Chapter 1

Introduction

Structural components must resist various applied loadings. Their nature is very diverse: aggressive environments, temperature and mechanical loads. However, we will only consider this last area in this book. Engineers must design parts so their deformations under these loads remain acceptable and they are not damaged or broken. In many cases structures need to be as light as possible, in order to save materials on the one hand, but above all to decrease energy consumption on the other hand. It is thus important to optimize the shape of parts and to choose the materials they are made of so that they perform without excessive deformations and without loss of integrity. Following design, problems can arise in service, such as crack initiation, which require calculations of the stress and strain distributions. Finally, failure assessments also require such analyses. To reach these objectives, more and more sophisticated design tools are available for engineers, provided that they are suitably supplied with reliable data concerning the mechanical behavior of materials. This is the aim of mechanical testing.

The design of a part requires the knowledge of the relations between applied loads and deformations, as well as the limits not to be exceeded at the risk of damage or fracture. This will be the case, for example, with the stiffness of a spring and with its yield load. More generally, these relations involve the stresses and the strains, and more precisely the two corresponding tensors. Solving the problem is achieved by integrating the three stress equilibrium equations together with the boundary conditions. As there are six unknowns, the six components of the stress tensor, there is a lack of equations to reach a solution. They are provided precisely by the constitutive equations between the six components of the stress tensor and

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the six components of the strain tensor, which, it must not be forgotten, derive from the displacement field, which itself includes three components. The problem thus involves nine unknowns: the six components of the stress tensor and the three components of the displacement, and nine equations: the three equilibrium equations and the six constitutive equations.

These constitutive equations, as a general rule, involve not only the stresses and the strains at a given time, but also the elapsed time. Without even considering the aging effects, the strain state preserves the memory of past deformations. It is only for an elastic material, for which there is no residual deformation after unloading, that the past does not operate. The constitutive laws are empirical laws, which need to be determined experimentally. Nevertheless, various theoretical considerations, which are deduced from the knowledge of deformation mechanisms, enable us to formulate hypotheses regarding the structure of the constitutive equations. If, for example, it is permissible to assume that the material is isotropic, the stress and strain invariants can only appear in those constitutive equations, as the orientation of the coordinates has no influence.

Influence of past time can appear explicitly in the formulation of constitutive equations. More generally, it appears implicitly through the derivatives of the components of the stress and strain tensors, and the strain rate only in most cases. In this way, the influence of the loading path, i.e. the evolution of the eigen stresses and directions at a given point, can be introduced before being followed by the present instant. The cyclic character of the loads needs to be introduced, namely in the study of fatigue. The number of variables then becomes large: amplitude and mean level of stresses, frequency, loading paths. The constitutive equations also depend on temperature. In this way, their most general formulations are rather complex and involve a very large number of parameters. Their identification can then require a significant number of tests.

A major difficulty immediately appears in the determination of constitutive equations: the deformation of any test specimen under a given load can be calculated only if those equations are known, which assumes that the problem is solved. It is only for very simple shapes for which the stress and strain fields are homogeneous that direct determination is possible. This is the case for the gage of a tensile specimen, in an approximate way for the wall of a thin tube in torsion or under internal pressure. It is nevertheless necessary to perform more complicated tests to explore various three-dimensional stress and strain states. In that case, it is absolutely vital to couple experimentation with theoretical hypotheses concerning the form of the constitutive equations and with calculations.

As underlined above, the task of an engineer is far from being achieved when he has determined the deformation of a part; he still needs, and this is often the main part of the work, to fix the limits not to be exceeded, in term of stresses and strains, so as to avoid excessive yielding or worse fracture, or in order to reach a given life. It is then required to express these conditions at the level of the basic components of the stress and strain tensors. More or less solid hypotheses allow us to do this using simple tests results: for example, the Von Mises yield criterion depending on the yield strength as measured in a tensile test, and the Goodman diagram for the endurance limit as determined from rotary bending tests results and from the ultimate tensile stress. Otherwise, transposition at the level of parts of tests results of not so easy an interpretation, such as Charpy or fracture toughness K_{Ic} tests, needs to be possible. The development of underlying theories is out of the question here. The reader will need a sufficient knowledge of resistance of materials, solid mechanics and fracture mechanics, concepts which are developed in other books.

This book is also not intended to cover the entire scope of tests which are performed routinely for the complete determination of constitutive equations in their full generality. Specific tests keep being designed for the determination of a particular parameter. On the contrary, the emphasis will be placed on the most widely used tests, those which are common practice in industrial laboratories, or otherwise, those which can be obtained from various specialized laboratories, without new adjustments and at reasonable costs. A number of them provide access directly to the parameters of the constitutive equations, whereas others do so only indirectly: for instance, hardness tests. Nevertheless, they will be discussed inasmuch that they are of current use, although we will not go into all the information, which they are able to provide. A number of tests are useful not only for the determination of the constitutive equations but also for the determination of the damage and fracture limits. Some essentially deal with these last aspects.

The majority of the tests to be discussed are normalized. Of course, it is important to conform rigorously to the standards, in order to avoid any dispute between client and supplier, and also to achieve the most meaningful results as possible. The provisions of standards result partly from compromises based on considerations that are barely scientific, but also on sound theoretical considerations and on round-robins. It is not always easy to understand the reason for which a particular requirement is imposed, and its importance is sometimes underestimated, particularly when difficulties are found in the literal application of procedures. Actually, as far as possible, explanations for the reasons behind the introduction of various provisions in a standard will be given, so that their scope can be suitably appreciated, and the validity limits of these tests can be understood. However, the purpose of this book is not to provide an exhaustive description of the various tests when they are standardized. For this, it will be more useful to refer directly to the standards.

One of the drawbacks of normalized tests is that they often require the entry of only a few specific pieces of data: for example, engineering yield strength, ultimate tensile strength, elongation at fracture. Merely settling with those, a large part of the information that could be extracted from the tests is lost for the determination of constitutive equations. This impoverishment can paradoxically be increased by the computerized entry of data, when what is not explicitly required is deleted. Paper records do not have this drawback. It must not be forgotten either that the specimen themselves, which were used in the test, constitute results to be carefully processed by various inspections such as dimensional measurements and macro and micro-fractographies. One of the aims of this book is to provide the means to exploit as completely as possible the whole test dataset.

Following this introduction, a chapter will be devoted to constitutive equations. Without entering in the entire justification of the forms which they take up, it will allow us to understand their structure and to envisage the parameters to be determined, which are more or less numerous according to the complexity of the problem to be solved. Then, various mechanical tests will be discussed in turn, beginning with those, which are mostly used for the determination of the parameters of these constitutive equations and finishing with those which are specifically intended for the study of damage and fracture.