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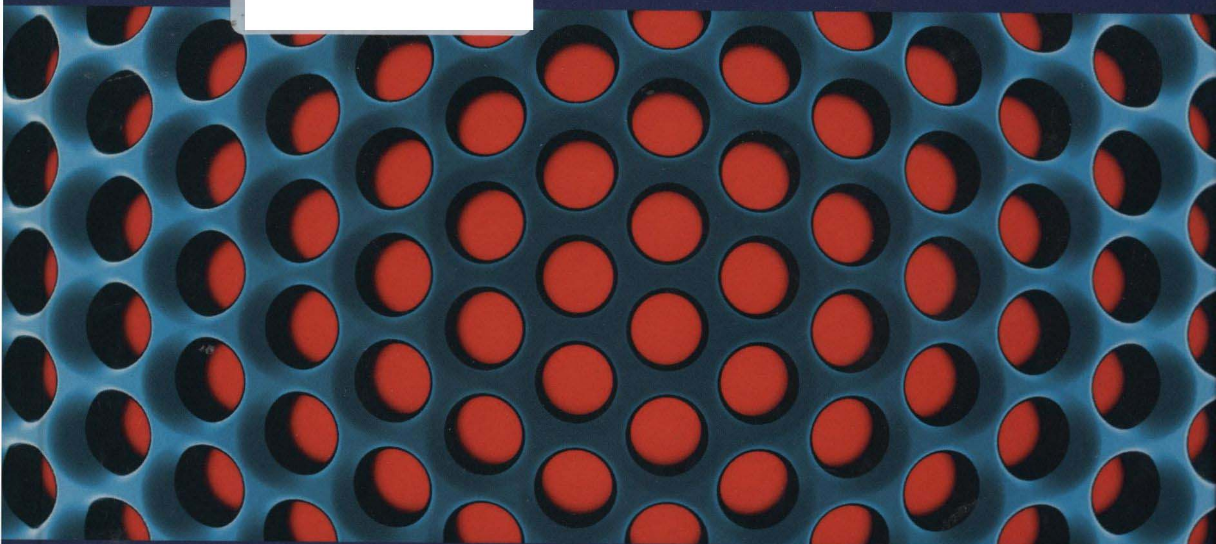

Experimental Mechanics of Solids and Structures

Jérôme Molimard

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Experimental Mechanics of Solids and Structures

Foreword

Mechanics is an ancient discipline that has been through major changes in recent decades with the advent of the finite element method. The possibility of calculating the spatial distribution of variables such as displacements, strains, and stresses, using adapted models for geometries and complex loading conditions, had initially led to the purely experimental aspects related to characterization of the mechanical behavior of materials and structures to be pushed into the background. Even though the final validation tests have always remained necessary to validate geometries or choice of materials, the number of preliminary tests carried out on the structural elements has naturally decreased the calculations which enable us at least to significantly "refine" the designing of systems and structures, if not to propose near-optimal solutions. Material characterization tests, though still indispensable for providing the calculation codes with finer laws, have for a long time remained somewhat rigid in well-established procedures, along with the measurement methods which have also changed very little over a long period of time – since the release of "classic" sensors such as point displacement sensors or strain gauges.

In recent years, however, there has been an increased interest in experimental mechanics. The emergence and rapid dissemination of new investigative methods, such as kinematic measurement systems, have enabled access to spatially continuous information, at least on the surface of tested specimens. Several heterogeneities were thus brought to light in the fields of displacements and deformations which were only partially seen using classical instrumentation based on point measurements. However, with the numeric sizing calculations improving over time, it has become necessary to provide experimental information also in line with the improved calculation results. Though the above-mentioned full field measurement methods are effective, the proliferation of conventional sensors distributed over large structures requires optimal management of the information collected. Finally, the increasing overlap between numerical models and elaborately instrumented test results has led to the emergence of identification strategies for material and structural properties in contrast with conventional procedures which are well-established, but unsuitable for mining of data available in large volumes.

It is in this context that this book written by Jérôme Molimard is presented to us. Its content covers many of the issues mentioned above in a language particularly adapted for technicians or engineers. First, the author briefly reviews the principles of "classic" standardized tests. He then addresses the performance of the usual force, displacement, and deformation sensors, with particular attention drawn to the metrological performance that users can expect. The author then continues with the main techniques, whether purely geometric or interferometric, for measuring kinematic fields; and finally, discusses the consideration of uncertainties related to measurement procedures. The book includes the description of experimental designs to provide the reader with a rigorous framework to address the optimal management of a large volume of data and unknowns.

In terms of the form, the author shares his knowledge from extensive experience in mechanical testing through many short exercises that appear throughout the book, and a final chapter dedicated entirely to case studies.

In conclusion, the work of Jérôme Molimard is well-timed to respond, in a clear and concise manner, to the queries raised by traditional tools and methods of experimental mechanics, but also related to recent changes within this discipline. Amply illustrated, the book will certainly help the reader to find examples of application close to their own interests, complemented with insightful background information on the experimental mechanical techniques and methodologies found in the book.

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February 2016

Introduction

I.1. Experiments for solid and structural mechanics

The modern mechanics of solids and structures relies heavily on the numerical solution of a mechanical problem. Since the early 1970s, the Finite Element Method was widely used for very complex cases. In the present day, a Computer-Aided Design software which generally integrates a small calculation module predicts the behavior of complete mechanical systems, something impossible as few as twenty years ago. The training of a mechanical technician or engineer today largely incorporates this tool, sometimes abandoning the practical work altogether. However, the numerical calculation only responds, in a more or less accurate manner, to an inevitably idealised mathematical problem. It is therefore necessary to *validate the simplifying assumptions* introduced in the modeling. Furthermore, the *values used* in the calculation should be *well-known* (structural damping, binding strength, or boundary conditions). This all requires experimental work which is sometimes difficult, even in the case of a relatively simple behavior that can be easily modelled. Firstly, numerical codes have to be fed with *experimental data*. For example, the current development of elaborate composite parts requires characterization of the anisotropic stiffness tensor (9 parameters), whereas the contemporary practice reflects only the properties of the plate (4 to 6 parameters) where one dimension is negligible in the face of others. Furthermore, the boundary conditions, either restraint or contact, are often subject to strong assumptions that an experimental approach can improve, by defining a recessed stiffness, for example.

But mechanical design is based on various functioning patterns of the proposed device. There is of course normal functioning, very often under static loading, but also a dynamic functioning linked to possible shocks, abrupt load changes (e.g. emergency stop), or a challenging external environment with variations in temperature or humidity. Moreover, any mechanical device must guarantee a certain lifetime. In a conventional design approach, it is possible to size the apparatus by numerical method for some cases and then *experimentally test the prototype* with the objective of validation, whereas other cases will only be studied experimentally.

Finally, even though Mechanics is an ancient discipline, the formalism is sometimes lacking. It is then necessary to return to the basic approach of experimental science and conduct *experiments for understanding*. These situations beyond the mathematical formalism are very common in everyday life: in the study of interaction between two solids in contact – tribology – friction and wear are beyond the scope of intrinsic material properties and modeling of infinitesimal elements, as is usually done in mechanical modeling. More recently, mechanicians were interested in the mechanics of powders, where the material studied is neither a liquid nor a solid. The recent interest in biomechanics also raises the question of the nature of the medium studied; the skin, for example, could be considered as a linear elastic material, or hyper-elastic, anisotropic, viscoelastic, poro-elastic… Therefore, presently, a well-conducted experimental study is the only reasonable approach to this category of problems.

These different types of experiments rely on common concepts such as data processing, choice of sensors, or experimental modelling. However, the strategies are quite different, depending on whether we can or cannot rely on a reliable formalism. The three following examples will illustrate the experimental approaches for different purposes, directly related to the degree of knowledge of a system.

I.1.1. *Study of a bicycle wheel; an example of a complete structural validation*

This work was conducted as part of a technology transfer from a university lab to an SME, in the form of a doctoral thesis [MOU 98]. The objective was to provide the company with a software to assist the designing of bicycle wheels. In particular, the software should be able, via a Finite Element analysis, to recognize and analyze the natural modes of a wheel.

The program was written in MATLAB© using a graphical interface and numerical analysis facilities. This solution enables the SME not to invest human and financial resources in a generic finite element software; the developed application can be used by the technicians of the research department without any special knowledge of the calculation method.

From the mechanical point of view, the numerical modelling is as follows:

– the spoke beams are highly slender structures with negligible flexural rigidity and compression. Their behavior has a geometric nonlinearity. So we have:

$$\in_{xx} = \frac{\partial u}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2\right] \quad [I.1]$$

– given the number of spokes and considering the thickness of the rim relative to its diameter, it is approximated as a simple beam element (not a curve). The section of the rim is complex, such that the beam element is a strong approximation required to maintain a reasonable calculation time;

– the hub is considered infinitely rigid;

– the connections are assumed to be perfect; the point of application of stress of the spokes is shifted with respect to the torsion center of the rim.

The main elements of the research method of eigenvalues and eigenvectors are:

– a search for solutions to the dynamic equation in a pseudo-modal base which enables a reduced calculation time;

– numerical method of resolution of the nonlinear behavior of the wheel is the incremental Newton–Raphson method. The change of state is divided into n steps, for which the stiffness matrix is updated at each step; the total change is the sum of individual changes.

The software developed is used to find the static behavior, frequency response, and the time response of a bicycle wheel with defined assembly.

This software has been validated by an experimental approach, particularly for the frequency response. The assembly is reproduced in Figure I.1.

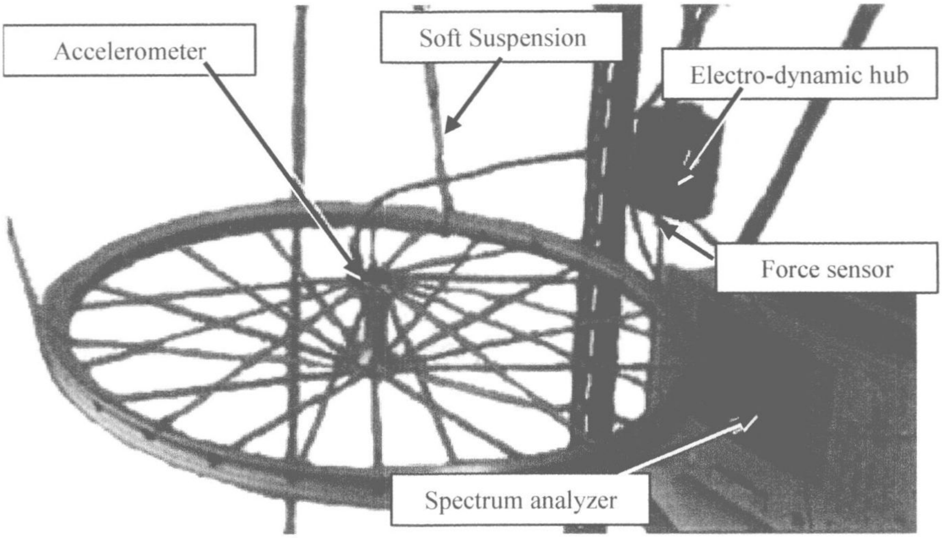

Figure I.1. *Assembly for frequency analysis of a bicycle wheel (according to [MOU 98])*

The wheel is mounted on flexible supports simulating free-free boundary conditions. An accelerometer is placed on the upper side of the hub. The excitation takes place on one side of the rim. This excitation requires movement off the periodic plan.

Just as the digital model is questionable due to various assumptions and required approximations, a test like this is only an approximation of the real situation. This is an *experimental model*, simplifying the structure, the boundary conditions and the load. The experimental model also offers only a few measuring points, based on *a priori* judgment of the designers of this model, which gives a limited view of the examined physical reality. Finally, the modifications of the experimental model in relation to the physical reality it explores leads to distortion of the obtained solution.

In this specific case, an accelerometer weight sensor is generally likely to alter the natural modes of the wheel. Likewise, the positioning of the accelerometer may also affect the observation of certain occurrences. Therefore, an accelerometer placed at the node of a mode does not allow its identification.

It may be noted, according to these rules, that the choice of positioning is especially important: in an infinitely rigid zone, the accelerometer does not change the stiffness matrix. With regard to assumed or calculated modes, it can be predicted that the accelerometer will be sensitive to different degrees. For example, Figure I.2 shows the "2Φ–plan" mode which is barely visible and the "umbrella" mode that should be easily identifiable.

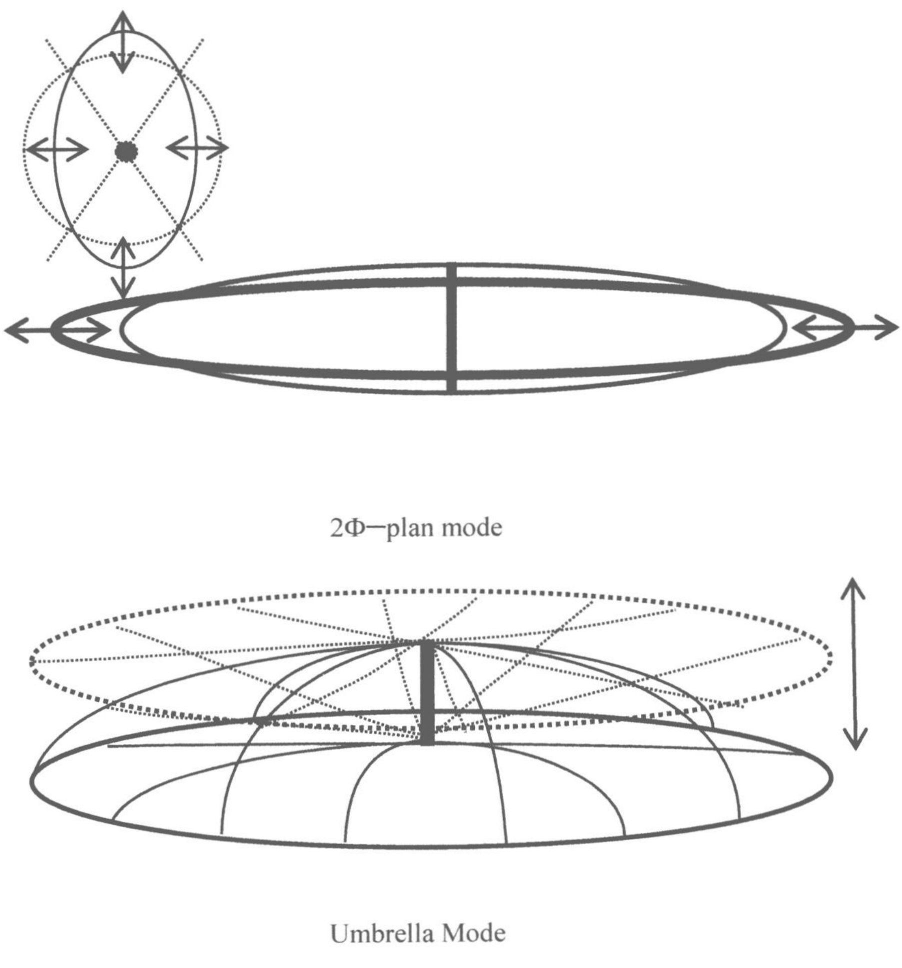

Figure I.2. *Examples of vibration modes of a bicycle wheel (according to [MOU 98])*

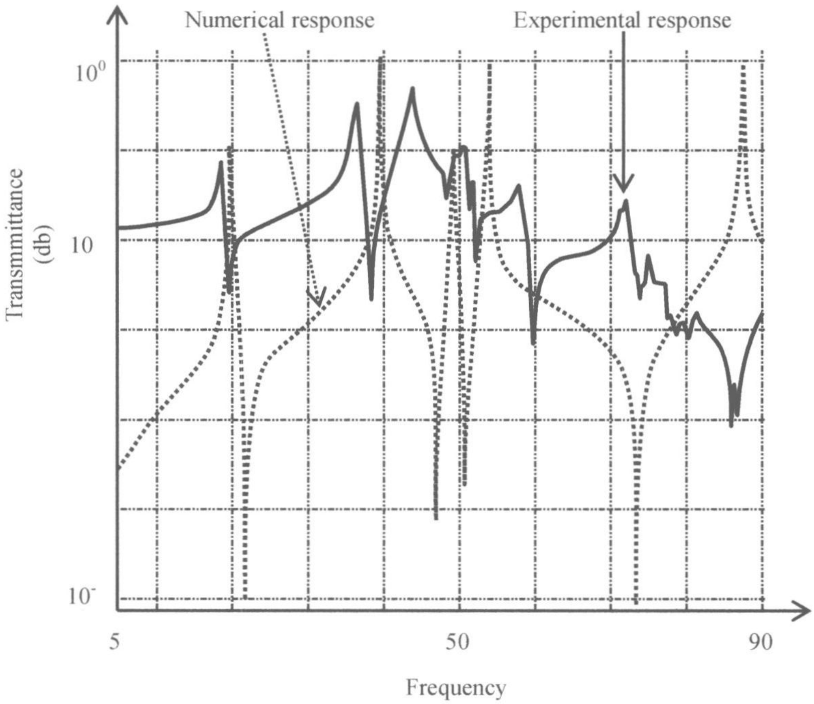

Figure I.3. *Numerical and experimental response of a bicycle wheel (according to [MOU 98])*

Comparison of numerical and experimental approaches gives the results shown in Figure I.3. The first resonance, which corresponds to the "2Φ off-plan" mode shows a very good theory/experiment correlation. In contrast, the frequencies corresponding to other modes differ more and more, until the error reaches 15%. Even if the prediction model works well, this variance is a representative of many modal analyses: the approximations are manifested especially when the frequency is high.

On the other hand, the theoretical and experimental values of the transmittances are somewhat similar. But these values, which are directly related to damping (structural damping, spoke connections), show the acuteness of the natural frequency to be taken into account: with zero damping, the structure will break; with a critical damping $(c = 2\sqrt{km})$, the natural frequency will be in noise.

This example shows that a mechanical analysis cannot be conducted without the three traditional pillars of science: a well-established mechanical model, a predictive tool using numerical analysis, and experimental tool for validation. From this point of view, the numerical model and the experimental model are both based on a set of assumptions that are generally not the same. A discussion between the numerical and experimental approach of both these sets of assumptions is required to ensure proper understanding of what is being studied.

I.1.2. *Mechanical effect of lumbar belts: an example of phenomenological analysis*

Biomechanics presents many examples illustrating another use of the experimental approach in the design process or product optimization. Biomechanics is concerned with subjects that are lesser-known and difficult to describe. Soft tissues (muscles, liver, skin, etc.) are nonlinear elastic, viscous, porous, anisotropic, and are subject to pre-tension. In some cases, their properties also vary spatially. Simplifications in their behavior allow modelling, but corroboration with experiments is essential. However, the context presents even more specifics: the work on model geometries allowing simplifications is usually impossible and load types are often limited because the studies involve live subjects. This requires unconventional experimental methods often based on imaging. Furthermore, there is great variability in geometry and mechanical properties within subjects, with significant temporal variations (circadian cycles, external factors such as stress, pollution) and between subjects. The development of medical devices must, therefore, rely largely on an experimental approach in a high variability context. Tests on patients or healthy individuals are also limited by ethical and medical considerations. The probability of an occurrence of a medical complication increases with the number of cases but if this number is too low, the power of the tests will not always be sufficient to achieve a significant result[1].

For illustration, a recent study was conducted on lumbar belts, frequently used in the treatment of lumbago [BON 15]. Though the feedback from doctors and patients is very positive and clinically proven, there are very few

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1 The power of a statistical test measures its ability to separate two groups of results. Refer to section 5.4.

scientific studies objectifying the mechanical effect of these belts. A belt, by applying external compression around the abdomen, is assumed to cause a change in the posture and thus exert pressure on the intervertebral discs which are the site of pain in the lower back. However, this mechanism is little-documented in the scientific literature. The adopted method consists of a pairing of both numerical and experimental approaches.

The pressure and the deformation of the belt is measured. Thus, a clear link between the level of stress on the belts and transmission to the torso can be established. As distributions of pressure and deformation are not a priori known, and as the peak pressure values can be of major interest in the analysis of the comfort of the belts, a full field measurement is the chosen method. Finally, a measurement of the shape of the torso, with and without belt, allows monitoring of the changes in posture, which is then compared using a subjective pain rating scale from 0 to 10.

Then, as in any mechanical design, the nature of representative load must be addressed. This issue should be dealt with in the context of the possible interpretation of the results and prior knowledge level. So, the choice was made to compare, in static, a situation where the brace has no apparent mechanical effect (in place, but not tight) and a situation where the effect was felt (close brace). To avoid the temporary effects related to the fitting of the belt, each patient is asked to make a few movements, in a particular order at pre-set amplitude.

Finally, the elements that were more likely to change the posture were selected using a very simplified numerical model: the torso is assumed to be linear elastic; the geometry is reduced to sets of ellipses; the role of the belt is stated as pressure output given by Laplace's law. This law describes in first approximation the pressure P generated by a taut band with a force T on an object with radius of curvature R:

$$P = \frac{T}{R} \qquad [I.2]$$

The parameters of the belt (height and rigidity), the shape of the patient's torso (radius of curvature, size) and the applied tension (deformation and rigidity of the belt) are selected. In practice, three belt models (hence, three rigidities) are available for two different heights. Fifteen subjects were called; their sizes were measured. Six subjects were measured to be of normal build, six were overweight, two were moderately obese and one was severely obese. The tension is set according to the manufacturer's recommendations, which prescribes a belt deformation of 20%. It is not possible for each subject to test six belts, owing to the length of time of each experiment and due respect to the patient. Therefore, to obtain the maximum information, each patient is to test two belts as per the experimental design in incomplete blocks.

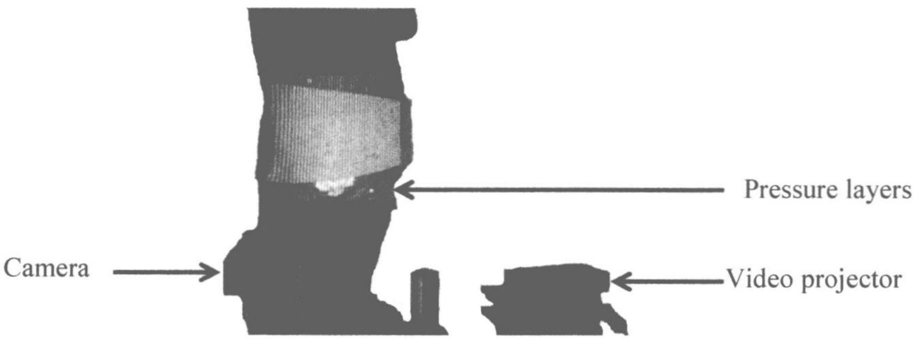

Figure I.4. *Study of mechanical effects of a lumbar belt (according to [BON 15])*

This study involves a very large amount of data with 67 field measurements generated for each patient. Statistical tools had to be used to discriminate the descriptive parameters of the mechanical brace (Principal Component Analysis): the pressure on the torso and the circumferential strain of the belt are sufficient discriminating factors to explain the different belts tested. The transverse and shear deformations, therefore, are not measured. Given the variability of the results, a difference related to a parameter (e.g. sex of the patient) is analyzed using a hypothesis testing approach to determine its significance. For example, in all cases, the load on each of the iliac crests is significantly different, showing an unbalanced mode of action between the right and left sides.

The study indicated that the lumbar support belts reduce pain and seem to change the posture. The belts are identical in their mode of action for even tightening. However, they differ in terms of pain relief, their tolerance by the subject and different possibilities of their tightening. Moreover, Laplace's law (Equation [I.2]) is valid on an average but does not apply locally: additional efforts to fully understand the transmission of mechanical effect to the torso are still required.

This type of study is common in biomechanics, but also in many other fields of application where mechanics or modelling is not sufficiently effective: tribology and powder mechanics, for example. The experimental approach must rely on tools from the statistics (experimental designs, hypothesis testing in particular). A numerical approach can be used to support the experimental approach, either before selecting the priority study parameters or after building or validating a mechanism. The result of the experimental study is primarily a set of trends to determine optimum functioning. This result is sufficient for many applications in engineering, but in the context of research and development, further understanding of what is being studied is also necessary. It often requires further study where the learning process becomes iterative.

I.1.3. *Coefficient of rolling friction: identification of parameters*

Rolling is a method widely used for manufacturing semi-finished flat products (steel or aluminium sheets) or rods as well as finished products (rail tracks). This method involves thinning out a metal by way of friction between two rollers. The diagram in Figure I.5 shows the two-dimensional structural analysis of the rolling process. This means that any possible enlargement is considered negligible.

The objective of rolling is to reduce the thickness e_1 of a metal sheet to a value e_2 under the action of a compressive force F and a driving torque C. The reduction rate $(1-e_2/e_1)$ is an essential element in the process, as an increased rate means a shorter and less expensive dimensioning range. As the material flow rate is constant, the reduction in the thickness of the sheet means that its speed increases during the rolling.

The area where the reduction of thickness takes place is called the roll-gap. It can be broken down into different parts (from left to right as in Figure I.5): first, the strip and the rolls deform elastically. Then the plastic deformation of the strip occurs before elastic recovery and the contact output. The speed of the rolls is constant while the speed of the strip increases from V_1 at the input of the contact to V_2 at the output according to the deformation, and thus from the position in the roll-gap. This means an area exists where the strip is slower than the cylinders (at the input of the roll-gap) and an area where it is faster (at the exit of the roll-gap). In