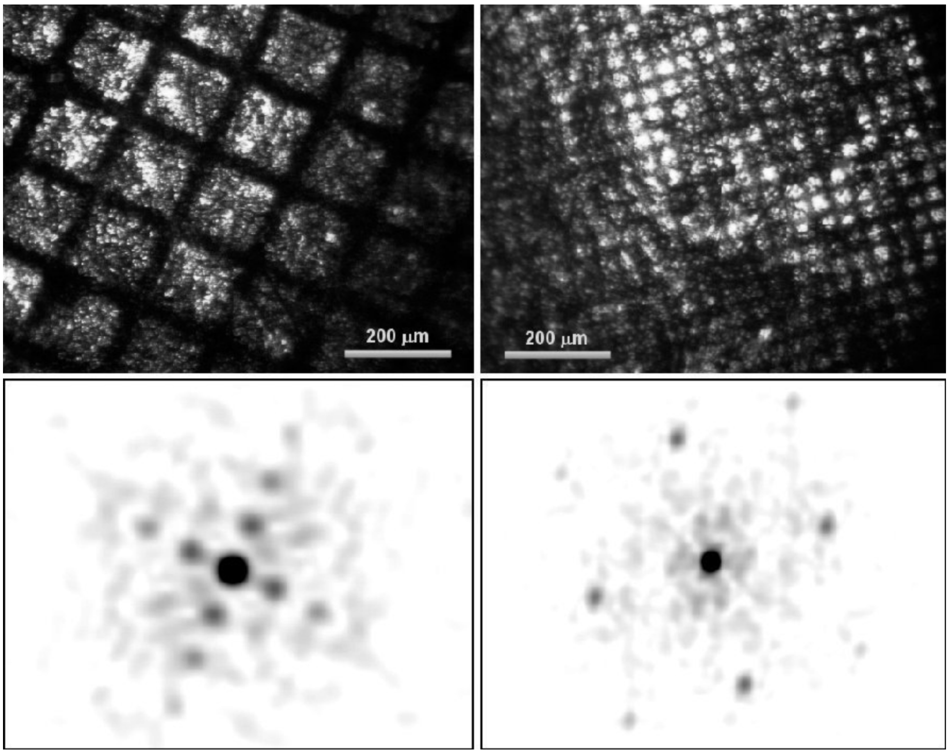

Fig. 6. Examples of real marker images along with their respective Fourier distributions

images along with respective Fourier distributions are presented in Figure 6. It is possible to determine the mean strain of tested specimens by observing changes in the positions of vertexes in Fourier distributions.

The "brocade" method enables to establish simple relationships between strain and stress within the tested material. Since the automatic averaging of results does not take place in this case (as in that with the Fourier distribution method), it is necessary to average the results received for many pairs of markers in the direction of tension as well as in the direction perpendicular to

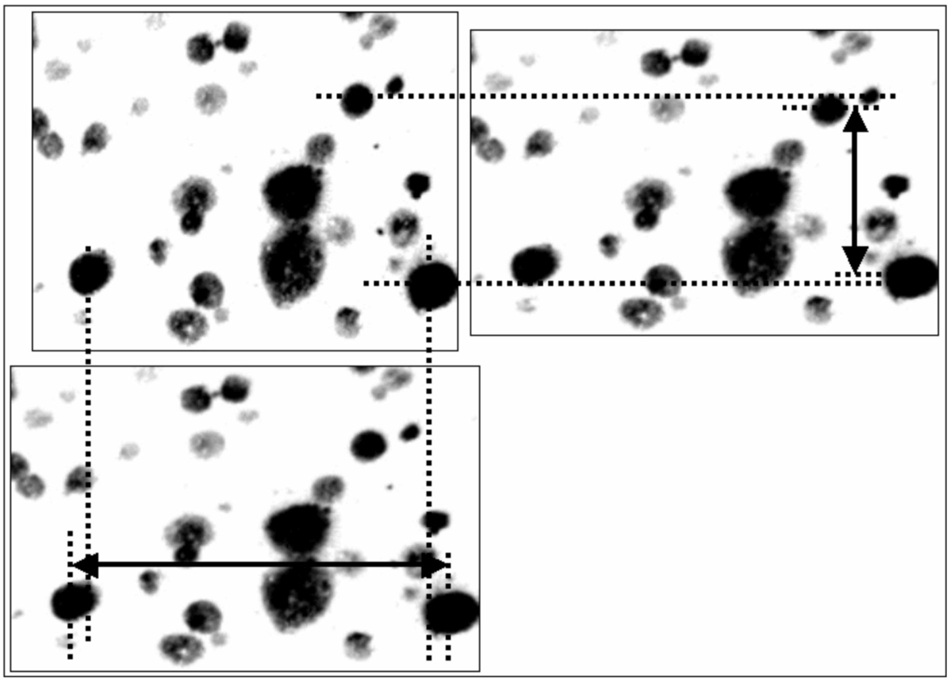

Fig. 7. Examples of two pairs of markers (one in each direction) in the “brocade” method

tension. An example of two pairs of markers (one in each direction) is shown in Figure 7. It should be stressed that the application of the “brocade” method allows to track changes in the relative positions of markers, while strains ε_x and ε_y are acquired based on changes that take place only in the x and y directions, even if the markers are not located on one line parallel to the tension axis or its perpendicular direction.

Results

Figure 8 presents examples of dependencies between strains ε_x and ε_y and stress σ obtained for bean (*Phaseolus* L.) seed coats using the “brocade” method. The tested specimen was 6.9 mm wide and 0.21 mm thick in the measuring range. The moisture content of the specimen was 42%. The straight-lines were inscribed into the measuring points by the least squares method. As a result, the values of the Young modulus and the Poisson’s ratio could be determined for the tested coats. The acquired results were: E = 36.5 MPa and ν = 0.83. This is of course only an example of results, on the basis of which no further conclusions may be reached. It is included in this paper in order to present the functioning of the described testing machine.

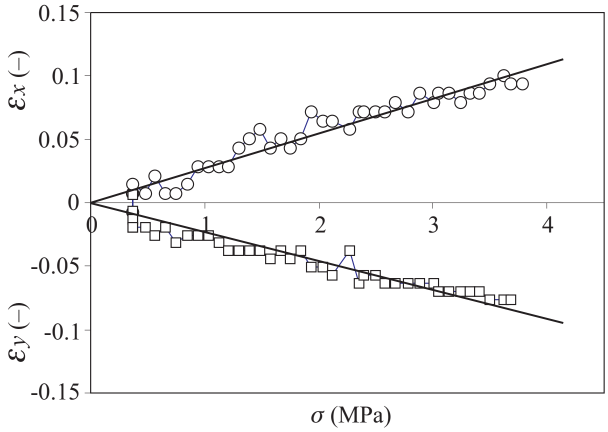

Fig. 8. Examples of dependencies between strains ε_x and ε_y and stress σ acquired for bean (*Phasoleus* L) seed coats using the "brocade" method

Summary

The proposed testing machine allows to conduct tests on the mechanical properties of biological materials. It enables to determine the values of the Young modulus and the Poisson's ratio. This is of primary importance since changes in the Poisson's ratio during various processes (e.g. seed germination) reflect structural changes in the tested material.

In combination with the two previously proposed methods for analysis of changes that occur under tension, the described testing machine is an interesting and viable alternative to expensive devices, which are not always more precise.

By applying the Fourier distribution method, the acquired results are automatically averaged for the entire specimen area under analysis. This is also possible with the "brocade" method, but requires establishing a program procedure, according to which strain ε_x and ε_y would be determined based on changes in the distances between of a large number of markers, while the values of strains would be the result of averaging the changes for all markers. Such a procedure is currently in preparation. It will increase the complementary value of both methods as well as widen the range of applications of the described testing machine.

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