The problem of scale in design-implement experiences in civil engineering

Lotte Marianne Bjerregaard Jensen

Technical University of Denmark

Henrik Almegaard

Technical University of Denmark

ABSTRACT

Engineering knowledge has been subject to software development for decades. Software opens the door for new kinds of multi-disciplinary collaboration between architects and structural engineers. Software gives architects access to specialist knowledge and engineers can test and compare many more solutions faster because of the software. But simulations of e.g. structural behaviour must be based on real-life experience of the effect of forces and of various structural concepts or they will lead to errors or processes and designs that are too costly. Design-implement experience for students of civil engineering poses a special challenge because of the large scale involved in civil engineering. The dilemma is defined by cost on the one side and on the other by the need for the design implement experience to grasp issues of real civil engineering.
The paper describes how the testing of scale models and fragments of structures is problematic, and how a chain of design implement experiences can be arranged to lead up to a reflective use of digital simulation as a professional tool.

KEYWORDS

Design-implement experiences, civil engineering, architectural engineering, structural engineering, scale, digital simulation, Finite Element Analysis, models, structural concepts.

A NECESSARY CONTEXT FOR DIGITAL SIMULATION

Digital simulation of structural behaviour is an integral part of the working methods of civil engineers. Digital simulation tools were developed through the last generation's focus on numerical methods. Finite Element Analysis is used at many different levels in the design and construction process. Over the last decade, the speed and precision of these digital simulation tools has increased. This opens the door for new ways for structural engineers to work. Numerical information on design proposals can now be generated along with the very first and blurry sketches from the project start-up phase, and this information can be continuously updated as the design process proceeds. It was quite different 20 years ago, when the calculation of exact dimensions was done at the end of a design process as a kind of final documentation because it consumed so much time and money. The modern design engineer is a new professional character in civil engineering and depends heavily on the technological revolution that has taken place in digital simulation tools. The potential gain in terms of aesthetics and finance in this new kind of design process seems to be enormous. Ideally, solutions with serious drawbacks should get exposed clearly early in the design process and there should be new opportunities for collaboration between engineers and architects.

But has Finite Element Analysis led to refined and optimized structures through better understanding of structural behaviour? [1] When dimensions (thickness) of concrete shells and plates from 1930-1960 are compared with those of recent projects, a regression is observed. [2] Either industry lacks real confidence in the results of the simulations or the simulations are being made wrongly or based on inadequate understanding of structural principles. As a consequence, the dimensions of structures exceed what is necessary. Closely related to this observation is the phenomenon that in many projects senior or even retired engineers with great experience are engaged to give input at a conceptual level and late in the process to check that common sense has been observed in the interpretation of the results from Finite Element Analysis. One example is Professor Niels-Jørgen Gimsing's role in the present project for a new bridge over Firth of Forth by a large British engineering firm.

There is apparently a missing link between digital simulation and real-life civil engineering. To take full advantage of digital simulation of structural behaviour, a real-life context needs to be taught and experienced already at university. What should this context consist of? First of all, it is important to have an overview at a conceptual level – of structural concepts. Second, but closely related, the student needs a good sense of the effect of the structural forces at work.

Using digital tools requires "old-school" knowledge of structural concepts

Understanding structural concepts
Galileo Galilei showed in the 17th century that you cannot simply enlarge a structure – at a certain point a change in structural concept is demanded. [3]
The very notion of structural concepts is too often absent in the education of civil engineers; it seems to have been pushed into the background, to make room for numerical methods (Finite Element Analysis).

Figure 1. Students work with cardboard and plaster scale models

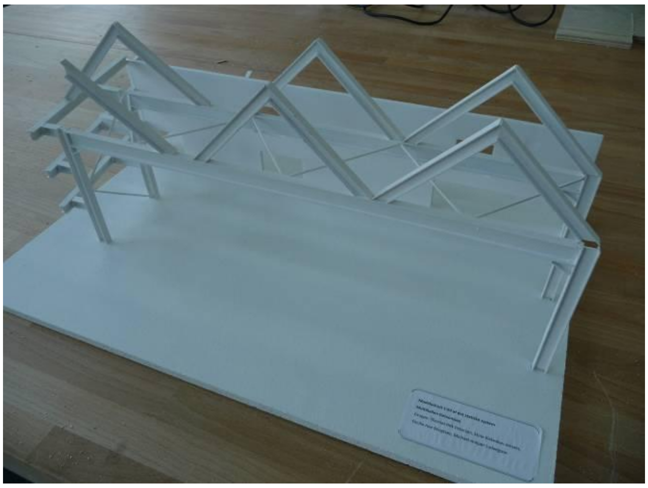

Figure 2. Cardboard models of structural concepts of existing buildings in the vicinity of the university campus

What civil engineers actually do when they design a structure is use their knowledge of how forces work in the structure. But as one of the grand old men in Danish civil engineering, Jørgen Nielsen, put it, “No one has ever seen a force”. He still works (in his 90s), as always, by designing structures in accordance with how the force lines run through the structure. [4]
In his generation, the analytical tool called ‘grapho-statics’ helped develop this visual understanding of forces in structures. [5] Today, the colourful graphics of the new digital simulation tools do a similar job. But there is still a mental transformation to make from the digital graphics to the structural behaviour of real-scale civil engineering structures. In spite of the digital graphics, it is clear that there is still a missing link in terms of the notion of structural concepts. Analysing structures at a conceptual level demands a kind of mental ‘X-ray’ view, with which the engineer looks through the many layers of information and sees the core, the skeleton of the building, and has a clear vision of whole sets of related concepts. When a scaled-down cardboard model of a structure is built, it becomes a concept and ceases to be numbers and equations, blue and red graphs running up and down the computer screen. Scale-models in cardboard work in a straightforward manner and give an instant impression of how forces run. If you press down one corner of the model you can observe how it deforms and feel how it pushes back. And you may realise where the balancing tension will appear. In fact, you can sense the forces in the structure in this way with the body. [6] Once you have this experience and an overview of categories of structural concepts, the digital tools have an adjusting and error-finding role.

Getting an idea of the forces at work by experimental testing of scaled-down models

In the education of civil engineers, the large dimensions of structures have always been a challenge. As a student of civil engineering, it is difficult to get a hands-on experience of the real forces we work with. Scale models give a chance to experience with all senses and look at structures in a holistic manner. Much more complicated is the use of scale models for experimental and accurate testing in order to understand the effect of forces and as a professional tool for giving exact dimensions.

In Germany, Switzerland and Spain, there is a long tradition of working with scale models in designing real-life civil engineering structures. Engineers Frei Otto and Heinz Isler set up advanced workshops with test facilities in order to develop structures solely through scale-model testing of structures. The famous structures of the 1972 Munich Olympic Games were conceived and constructed by means of scale models.

But it is not possible to 'translate' directly between scale models and real life. Transforming results from the testing of scale models into real-life structures is a scientific speciality in itself. The complex layer of theory acts as a barrier to students' understanding of the forces at work in a structure. The complexity is such that, unfortunately, it is not for bachelor-level students to work with. And there are a number of problems in the practical set-up of scale-model testing. In general, the geometrical requirements for tolerances are high. Some materials are difficult to scale up and down (e.g. wood and concrete), fittings need to be custom-made, etc. All this 'translation' moves the student away from the goal: to have a better sense of the effect forces in real life. So long as exact dimensions are aimed at, the potential in scaled-down testing as an option for design-implement experiences is limited.

If the aim is a conceptual understanding of structures, scaled-down testing is useful as described previously, but in that case quick and cheap mock-ups in card work better.

Testing real-scale (1:1) fragments of structures (timber joints)

One solution to the problems of the large dimensions of real-scale civil engineering structures and the problems of scale models aimed at giving the exact dimensions of structures is to create a design-implement experience with a fragment of a 1:1 structure. The idea was to calculate, build and test various joints in a wooden frame structure. First of all, the second-semester students designed a small summer cottage in an architectural studio course using the structural concept of wooden frames. Then some of the various kinds of joints were chosen by the teacher of statics. The students then calculated on a theoretical basis the maximum load capacity of the joints. Then they went to a workshop, made the wooden joints, and finally tested these timber joints. Comparisons between the calculations and the test results were recorded in a report.

Figure 3. Testing 1:1 timber joint

Unfortunately, students did not give this design-implement experience a positive evaluation (table 1). There were several lessons to learn. The most important was that joints or fragments of structures are difficult to calculate from a theoretical point of view. Understanding how forces meet and distribute in a fragment requires a lot of experience and knowledge. It is actually too demanding and complex for second-semester students. Apart from this important obstacle, there were also other minor problems with the design-implement experience. The workshop facilities were not adequate and perhaps this is why, the students assembled the joints in a crude and inadequate manner. The large tolerances involved resulted in completely different test results than they had expected from calculations. But it also drew attention to another important outcome of design-implement experiences: good craftsmanship and the issue of tolerances are not just about looks and finish. Students observe the consequences of a poor construction process in term of structural collapse. Due to inadequate communication between the three courses involved, the assessment of the process had not been agreed and students were quick to notice that no separate mark would be given for this design-implement experience. Communication with the students at the planning level was also poor. However, it was a true eye-opening experience to see a structure tested to destruction. The impressive power involved and the outburst of energy and sound at the point of destruction gave students a new perspective on theoretical statics.

Table 1
Assessment of the first version of second-semester design-implement experience
18 students out of 42 replied (N=18)

Q: The learning outcome of the CDIO design-implement experience was:

Very good	Good	Medium	Poor	Very poor
0%	0%	5.6%	27.8%	66.7%

Q: Having collaborative projects between several courses in the curriculum creates a better overall study:

I fully agree	I agree	I agree to some extent	I do not agree	I do not agree at all
22.2%	27.8%	38.9%	11.1%	0%

Q: If we are to build models we need better workshop facilities:

I fully agree	I agree	I agree to some extent	I do not agree	I do not agree at all
50%	38.9%	11.1%	0%	0%

The evaluation was carried out by DTULearningLab, Assessment and Evaluation Specialist Peter Hussmann, November 2008.

A CHAIN OF DESIGN-IMPLEMENT EXPERIENCES IN THE FIRST 3 SEMESTERS

Based on the above experience and evaluation, a chain of design-implement experiences for first to third-semester students was organized to provide an understanding of the forces and structural concepts before introducing digital simulation.

In the first three semesters, the basic theory of statics is taught with lectures, literature and exercises. But in a process parallel in time, the students are gradually prepared for using the digital simulation tools.

First semester – cardboard models & structural concepts

Their preparation starts during their first semester, where they do case studies of buildings in the surroundings of the university. Three different courses work together in a teacher team to create an eye-opening experience: structural concepts are all around us! The students develop their notion of structural concepts by building cardboard models of structures in the neighbourhood. After some weeks, the students are then asked to take their specific case-study structural concept and transform it into a small tower. This demands a high level of skill in relation to Bloom's taxonomy. If the student does not understand the notion of structural concept it will show in the tower design. The tower design is presented in a 3D digital model.

Second-semester – real-scale testing

To include the lessons of the first version of the design-implement experience, students were involved in the planning from the beginning. The following alterations were made: instead of a fragment (joint) of a real scale 1:1 structure, a complete structural member is built and tested. This, of course, is far more time and money-consuming, but it had proved too difficult for second-semester students to calculate joints, and the way forces work in a structure becomes much more apparent when a whole structural unit is built and tested. Students calculate dimensions and make their own accurate construction drawings. A better workshop was organized with a professional air to it. Students were told to pay attention to the precision of execution and that their craftsmanship skills would be a large part of their grade for the design-implement project. Actually there was an unexpected bonus in having the focus on tolerances in execution, because this is one of the rare occasions where ethics can be directly discussed in connection with engineering. Furthermore, of course, there are consequences in terms of the behaviour of the structural member.
New assessments of the revised CDIO design-implement experience (now running) will be presented at the Conference in June 2009 to be compared with previous results (presented above).

Figure 4. Building 1:1 timber frames in the new workshop

Third-semester – using professional digital simulation

The design-implement experience for third-semester students finally involves professional simulation tools (STAAD.*Pro* software). Although valued low in the CDIO hierarchy of design-implement features [7], it can be argued that we build up thoroughly for this first experience of using professional simulation tools with other more 'hands-on' experience. To be part of a design team with architects at an early stage in a project, it is important to know how to use fast simulation tools that give feed-back as you go.

In the first week, students develop structural concepts for a small footbridge using STAAD.*Pro*. Each group has in fact outlined a specific group of structural concepts to work in (cable stays, beam, arch and trusses) and an effective height and width, but no specific location. The concepts are therefore easy to calculate because they are ideal and abstract. Students present their work in sketches and graphical results from STAAD.*Pro* software.

After the first week, students are asked to redesign their ideal structural concept to meet the demands of a complex urban context. After two weeks of simulation and design they present their footbridge proposal in Indesign posters together with 3D Studio MAX animations and a static reports with both simulation results from STAAD.*Pro* and hand-calculated ‘safety checks’.

CDIO design-implement experiences in civil engineering form a necessary context for software-based engineering. They can be combined in a series with good results, where only one of them implies real-scale structures. The design-implement experiences create a better understanding among students for the reality behind the simulations.

Figure 5. Students presenting results from STAAD.*Pro* simulations of structural behaviour

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Biographical information

Lotte M. Bjerregaard Jensen is an associate professor and the head of studies for the B. Eng programme in Architectural Engineering at the Department of Civil Engineering at the Technical University of Denmark (DTU). Her current research focuses on educational theory and practice and how scientific knowledge can provide information for a design process and be integrated in architecture.

Henrik Almegaard is an associate professor at the Department of Civil Engineering at the Technical University of Denmark (DTU). His current research focuses on ways of supporting and qualifying the conceptual structural design process as well as the dialogue between the structural engineer and the architect.

Corresponding author
Dr Lotte Marianne Bjerregaard Jensen
Technical University of Denmark
Department of Civil Engineering

Building 118
Brovej
2800 Kgs Lyngby
Denmark
+45 45251682
lbj@byg.dtu.dk