1

Mechanical Tests

1.1. Introduction

The mechanical tests performed in solid and structural mechanics have different objectives, depending on the level of knowledge sought through these tests:

– primarily, *the characterization tests* allow *understanding* of undefined mechanisms. They are particularly useful when the level of knowledge of a problem is low, such as in biomechanics and tribology. They are, therefore, essential elements of modeling and enable the development of analytical, numerical, and experimental models;

– *reference tests* can *quantify intrinsic values* (Young's modulus) and *classify technical solutions* according to extrinsic parameters (e.g. coefficient of friction). These tests should be finely described and reproduced by the scientific community in order to enable valid comparisons. This description, which increases the reliability of a test, is the standard. Various tests performed under sufficiently near operating conditions can be compared and stored in databases;

– the result of reference tests cannot be considered "as is" without verification. In particular, the actual geometry, size, or production conditions require *validation tests* scaled to a structure.

The diversity of the available standardized tests as well as tests related to a product (for example, the maximum deflection of a ski, the elasticity of a support stocking, etc.) render a comprehensive approach quite impossible. Moreover, it is more interesting to draw from certain examples how to design a mechanical testing device and how to establish the test-calculation dialogue. The examples selected below are conventional tests of solid mechanics, allowing analysis using a mechanical model of beams. The approach developed for these simple cases is absolutely transposable to more complex cases, where calculation-test dialogue involves high-level tools (optical full field methods, finite element modeling).

The selected tests correspond to the simple loading of a beam: traction, bending, and shear. Fields of stress and strain in the area of analysis must be higher than in other areas so the desired phenomena (e.g. occurrence of cracking or plasticity) appear in this area. For a quantitative analysis, the fields must be described by few parameters, and they must ideally be uniform.

NOTE.– Why use all these test categories? A numerical model, however powerful, cannot describe the complexity of a real object; as it is limited by the computing capacity, imagination of designers, and especially the various assumptions. The most debatable points in any modeling are often the boundary conditions: the rigid (welding, bonding, etc.) or mobile links.

1.2. Measurable quantities

A designer may require various mechanical quantities to design a test, depending on the material and the loading mode. Here are a few examples.

Most materials are linear, elastic, and isotropic. Two parameters are required for their characterization: *Young's modulus*, which represents the proportionality of stress to strain $(\sigma = E \in)$ and *Poisson's ratio*, which describes the cross-sectional reduction during unidirectional loading $(\mathrm{v} = -\frac{\in_1}{\in_2})$. Other representations commonly used include Lamé coefficients. In the case of an anisotropic material, the modules are dependent on the direction considered, which considerably increases the experimental protocol. Sometimes, the linear elastic model is set to default; the material may be elastic and nonlinear. In this case, the law of behavior is described by a higher number of parameters.

In most cases, elasticity is a convenient approximation of a material behavior. However, we must remember that more often, even for metals or glasses, the materials are viscoelastic, which results in a deferred deformation over time, which can be illustrated during a relaxation or creep test. The first step is to observe the variation of force over time to a fixed deformation level, and the second is to observe the variation of deformation for fixed force. In both cases, the elastic behavior is coupled with viscous behavior, characterized by a viscosity μ reflecting the proportionality between shear stress and shear rate $(\tau = \mu \dot{\Upsilon})$.

In order to ensure the behavior of a mechanical part over the short time, the designer uses the *elastic limit* of the material under traction and/or compression, or sometimes resistance to traction. Over the long term, however, there was fracture for light loads, due of the repetition of load. An endurance test is performed to determine the *endurance limit*.

Further, during the shaping of metal parts, permanent deformation is obtained by subjecting the material to plastic deformation. The perfect elasto-plastic model is often too limited. In particular, the more the material is deformed, the greater is the yield strength. The strain hardening rate characterising this phenomenon can be described by the power law or Hollomon law $\sigma = K \in^n$, where n is the strain hardening coefficient.

These quantities are probably the most important however there are many others that could be added to the list. Similarly, different types of tests may sometimes lead to identical values. Thus, a static tensile or bending test, a dynamic ultrasonic test or an indentation test all enable us to determine Young's modulus. Therefore, it is more important to outline the logic leading to the selection of a test and the validity of the test selected than to review all possible tests.

1.3. Tensile test

A tensile testing machine consists of two jaws, one on a fixed cross-member, and the other on a movable crosshead. The test specimen is fixed between the two jaws. Then, two measurement systems are used, one to measure the applied force (a load cell) while the other to measure the relative displacement of the jaws (displacement sensor) or the deformation of the specimen (knife extensometer, strain gauge, etc.).

Basically, a tensile testing machine is used to apply a controlled displacement of one of the jaws while the other remains generally fixed to the frame. The process is controlled by controlling displacement and speed of displacement. It is possible on most systems to impose a force ramp via a Proportional-Integral-Derivative (PID) control loop. This feature is advantageous but presents practical difficulties due to the behavior law of the tested material: plastic deformation of the material may lead to never reaching a force set point, as the maximum force is low; fracture may result on returning of force to zero, which induces an infinite displacement set point on PID. Further, the forced displacement speed control does not mean a constant strain rate. Very specific devices have been developed for some polymer materials. They have controlled deformation speed due to optical measurement following markers placed in the area of interest of the specimen.

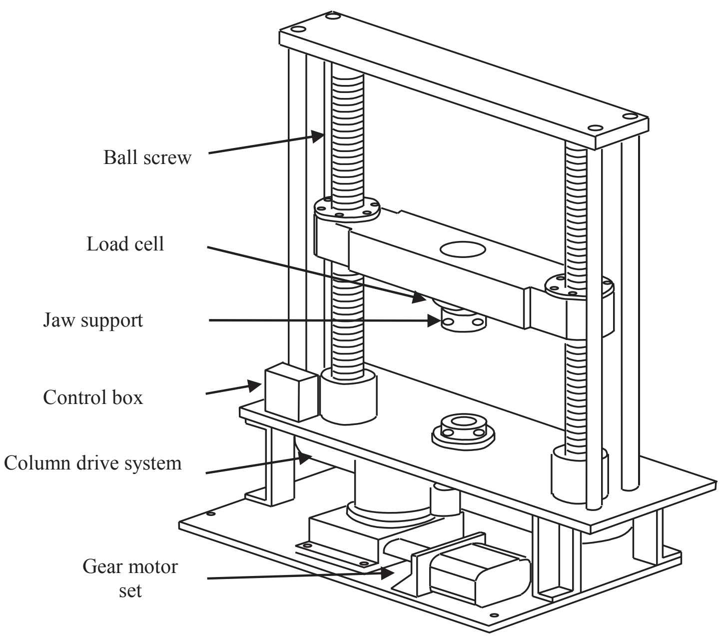

Figure 1.1. *Screw tensile testing machine*

A tensile test does not measure Young's modulus, but measures force (section 2.4) and distance or deformation. While implementing the test, the introduction of an analytical or numerical model enables to deduce the desired value. This model is based on assumptions that we are trying to prove realistic in the test.

In the case of tensile test, model is provided by the beam mechanics which involves establishing of a uniform stress field through pure traction over the volume under consideration.

1.3.1. *Optimal testing conditions*

In order to obtain a uniform stress in the measurement area, a certain number of precautions must be taken. The shape of the test piece must allow for a well-founded mechanical modeling: its slenderness must be compatible with the rules of the beam mechanics. The ends must be shaped in such a manner that the maximum stress and therefore, the breakage appear in the useful area of the test piece – where the beam mechanics allow correct estimation of the stress.

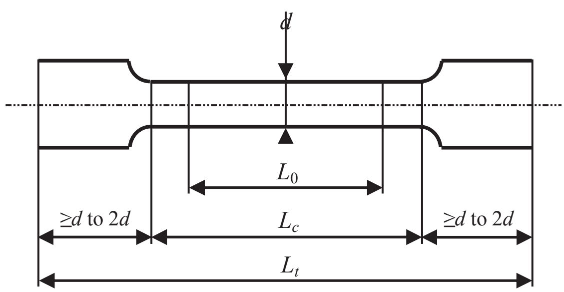

Figure 1.2. *Example of test specimen shape (according to [GOË 92])*

The shape criteria of the test specimens and the selection of anchorages are given by the standards, but an engineer must understand the provenance of these selections. For example, Figure 1.2 shows a test specimen used for determining the elastoplastic characteristics of a metal. The length L_c is the length of the specimen between the jaws; the useful area L_0 corresponds to the area where approximation of stress field by beam mechanics is acceptable. When the test specimen is held between the jaws, the length measurement taken varies from *d* to *2d*, according to the case. Its cylindrical shape and the presence of large corner radii near the edges provide a break in the relevant area with such consistency that this rupture can occur anywhere in the area. The heads are in a “dog bone” shape to prevent slippage of the specimen into the jaws during the tensile test. And, the ratio of diameter and length allows establishing a uniform stress field in the useful zone.

However, the anchoring and the length of the test specimen may differ depending on the material and the desired target. For example, in the case of composite materials, the specimen is flat, as the material consists of stacked plies. Therefore, the edge effect is reduced through sealing of wedges whose rigidity is controlled rather than using a dog bone shape, which is difficult to achieve and is less effective. Further, because of anisotropy, the shape of the test specimen can move from one composite to another. The length – width ratio of the specimen depends on the anisotropy of the material, but the width – thickness ratio determines “membrane” or “plate” behavior, as the thickness is not an adjustable parameter; a product is defined specifically by the number of folds it comprises and therefore its thickness: depending on the case, the interpretation model to be used will be different.

For the test to be a tensile test, the movable crosshead displacement vector must be along the axis of the specimen, otherwise the stress field is modified by bending or twisting which disturb the determination of the stiffness of the material and its final properties. However, guidance cannot be linear over a wide range: therefore, it is necessary to take into account the defects in the machine. To minimize these problems, it is a common practice to work along the axis of symmetry, in a known displacement zone. A control and validation protocol is required before running a test campaign: the settings of the jaw position exist on most traction devices. The protocol includes purely geometrical controls, with comparators to check the kinematics of the assembly. It concludes with a test on a test specimen which must be instrumented in order to measure the undesired effects of bending or twisting (for details refer to section 2.2). The test specimen itself must be properly inserted in the tensile testing machine along the axis of traction of the machine. It must not slip into the jaws, especially if the only estimate of the deformation is based on the movable crosshead displacement, a method which is often not recommended for this reason.

Furthermore, in order to approach the conditions set by the test operating model, it may be important to take a number of precautions to prevent the occurrence of undesired phenomena. For certain classes of materials, such as polymeric materials or biological materials, controlling temperature or humidity conditions is a necessity imposed by the high sensitivity of mechanical properties to these parameters. Similarly, the choice of the speed of displacement of the mobile jaw may change the apparent elastic modulus of the viscoelastic materials: depending on the purpose of the experimental study, tests will be carried out at different speeds so as to explore this behavior, or deliberately placed in a specific location corresponding to the instantaneous or long-term behavior.

All these precautions are intended to have the healthiest possible picture of the intrinsic properties of the material to be studied by freeing approximations related to analytical model used in testing.

EXERCISE 1.1.– Approximate the criteria given in Figure 1.2 using Bernoulli conditions.

1.3.2. *Result of a standard tensile test*

The typical stress–strain curve of a metallic material is given in Figure 1.3. While carrying out a tensile test on a specimen, the stresses are reduced to the axial component and they are assumed to be constant over a section. Hence, $\sigma = \frac{F}{S}$. On the other hand, if the deformation is small compared to other dimensions, we can approximate $\sigma = \frac{F}{S_0}$. Similarly, if the deformation is low if compared with the other dimensions over a length ΔL, then $\varepsilon_{11} = \frac{\Delta L}{L_0}$. However, at the beginning of loading, it is common that parasitic phenomena such as slack recovery may occur. This results in a nonlinear area in the stress-strain curve at the beginning of loading. This area, which is commonly called “toe of the curve” is not representative of the material and must therefore be rejected. Finally, the estimate of the modulus is made in an area defined by the toe of the curve and by early onset of plasticity. Thus, we obtain the equation:

$$E = \frac{\Delta\left(\dfrac{F}{S_0}\right)}{\Delta\left(\dfrac{\Delta L}{L_0}\right)} \qquad [1.1]$$

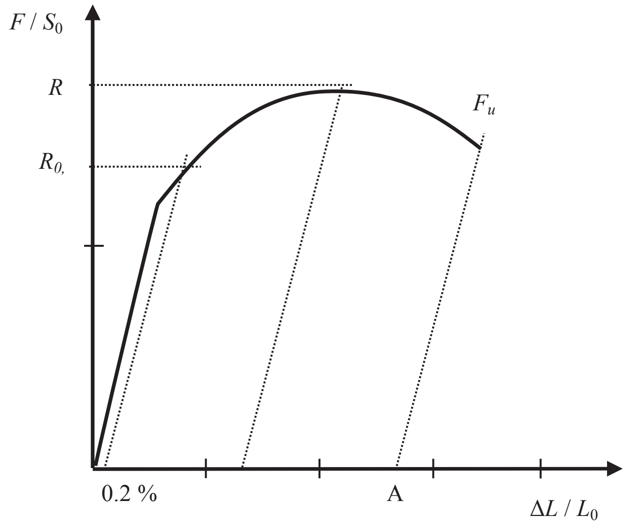

Figure 1.3. *Typical traction curve of a metallic material*

The tensile curve provides other essential information for dimensioning of structures. It is noted that the *apparent elasticity limit* R_e corresponding to the end of the reversibility area of the force/displacement curve, in general, is also the end of the linear area. As this limit is difficult to estimate, we use the *residual elongation limit* $R_{0,2}$ corresponding to an elongation of 0.2%. The *tensile strength limit* R_m is also a determining quantity in mechanics as it characterizes the maximum stress that can be tolerated by the material – and therefore the ultimate limit before failure – whereas the yield point determines its use limit. It must be remembered that the mechanical engineer systematically uses a safety coefficient to take into account the approximations and uncertainties related to operation and production procedures. Lastly, the *percentage elongation after fracture A* corresponds to the variation of ultimate length of the specimen. The interpretation of this data as longitudinal strain would be very hazardous, due to strain localization in the area of striction.

The above curve is that of a hardenable metal; for others, the plastic area can be totally absent. This is the case of brittle materials, the failure limit is then guided by the probability of existence of a defect of sufficient size for a given level of force.

1.3.3. *Stiffness of a tensile testing machine*

The support structures of the machine are not infinitely rigid; they give way to deformation under load, thus changing the movement of the movable jaw. If u is considered as the total displacement, $u_{machine}$ the displacement due to deformation of the tensile testing machine and $u_{specimen}$ is the displacement due to deformation of the test specimen, then

$$u = u_{\text{machine}} + u_{\text{specimen}} \qquad [1.2]$$

or, if F is the force measured by the load cell, K is the rigidity of the tensile testing machine, then S and L_0 respectively are the section and initial length of the sample and ε is the deformation, then

$$u = \frac{F}{K} + \varepsilon L_0 \qquad [1.3]$$

The strain rate is an important factor in the study of visco-elastic-plastic materials and must be controlled; many tests are ideally performed at constant strain rate. By deriving the expression [1.3] with respect to time, the relationship between transverse displacement rate and strain rate is given by:

$$\frac{\dot{u}}{L_0} = \left(1 + \frac{S}{KL_0}\frac{d\sigma}{d\varepsilon}\right)\dot{\varepsilon} \qquad [1.4]$$

where $\dot{u}$ is the movable crosshead displacement rate and $\dot{u}$ is the strain rate of the material.

There is a difference between apparent strain rate, $\dot{u}/L_0$ which is a constant for controlling a conventional tensile testing machine and the average strain rate $\dot{\varepsilon}$. The condition $\dot{u}/L_0 \approx \varepsilon$ is fulfilled only if K i.e. the rigidity of the frame is sufficiently large. In addition, the value $d\sigma/d\varepsilon$ represents the hardening of the material. In many cases, the material has several consolidation stages; therefore, hardening is not a constant with respect to deformation level and consequently with respect to the strain rate.

In the elastic range, the stiffness of the test device has no influence; however, in the plastic range, the stiffness disturbs the strain rate of the specimen, thus complicating the interpretation of the test results. It is therefore necessary to have an estimate and make the necessary corrections.

1.4. Bending test

1.4.1. *Test principle*

In the case of particularly soft materials, the degradation of the surfaces in the jaw leads to another test, the bending test. The application presented here is a three-point bending test for the characterization of unidirectional composites[1]. The bending test involves placing a rectangular bar on two supports and applying “punctual force” in the center, as shown in Figure 1.4.

The load and the resultant deflection are recorded until the occurrence of damage on one side of the specimen. During the operation, the flexural modulus and admissible maximum load are the two main results considered.

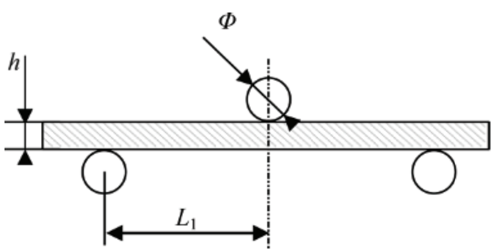

Figure 1.4. *Three-point bending*

1.4.2. *Optimal realization conditions*

The main parameters to be adjusted are summarised in Figure 1.4. This primarily involves ensuring the conditions of a typical beam pattern, by creating conditions of small disturbances. The load should be as close as possible to pure bending. However, for a three-point bending, the bending moment increases linearly from zero to its maximum value between the first and second point, and then decreases from the maximum value to zero between the second and the third point. However, the shear force is equal to and opposite to the bending moment gradient. In a three-point bending test, bending is always combined with shear. In order to approach the pure bending condition, it is necessary that the bending gradient is negligible. For this, the sample must be sufficiently slender. In other words, the ratio L_1/h must be greater than a limit value, usually set at 8. A test with close edges

1 NF EN 2562 standard.

will induce shear stresses and inter-laminar shear failure. This possibility is also used in the “short beam shear test”[2]. In this case, $L_1/h \leq 2.5$.

In this test, the *support structure* plays an important role. On the one hand, it must not generate too much local pressure, and thus damage the surface; secondly, the contact must remain “punctual”, i.e. must be of the smallest possible width. A “punctual” contact in the model becomes in reality a contact area on a given depth, called a “linear” contact. It is therefore necessary that both lower and upper supports are parallel. It is also necessary to ensure sample faces are parallel to each other. Finally, the force applied in the form of a translational movement of the upper cylinder, must be normal to the plane formed by the lower contacts. In practice, these conditions are guaranteed by some design precautions: one of the two lower supports is mounted on a pivot connection, so that it can tilt back and forth; and similarly for the upper supports.

As previously stated for a tensile test, the test specimen shall be placed in the machine’s plane of symmetry to avoid any undesirable effect.

1.4.3. *Determination of flexural modulus*

In order to determine the flexural modulus, we must find a mathematical model representing the mechanical phenomenon reproduced experimentally during the test. Here, the test conditions are selected such that the assumptions of the beam mechanics are valid. If $(\vec{x}, \vec{z})$ is the reference of the beam, where $\vec{x}$ is the longitudinal axis, M_f the bending moment, E the Young’s modulus of the beam and I_f the bending inertia, the transverse displacement W along the beam axis is given by the equation:

$$\frac{\partial^2 W(x)}{\partial x^2} = -\frac{M_f(x)}{EI_f} \qquad [1.5]$$

For each section at position x, the strain $\sigma_x(x, y)$ is given by: $\sigma_x(x,z) = \frac{zM_f(x)}{I_f}$, where y is the distance to the neutral axis. The bending

2 NF EN ISO 14130 standard.

moment is $M_f = \dfrac{Fx}{2}$ before the central cylinder and $M_f = \dfrac{F(L_1 - x)}{2}$ after (F is the applied force). The maximum stress is, therefore, given by $x = L_1$ and $z = h/2$.

$$\sigma_{\max} = \sigma_x\left(L_1, \frac{h}{2}\right) = \frac{FL_1 h}{4I_f} \tag{1.6}$$

Similarly, the deflection can be calculated using the tools for beam mechanics. Thus, by integrating equation [1.5], and considering that at $x = L_1$, slope is zero, as the fixed jaws are on the exterior,

$$W(x) = \frac{FL_1^3}{12EI_f}\left(3 \times \frac{x}{L_1} - \left\{\frac{x}{L_1}\right\}^3\right) \text{for } x \leq L_1 \tag{1.7}$$

The maximum deflection corresponding to $x = L_1$, given by:

$$W_{\max} = \frac{FL_1^3}{6EI_f} \tag{1.8}$$

From the measurement of deflection and the force applied, it is easy to estimate a flexural modulus of elasticity. Note that the standard recommends the use of the central part of force/deflection curves. This means that larger values must be discarded to eliminate the loosening due to the onset of defects ("pseudo-plasticity" of composites). The *toe of the curve* must also be ruled out.

Furthermore, the model described above assumes that a section normal to the neutral axis remains normal during loading, which neglects the shear (Euler–Bernoulli hypothesis). For some anisotropic materials, whose shear stiffness is significantly lower than other rigidities, this assumption is no longer valid and the deflection is due both to bending and shear. A beam model must be used to turn the right sections during the deformation which leads to the expression of a constant shear in the section (Timoshenko hypothesis).

1.4.4. *Damage to the structure*

In this bending test, three types of damage may be encountered (Figure 1.5), of which only two are admissible: tensile damage and compressive damage. They are related to the effect of bending and therefore enable to quantify the maximum stress with the above-stated assumptions. If shear damage is observed, then this quantification is not possible, and it is observed that the test assumptions are not met.

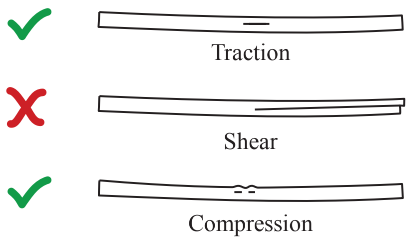

Figure 1.5. *Types of damage during a 3 point bending test. Damage due to traction and compression are consistent; inter-laminar shear damage is non-consistent*

From the force, the maximum stress is known, which allows estimation of the bending resistance of the material. However, it is notable that the resistance values for bending are always higher than those for traction. The reason is the cause of failure, which is always related to the presence of a defect. In tensile test, the entire volume is subjected to maximum stress, whereas in bending only the skin is at maximum stress. The probability of finding a fault in a volume increases therewith. It is described using Weibull distribution law: $F(x) = 1 - \exp\left\{-\left(\frac{x-d}{\eta}\right)^{\beta}\right\}$.

NOTE.– We often speak of "flexural modulus" or "tensile modulus" or "compression modulus". These modules are unique and often confused with the elastic modulus or Young's modulus. If this practice exists, it is reflected as a reality difficult to circumvent: *in most cases, the result depends on the test methods*. A designer therefore must adapt the test carried out to the load type experienced by the actual structure.

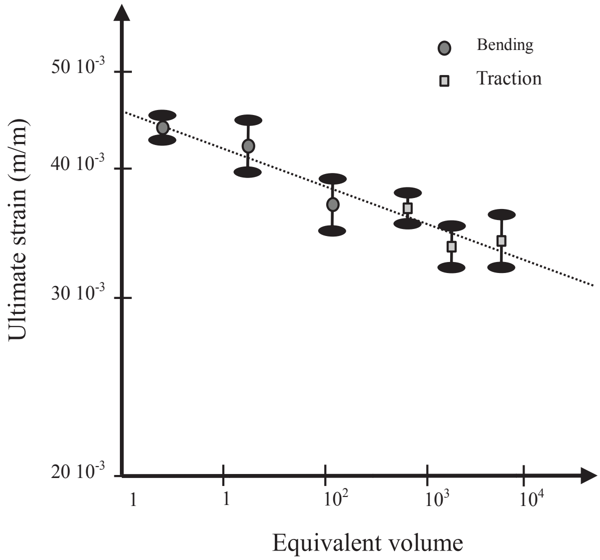

Figure 1.6. *17 Variation of ultimate strain with volume (according to [WIS 97])*

EXERCISE 1.2.– A four-point bending test also exists (refer to Figure 1.7).

Prepare the model for the test. What are its advantages? What are the specific precautions required for this testing? In particular, how to measure the deflection using this method?

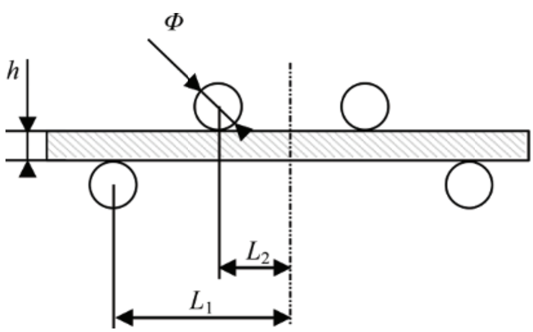

Figure 1.7. *Four-point bending*