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Testing plastic deformations of materials in the introductory undergraduate mechanics laboratory

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Abstract

Normally, a mechanics laboratory at the undergraduate level includes an experiment to verify compliance with Hooke's law in materials, such as a steel spring and an elastic rubber band. Stress–strain curves are found for these elements. Compression in elastic bands is practically impossible to achieve due to flaccidity. A typical experiment for the complete loading–unloading cycle is to subject a tubular object to torsion. This paper suggests simple experiments for studying properties concerning elasticity and plasticity in elements of common use, subjected to stretching or compression, and also torsion reinforcing. The experiments use plastic binders, rubber bands and metal springs under a moderate load. This paper discusses an experiment with an original device to measure torsion deformations as a function of applied torques, which permitted construction of the hysteresis cycle for a rubber hose and various tubes. Another experiment was designed to define the temporal recovery of a plastic spring with initial stretching. A simple mathematical model was developed to explain this phenomenon.

(Some figures may appear in colour only in the online journal)

1. Introduction

Plasticity is defined as the propensity of a material to undergo permanent deformation under load. On the other hand, elasticity is the tendency of a body to return to its original shape after it has been stretched or compressed. These are important properties of materials with application in science and engineering, and even in situations of daily life.

Plastics are deformable materials with a certain degree of elasticity and thus present singular properties. Studying the behaviour of plastic materials is important due to their increasing use in daily life, having come to replace to a large extent metals and wood. This is important in many areas of study: acoustics; the absorption of acoustic vibrations [1], car design in relation to impact damage [2], sports in relation to the restitution coefficient of balls [3, 4]; anti-seismic buildings in relation to absorption of the energy of seismic waves [5], etc. Studies of deformations of manufactured pieces [6] and mechanical hysteresis [7, 8] are recommended for laboratory exploration in a mechanics course. This paper suggests activities for studying plastic materials through experiments of easy execution, using simple elements available in any elementary laboratory.

1.1. Basic experiments

The following experiments are related to the stress–strain curve of the materials, where the stress σ is defined as the quotient between the force and the cross-sectional area $\sigma = \frac{\mathrm{F}}{\mathrm{A}}$ and the strain ε is the quotient between the deformity and the initial length $\varepsilon = \frac{\Delta x}{x_0}$. A typical mechanical laboratory at undergraduate level includes an experiment to determine the range of application of Hooke's law. Usually, this laboratory experiment begins with the use of a steel spring hung vertically with weights placed at its lower end to measure the amount of stretch from its initial length (figure 1), making sure that the elasticity of the metal is not exceeded. This measurement leads to a graph of proportionality between the applied force F and the obtained stretch Δx showing that this law holds for the steel when it is within the normal elasticity regime (a 'perfect' steel spring). Next, materials that do not satisfy Hooke's law are analysed. A common elastic rubber serves this purpose well. When weights are added sequentially, the behaviour of the rubber band is as follows. A slow stretching at first is followed by a marked increase and, finally, almost no stretching (the band becomes very stiff before it breaks). That is, the stress–strain curve has a positive slope at first, then a steeper slope and finally a slope close to zero. To complete the experiment, weights need be removed sequentially. The unloading curve obtained is not the same as the former load curve. Also, when all weights are removed, the elastic band maintains a permanent stretch. This suggests a hysteretic behaviour for this material, in which the stretching state depends on its previous history. In strict rigour, one cannot refer to a rubber band as an 'elastic material'. Only in a limited range of stretching of the rubber is a purely elastic behaviour observed [9]. Additional stretching results in a deformation that can be permanent or time dependent. This temporal behaviour is usually not studied in the laboratory.

To see the full hysteresis loop for this rubber band, it is necessary to apply forces in the opposite direction, reaching a value equal to the negative value of the maximum force applied in the original sense, e.g., $F_{\mathrm{min}} = -F_{\mathrm{max}}$. It is extremely difficult to compress a flexible band without causing other effects; therefore, the experiment normally ends here. However, other devices may be useful to demonstrate the complete hysteresis cycle in elements, such as the plastic rings used as binders for notebooks. We can also test materials under torsion deformation. For angular deformations, we can expect an analogous form of Hooke's law. The angular form of Hooke's law was tested in different longitudinal elements.

Normally, any material is transformed into plastic material under certain loading conditions. This is true even for a steel spring, which when subjected to high load may form a permanent deformation. But for the purposes of these experiments, the elements will be handled only in their normal operating conditions. However, in the elastic band case, the coefficient of restitution is less than unity. This results in a hysteretic behaviour in the stress–strain cycle, and therefore, a deviation from Hooke's law.

Figure 1. The typical assembly used to test the Hooke's law. A press on the top of a universal support fastens a plastic spring and a ruler to measure its elongation.

2. Experimental procedure

2.1. Stretching/compression curve

In order to complete the entire stretching/compression cycle with a flexible longitudinal element, like the elastic band, a common PVC spiral binder was used. The assembly is as follows. With one end of the binder fixed, the other end is attached to a sewing thread that passes through pulleys at each end of the table. Stretching or compression of the coil is achieved by placing different weights on each side of the thread and held in a straight line by a steel rod inside the coil. A ruler is placed parallel to the rod-filled coil in order to measure the stretching or shrinkage of the coil. This experiment was complicated by effects of friction between the plastic coil and the interior steel bar, distorting the data. An improvement to solve this problem is suggested in section 5.

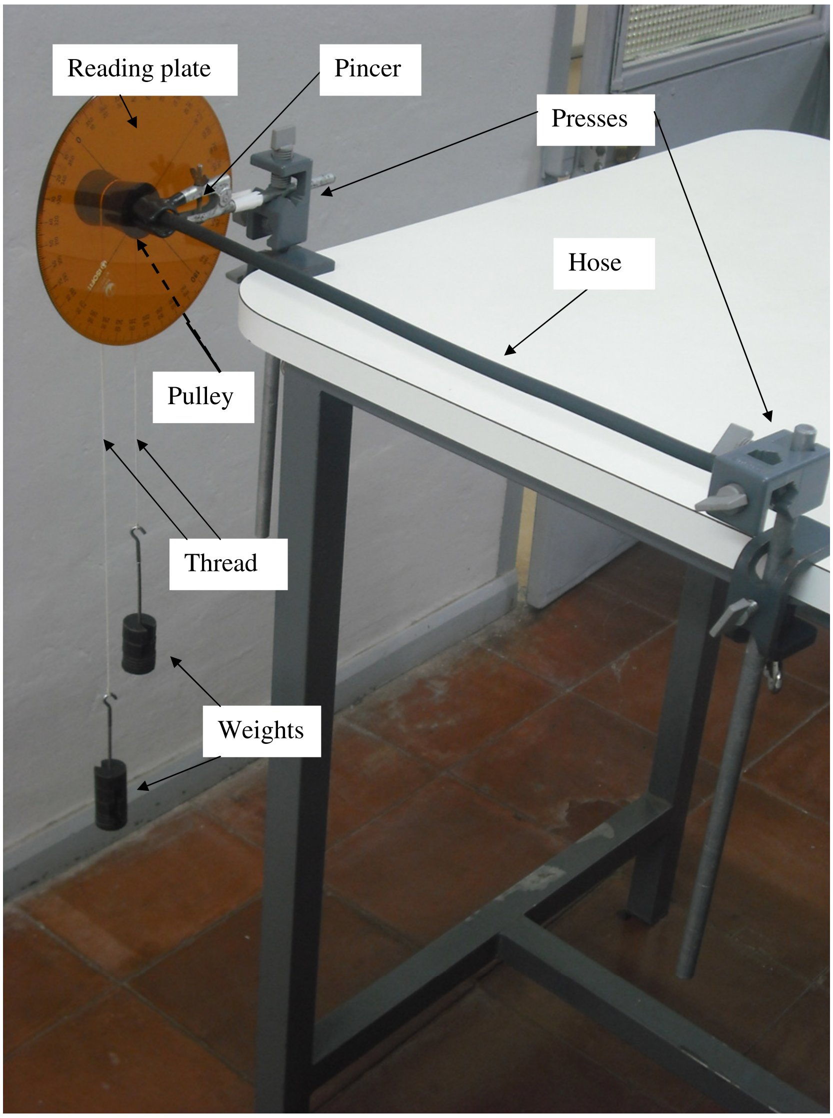

Figure 2. This photo shows a system to study the influence of torques on the torsion of a rubber tube. A bearing is clamped by the jaw of the pincer. The shaft of the bearing fastens the left end of the tube, together the circular plate and the pulley. The shaft is free to rotate, while the right end of the hose is static, trapped to the right press. In this way, angular deformations can be registered when torques are applied by the weights.

2.2. Load/angle curve

Through the practice of angular deformations, we can study the complete cycle, including deflections in both directions. Figure 2 shows a system to study the influence of torques on the torsion of a rubber tube. The external case of a bearing is clamped by the jaw of a pincer fastened to a press. The internal axis of the bearing is free to rotate with one end of the tube anchored in it. Also, a circular reading plate and a rubber pulley are clamped to this internal

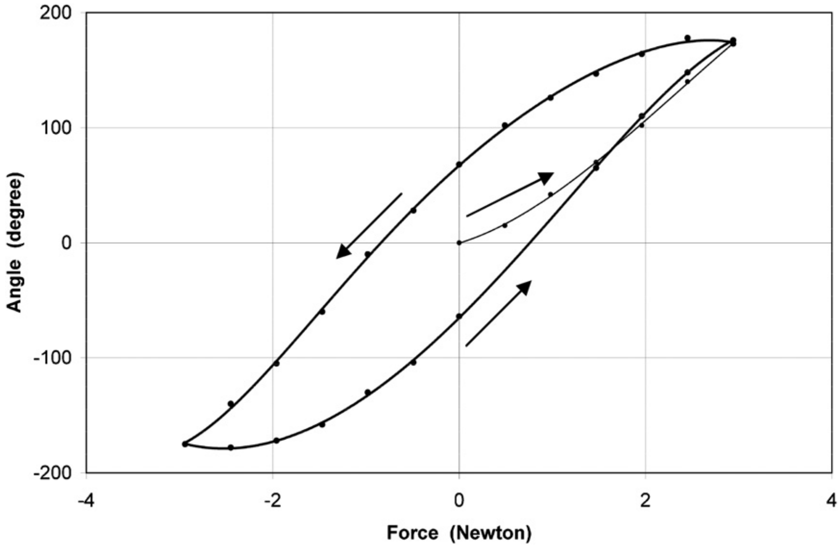

Figure 3. A series of experimental points obtained for the rubber tube in the assembly of figure 2. These are data for torsion angle as a function of the net applied force (which induces the torque). The tube is 0.48 m in length, 11 mm in diameter and 2 mm in thickness. Starting from the origin, the hysteresis cycle ends completely closed after successive measurements. Curves are the result of a fifth-degree polynomial fit. Arrows indicate the sequence of measurements.

axis. The other end of the hose is stabilized by another press. A latex rope with weights at each end is put on the rubber pulley to produce the torque in the hose without slipping. The hose is 0.48 m in length, 11 mm in diameter and 2 mm in thickness. The angular deformations from the applied torque are registered on the reading plate. Other tubes of PVC and Tygon were also used, and even a steel spring was tested in this apparatus, showing complete linearity between torque and angle of rotation. This kind of torsion balance is driven by the torque produced by hanging weights. The rotational torque is proportional to the pulley radius and to the applied force (the difference between the weights hung on the device). By using the known weights in both hangers, it is possible to construct the curves for applied force versus angle deformation. Figure 3 shows results of this experiment, which show a typical hysteresis result for this experiment in mechanics.

2.3. Time-dependent deformations

Longitudinal deformations as a function of time were tested with plastic coils and elastic bands. The typical arrangement for this experiment is with the spring hanging from a universal support with weights hung from its lower extreme and with a ruler in parallel for measuring stretch and deformation (figure 1). PVC plastic coils of 15 and 25 mm diameter were used, with weights between 3 and 5 N. Initial and subsequent lengths were measured at 1 and 2 min intervals. The time-dependent recovery that follows after an initial stretching in the plastic coil was studied. Also, the time longitudinal expansion after a load was put at the end of one of the plastic coils was studied. Similar measurements were made by producing an imbalance in the forces acting on the pulley, in the assembly shown in figure 2.

2.4. Strain as a function of time

As discussed, the length of a body (elastic band or plastic spring) as a function of time was studied when it was subjected to a given load. Another alternative to that experiment is to measure the temporal variations of the force exerted by the body when it is stretched and maintained at a constant length. Experiments were conducted in which a rubber band is stretched to a certain length and the force is sequentially measured on a dynamometer. One end of the rubber band was set at a fixed point, and the other end fixed to the free hook of the dynamometer. This arrangement had the problem of having two variables in play. Along with the change in the force, there is variation in length due to contraction of the dynamometer spring. To avoid this unwanted variation in length, an indirect method was used to measure the force exerted by the band. With the upper end of the rubber band at a fixed point, the other end is hooked to a heavy metal body on the plate of a digital scale (see figure 5). The scale records the difference between the body weight and tension of the band, as time elapses, but this occurs without changing the length of the stretched band.

2.5. Damping effects

Damping capacity is another important property of materials [1]. This important characteristic of plastic materials is important to study in a basic mechanics laboratory. Figure 4 suggests a classroom demonstration experiment in order to visualize this characteristic. Two graduated rulers, one of plastic and the other of steel, are put in a mechanical screw to make them vibrate with an initial impulse. Lengths along the screw are regulated to obtain the same frequency of vibration. It can be noted that the amplitude of oscillation decreases much faster in the plastic ruler. Another experiment to illustrate this effect was performed by oscillating a mass hanging from a steel spring and another mass hanging from a plastic spring (a copybook spiral binder). The masses were regulated to obtain similar frequencies. It was verified that the mass in the steel spring may oscillate for up to 1 h, while the mass in the plastic spring oscillated for less than 10 min. It is instructive to compare the behaviour of plastics and that of steel, a material considered nearly 100% restorative under normal conditions.

2.6. Effect of temperature

All experiments described above were performed with a constant ambient temperature inside the laboratory, because this work focuses only on mechanical effects on material bodies. The thermodynamic effects on these bodies are also an important subject in physics [9], but need to be considered separately from the stretch/deformation experiments, or purposefully included and measured. However, in order to visualize potential effects of temperature increase or decrease using the same assemblies of the previous experiments, a rise in temperature in the rubber band was achieved by bringing a hot air jet to it. When the band is connected to a dynamometer, in the manner described earlier, a hair dryer operated in a direction parallel to it can also be employed to heat the band. In this way, the dynamometer (or the balance) shows the changes in tensile strength resulting from the temperature increase in the band. A time-sustained experiment made it possible to distinguish the immediate effects and those due to prolonged exposure to temperature.

2.7. Data recording

Two experiments, the elastic band elongation versus time and the strain versus time, described in sections 2.3 and 2.4, were recorded on video. A digital camera FUJIFIL model FinePix

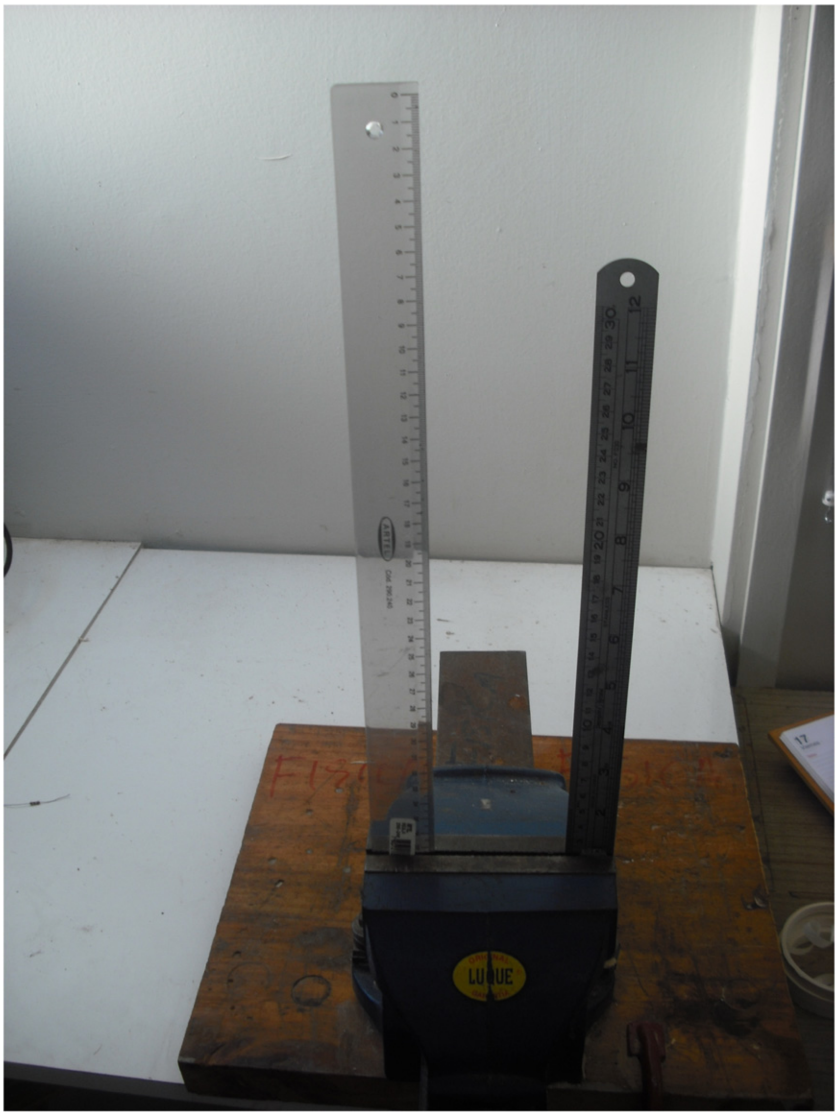

Figure 4. Two rulers, one of plastic and the other of steel, are put in a mechanical screw to make them vibrate. The same vibration frequency is obtained for each ruler by means of adjusting the lengths over the screw. A significantly higher damping is observed in the plastic ruler.

J10 was used, with 8.2 megapixels, 8 MB internal memory and 30 frames per second. These videos were analysed by means of the video editor program AVS4YOU. In the case of strain versus time, the video enabled accurate correspondence between the scale reading and the time elapsed to be established. Because a used elastic band cannot be used in a new experiment, a special procedure was carried out to define the statistical error of the measurements. It worked using three identical digital scales. On each of them was placed a weight of 800 g. Three elastics taken from the same factory package pulled the weights. The elastics were suspended from a horizontal bar which was movable up to a fixed height (figure 5). The readings from each scale, taken at the same instant, allowed an average value of force to be taken as a function

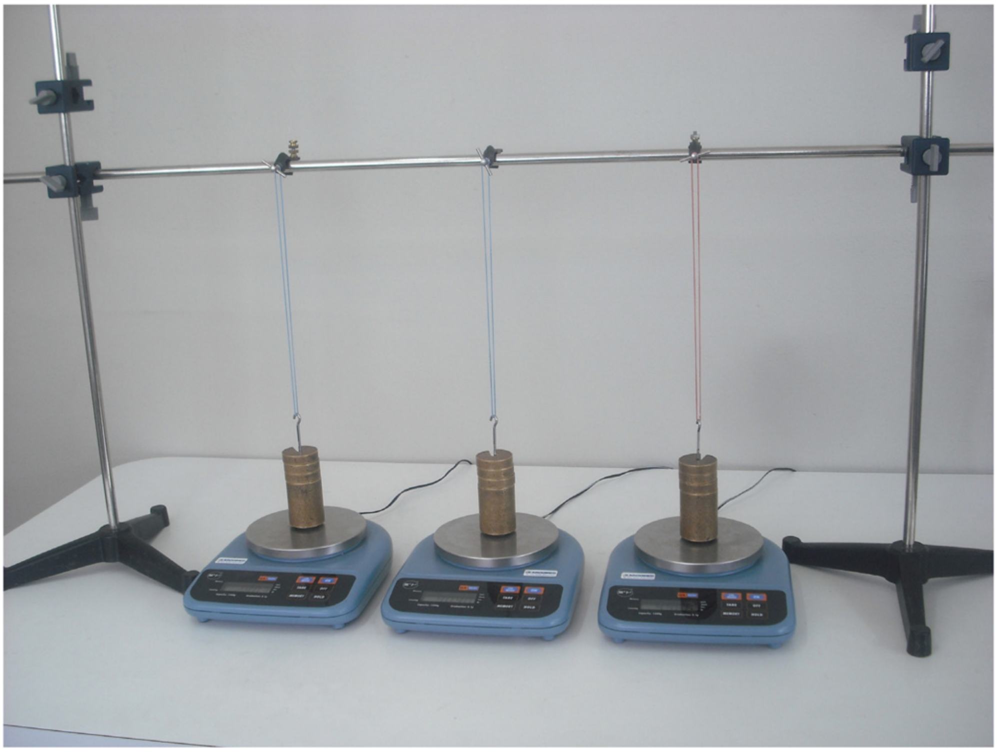

Figure 5. Three scales that were used to determine the force with which the elastics pull weights, and so obtain a statistical result. Elastic tensions as a function of time can be inferred from the record of the scales. The movable bar that holds the elastics is raised horizontally up to a cap on each side.

of time with corresponding statistical error. The initial length of elastics was 10 cm, and they were stretched to 25 cm. Consecutive readings of the scales were recorded on video during the relaxation of the elastics, and the camera lens was zoomed for better definition of the reading of the digital scales. Figure 5 demonstrates the arrangement operating with the three scales.

3. Theory: temporal behaviour of deformations

When a plastic material is deformed by the application of a force and then left free, it experiences a recovery which is time dependent. Materials deformations (or recoveries) as a function of time are measurements easy to perform in a mechanics laboratory.

A macroscopic deformation (elongation or rotation) in a plastic piece and its following time-dependent recovery could be explained as a dislocation process of the infinity of microstructures that compose the body [10], although the exact mechanism is not completely understood [11, 12]. There are interesting studies on the relationship between the temporary deformation of the bodies and the evolution of their microstructures, including theory and simulations [13–17]. The following is suggested as a simple model for the temporal evolution of these microstructures

A number of N_0 microdislocations are generated in the initial deformation. These dislocations consist of at least two types of dislocations. The first type of dislocations include those dislocations (number N_{01}) that remain as permanent dislocations. The second type of dislocations (number N_{02}) recover their initial locations spontaneously during an average time, which depends on the material and environmental conditions (temperature, etc). Thus, we have for the initial time $t = 0$ the following:

$$N_0 = N_{01} + N_{02}. \tag{1}$$

Also, for the dislocations at any time t, we have the following:

$$N = N_{01} + N_2. \tag{2}$$

Here, $N_0 = N(0)$ is the initial number of dislocations, $N = N(t)$ is the total number of dislocations at any time t and $N_2 = N_2(t)$ is the number of dislocations of the second type at any time t. N_0 should be proportional to Δx_0, the initial macroscopic deformation of the plastic body (rubber band, coil, hose, etc). Also, N, the temporal number of dislocations, will be proportional to the deformation at any time t, i.e. Δx.

In the same way as in the decay of a radioactive sample, where the isotopes contained in it undergo spontaneous disintegration, we can establish, for the rate of variation of N_2 at any time,

$$\frac{\partial N_2}{\partial t} = -\lambda N_2, \tag{3}$$

where λ is a constant of proportionality. By means of integration and exponentiation, an exponential function for N_2 is derived of the form

$$N_2 = N_{02}\,\mathrm{e}^{-\lambda t}. \tag{4}$$

Thus, we have for the temporal behaviour of plastic deformation:

$$\frac{\Delta x}{\Delta x_0} = \frac{N}{N_0} = \frac{N_{01} + N_{02}\,\mathrm{e}^{-\lambda t}}{N_0}. \tag{5}$$

Expression (4) is in agreement with the behaviour of the experimental points in figure 4.

The constant λ is related to the half-life of migrating dislocations $t_{1/2}$ by

$$\lambda = \frac{0.693}{t_{1/2}}. \tag{6}$$

N_{01} could be associated with the permanent deformation of the plastic object.

In the experiment described in section 2.4, the body is stretched and maintained at a constant length. In this case, the variable that depends on time is the force exerted by this body. This situation can be modelled as a set of N_0 dislocations produced during stretching, each exerting a restoring force. A number of these N_{01} remain unchanged over time. The remaining dislocations N_{02} spontaneously degrade within a characteristic time to stop exerting force for a sufficiently long time. The result is a macroscopic time-dependent force F exerted by the body, as follows:

$$\frac{F}{F_0} = \frac{N}{N_0} = \frac{N_{01} + N_{02}\,\mathrm{e}^{-\lambda' t}}{N_0}, \tag{7}$$

where F_0 is the force exerted by the body at $t = 0$, N is the number of dislocations exerting a restoring force at the time t, λ' is the constant related to the half-life of degrading dislocations when macroscopic length remains constant.

When data were recorded for longer than 20 days, the best fit was to a curve composed of two decays: one with a short half-life of a couple of minutes and one of a much longer half-life of over 1 day. The final permanent deformation values (after several days) remained higher than 2% of the initial deformation. Thus, for longitudinal deformations, as in equation (5), the final curve becomes

$$\frac{\Delta x}{\Delta x_0} = \frac{N}{N_0} = \frac{N_{01} + N_{02}\,\mathrm{e}^{-\lambda_S t} + N_{03}\,\mathrm{e}^{-\lambda_L t}}{N_0}. \tag{8}$$

S and L refer to short and long half-life.

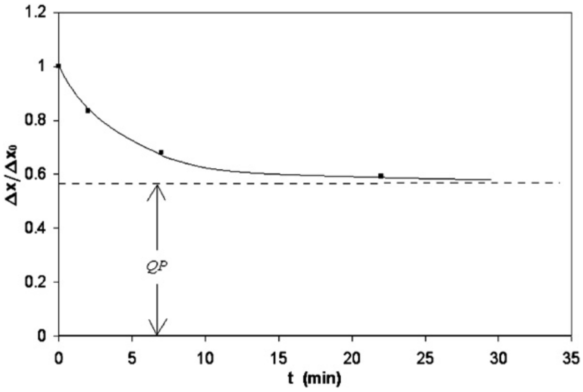

Figure 6. Temporal evolution of the length of a PVC spring, a PVC spiral binder 26.9 cm long and 2.5 cm in diameter, after having been stretched ten times its initial length. Δx_0 is the initial stretching, Δx is the deformation at elapsed time t and QP is the quasi-permanent deformation, described in the text.

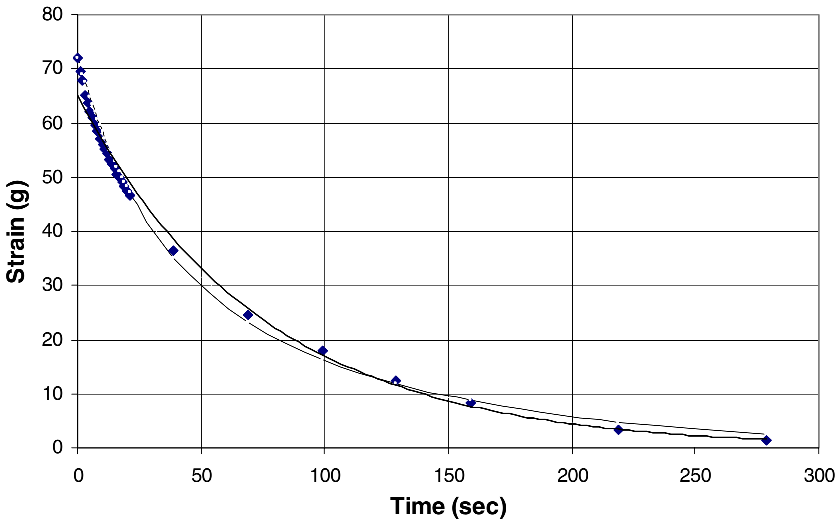

Figure 7. Experimental data on the strain of one of the elastics described in sections 2.4 and 2.7 (figure 5), i.e. the force (F) pulling the weight on one of the scales as a function of time (t); the experimental points and two fit curves. The solid curve is the fit to a one-exponential function: $F = 65\,e^{-0.0134t}$. The dashed curve is the fit to a double-exponential function: $F = 22\,e^{-0.04t} + 50\,e^{-0.015t}$.

4. Results and discussion

All the activities presented here are highly instructive and useful in an undergraduate mechanics laboratory for learning about the behaviour of materials. The experiments described in section 2 yielded important results, as shown in figures 3, 6 and 7.

As noted, figure 3 shows a series of experimental points obtained in an experiment with the assembly shown in figure 2. These data indicate the torsion angle of a rubber tube, as a function of the net applied force. This force multiplied by the radius of the rubber pulley (1.7 cm) is equal to the applied torque. The curve corresponds to a typical hysteresis cycle. Starting from the origin, the hysteresis cycle is completely verified after successive measurements. Curves are the result of a fifth-degree polynomial fit.

The experiment described in section 2.3, to measure length as a function of time after releasing the plastic coil and after being submitted to initial stretching, had the following performance. As discussed, when deformation data were collected for several days, two decays were observed: a short half-life of a couple of minutes and a longer half-life of a couple of days. We can define QP as the sum of the permanent final deformation and the deformation with very slow recovery. With this renaming, equation (8) can be rewritten as follows:

$$\frac{\Delta x}{\Delta x_0} = \frac{N_{01} + N_{02}\,\mathrm{e}^{-\lambda_S t} + N_{03}\,\mathrm{e}^{-\lambda_L t}}{N_0} = \frac{N_{02}\,\mathrm{e}^{-\lambda_S t}}{N_0} + \mathrm{QP}. \tag{9}$$

Figure 6 is the time evolution of the length (shrinkage) of a plastic coil after having been stretched by about ten times its initial length and then released. Time zero was taken a minute after initial stretching. In this figure, the horizontal line corresponds to the former described quasi-permanent deformation (QP). When equation (8) was applied to the data from this experiment, the best fit provides the following result:

$$\frac{\Delta x}{\Delta x_0} = \frac{N_{01}}{N_0} + \frac{N_{02}}{N_0}\,\mathrm{e}^{-\lambda_S t} + \frac{N_{03}}{N_0}\,\mathrm{e}^{-\lambda_L t} = 0.25 + 0.42\,\mathrm{e}^{-0.24t} + 0.33\,\mathrm{e}^{-2.4\times10^{-4}t}.$$

$\mathrm{QP} = 0.25 + 0.33\,\mathrm{e}^{-2.4\times10^{-4}t}$ is the quasi-permanent deformation, and it can be seen as the horizontal line in figure 6. Here, t is in min and constants in the exponents are in min^{-1}. In this experiment, the characteristic times, for the short-time and the long-time decays, were 2.9 min and 48 h.

The experiment described in section 2.4, to measure the forces exerted by elastic bands on bodies standing on the plates of digital scales, has the following results. The readings of the scales reflect a gradual increase, which indicates a reduction of the force exerted by the elastics pulled by the weights, due to the relaxation of bands. The statistical error in this experiment was associated with the standard deviation of the scale readings. Some systematic error, perhaps attributable to a difference between the scales or the elastics, led to greater statistical error. Statistical errors are a larger percentage at the beginning of the measurement, about 50%, and then stabilize to less than 30%. When the values of the readings of the scales are adjusted to a single initial value, the statistical errors are reduced considerably, to a typical value of 5%. The graph in figure 7 presents the experimental data on the strain of one of the elastics described in sections 2.4 and 2.7 (figure 5), i.e. the force (F) pulling the weight on one of the scales as a function of time (t). Two curves were fit to the experimental points. One of the curves is constituted by a single-exponential function $F = 65\,\mathrm{e}^{-0.0134t}$, like as would provided by the EXEL program. The other curve consists of a double-exponential function: $F = 22\,\mathrm{e}^{-0.04t} + 50\,\mathrm{e}^{-0.015t}$. It is verified that the composite function best fits the experimental points from the start.

Several results are obtained in the experiments discussed in sections 2.5 and 2.6. For example, the mass on a plastic coil remains oscillating for considerably less time than for a steel spring. The same is true when comparing the times of vibration of plastic and steel in the plastic ruler and that of steel. A sudden rise in temperature caused an increase in the tension of the elastic band, but more prolonged exposure to high temperature tended to loosen or relax the band.

5. Conclusions

Any material becomes plastic at a given load. For practical purposes in a mechanics laboratory, however, the steel spring is fully restorative, unlike the common petro-based plastic presented as a material that maintains its deformation. The macroscopic behaviour of a plastic piece, its deformation and recovery, can be described in terms of the temporal changes in its microstructure (rotation, strain, growth or shrinkage of micrograins) [14].

The experiment described in section 2.1 is instructive, especially for undergraduate students, because it measures length changes for a longitudinal flexible object, which they encounter in many aspects of their collegiate and personal lives. Nevertheless, this experiment needs more refinement in order to avoid friction problems. For example, it might be possible to immerse the entire assembly in an oil bath to avoid friction between the plastic coil and the inner bar. In this way, the curve for the entire stretching/compression cycle could be obtained.

In the experiments on deformation as a function of the net applied force, e.g. as in figure 3, care must be taken to make measurements immediately after applying a force due to the time-dependent recovery of the material. This characteristic of plastic deformation is not found in the hysteresis of magnetization, in which the magnetic dipoles remain permanently reoriented after the application of a magnetic field. In the opposite case, a steel spring presents an immediate recovery after removing the force. This is a case in which the deformation depends on both instantaneous force and the history of the applied force. All this discussion enables students to learn to distinguish three types of effects from force on various materials: (1) a permanent distortion after the application of a cause (the presence of a magnetic field), (2) a deformation that is recovered in a time-dependent manner and (3) a deformation that disappears immediately after eliminating the condition that caused it (the applied force).

When longitudinal and angular deformations were tested in plastic coils, tubes and elastic bands, the behaviour was almost the same: a rapid recovery at first followed by a slower stabilization. In both cases of deformation, the decay of the number of microdislocations applies. The quotient $\Delta x / \Delta x_0$ does not reach zero; it starts from unity and goes to an asymptotic value greater than zero. This implies the existence of a permanent deformation in the material. This is a feature common to all plastic materials that can be verified by measuring the length several days later.

Attempting to measure stretch as a function of time has the following disadvantage. At first, when the weight is hung on the spring or elastic, it starts to oscillate. This inertial effect competes with the physical phenomenon studied. This difficulty is overcome when studying the evolution of the force on the body exerted by the elastic (section 2.4). Here, there is no possibility of oscillation, and one is able to measure from the very beginning of the force action. Recording data on video, with a digital camera, has the advantage that it is an accurate record from the beginning of the experiment with a very good temporal resolution. In addition, the video can be replayed for verification or future reference.

For the experiment where the rulers or the masses under the springs oscillate, it was noted that the amplitude of oscillation decreases much faster in the plastic ruler than in the steel ruler. The same variation occurs in the plastic coil compared with a steel spring. Damping in the plastic objects is produced by an internal dissipation of energy and not by an external agent. In the laboratory, the displacement of microstructures in plastic materials is a good topic for discussion and future experiments.

Most of these experiments can be performed during a single standard laboratory session. Measurements of long-term decay, as described for the plastic coil, could be grounds for additional research by students and make for excellent group projects. Other experiments, such as oscillating masses in plastic and steel springs, could be verified in parallel to other activities in the laboratory. The demonstrative experiments, such as the vibrating rulers (section 2.5) or that of the rubber band heated by a hot air stream (section 2.6), require only a little time for verification.

Common plastic materials, as those studied here, are not totally restorative and also not totally deformable. As can be seen, they are partially restored after an initial deformation and their restoration is time dependent. And, as shown, this behaviour can be modelled by a mathematical algorithm, which also enables students to see the application of these principles to other areas.

The experiments can be performed with minimal instrumentation, present in any laboratory, and include elastic bands, plastic coils or springs, flexible hoses and steel springs. Also, presses, clamps, bearings, rulers and a graduated disc are useful to aid in setting up the experiments. Pulleys and weights were used to replace a gravimetric balance. Thus, in a basic undergraduate mechanics laboratory, these experiments establish a basis for discussion of the fundamental elasto-plastic properties of materials. These experiments also enable students to relate to other branches of physics such as magnetism (in relation to the phenomenon of hysteresis) and nuclear physics (in relation to radioactive decay).

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References

[1] Xie Z, Tane M, Hyun S, Okuda Y and Nakahima H 2006 Vibration-damping capacity of lotus-type porous magnesium *Mater. Sci. Eng.* A **417** 129–33
[2] Hadrys D and Miros M 2008 Coefficient of restitution of model repaired car body parts *J. Achiev. Mater. Manuf. Eng.* **28** 51–4
[3] Cross R 2002 Measurement of the horizontal coefficient of restitution for a super-ball and a tennis ball *Am. J. Phys.* **70** 482–9
[4] Elert G 2006 http://hypertextbook.com/facts/2006/restitution.shtml (an educational website)
[5] Rahimian A 2007 Damped link element in coupled truss or wall system *Struct. Mag.* November 2007, pp 30–4
[6] Beléndez T, Neipp C and Beléndez A 2002 Large and small deflections of a cantilever beam *Eur. J. Phys.* **23** 371–9
[7] PHYWE 1998 Mechanical hysteresis *PHYWE Report* LEP 1.2.03 (http://www.nikhef.nl/~h73/kn1c/praktikum/phywe/LEP/Experim/1_2_03.pdf)
[8] Universidad Complutense de Madrid 2012 Torsion balance, mechanical hysteresis *Course 02/03: Técnicas Experimentales II* (http://material.fis.ucm.es/myo1/torsion.pdf) (in Spanish)
[9] Savarino G and Fisch M R 1991 A general physics laboratory investigation of the thermodynamics of a rubber band *Am. J. Phys.* **59** 141–5
[10] Padmavathi D A 2011 Potential energy curves and material properties *Mater. Sci. Appl.* **2** 97–104
[11] Mishra A, Kad B K, Gregori F and Meyers M A 2007 Microstructural evolution in copper subject to severe plastic deformation: experiments and analysis *Acta Mater.* **55** 13–28
[12] Wei Q, Jia D, Ramesh K T and Ma E 2002 Evolution and microstructure of shear bands in nanostructured Fe *Appl. Phys. Lett.* **81** 1240–2
[13] Messerschmidt U and Bartsch M 2003 Generation of dislocations during plastic deformation *Mater. Chem. Phys.* **81** 518–23
[14] Pantleon W, Wejdemann C, Jacobsen B, Lienert U and Poulsen H F 2009 Evolution of deformation structures under varying loading conditions followed *in situ* by high angular resolution 3DXRD *Mater. Sci. Eng.* A **524** 55–63
[15] Jakobsen B, Poulsen H F, Lienert U, Bernier J, Gundlach C and Pantleon W 2009 Stability of dislocation structures in copper towards stress relaxation investigated by high angular resolution 3D x-ray diffraction *Phys. Status Solidi* a **206** 21–30
[16] Yamanaka A, Takaki T, Tomita Y and Yoshino M 2009 Crystal plasticity phase-field simulation of deformation behavior and microstructure evolution in polycrystalline material *COMPLAS. Proc. 10th Int. Conf. on Computational Plasticity (Barcelona, 2009)* pp 1–4
[17] Wilson S R, Hefferen C, Li F, Suter R and Rollett A D 2010 Microstructural characterization and evolution in 3D *Proc. 31st Risø Int. Symp. on Materials Science (Technical University of Denmark)* pp 201–17 (http://www.andrew.cmu.edu/user/suter/3dxdm/wilson_cmu-3d-evolution.pdf)