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DESIGN GUIDELINES FOR LABORATORY LEARNING ACTIVITIES IN STRUCTURAL MECHANICS

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ABSTRACT

Structural Mechanics (SM) is a fundamental subject in engineering bachelor curricula. Since experimental investigations play a central role in the discipline, laboratory practice is often present in SM courses. Many instructors recognize in laboratory activities, not only a way to develop laboratory skills and appreciation of the scientific method, but also a chance to reinforce students' conceptual understanding of the discipline. However, there is evidence that laboratory instruction is not always successful in achieving conceptual understanding.

To address this problem, the goal of the presented study is to investigate how laboratory activities can be designed to support students' conceptual understanding of SM. First, the disciplinary body of knowledge is analysed through Johnstone's model of multilevel thought. In SM, as in Physics and in Chemistry, phenomena are analysed at different scales: the phenomenological level, the invisible level, and the symbolic level. The understanding of most Structural Mechanics concepts relies on linking the phenomenological world to the underlying invisible world using symbolic representations such as equations, diagrams, experimental data plots, and physics models. To transition and translate between "levels of thoughts" and understand SM

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concepts, representational competence and abilities in model-based reasoning are needed. In the next paragraphs, a review of successful studies from similar subjects is presented, where the learning activities targeted representations and model reasoning in laboratory settings. The findings are summarised in a set of design guidelines to help instructors develop successful laboratory learning activities for SM.

1 INTRODUCTION

1.1 Problem analyses and research question

This paper explores the design of instructional laboratory practice for the discipline of Structural Mechanics (SM), a fundamental subject in bachelor engineering curricula. Laboratory practice is of central importance in the engineering professions in general. Specifically, experimental data are needed in the characterization of materials, in the design of new products, and to measure design performances [1]. Laboratory practice is also a fundamental part of knowledge creation in SM. Although research is mainly carried out through simulations and computational methods, new models and theories are validated experimentally [2]. Students are expected to acquire practical laboratory skills as well as the ability to design and conduct experimental investigations to be ready for their future professions. To fulfil these requirements, laboratory practice is often present in SM undergraduate curricula, either as a stand-alone course or integrated into lecture-based courses.

The complexity and the high level of formalism of Structural Mechanics tend to hinder students' understanding of disciplinary concepts [2]. Therefore, many instructors recognize in the experimental practice also a chance to reinforce students' conceptual understanding of the discipline [3]. However, there is evidence that laboratory instruction is not always successful in achieving that aim. In fact, during laboratory practice, students often follow provided step-by-step procedures focusing on procedural issues rather than elaborating on the disciplinary concepts for which the activity was designed. Hofstein and Lunetta already came to this conclusion in a first review in 1982 [4], and their conclusions are still currently valid for many laboratory courses [5]. Nevertheless, there have been also successful initiatives, especially at secondary level science education. For example, the European Labwork in Science Education project [6] provided a framework to reflect on the effectiveness of practical work in science.

Moreover, there are very few studies investigating how laboratory practice can scaffold conceptual understanding in engineering. Specifically, there is a lack of research focusing on instructional laboratories in Structural Mechanics and on the specific challenges linked to Structural Mechanics disciplinary concepts. As a consequence, there is a need for clear guidelines that instructors can use in the design of effective instructional laboratories, useful at scaffolding students' conceptual understanding and applicable in the everyday classroom learning environment. Hence, the main research question that guided the presented study is: "How can laboratory activities support students' conceptual understanding of Structural Mechanics?". The aim is, on the one hand, to define requirements for laboratory instruction in a Structural

Mechanics course, and, on the other, to investigate the link between laboratory activities and conceptual understanding in Structural Mechanics. Design guidelines serve both aims, they provide practical goals for the intervention and they are useful for sharing the theoretical understanding.

1.2 Methodology

In determining the design guidelines, an approach developed by Van den Akker (1999) has been followed, as suggested by Bakker in [7]. The approach consists in the formulation of every design principle in terms of intervention characteristics and implementation procedures, providing theoretical and empirical arguments. In order to define the theoretical arguments, first conceptual understanding is defined, as well as its relationship with models and representations. Secondly, the disciplinary body of knowledge is analysed through Johnstone's model of multilevel thought. Skills necessary to reach conceptual understanding in Structural Mechanics are identified. Successively, discipline-specific challenges that students face are considered, as described by relevant research studies in the domain of SM teaching and learning. Finally, for the empirical arguments, studies that addressed those challenges with laboratory activities in similar domains are presented. Existing recommendations from the literature have also been noted.

2 CONCEPTUAL UNDERSTANDING IN STRUCTURAL MECHANICS

2.1 Conceptual understanding, models, and representations

The revised Bloom's taxonomy [8] defines conceptual understanding as the abstraction from factual knowledge, the understanding of the disciplinary core ideas and principles and their interrelationships. From an epistemological perspective [9], students with a correct understanding of the discipline, have concepts organised and related to each other in a coherent and robust mental model, from which they derive correct reasoning under different circumstances and contexts. In a similar manner, scientific disciplines provide models to describe and explain real-world events and phenomena, and to predict the outcomes of new events. Therefore, modelling is often considered the ultimate goal of science. Scientists generate models using experimental evidence, and they search for new evidence using models. Such intertwining of evidence- and model-based reasoning supports the understanding of phenomena [10].
Models are dependent on a broad spectrum of representations, in order to fully represent the salient characteristics of phenomena and their interrelationships. In fact, every representation affords access to some attributes of the phenomenon and hides some others. Taken together and coordinated, disciplinary representations provide the opportunity to fully 'see' the phenomenon [11]. Therefore, as Etkina et al. point out [12], effective instruction guides students in achieving representational competence: extract information from representations; translate between types of representations and build one representation from another; use them to construct meaning of phenomena under-study. Hence, modelling and representational competence are

necessary for concept learning. In the next section, the models and representations necessary in the case of Structural Mechanics are described.

2.2 Johnstone's model applied to Structural Mechanics

The discipline of Structural Mechanics (SM) studies the effects of loads on deformable bodies and physical structures. Unlike many scientific disciplines, the purpose of SM is practice-oriented: its knowledge system is meant to be used as a resource in engineering activities, such as the design of structures [2]. The results of the structural analysis are employed to compute deformations and stresses, to predict and avoid structures failure and to evaluate and verify structures suitability for use.
In order to fully describe the structural phenomena, the physical system is analysed at different scales. A useful tool to represent the levels at which phenomena are explained is Johnstone's model [13] of multilevel thought, frequently used in science education and especially in chemistry education [14]. Johnstone's model recognizes three levels of thought in physics and chemistry: the phenomenological or macro level, the invisible or micro level and the symbolic level. Since Structural Mechanics is closely linked to Applied Mechanics and Material Sciences, we argue that this explanatory framework is applicable to Structural Mechanics as well.
As seen in the example in Figure 1, in the analysis of deformable bodies, the physical system is modelled at the phenomenological and at the invisible levels.

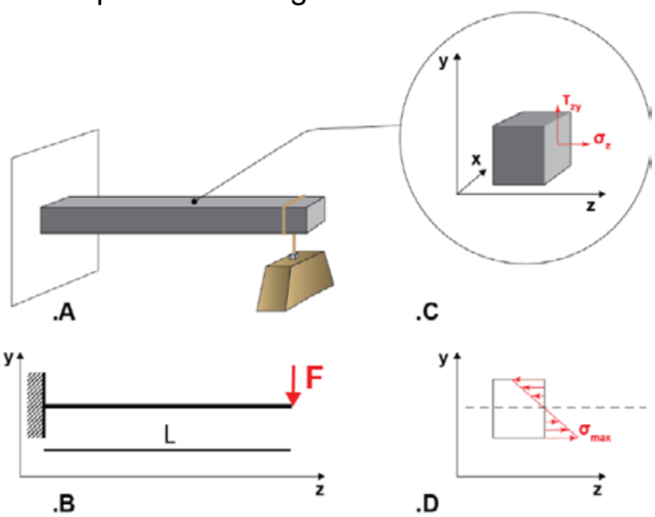

Figure 1- Examples of symbolic representation at phenomenological level (1.A and 1.B) and invisible level (1.C and 1.D)

At the phenomenological level, the observable features of the system are considered, such as the structure geometry, supports, applied loads and displacements. These concepts are formal conceptualisations of processes or features that students can experience directly.
The invisible level in SM is better defined with the term 'local level'. At this level, material properties, internal forces, stresses, strains are considered. Depending on how detailed the analysis is, materials can be modelled as a continuous mass, or considering material micro or nano structure (such as the crystal lattice and/or fibres

and defects). Usually, at bachelor level, the first approach, based on continuum mechanics principles, is followed. Therefore, representations such as the infinitesimal cube (figure 1.c and. d) are used in the analyses [15].
SM provides models that describe, explain, and predict what is observed at the phenomenological level thanks to the integration of local level properties. This is achieved through the coordination of symbolic representations, for instance equations, graphs, free body diagrams. The understanding of most Structural Mechanics concepts such as stress, strain or deformation rely on linking the phenomenological world to the underlying local level using symbolic representations. In many cases, several representations are needed to fully represent concepts and their interrelationships. Therefore, in order to translate between "levels of thoughts" and understand Structural Mechanics concepts, representational competence and abilities in model-based reasoning are needed.

2.3 Teaching and learning Structural Mechanics

Structural Mechanics is often considered a difficult subject, due to the level of abstraction of its symbolic representations [16]. As noted by Kurrer [2], this high level of formalism is intentional. Structural systems have a high degree of indeterminacy and interdependency between variables, so, historically, the solution of complex problems became possible only when new mathematical tools such as calculus and matrix notation were implemented. This new formalism generated new concepts that cannot be directly inferred from experience; in other words, some symbols and relations are not directly linked to physical characteristics of the system. However, this formalism also enabled the solution of complex structural problems by fast manipulations of symbols, without having to interpret the symbols or knowing what they mean.
Because of the complexity of the symbolic representations, instructors and students tend to focus more on formulae and mathematical procedures for problem solving [17], which do not directly afford the visualization of the system behaviour at a phenomenological and local scale. Students become proficient at dealing with the symbolic representations, but they do not connect them to phenomenological and local levels. Therefore, students often acquire the procedural skills needed to pass the exam but fail to grasp the physical reality hidden behind the equations. For example, Montfort et al. [17] studied the development of conceptual understanding from a sophomore-level mechanics of materials class to a graduate-level advanced steel design class. They proved that students in higher-level courses were better at solving problems but did not demonstrate significantly more conceptual understanding than students in the earlier courses, which is a typical result found in many sub-disciplines of Physics and Chemistry.
In a recent study, Brown et al. [16] investigated students' difficulties of acquiring conceptual understanding of Mechanics of Materials. This research highlighted how students had the abilities to correctly calculate outcomes of phenomena they could not properly explain. Students' wrong explanations appeared to stem from attempts of linking observable features of the problem (the direction of loads, point of application)

directly to local level features in a rather simplistic manner (for example “the maximum stress is always at the application point of the load”; “normal load only creates normal stresses and shear load only creates shear stresses”.)
The present study recognises that to help students develop proper explanations, instruction should provide different representations, showing the relationships between loadings and stress distributions. Laboratory activities can provide students with the direct experience of Structural Mechanic phenomena, bypassing the analytical formulation scaffolding conceptual understanding.

3 CONCEPTUAL UNDERSTANDING AND LABORATORY ACTIVITIES

3.1 Guided inquiry-based instruction style

Conceptual understanding is the main learning goal pursued by instructional laboratories [3]. However, this kind of laboratory activities is not often successful. In fact, the goal of increasing conceptual knowledge is commonly tackled by verification laboratories, i.e. instruction focused on verifying analytical formulas and theory through experimental observation. Learning outcomes are likely to be influenced by the style of laboratory instruction employed and, as discussed by Holmes et al. [18], verification laboratories tend to be overly structured in an attempt to make students perform the experiment correctly at the first trial. As a result, students blindly follow the provided step-by-step procedure without engaging in the learning process. For this reason, verification laboratories are also called cookbook laboratories [19].
An alternative instruction style is the guided inquiry-based approach, also known as discovery learning, whose central focus is students’ investigative work. The general principle of guided inquiry-based learning is to present students with problems and questions and to guide their curiosity into the discovery of solution and answers [20]. The guided inquiry-based approach has been widely developed in the years, with implementation heuristics being clearly defined [21]. The main ones are:

- Students do not know the outcome of the experiment and are only given the information they need to design and carry out the experiment.
- Students should be actively involved in developing or deciding upon at least some elements of the procedures of the laboratory exercise.
- Students should have opportunities to encounter both positive and negative results.
- Students’ learning is guided with questions for discussion and reflection on the implications of the experiment they perform or the data they collect.

3.2 Model-based reasoning and representational competence

Von Aufschnaiter & Von Aufschnaiter [22] brought new evidence in support of the inquiry-based approach, studying conceptual understanding and model-based reasoning in higher education instructional laboratories. Their research aimed at characterising the learning process taking place in a laboratory setting, video recording several different students’ activities within typical laboratory instructions. They observed that whenever laboratory instruction tries to ‘inform’ students about the theoretical model and symbolic representation at an early stage in the learning

process, students make no use of that information. Less than 10% of the time spent in the laboratory is usually given to explicit discussions of concepts or conceptual reflection on practical activity. Instead, students tend to first explore tool functions and find the shorter way to the numerical result. From these results, Von Aufschnaiter & Von Aufschnaiter suggest that laboratory activity designed to promote learning of unfamiliar concepts should not focus explicitly on the symbolic level at the beginning. Instead, instruction should facilitate experiences at the phenomenological level, as these are a prerequisite for students to arrive at an understanding of the phenomena based on their observations. Thus, post-processing should be the phase when students integrate their experiences in the laboratory with physics concepts.
Bernhard et al. [23] argue that the fundamental purpose of laboratory work in physics and engineering is linking theory (symbolic level) to experimental observations (phenomenological and local level). Because of the complexity of the learning environment, it is difficult to see and analyse how students perform those links and construct their understanding. Therefore, Bernhard et al. developed an analytical tool to study student learning in the laboratory, the “learning of complex concepts model”, reported in Figure 2.

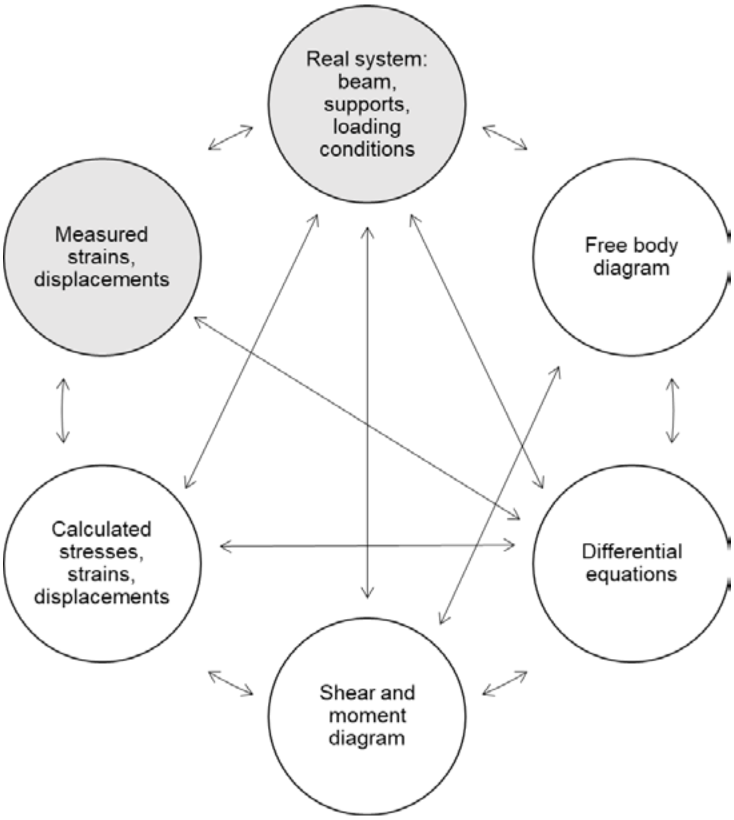

Figure 2- An example of an analysis of learning in a laboratory on the topic of bending of the beam, using the model for learning a complex concept

First of all, the representations that an expert would use in performing the experimental task are identified and illustrated by circles. Representations are divided into two groups, one pertaining to the experimental evidence, which in Figure 2 are coloured in light grey, and the other pertaining the analytical model, coloured in white. Through model-based (mathematical transformations, physical modelling) and evidence-based reasoning (collection of data, interpretation, qualitative judgment) experts translate from one representation to the other in order to analyse the experimental results [24]. These links are represented with arrows between the circles. As a result, an ideal path through the representations is identified, upon which the instructional laboratory activity is built. Students are provided with some representations; they are guided by assignment questions and cues in producing missing representations and connecting them together. The model can be also used to assess students' work, highlighting the links that students were able to make, either by observing students during the laboratory practice or assessing their lab reports. Moreover, the model can be used to refine the design of the activity, identifying gaps between what students were expected to do and what they actually did.

4 DESIGN GUIDELINES

The findings discussed in previous sections have been summarised in a set of design guidelines that can help instructors in the development of instructional laboratory activities in Structural Mechanics.

1. Prefer the guided inquiry-based style of laboratory instruction over the validation and cook-book approach because it scaffolds students' engagement with disciplinary concepts.
2. Create the opportunity for students to directly observe and experience the phenomenon bypassing the analytical model, because this allows students to arrive at an understanding of the phenomenon based on their observations. Ask students to link observed episodes to the theoretical propositions only in a post processing phase.
3. Develop data processing tasks based on the use of different representations, such as free body diagrams, infinitesimal cube, load-displacement plots, and strains distributions. Many representations beyond formulae are needed to fully characterise what happens at local level and the events visible at the phenomenological level.
4. Ask students to analyse data linking the observed physical events at the phenomenological level to the theoretical propositions at the symbolic level. Guide students in extracting information from representations; translating between types of representations and build one representation from another. This helps students intertwine model and evidence-based reasoning and expanding their understanding of concepts.
5. Track how students move from experimental data and analytical model during data processing because this provides feedbacks on how students construct meaning of the phenomenon under-study and on the effectiveness of the laboratory activity.

5 DISCUSSION AND CONCLUSIONS

To answer the research question: "How laboratory activities can support students' conceptual understanding of Structural Mechanics?", first a definition of conceptual understanding is provided, highlighting the importance of representational competence and modelling in understanding science. Then, the body of knowledge of Structural Mechanics has been analysed with Johnstone's model of multilevel thought, discussing how representational competence and abilities in model-based reasoning are needed to translate between "levels of thoughts" and understand Structural Mechanics concepts. These theoretical lenses have been used to study students' difficulties at learning Structural Mechanics, identifying the main issue as linking the symbolic representations, especially the analytical model, to the underlying physical phenomena.

Then possible ways in which this issue can be overcome in laboratory settings have been addressed. Inquiry-based instruction helps students engaging in the process of constructing meaning of physical phenomena. Von Aufschnaiter & Von Aufschnaiter suggests to first let students experience the phenomenon without the mediation of the symbolic representation. The experimental observations can be linked to the analytical model in the post processing phase. Bernhard et al. developed a model to track the links students build between the phenomenological word and the symbolic representations.

These findings are summarised in a set of design guidelines to help instructors develop successful laboratory learning activities for Structural Mechanics. The design guidelines are grounded in the Structural Mechanics domain and the specific challenges students face learning it. However, the same procedure can be followed to develop design for other domains.

The presented analyses are the first step of a design-based educational research project, in which the presented framework will be used for the design of a laboratory activity in a real Structural Mechanics classroom setting. Validation, feasibility, and robustness of such guidelines will be tested in a subsequent design iteration, having the design guidelines do real work in educational practice. This will be the first trial and test, consequently and informed by evidence and experience, the design framework could be edited and refined.

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