PRACTICAL DEMONSTRATION OF STRUCTURAL PRINCIPLES IN SIMPLE SYSTEMS

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Abstract

The Bologna Declaration began the rapprochement of the higher education in the European Union countries. Since then, the learning process of the students is quantified by means of the ECTS credits (European Credit Transfer System) which are focused on their workload. The methodology considers the student as the centre of the educational progression, being necessary to maintain a balance between their theoretical, practical and autonomous assignments. Therefore, classroom and practises should be harmonised in order to acquire the required competences. In particular, the use of teaching laboratories in the university strengthens the theory classes by completing them with experimental techniques and, besides, the practical activity helps to develop the social and communication attitudes of the students.

In the University of Castilla-La Mancha (UCLM), the Architecture School of Toledo (EAT) has been created very recently. Due to this, it misses a laboratory of structures that could allow the students to complete their training on the basic mechanical properties of materials and their influence on different structural parameters. The best understanding of these concepts is especially fundamental for the architects’ preparation and their future professional life. This has motivated the proposal of designing a simple and inexpensive laboratory for developing specific practical activities related to the structural behaviour of different materials. The equipment should be projected for complementing the teaching activities of the subject “Estructuras I” from the Degree in Architecture of the EAT-UCLM. Taking into account the structural design and analysis, the scope is to define and set up a series of activities that will help to comprehend better the concepts of equilibrium, stiffness, strength and stability. The definition of complicated instruments will be avoided in order to escape from learning difficulties due to their sophistication. As a result, the cost of the tools and basic material should be minimal since the practices are expected to be manufactured with our own resources.

Keywords: teaching laboratory, strength of materials.

1 INTRODUCTION

In the European space of higher education one of the main premises that is demanded to the member countries is that the education system improves the practical skills of the students. However, the connection between theoretical concepts and their different applications is not necessarily obvious during the learning process. One of the teaching schemes that allows to improve the transition from theory to practice is based on the realization of activities in workshops and laboratories, complementary to the lectures [1-8]. Teaching laboratories at the university are able to reinforce the theory classes and they help for a better understanding of the concepts. Then, tests and experiments can be used as a tool to strengthen and complete the knowledge acquired during the learning process of the student. Moreover, the practical work allows to show and to utilise a part of the scientific method by means of verifying the studied models, limiting assumptions, validating the theory and favouring predictions. In addition, the experience in the laboratory provides the opportunity to develop the oral and written communication skills of the students, as well as the leadership and cooperation attitudes. It has also been confirmed that students seem to be more involved when they can do physical tests which can bring them closer to real situations.

Therefore a well-designed laboratory is an excellent tool that helps to improve the students’ preparation, reaching a perception that is very difficult to achieve by any other methodology. The EAT-UCLM, founded in Toledo in 2010, still does not have enough facilities to develop practical activities complementary to the theory classes of subjects related to structural calculation. Because of this, a teaching laboratory is proposed for carrying out the practical work of “Estructuras I”, subject of 2nd year from the Degree in Architecture of the EAT-UCLM. This space should allow students to discover the concepts learnt in the theoretical classes and to find out that the idea of “an exact result” is sometimes an utopia.
2 OBJECTIVES

The proposal of design and set-up of a structures laboratory is based on the main scope of applying to a practical situation the knowledge about structural calculation and materials behaviour that the students have acquired. In particular, they are intended to understand better the concepts of equilibrium, stiffness, strength and stability [9] by means of comparing experimental and theoretical results. Bearing this in mind, the main objectives to be achieved with the start-up of the teaching laboratory are:

- The definition of an experimental area for developing practical activities related to the structural behaviour of different materials, which should be uncomplicated for escaping from learning difficulties due to the sophistication of the installation.
- The use of low-price tools and basic material, since the practices are expected to be fabricated with our own means.
- The experimental determination of the elastic mechanical properties of materials and their influence on different structural parameters.
- The students’ apprenticeship of the proper selection and utilisation of instruments for practical measurement of magnitudes.
- The development of the undergraduates’ capacity to take in-situ decisions, to write a critical analysis of the results, to arrive to relevant conclusions from the tests performed and to work their ability of synthesis in the final report.
- The improvement of the communication skills of the students. As well, the leadership, teamwork and cooperation attitudes should be promoted: being objective, avoiding hasty judgements and taking into account the ideas and suggestions of other people.
- The increase of the student motivation, by means of stimulating their interest.

3 BASIC STRUCTURAL ELEMENTS

Simple structural systems based on metallic bars or cables under different loading cases are proposed to be mounted. The principal elements that would be needed for constructing the practises are listed in the following subsections.

3.1 Bars and cables

Flat and long bars of rectangular cross sections and cables with small transversal areas are recommended to be utilised (Fig. 1a). These kinds of components are widely employed in general applications, going from the industry to the artwork. They are chosen because their reduced price and their ease to be shaped, cut, formed and machined with the proper equipment and knowledge.

3.2 Slotted weights and weight holders

A set of slotted weights and weight holders for routine testing are suggested to ensure a reliable application of the load in the structures. Weights of 1 N and 5 N (see the example of Fig. 1b) can be applied for an easy and rapid testing with enough precision guaranteed.

3.3 Springs

A linear longitudinal spring (Fig. 1c) is an elastic object which can be extended from its resting position, exerting an opposing force proportional to its change in length under the premise of small deflections. The rigidity of the spring is defined in terms of the spring constant $k$, which can be calculated as the change in the applied force $P$ divided by the change in length $d$ of the spring. Therefore $k = P/d$, being this longitudinal stiffness expressed in N/m and in the international system of units (SI).
4 MATERIALS

The structural members are planned to be made of several metallic materials used in typical constructive applications. Therefore the bars and cables are intended to be metals, predominantly steel, aluminium, copper or brass. The average mechanical properties expected from each of these materials are listed in Table 1. The elastic modulus $E$, the yield strength under tensile loading $f_y$ and the ultimate tensile strength $f_u$ are the basic parameters that an engineering or an architect needs to know for the definition and design of structures.

**Table 1.** Standard properties of the stainless steel [13], aluminium [14], cooper [15] and brass [16].

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic Modulus $E$ [GPa]</th>
<th>Yield strength (tensile) $f_y$ [MPa]</th>
<th>Ultimate tensile strength $f_u$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>207</td>
<td>275</td>
<td>515</td>
</tr>
<tr>
<td>Aluminium</td>
<td>68</td>
<td>85</td>
<td>100</td>
</tr>
<tr>
<td>Copper</td>
<td>130</td>
<td>117</td>
<td>210</td>
</tr>
<tr>
<td>Brass</td>
<td>97</td>
<td>124</td>
<td>338</td>
</tr>
</tbody>
</table>

5 MEASURING INSTRUMENTS

Mainly inexpensive and easy to use working tools are intended to be utilised in the experiments. In order to measure the dimensions of the different components or samples, a Vernier calliper and a tape measure should be employed for determining both small dimensions and longer lengths respectively. As well, dial indicators are proposed for acquiring the displacements produced in the structures due to the loading conditions.

5.1 Dial indicator

A dial indicator is an instrument which can be used to obtain the deflection of a system in a laboratory environment by means of the differential displacement measured with a spherical contact tip. In order to develop the measurements, the dial indicator must be well fixed to a support or attached to a frame. The small displacements computed by the palpation tip are mechanically amplified and transmitted to a clock face. The dial containing the graduated scale can be rotated. Then the zero can be set coincident with the needle location and, therefore, the measurement can be carried out by comparison with the initial position. For reading the measurements, in the clock face there are two needles: the shorter one indicates the millimetres and the longer one the hundredths of millimetre. When the needle is between two divisions, the nearest one is taken rounding the measurement to the resolution of the instrument.
5.2 Vernier calliper and tape measure

A Vernier calliper gives a direct reading of a length measured with high accuracy and precision. It comprises a fixed jaw with a calibrated scale and a sliding jaw with a pointer. Not only the external dimensions of a piece can be obtained by reading the distance between both jaws, but also the internal dimensions and depth of a sample can be measured. They commonly permit to obtain measurements with a precision of 0.01 mm.

A tape measure is a flexible ruler, which allows to measure long lengths and it permits to obtain dimensions in curve shapes and even corners. It is a typical measuring tool which allows to measure distances of the order of the millimetre.

6 DESCRIPTION

Uncomplicated structures consisting of one-dimensional bars or cables, primarily submitted to either flexural or axial loading, are intended to be studied. Four main ideas have to be transmitted, providing the student the basic tools for assimilating correctly the concepts of equilibrium, stiffness, strength and stability on which the calculation of structures is based. With this scope, the definition of the facilities and working materials should be established, along with the fabrication of the equipment, the set-up of the practices and, finally, its use by the students. The teaching needs have to be analysed in order to avoid the proposal of expensive equipment, because the main purpose is to achieve a basic understanding of the phenomena but escaping from complicated installations that may cause learning difficulties due to their sophistication. The four principal tasks pursued in the practical sessions are addressed in the following subsections, along with some simple examples which could be used with some adjustments as models of study.

Once the laboratory will be set up, the experimental work should be temporally coordinated with the classes of theory and problems, always bearing in mind that this requires additional time than a conventional lecture. An active participation of the students and the stimulation of their initiative are encouraged, making efforts to form groups with a small number of members for favouring the discussion among them and for keeping them active throughout the course of the practice. The students should be able to distinguish the differences between the real system and the ideal model, which is a likely source of deviation of the theoretical results from the experimental ones, as well as the possible errors of the measurement tools. In order to evaluate the assessment of the practical work, not only a continuous monitoring of the students procedure should be applied but also the full evaluation should require the presentation of a final report. This should allow to measure the assimilation level of the concepts, as well as the ability to report the experimental work and the synthetization of what has been learnt.

6.1 Concept of equilibrium

In the classroom sessions the students are expected to see a brief introduction of the structural requirements and some basic definitions. These general concepts have to be particularised for the laboratory systems, in which it is expected that the student will be able to relate the symbology used in
the theory with the actual boundary conditions. Some configurations of interest for understanding the concepts of global and internal equilibrium are proposed to be studied analytically and experimentally. As a matter of example, Fig. 3a shows a sketch of a simple system, formed by a metallic cable submitted to an axial load. Special emphasis will be placed on the calculation of the reactions (Fig. 3b) and the internal efforts (Fig. 3c), explaining the difference between an isostatic and a hyperstatic system. The transmission of the axial force can be shown by means of interposing a spring in an intermediate position of the cable (Fig. 3d).

![Figure 3](image)

**Figure 3.** (a) Simple isostatic system. (b) Global equilibrium. (c) Partial equilibrium. (d) Load transmission observed by means of interposing a spring in the original system.

### 6.2 Concept of stiffness

Similar to the spring, the rigidity $k$ that a structure presents under loading can be calculated dividing the applied load $P$ by the displacement $d$ that it produces. Therefore, this task mainly requires to calculate analytically and to measure experimentally the displacements produced in simple systems due to external actions, comparing finally both results. With this scope, in the workshop the students should instrument the structures with dial indicators in order to obtain the state the deflections during the test, being the observables for the subsequent analysis the applied forces and the vertical displacements. Then, following the given examples, the rigidity of the system indicated in Fig. 3a can be calculated as $k = P/d = EA/L$ while the stiffness of the cantilever beam proposed in Fig. 4a has to be equal to equal to $k = P/d = 3EIz/L^3$. In these equations $A$ is the area of the cross section, $I_z$ is the moment of inertia of the cross section with respect to the out-of-plane axis and $L$ is the non-negligible length of the components.

### 6.3 Concept of strength

The structures that would be definitely implemented in the laboratory have to be able to train the students’ capability to determine analytically and experimentally the apparent elastic properties of the chosen metals. Hence, simple truss systems consisting of cables submitted to tensile axial forces are recommended for analysing the yield strength $f_y$ that delimits the elastic material behaviour from the plastic one and the value of the ultimate strength $f_u$ in the moment of failure. The determination of these parameters is crucial for the design of structures, which are modelled to avoid overpassing the yield strength of the material. The procedure would request to develop a test in which the value of the applied load is incremented step by step. Then the slope of the normal stress-strain relationship during the linear response of the material, known as the elastic modulus $E$, can be also estimated.
For example, in the case proposed in Fig. 3a the Vernier caliper has to be used for measuring the cable diameter $D$ and the dial indicator for evaluating the evolution of the deflection $d$ during the test. By means of simple data treatment, the area of the circular cross section is $A = \pi D^2 / 4$ and the cable’s strain state $\varepsilon = d / L$. During the linear response of the material the relation between the normal stress produced by the axial force and the strain is $\sigma = E\varepsilon$ and, therefore, $P/A = E d / L$. Then, the modulus of elasticity can be calculated as $E = P L / A d$.

Similar reasoning can be applied for obtaining an approximate value of the elastic modulus in cases in which the system is submitted to flexural loading, like the one shown in Fig. 4a. Taking into account a beam with a rectangular cross-section with base $b$ and height $h$, the maximum deflection can be obtained analytically as $d = P L^3 / 3 E I_z$, considering $I_z = bh^3 / 12$. Measuring experimentally the bar dimensions and its maximum vertical displacement by means of the tape measure, the Vernier caliper and the dial indicator, the elastic modulus of the material can be calculated from the expression $E = 4 P L^3 / 3 b h^3$.

### 6.4 Concept of stability

The last aim is to observe during the laboratory sessions the buckling of compressed bars, typical in vertical elements (columns) as the one sketched in Fig. 4b. This instability phenomenon is produced whenever the applied axial load reaches the so-called critical load or Euler load, whose first order approximation is given by the equation $P_{\text{critical}} = \pi^2 E I_{\text{weak}} / (\beta L)^2$. Then, the student must be able to observe the boundary conditions and define from them the theoretical effective length factor $\beta$ of the system. Besides, they should be capable of recognising and calculating the inertia of the cross section with respect to the weak axis $I_{\text{weak}}$. The critical load analytically calculated should be subsequently experimentally validated, applying it to the column system and accomplishing the buckling of the bar.

![Figure 4. (a) Cantilever beam. (b) Column-bar on two supports.](image)

### 7 EVALUATION

A continuous evaluation of the evolution and learning level of the student during the practical sessions will be produced, what will allow to estimate the accomplishment degree of the experimental workshops. The instructor should become a mere guide, expecting the maximum participation of the students. Through the proposed activities each person should expose his/her previous ideas, explore alternatives and get used to the scientific methodology. As a key point, metaphorically speaking, not only the "know how it is done" but the "know how to do it" is pursued, competence that it can only be achieved in spaces of practice. A final report will be requested for evaluating the assimilation of the different concepts, along with the ability of describing the work developed and synthesizing what has been learned. This report should specify the title of the practice, the author or authors, the objectives, the description of the process, the measurements, the data treatment and results, discussion and conclusions.

### 8 CONCLUSIONS

The working plan constituted by practical sessions or workshops is proposed to achieve the tasks set out. Mainly, a better understanding of the concepts of equilibrium, stiffness, strength and stability is
pursued. With this scope, the construction of an inexpensive laboratory is feasible in order to contrast experimentally the basic ideas studied previously in the classroom from the analytical point of view. In particular, the students can become aware of the importance of the experimental testing for determining the material mechanical response needed in the design of structures. Due to the simplicity of the systems proposed, the student can participate actively in the phases of calculus and characterization of the material. Thanks to the practical sessions, the verification of the elastic properties is developed by using both the calculated parameters and the results obtained from experimental testing. The reduced number of students can facilitate a better monitoring of their evolution, the exchange of opinions and the teamwork.

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