A comparative study of the physical model as a tool for structural education

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ABSTRACT: Six courses taught by the four authors at four different design faculties, are investigated for their use of physical models in structural education through an open-end questionnaire and peer discussions. Various characteristics of structural model applications are brought to the fore. They show that all investigated courses provide their model application within a project-based, student-centred learning. In the courses structural models are used for the student’s development of structural knowledge, but also as tools for structural design exploration in a studio setting. Through model constructing and testing, students develop sensorimotor experiences with structural behaviour which allows for higher levels of structural cognition. The paper ends with a recommendation for using physical structure models throughout the education programme starting from structure theory to design studios.

1 INTRODUCTION

1.1 The use of physical models in product design, architecture and engineering programmes

Over the years, physical models have been part of practices in product design, architecture and engineering: for example as representation models for communication with clients (e.g. in architecture), as prototypes (e.g. in product design) and scale models (e.g. in structural engineering) for testing, and as tools to investigate form and space of the designed object. Possibilities in digital computing have enabled to add to this arsenal the digital model as an important tool in design practice, taking over certain applications of physical model: for example in structural design the digital model with its possibilities in software simulations, have importantly gained interest at the expense of the physical model.

In relation to this practice current design education makes also use of physical and digital models, not only to prepare students for future practice, but also as pedagogical tool to support the students’ development of disciplinary knowledge. This paper aims to contribute to a mapping of the physical model as pedagogical tool for structural education in product design, architecture, interior architecture and civil engineering programmes.

1.2 A comparative study

All authors of this paper are involved as teachers in the structural education programme of their faculty, and use physical models as a pedagogical tool in their courses. They experience a lack of guidelines and documented information on an adequate use of such models for structural education, and have therefore decided to compare their teaching experiences. By investigating their own applications of physical models in structural education, the authors aim to develop a better understanding of such application as a pedagogical tool, and provide a set of differentiating characteristics of model applications as an inspiration for course design.
In this study the structural education programme is understood as the teaching of structural concepts (e.g. stress, strain and force) and their interrelations (e.g. higher stress delivers higher strain), the design of structural systems (e.g. a truss-girder to cross a river), and the calculation and dimensioning of structural elements (e.g. determine the cross-section of a concrete column under load).

For this study an open end questionnaire was developed which investigates the application of physical models through a pedagogical framework briefly described in the following chapter. These questionnaires were filled in for six courses which the four authors taught at four different faculties. By comparing and analysing these results, various differentiating characteristics could be identified and, through peer discussion of the authors, have led to the conclusions presented in this paper.

2 THEORETICAL FRAMEWORK

The theoretical framework used for this comparative study is based on various existing concepts within pedagogy and cognitive psychology. A short introduction to these concepts is given in this chapter.

2.1 Bloom’s revised taxonomy and meaningful learning

Benjamin Bloom initiated the development of a taxonomy of educational objectives, which was later on revised (Krathwohl 2002). It provides means of expressing qualitatively different kinds of thinking. Distinctions in cognitive processes are made from basic to more complex levels: remember, understand, apply, analyse, evaluate and create. (The three last levels are considered higher-order thinking). Students reaching a higher level of thinking within a taught subject attain thus a deeper form of understanding and mastery of this subject.

Richard Mayer (2002) makes a distinction between rote and meaningful learning. In rote learning only the first level of thinking (i.e. remember) is reached. ‘Meaningful learning occurs when students build knowledge and cognitive processes needed for successful problem solving.’ (Mayer 2002, p.227) It starts from the second level of thinking (i.e. understand) and increasingly more relates to the higher levels of the cognitive processes.

2.2 Tacit knowledge and implicit learning

Polanyi (1966) describes the concept of tacit knowledge as knowledge one can possess even though this knowledge neither has, nor can be given, a linguistic form (e.g. riding a bike). It has also been described as ‘know-how’ in contrast to ‘know-that’. Essential in acquiring tacit knowledge is experience.

Related to this tacit knowledge is implicit learning which is a learning without a full awareness of what has been learned. Such implicit learning can also involve complex matter (Sun 2008).

2.3 Inductive and deductive teaching

Inductive teaching aims to build knowledge from a learner’s experiences and interactions with phenomena. Students are confronted with a concrete situation of general principles and encouraged to observe, question and derive generalizations from their observations. The teacher provides an adequate learning environment and guides the students to successfully build knowledge. This teaching style is student-centred and aims at intrinsically motivating the learner by creating a ‘need to know’ for the student (Prince & Felder 2006).

On the other hand deductive teaching starts from the teacher presenting general principles through their definition after which examples are provided to demonstrate these principles. Students practice through exercises until the general principles are mastered. This approach is teacher-centred and relies more on an external motivation of students (Prince & Felder 2006).
2.4 Embodied cognition

Embodied cognition is an emerging viewpoint in cognitive science and holds that cognitive processes are deeply rooted in the body’s interaction with the world, and thus are not limited to the brain alone (Wilson 2002). Cognition is depending on the kind of experiences that come from having a body with various sensorimotor capacities (Varela et al. 1992). This means that learning is a process in which bodily experiences take part in the acquisition of knowledge.

3 COURSES UNDER STUDY

Six courses in four design programmes of four universities have been investigated on their application of physical models in structural education. The course content varies between structure theory and design studios, and is positioned from the start of the structural education programme till the end.

Table 1. Compared courses with physical model application

<table>
<thead>
<tr>
<th>Course</th>
<th>Programme</th>
<th>Year</th>
<th>ECTS credits</th>
<th>Students in group</th>
<th>*Structure theory remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Studies (TS)</td>
<td>Design/Form Studies, HKU</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>94%</td>
</tr>
<tr>
<td>Problem Solving &amp; Design III (PSD)</td>
<td>Engineering Sciences, KUL</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>59%</td>
</tr>
<tr>
<td>Lab Form-Material-Structure (FMS)</td>
<td>Architecture, ULB</td>
<td>2</td>
<td>2</td>
<td>2-3</td>
<td>53%</td>
</tr>
<tr>
<td>Structure (S)</td>
<td>Interior Architecture, KUL</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>14%</td>
</tr>
<tr>
<td>Workshop of Integrated Design (ID)</td>
<td>Architecture, ULB</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>0%</td>
</tr>
<tr>
<td>Studio Built Architecture (BA)</td>
<td>Architecture, ULB</td>
<td>4+5</td>
<td>11</td>
<td>3</td>
<td>0%</td>
</tr>
</tbody>
</table>

*Structure theory remaining provides the percentage of ECTS-credits of structure theory courses still remaining in the programme, following on the investigated course.

Figure 1. Physical models in courses (left to right): Technical Studies; Problem Solving & Design III; Laboratory ‘Form-Material-Structure’.

3.1 Technical Studies (TS), Design and Form Studies, HKU

This course is taught at the first Bachelor Design and Form Studies of the Hogeschool voor Kunsten Utrecht (HKU), in the beginning of the technical education programme. The course provides an introduction to the material family of natural polymers, and to the span of structures. Students working in groups of two, explore the behaviour of structures by making small models from basic materials like popsicle-sticks, rubber bands and tape. After this model creation, students use the identified success aspects of this short exploration to design a spanning or tall structure in the following weeks using wood as a main construction material.

The students are provided with online tutorials to create the physical models. They progress through trial and error which provides them insight in structural behaviour and general structural concepts like bending and tension. Students work very independently with little coaching.
from the tutors. The coaching during creation and the feedback on the end result is used to introduce the various structural concepts and explicit the structural behaviour.

3.2 Problem Solving & Design III (PSD), Engineering Sciences, KUL

This course is taught at the second Bachelor Engineering Sciences of the Katholieke Universiteit Leuven (KUL), after which still 2/3 of the structural education programme is still to follow. The course focuses on the design of masonry arches and the calculation of their load bearing capacity. In addition, mechanical behaviour of building materials and generic skills, such as report writing, group work and presenting, are also part of the learning outcomes. Students, working in groups of six, theoretically design an appropriate shape for the arch according to given boundary conditions and calculate its load bearing capacity. A 1/1 prototype of the designed arch is then built with bricks and mortar and tested by the students. For both parts, theoretical design and model construction, students write a technical report on which they are given feedback. Afterwards they present their work on two occasions: to a jury and on a demonstration day.

The masonry arch is created according to the method and shape as designed by the students. The construction takes place under supervision and after a bricklaying demonstration by a technician. The testing of the arch relates the theoretical knowledge on the load bearing capacity and the behaviour of arches with experiment experience. Three arches are constructed per group for different observations on structural behaviour.

3.3 Laboratory ‘Form-Material-Structure’ (FMS), Architecture, ULB

This course is taught at the second Bachelor Architecture of the Université Libre de Bruxelles (ULB) after which more than half of the structural education programme is to follow. It introduces the student into the importance within architectural design of integrating aesthetics, materiality—including connection technology—and structure as an efficient form. Within the limited time of a workshop, students working in groups of two or three, are confronted with a structural challenge they need to meet (e.g. a height to reach or a span to achieve) by building a physical model using specific materials (e.g. drinking straws and twigs) and connection technologies, while developing at the same time an aesthetic position. The result is briefly analysed at the end of the workshop by the tutors. Afterwards students report their creation process and reflection on it. Examples of the models are used later on in structure theory courses.

The students create their physical models through trial and error with a limited coaching of the tutors and within a strict time frame of four hours. They are familiar with this setup from previous workshops even though these did not contain structural challenges. A limited amount of structural precognition is required to build the model. Models are investigated through a look and feel, but not through testing to failure.

Figure 2. Physical models in courses (left to right): Structure; Workshop of Integrated Design; Design Studio ‘Built Architecture’.
3.4 **Structure (S), Interior Architecture, KUL**

This course is taught at the second Bachelor Interior Architecture of the *Katholieke Universiteit Leuven*, and contains the main part of the structural education programme. It gives a broad insight in structural behaviour from internal forces and stresses to structural materials and typologies. In class, theory is combined with simple exercises to get acquainted with structural concepts and formulas. Three workshops spread over the second part of the course, are used to link the theory with sensorimotor experiences. Examples of students’ models are used in theory class.

Each workshop has a different assignment, in which students create physical models in groups of three: for example, a tower built with cardboard or a bridge with skewer sticks. There is little precognition required to create these models: students explore during the workshop through trial and error with an occasional coaching of the tutors. In two out of three workshops the final model is tested to collapse with direct feedback from the tutors in which structural concepts and behaviour are made explicit. Students write a report after the workshop to express their understanding of the structural behaviour of the various models they created.

3.5 **Workshop of Integrated Design (ID), Architecture, ULB**

This course is taught at the first Master Architecture of the *Université Libre de Bruxelles* after which no more courses of the structural education programme are scheduled. It aims to improve the students’ structural design skills for later architectural design projects by focusing on the interrelation between architectural form, structural behaviour and technology. The course is setup as a design studio in which a piece of furniture needs to be designed and built with a predefined material. Students, working in groups of four, start from studying structural scale models to end with constructing a 1/1 prototype. They hand in a report on their work and give an oral presentation to a jury.

The creation of the scale models and the 1/1 prototype is based on trial and error, and supervised by tutors of structure and technology alternating every week. The students follow a short training in building and analysing structural models. Focus lies on the connection technology, but also allows for experimentation on general structural behaviour. Testing (to failure) of the model occurs on the scale models but not on the prototype.

3.6 **Design Studio ‘Built Architecture’ (BA), Architecture, ULB**

This course is taught at the first and second Master Architecture of the *Université Libre de Bruxelles* after which no more courses of the structural education programme are scheduled. It is a design studio of an architectural project in which structure is integrated into the architectural concept. This course aims at improving the students’ architectural design skills with a focus on tectonic qualities. Students work in groups of three, rather independently from the tutors. Their preliminary outcomes are reviewed by the tutors and their final result is presented to a jury.

Students create structural models to inform their architectural design project when necessary: their creation is not part of a separate workshop or tutoring. Through the model creation and deflection testing, students are able to provide a better structural understanding of their structure proposal. The structural scale models are used during design consult with tutors for communication and feedback on the designed structure.

4 **COMPARATIVE STUDY FINDINGS**

By comparing the different applications of physical models in the above courses, different characteristics of such applications in structural education have been identified and are listed below under three headings: physical model creation; pedagogical purpose of model application; learning environment. The fourth and last heading presents various observations made by the authors.
4.1 Physical model creation

- **Scale model versus prototype**: a prototype is a model on scale 1/1 equalling the object of design in various characteristics, while a scale model only represent this design object on a smaller scale and in a limited way. A prototype has the advantage to contain all (structural) characteristics of the design, while scale models require correct transformations. In all investigated courses prototypes are used, providing correct structural information. Scale models are only used in course ID for quick investigation of the final prototype and in BA as part of the architectural design studio. (No scale models were used for calculating structural dimensions: software simulations are more appropriate as they provide more accuracy even though students require sufficient training to correctly operate such software).

- **Model design**: in all courses students design the model to be constructed (student-centred learning). The model can be theoretically designed before construction starts through formulas and calculation from structure theory (e.g. in PSD), or can be designed through direct sensorimotor experiences during construction of the model (e.g. in TS, FMS and S). In the latter, students create and adjust their design in the process of making (cf. reflection in action of Schön (1983)).

4.2 Pedagogical purpose of model application

- **For structural knowledge creation or as a structural tool in design**: the model application can be used to add sensorimotor experiences to structure cognition (embodied cognition), or can become in itself a tool to support design exploration. The former focuses on a student’s learning of structure knowledge (e.g. TS, PSD, FMS and S) the latter uses the student’s established structural understanding to explore structural design possibilities through model creation (e.g. ID and BA). Both are often combined.

- **To activate students**: in all courses the creation of the model involves hands-on, project-based learning. Together with the dynamics of working in groups, students become intrinsically motivated.

- **Physical models for peer, external and internal communication**: the three-dimensional representation of the model enables a rich design communication between the students (i.e. peers), with tutors or jury members (i.e. externals) but also internally for the designer to have the design proposition talk back as Schön (1983) describes it. All investigated courses exhibit these three communication types.

- **Learning through testing**: physical models are loaded and displacements are observed to retrieve structural information. In certain cases models are even loaded to failure (e.g. PSD and S). This testing enables students to learn structural behaviour (e.g. in TS, FMS and S), to check a calculated design and learn how to scientifically test models (e.g. in PSD), and to check a student’s intuition of a structural behaviour in a designed project (e.g. BA).

- **Making tacit knowledge explicit through reporting**: reporting of the own structural understanding of the model behaviour encourages students to reflect and express possible implicit learning, and link their sensorimotor experiences with theoretical structure cognition. The reports also enable tutors to check the lessons learned. In the studied courses this strategy is mainly applied when developing basic structural understanding (e.g. PSD, FMS and S).

- **To enhance learning outcomes through direct feedback**: by providing feedback on the model application students get direct answers to their immanent questions and build knowledge in a student-centred setting. This feedback is provided by tutors or jury (e.g. TS, PSD and S) but requires an allocation of time and energy in coaching.

4.3 Learning environment

- **Experiment versus exploration**: the model application can be used for experiments or for explorations. The former follows a deductive teaching style, starting from general principle in structure theory with exercises, to theoretically design a model that then can be constructed and tested to check the expected calculated results (e.g. PSD). The latter follows an inductive teaching style and engages students in an exploration of general principles through model creations and observations, guided by tutors’ coaching and feedback (e.g. TS, FMS and S).
– *Model application linked with previous and/or future structure courses*: the students’ experiences of the model creation are in connection with their previous and/or future courses of structure theory. Developed knowledge on structure theory is engaged in students’ model creation (e.g. PSD, ID and BA) and created models are used by teachers as examples in later courses to link students’ experiences with structure theory (e.g. FMS and S).

– *Hands-on, project-based learning*: models are applied in projects such as short workshops (e.g. TS, FMS and S), design studios (e.g. ID and BA) and scientific experiments (e.g. PSD).

– *Collaborative learning*: in all courses students work in group, enabling peer learning.

– *Coaching by tutors*: the application of models is mainly student-centred in all investigated courses, requiring limited (e.g. BA) to a more significant (e.g. PSD and S) coaching by tutors, but never extensive.

4.4 *Teaching experiences of the authors with model application*

All authors have several years of teaching experience in the structural education programme. Within this body of knowledge their experiences of teaching with physical models is assessed and several observations are listed here:

– Students often need guidance to transpose their tacit knowledge gained from their experiences with the models, to an explicit knowledge that goes beyond the specific case (i.e. going from the single example to the general principles).

– The application of physical models enables students to investigate and develop an (embodied) cognition of structural behaviour without the need to understand all of the structural concepts and formulas presented in the theory. It allows them to set aside the mathematical threshold of the formulas and go straight into a bodily experience of structural behaviour.

– Students often experience an aha-moment of understanding when finding a general structural principle known to them from previous courses, that manifests itself through experimentations in a physical model (cf. the difference between learning by rote and meaningful learning).

– Project-based learning fits current Millennial students’ learning styles in design education: current students are activated when confronted with hands-on projects.

– The shift from teacher- to student-centred learning requires an essential adaptation of the teacher’s role from ‘sage on the stage’ to ‘guide on the side’. Such adaptation should be implemented over the whole programme - wherever meaningful - and asks for sufficient support in educational professionalism.

– In order to develop sufficient sensorimotor experiences with structural behaviour, students need to explore and benefit from moments of trial and error in model construction (e.g. in S). This requires projects descriptions pushing students towards unknown territories to prevent them from mimicking existing structural designs that do not fail nor ask for their well-thought adjustments.

– The structural tutoring in model application courses needs allocation of sufficient staff time which is less common in structure theory education (certainly compared to the tutoring in design studio education).

5 CONCLUSIONS

The use of physical models in structural education of design students has various assets:

– Physical model applications fit well in project-based, student-centred education which activates design students in learning structure theory through their engagement in making (with a low mathematical threshold). In these projects students work in group allowing for collaborative learning and group dynamics.

– Physical models can be used for the development of the student’s structural knowledge, but also as a tool for structural design exploration in a studio setting.

– Constructing and testing physical structures allows students to develop sensorimotor experiences in structural behaviour which adds to and links with their knowledge on structure theory (cf. embodied cognition).
− These three dimensional models link structure as a spatial quality with the design object of architecture, interior architecture or product design, and thus incite for integrated designs.
− The three-dimensional representation of the structure model enables a rich design communication between the students as peers, with tutors and jury as externals, and also internally for the designer to have a conversation with his/her own design proposition.
− Even though digital models enable more accurate calculations of structures, the use of physical models are less prone to unforeseen creation and testing errors, and require little precognition to be created.

To take advantage of the use of physical models in structural education certain requirements need to be taken into account:
− The appropriate learning environment needs to be established. Project-based, student-centred education requires a coaching of tutors with time and facilities for students to explore and test their created models. Attention should be given in linking the students’ experiences in structural model making with structure theory. This can be achieved by having them report their experiences within the structural theory framework, and teachers using their created models in theory courses as examples.
− A factor for success in hands-on projects is the use of low key models: models which require little precognition to make, only need simple facilities and can be constructed with cheap and easy to acquire materials. If model making does require guidance, sufficient tutoring should be provided and/or instructional documentation or videos made available. Attention should be given to a proper construction of physical models that will provide the students correct information on structural behaviour.

Considering the investigated applications of physical models which occur throughout the structural education programme, the authors believe in the benefit of having structural model making as a constant in the design programme: from theory courses to design studios, starting in the first year of the programme and continuing until the last. Physical models can be used in a meaningful learning of general principles of structure theory, from the concepts and their interrelations to structural behaviour. And they can contribute in the students’ learning of creating structural designs and dimensioning of elements, while the spatial qualities of the structural models instigate students to integrate structures in their design projects of the studio.

ACKNOWLEDGMENT

This research has been made possible through the financial support of the Prince Philippe Fund of the King Baudouin Foundation.

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