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Pedagogic tools to support conceptual understanding in structural engineering education

Experiences from the Swedish Universities of the Built Environment

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Pedagogic tools to support conceptual understanding in structural engineering education

Experiences from the Swedish Universities of the Built Environment

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Preface

In my time as a structural engineering teacher, researcher, and previously practitioner, I have often had discussions with colleagues concerning the importance of a basic understanding of structural behavior, analysis and design. As a teacher, I have placed greater emphasis on this when I teach. However, this is not always straightforward given the emphasis we often put on calculations – especially in our examinations. A critical challenge I and my colleagues have observed with this is that too much emphasis on carrying out calculation tasks can inadvertently lead some students favoring procedural and factual knowledge over obtaining a conceptual understanding of the material. Is it not meaningless to carry out a complex calculation procedure if one cannot understand its meaning, evaluate the validity of the inputs and outputs, as well as appreciate the underlying assumptions and limitations? These questions were the basis for the project summarized in this report, where focus is on how we as teachers can support student conceptual understanding as a necessary complement and prerequisite to the complex calculations they must carry out when they become practitioners. The project has been supported by multiple colleagues from the Swedish Universities of the Built Environment: Jonas Niklewski, Eva Frühwald Hansson, Henrik Danielsson, and Susanne Heyden at Lund University; Ulf Ohlsson and Lennart Elfgren at Luleå University of Technology; John Leander at KTH Royal Institute of Technology; and Karin Lundgren at Chalmers University of Technology. We hope that our efforts will provide you, our fellow teachers, with some support with this task in the future!

Also, if you are interested in any of the tools that we mention in the report, feel free to contact us.

Ivar Björnsson

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Lund, 2026

Summary

In this report, we present findings from a Swedish Universities of the Built Environment (SBU) project (2023) where we collected and synthesized examples of pedagogic tools used to strengthen students' conceptual understanding in structural engineering—i.e., understanding key structural concepts, how they relate to each other, and how they connect to real-world structures and practice. The project responds to a perceived imbalance in engineering education where assessment and teaching can (inadvertently) over-emphasize procedural calculation at the expense of intuitive and critical understanding—an issue made more pressing by the widespread use of computational tools (and, increasingly, generative AI) in professional practice.

We within the project group are teachers and researchers from Lund University, Chalmers University of Technology, KTH Royal Institute of Technology, and Luleå University of Technology. We gathered input from our colleagues via e-mail or informal discussions. Nearly 80 examples of tools were collected from 20+ teachers. The tools clustered into four main types: digital demonstrations (e.g., videos and photos), interactive digital tools (apps and web tools), physical models and demonstrations (including scale models and “everyday objects”), and other printed or digital resources. Most examples targeted understanding of structural phenomena (e.g., behavior of beams, columns, frames, stability and torsion), followed by practical considerations (materials, construction tolerances and uncertainty) and structural design (procedures/codes and how design relates to real behavior). Many of the tools were judged to be low-cost and easy to adopt, with higher barriers mainly for tools requiring specialist laboratory equipment or certified skills. Student interaction and out-of-class access varied, with digital tools naturally supporting access and physical models sometimes requiring multiple copies and controlled availability.

To illustrate implementation, we develop two transferable tool families in more detail. First, we describe ‘everyday’ or low-threshold physical objects to support understanding of beam theory. Second, we elaborate on how small-scale building-frame models (custom kits or commercial sets) can be used to teach global stability of buildings. When embedded in active learning, these models improve conceptual understanding based on experiences from Lund University.

Overall, we conclude that pedagogic tools—especially physical models and well-chosen digital visualizations—are widely used to connect theory, calculation, and real structural behavior, and that many tools are practically transferable across institutions because they are inexpensive and require limited extra resources. At the same time, any learning gains should not be attributed to the tool alone: effectiveness needs further study and will likely depend on how the tool is integrated (task design, sequencing, assessment alignment, and course scheduling). With powerful modelling software (and emerging gen-AI support) becoming ubiquitous, strengthening students' ability to evaluate inputs/outputs and recognize limitations is increasingly important. Conceptual tools can help develop this critical judgment. We encourage teachers to adopt and adapt suitable tools reflectively and to share experiences to broaden good practice within structural engineering education.

Sammanfattning

Vi har skrivit den här rapporten som del av ett projekt finansierat av Sveriges Bygguniversitet (SBU) där vi samlade in och analyserade exempel på pedagogiska verktyg som används för att stärka studenters konceptuella förståelse inom byggnadskonstruktion. Projektet är ett svar på en upplevd obalans i ingenjörsutbildningen där undervisning och examination (omedvetet) kan lägga för stor vikt vid procedurmässiga beräkningar på bekostnad av intuitiv och kritisk förståelse — ett problem som blivit mer aktuellt i takt med att datorverktyg (och numera även generativ AI) används alltmer i praktiken.

Vi i projektgruppen är lärare och forskare från Lunds universitet, Chalmers tekniska högskola, KTH och Luleå tekniska universitet. Vi samlade in bidrag från kollegor via e-postutskick eller diskussioner. Nästan 80 exempel på verktyg samlades in från över 20 lärare. Verktygen grupperades i fyra huvudtyper: digitala demonstrationer (t.ex. filmer och bilder), interaktiva digitala verktyg (appar och webbverktyg), fysiska modeller och demonstrationer (inklusive skalmodeller och ”vardagliga föremål”) samt andra tryckta eller digitala resurser. De flesta exempel syftade till att öka förståelsen för konstruktionsfenomen (t.ex. balkars, pelares och ramars beteende, stabilitet och vridning), följt av praktiska aspekter (material, byggtoleranser och osäkerheters påverkan) och konstruktionsprojektering (rutiner/regler och hur projektering hänger samman med verkligt beteende). Många verktyg bedömdes medföra låga kostnader och vara enkla att införa, medan de som kräver specialutrustning eller certifierade färdigheter har högre trösklar. Studentinteraktion och åtkomst utanför undervisningssammanhang varierade, där digitala verktyg naturligt stöder tillgänglighet och fysiska modeller ibland kräver flera exemplar och kontrollerad hantering.

För att illustrera implementering utvecklar vi två överförbara verktygsfamiljer mer i detalj. För det första används ’vardagliga’ fysiska föremål för att stödja förståelse av balkteori. För det andra verktygsfamiljen används små skalmodeller av byggnadsramar (egna byggsatser eller kommersiella modeller) för att undervisa om stomstabilisering. När dessa modeller används inom aktivt lärande har de, enligt erfarenheter från Lunds universitet, visat sig stödja förbättrad konceptuell förståelse.

Sammantaget konstaterar vi att pedagogiska verktyg — särskilt fysiska modeller och välvalda digitala visualiseringar — används brett för att koppla teori, beräkning och verkligt konstruktionsbeteende, och att många verktyg är praktiskt överförbara mellan lärosäten eftersom de är billiga och kräver begränsade extra resurser. Samtidigt bör eventuella lärandeffekter inte tillskrivas verktyget i sig; effekten behöver undersökas mer och anses bero starkt på hur verktyget integreras i undervisningen. I takt med att kraftfulla datormodelleringsprogram (och numera generativ AI) blir allt vanligare är det viktigare än någonsin att stärka studenters förmåga att värdera indata/utdata och identifiera begränsningar. Pedagogiska verktyg för ökad konceptuell förståelse kan bidra till att utveckla denna kritiska bedömning. Vi uppmuntrar lärare att reflektera över, införa och anpassa lämpliga verktyg och att dela erfarenheter för att bredda god praxis inom utbildning i byggnadskonstruktion.

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1 Background

Historically, the general trend in engineering education has been towards favouring the analytical component of engineering knowledge, as highlighted by the engineering historian Eugene Ferguson in 1978:

The real ‘problem’ of engineering education is the implicit acceptance of the notion that high-status analytical courses are superior to those that encourage the student to develop an intuitive ‘feel’ for the incalculable complexity of engineering practice in the real world

The need for engineering intuition has been highlighted by several other authors and practitioners within the field. But how do we train our students to get a ‘feel’ for structural engineering and have a sound conceptual understanding of the material they are being taught? In our respective teaching practices, it is common that we provide references, demonstrate, or allow students to see, touch and interpret the ‘real world’ they, in their professional lives, will be charged with calculating. Examples include scale physical models illustrating structural engineering phenomena, case material (e.g., of a failed structures), study trips to construction sites, software/applications that visualize how structures behave, laboratory demonstrations or experiments (requiring lab reports), etc. These pedagogic tools may help provide students with a better conceptual understanding of the theories they are taught, connecting theory with the ‘real-world’, and are an integral complement to understanding and applying theory.

This report summarizes the findings from a project which collected examples on the use of pedagogic tools to improve conceptual understanding within structural engineering. The project was conducted by teachers and researchers at the Swedish Universities of the Built Environment (SBU) during 2023. SBU is a cooperative organization that includes the activities of research and education at four universities in Sweden which provide education of civil engineers:

- KTH Royal Institute of Technology, located in Stockholm
- Chalmers University of Technology, located in Gothenburg
- Lund University, Faculty of Engineering, located in Lund
- Luleå University of Technology, located in Luleå

Financial support for the study was provided by SBU. The contents of this report do not necessarily reflect the views of the financing organization.

1.1 Definitions

Conceptual understanding

As this report concerns the topic of student conceptual understanding, it is useful to discuss the definition of the term. Much of the pedagogic literature on conceptual understanding is focused on teaching science and mathematics, although clear definitions may not always be provided (Mills 2016). In a report from the National Research Council (NRC) of the National Academies in the U.S., conceptual understanding was defined as “an integrated and functional grasp of mathematical ideas, students with conceptual understanding know more than isolated facts and methods” (Kilpatrick et al. 2001). This definition highlights a distinction between two

interrelated types of knowledge: *factual (or procedural) knowledge* and *conceptual knowledge*. According to Rittle-Johnson et al. (2001), procedural knowledge is “*the ability to execute action sequences to solve problems*” while conceptual knowledge is the “*implicit or explicit understanding of principles that govern a domain and the interrelations between units of knowledge in a domain.*” Thus, conceptual understanding could be seen as encompassing factual and procedural knowledge while extending this to the relationships between these and even other types of knowledge. In fact, in a literature review by Mills (2016), conceptual understanding was found to have higher dimensions which included making connections, facilitating knowledge transfer, as well as metacognition (or how students organize their knowledge). Conceptual understanding can thus help students grasp a subject more deeply and aid them in applying this knowledge in future tasks.

For the purposes of this report, we will simplify our definition of conceptual understanding while acknowledging the nuances and complexities related to this term. Furthermore, we will focus our definition on structural engineering education. In this report, we define *conceptual understanding (in structural engineering)* simply as

understanding of structural engineering concepts, the relationship between these as well as how they relate to and are applied in real world applications.

Structural engineering concepts

Structural engineering concepts is a broad term which includes *structural behaviour*, *structural analysis*, as well as *structural design* or *assessment*. It thus concerns how a structure reacts, e.g., to external loading, how to calculate this response as well as assessing whether it will fail or determining the type of sections and materials required to avoid failures. To keep it broad, the definition of *structural concept* by Ji et al. (2016) will be used here:

A structural concept is a qualitative and concise representation of a mathematical relationship between physical quantities which captures the essence of the relationship and provides a basis for practical applications in structural engineering.

Pedagogic tools or aids

A tool or aid is something that helps with the completion of a task. In this report, we will use the words tool and aid interchangeably. A pedagogic tool supports teaching and learning. Our interest is in tools that specifically support improved conceptual understanding of structural engineering concepts. In this project, an explicit definition was not sought to be able to collect a wide range of examples. On the other hand, during data collection we did provide some examples as to the types of tools we were interested in, as well as specific concepts that may be valid; see Appendix A.

2 Method

The primary aim of the project was to collect and synthesize structural engineering teachers' knowledge and experiences of using pedagogic tools in their own teaching practice to support students' conceptual understanding. The project had two distinct phases:

1. Data collection, analysis and synthesis
2. Selected example development

During the initial stage we collected data from teachers at each of the four Swedish universities represented in the project group: Chalmers University of Technology, KTH Royal Institute of Technology, Luleå University of Technology, and Lund University. Data collection was achieved through a mix of e-mail correspondence (see Appendix A) as well as direct discussions between members of the project group and colleagues at their respective institutions. Each example should ideally contain a brief description of the tool as well as how it supports conceptual understanding. The aim was not to get an exhaustive list from each institution but to get a representative set of examples.

Once the examples were collected, these could be analyzed to determine some insights concerning their characteristics (e.g., if they are physical or digital), the structural concepts they support, as well as their transferability and potential usefulness to other teachers. This assessment provided the basis for the second phase of the project.

The second phase of the project included a selection of the collected examples for further development. This development essentially entailed providing more detailed descriptions of selected tools as well as direct support for how they could be implemented in a real teaching situation. Insights concerning their effectiveness in supporting conceptual understanding were also discussed with reference to previous experiences of their use in teaching and learning. The selection was based on the analysis in the second phase as well as internal discussions within the project group.

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3 Data collection

In total, nearly 80 examples of pedagogic tools were provided by over 20 teachers from within the Swedish Universities of the Built Environment (theme group Structural Engineering). Collection was carried out through a mix of e-mail correspondence and personal interviews by contacts at each university. The examples collected were in most cases added as firsthand accounts from teaching colleagues (e.g., as answers to the e-mail), although some were summarized by project members who had informally interviewed their colleagues. Members of the project group also provided their own examples.

3.1 Importance of conceptual understanding

The teachers who submitted examples were asked to indicate whether they think that conceptual understanding is an important learning outcome for structural engineering education. All the participants responded that it was important or even essential. This is quite expected given that the teachers who responded were those who actively used tools to support conceptual understanding in their own teaching. Thus, nothing can really be said about how widespread this belief is; although the collective experiences from teachers in the project group indicate that there are many structural engineering teachers that share this belief.

The need for conceptual understanding has also been highlighted by several researchers and practitioners in the published literature (e.g., Borthwick et al. 2013, Björnsson et al. 2016, Macleod 2016, May & Johnsson 2009). A common argument within these publications is the need to ensure understanding due to the ubiquitous use of computational software in engineering practice. To avoid unchecked errors and poor modeling assumptions, a user of these types of software needs to be able to determine the validity of their model, e.g., through simplified ‘back-of-the-envelope’ calculations. Previous research in Sweden has also highlighted that many within the construction industry also share this belief (e.g., Klasson et al. 2018, Björnsson 2022).

3.2 Categorization

The collected examples were all assessed to identify some common themes as a basis for categorizing them. This allowed for the examples to be synthesized and collated under varying “tool types”. The primary division into different categories considers (1) the characteristics of the tool (i.e., digital or physical artefacts) as well as (2) how it is implemented in teaching. A review of the examples provided (see Appendix B) yielded four categories (see Figure 1):

- **Digital demonstrations** – digital artefacts that are shown to the students but do not involve any direct interaction from the students with the tool itself.
- **Interactive digital tools** – digital tools which are interactive, i.e., there is a user (which can be the teacher and/or the student).
- **Physical models and demonstrations** – physical artefacts shown to students with the option of interaction.
- **Other printed or digital resources** – books or other digital resources may be available which may support conceptual understanding.

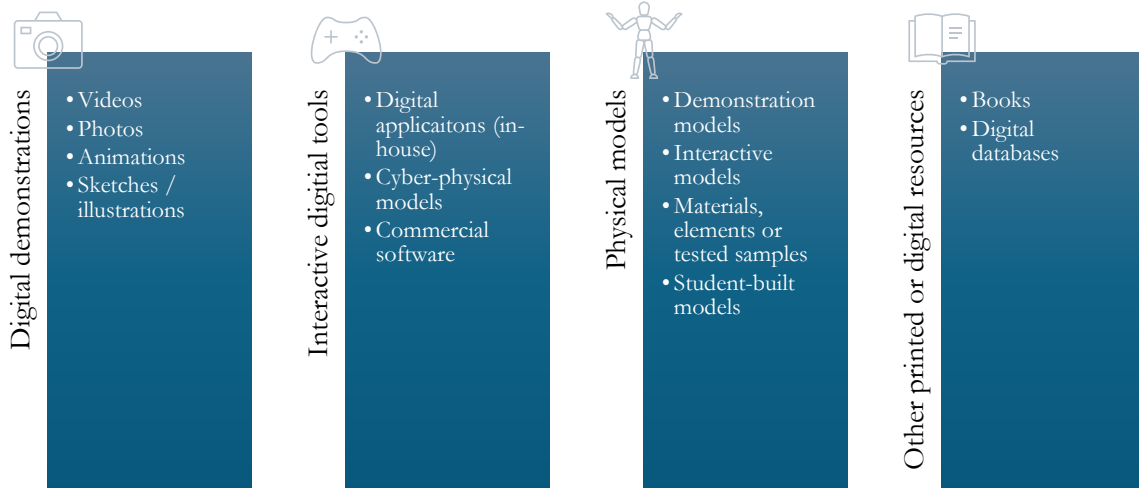


Figure 1. Primary categories and sub-categories of pedagogic tools based on collected examples; NOTE: teaching and learning activities, as well as assessment tasks were not included here.

Two additional categories of tools were also identified, but which were not analyzed further in the project. These were **teaching and learning activities** and **assessment tasks**. Both are very important parts of higher education; however, these are considered methods or approaches rather than pedagogic tools. On the other hand, these examples were useful for our project in that they often provided a context for which a tool could be used in or outside a classroom. In this way, they helped contribute valuable support for the final phase of the project.

An overview of the examples collected along with which category they belong is provided in Figure 2. Observe that the categories were not mutually exclusive and that some examples may be within multiple categories. Most of the collected examples were physical models and demonstrations, followed by digital demonstrations and interactive digital tools. In addition, 14 of the examples were categorized as teaching and learning activities, while 4 were assessment tasks. These results are expected as there is an established tradition for using physical models in engineering education and practice (Addis et al. 2020, Schaaf & Klosky 2005, Welch & Klosky 2007, Ji et al. 2016). In fact, the use of these types of models can provide students with an *intuitive* interpretation for the subject and in this way are very relevant in terms of supporting conceptual understanding (Ji & Bell 2018).

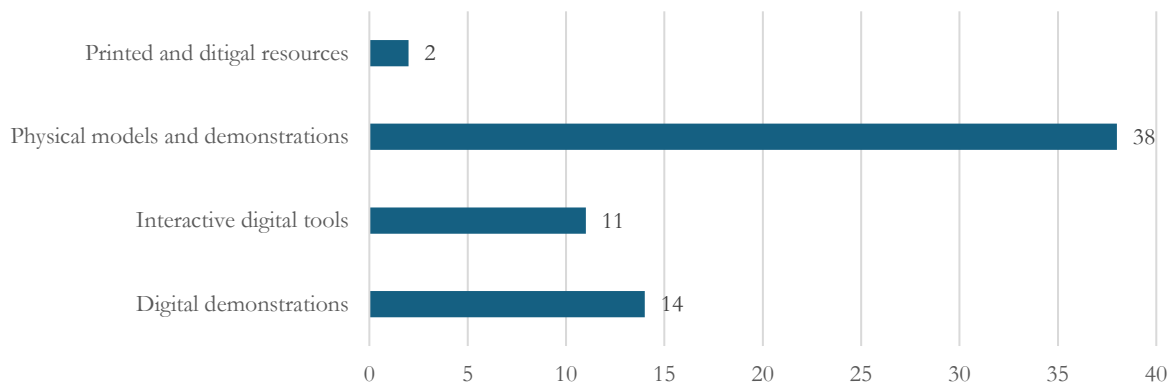


Figure 2. Overview of examples collected and how they were categorized; note that some examples may be within multiple categories.

3.2.1 Some examples

A complete list of all the collected examples is given in Appendix B while some figures are shown in Appendix C. Here we will provide some brief descriptions of the examples from the top three categories identified in the previous section.

Digital demonstrations

- Videos of structural failures (e.g., Tacoma Narrows Bridge failure)
- Videos from load testing (e.g., of a beam)
- Photographs of actual structures or structural details

Interactive digital tools

- Digital application for practicing influence lines
- Application for visualizing flow of forces (e.g., ForcePAD¹ and ObjectiveFrame²)
- Web application for illustrating behavior of a reinforced concrete section

Physical models and demonstrations

- Ruler or other long and slender object to illustrate column buckling
- “Duplo®-beam” with and without tape to illustrate reinforcement in a concrete beam
- Flexible beam element in bending, shear or torsion to illustrate varying beam theory phenomena
- Small-scale building frame models to illustrate global stability concepts

3.3 Analysis and synthesis

3.3.1 Concepts being taught

The collected examples were analyzed and synthesized to gain insights concerning their implementation in teaching and learning practice. The first important aspect to consider concerns the concept, or concepts, that the pedagogic tools are intended to support understanding of. As the examples collected were brief, this was not always explicit. However, some general structural engineering concepts were identified from a review of the collected examples. The following four (non-exclusive) categories were identified:

- **Structural phenomena** – this concept is related to the behavior of a structure and varying building mechanical phenomena. Example topics include beam bending and shear, local and global stability, fatigue, etc.
- **Practical considerations** – this concept concerns practical issues associated with structural engineering and in connecting theory with practice (the ‘real-world’). Example topics include the influence of tolerances during construction, uncertainties observed in practice, etc.
- **Structural design** – this concept relates to the design of structures, which can be seen as bridging the gap between the previous two concepts. Example topics include design procedures, design codes, etc.

¹ <https://www.microsoft.com/store/productId/9WZDNCRDY1MP?ocid=pdfshare>

² <https://apps.microsoft.com/detail/xpfpkppnd1dk4t?ocid=pdfshare&hl=en-US&gl=SE>

- **General understanding (or other concepts)** – some pedagogic tools can provide support which is more general and not easily associated with a specific concept. Example topics include the finite element method.

Most of the examples collected were focused on improving understanding of **structural phenomena** followed by **practical considerations**. Most of the examples in the former category concerned understanding how a structure, or a structural component such a beam or column, behaves and can be analyzed. Examples in the latter category included material samples (e.g., beam sections of varying materials, reinforcement), study visits to building sites, as well as structural labs which often required students to identify why theory did or did not match the lab results. Examples regarding **structural design** typically related to methods for designing structural elements for specific failure modes and the distinction between this and how the structure may behave in reality. For the final category, **general understanding**, the examples were often a type of teaching and learning activity, an assessment task, or a method of analysis (e.g., FE-method) which is not necessarily confined to one of the other categories.

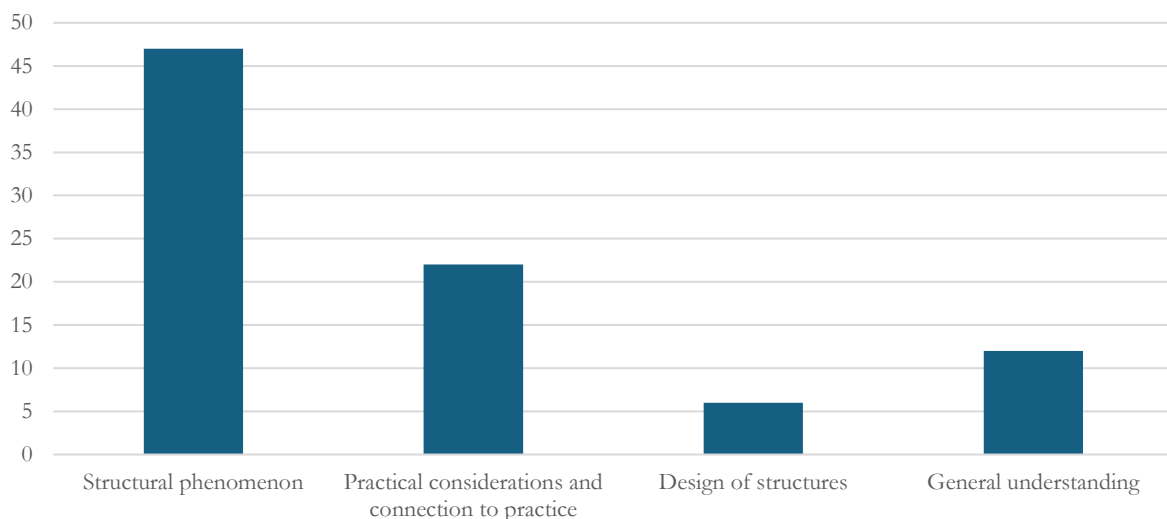


Figure 3. Overview of the general concepts that the collected examples aimed to teach and the number of examples within each concept; note that some examples may support multiple concepts

3.3.2 Tool characteristics and transferability

As the aim of the project was ultimately to provide other teachers with the possibility of adopting the same or similar tools in their own teaching, we investigated this transfer more closely. Important considerations included the efforts that would be needed by other teachers to use the same tools or something similar in their own practice and how the tools are used by the students. To investigate this further, we first jointly defined a set of criteria, followed by an assessment of how each tool is used in relation to these criteria. As the descriptions of the collected examples were often brief, the designation of each tool within a selected criteria were sometimes based on professional judgments of the members of the project group. The criteria used were the following:

- **Source** – How was the tool made/procured and where did the materials come from?
- **Cost** – Approximately how much would it cost a teacher to make or obtain this tool?
NOTE: Time for fabrication is not considered here.

- **Applicability** – Is the tool useful only in selected courses or topics or can it be used in multiple courses and is it relevant for multiple topics?
- **Knowledge/skills/equipment required** – How easy or difficult is it for another teacher within the discipline to adopt such a tool in their own teaching? Is there some extra specialized knowledge, skills, or equipment needed (e.g., programming, welding, lab facilities, etc.)?
- **Ease of use** – Assuming the teacher has the tool available, how easy or difficult is it for them to implement it in their own course? Is it ‘plug-and-play’ or is there a lot of preparation/time needed before it can be implemented (etc.)?
- **Classroom time** – How much time is required in class to implement this tool? Does it take time in only one class or maybe multiple? Would a course potentially need to be developed to some extent (e.g., extra classes)?
- **Student interaction** – Are the students somehow able to interact (physically or virtually) with the tool? E.g., using an app, helping to demonstrate something together with other students or teachers, working with the tool individually or in groups.
- **Student access** – Can the students access the tool outside of class time? E.g., use at home or at designated areas in school, etc.

Another relevant criterion which is not included in the list is the effectiveness of tools for improving conceptual understanding. This aspect is difficult to assess directly as learning efficiency is a complex issue which depends on multiple factors including implementation in a course as well as student engagement with the tool. In addition, it is important to highlight that simple adoption of a tool which has previously been observed to support student conceptual understanding may not necessarily achieve the same results as observed by the one providing the example. Some insights concerning this issue are provided in the second part of the project; see Section 4.

An overview of the results of the assessment of the examples in relation to the previous categories is provided in the charts in Figure 4. We observed that most tools are either created by the teacher themselves or readily available. The latter included everyday objects such as a ruler as well as objects which could be readily purchased. In addition, the cost of creating or procuring these tools was in most cases negligible or low (and rarely high). Furthermore, there was very often either relatively little to moderate specialized knowledge, skills or equipment required for a teacher to adopt the tool in teaching. Moderate cases included tools that require the teacher to have some skills in programming or basic carpentry to build their own models. Tools that were more difficult to adopt included those that relied on laboratory testing which require specialist equipment. Thus, overall, many of the tools could be readily procured or created by other teachers in the same discipline.

Concerning the relevance of the tool in teaching specific or multiple courses, most tools were either generally applicable (i.e., useful in multiple types of structural engineering courses) or more specific to a concept. Scale physical models, for instance, were often intended to support the understanding of a specific phenomenon, e.g., lateral torsional buckling of a beam. Generally applicable tools, on the other hand, were often designated so due to the description being quite general (e.g., using illustrations or sketches) or because it related to a more general topic such as the behavior of a structure in resisting an arbitrary load. In practice, a teacher may choose to adopt the tools specific to their course or adopt a tool which could be used across multiple courses; both types are relevant.

The ease of use of a tool in teaching was judged to be *easy* or *moderate* in most cases, with very few exceptions. An example of a tool which was deemed difficult to use was the welding of steel connections (which required a certified technician to carry out or supervise, unless the teachers themselves have this certification). The time required in class also varied although most required very little time. In these cases, the tool could be used as part of a traditional lecture, exercise or seminar without the need to allot much extra time. On the other hand, short student activities or even full one-to-two-hour seminars, which in some way integrate the tool, may be preferred to engage students actively in learning. Tools with high time requirements were related to project work, student competitions, theme-days, etc. The context within which the tool is used is very important and would certainly influence student learning, likely in proportion to the time and effort spent. However, this would need to be studied further.

Both student interaction and student access varied, and, in some cases, it was unclear how each tool scored in relation to these criteria. In cases where it was not clearly stated by the teacher who provided the example, we assessed whether it was possible for students to interact with a specific tool or to have access to it outside of class time. There are certainly advantages to allowing students to interact with a tool and use it outside of class. However, this may not be feasible in some cases. The tools which were both accessible outside class and involved interaction were often digital tools (which could be accessed through a website for instance). Scale physical models could include student interaction, but this may require the procurement or creation of multiple exemplars as well as a physical location (possibly with controlled access) where the students could access the tool outside class. Again, the choice of how to address this is a preference of the teacher; although there may be implications to student learning depending on the choices made.

Overall, this analysis highlights the potential for many of the tools to be readily transferred to other teachers to support conceptual understanding. This transfer would, however, require the teacher to decide how they want to implement the tool in their own teaching practice. It is beyond the scope of this report to go through the varying implications of adopting certain tools in specific contexts in terms of student learning. There are, however, multiple published articles specifically concerning the use of physical models in education and their implication for learning; the interested reader is referred to Schaff & Klosky (2005), Molyneaux et al. (2007), Welch & Klosky (2007), Behnejad (2016), Vontrissi et al. (2018), Ji et al. (2020), and Justo et al. (2023).

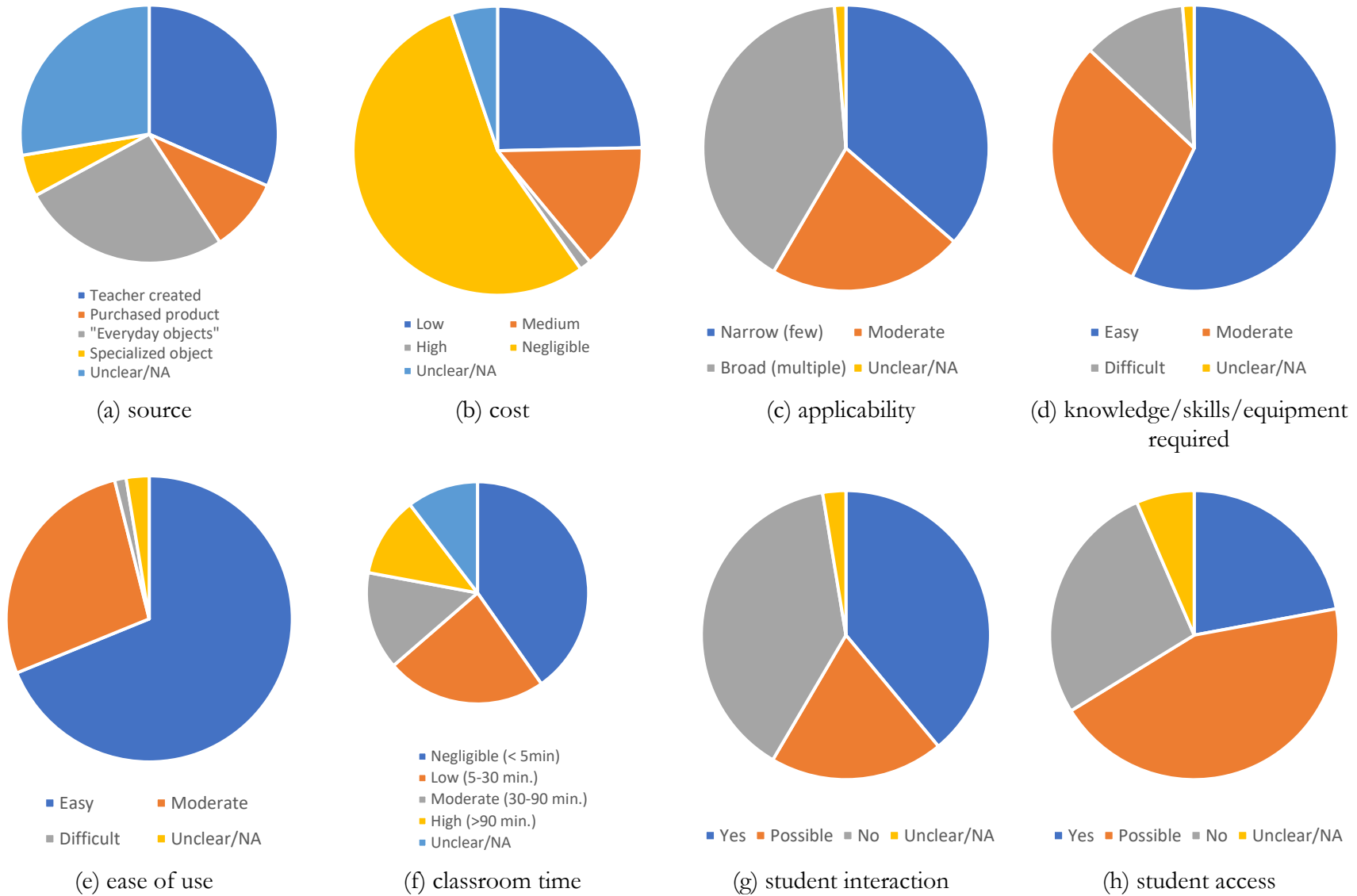


Figure 4. An overview of results in terms of how the collected examples are designated within each transferability-related criterion. (a)-(h) refer to the criteria present earlier on in this chapter

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4 Developed examples

4.1 Selection process

The analysis presented in the previous chapter revealed that many of the collected examples were some kind of physical model. This is one reason for focusing on this type of tool in the second phase of the project. Physical models are, and have been, very prominent in both structural engineering education and practice, as highlighted by Addis et al. (2020, p. 829):

Reduced-scale and full-size physical models continue to have an important role in structural design alongside the common use of computers... [these models] are also helpful in developing the understanding of structures in students of both engineering and architecture.

Sources highlighting the prominence of hands-on physical models include:

- Published books with pedagogic examples and books on the history of using physical models (see, e.g., Hilson 1993, Ji et al. 2016, and Addis et al. 2020).
- Published articles documenting, discussing and/or evaluating the use of physical models in teaching (e.g., Schmucker 1998, Schaaf & Klosky 2005, Unterweger H 2005, Welch & Klosky 2007, Vontrissi 2015, Behnejad 2016, Ji & Bell 2018, Vontrissi et al. 2018, Ji et al. 2021, Justo et al. 2022, Dart & Lim 2023)

There are also numerous websites which are either exclusively dedicated to the use of physical models or where these are mentioned frequently. Some examples include:

- <https://www.handsonmechanics.org>
- <https://www.sites.se.manchester.ac.uk/structural-concepts/>
- <https://casce.princeton.edu/teaching-resources/active-learning>
- <https://www.istructe.org/resources/case-study/education-building-with-chocrete/>

An internal discussion within the project group identified two specific types of physical models that were given further attention in the second phase of the project:

- Physical objects to illustrate behavior of beams, used to support conceptual understanding of varying beam theory related phenomena.
- Scale physical models of building frames used to support conceptual understanding of global stability of building structures.

The former was chosen as it concerns readily available and quite common tools according to the examples collected. The second type of model was chosen as it had been developed further as part of an interactive teaching and learning activity with results indicating improved conceptual understanding of what is often observed (based on the collective experiences of the project group) as a difficult structural concept. Both were assessed to have great potential for transferability between teachers in the discipline.

It should be mentioned that although digital tools were not chosen for further consideration in this project, there is certainly potential for developing teaching and learning material for these types of tools in the future. In fact, Justo et al. (2020), found that both physical models, as well as

virtual versions of these, can effectively promote students' conceptual understanding although the former further improved student motivation.

4.2 Physical objects to illustrate beam behavior

The use of physical objects as pedagogic tools in teaching the behaviour and analysis of beams appears to be very widespread and several examples are shown in Appendices B and C. These objects are typically composed of 'everyday' materials. For instance, a ruler can be used to illustrate of the influence of the cross-sectional shape on the of bending stiffness (second moment of area) of a beam and for illustrating instability phenomenon such as column buckling or lateral torsional buckling. Everyday objects can offer a valuable pedagogic pathway for illustrating basic structural mechanical behaviours by allowing the students to observe these directly, although usually at a reduced scale. This provides a concrete reference point for the mathematical models describing these behaviours analytically as well as assumptions of the underlying theory (e.g., classical Bernoulli beam theory).

4.2.1 Beam bending

While certain objects may be quite suitable for supporting conceptual understanding of a specific structural engineering concept, there may be limitations that need to be considered. The previous example of a ruler, for instance, is very convenient object for demonstrating the concept of instability. However, it may not be as suitable for the concept of bending stiffness. In this section, we will briefly mention two cases of physical tools for beam bending – the first concerns the concept of beam bending stiffness and the second relates the global bending behavior and sectional forces in beams.

For the first case³, we start by returning to the example of a ruler. A typical ruler usually has a (roughly) rectangular cross section, where the difference in bending stiffness between its two principal directions is relatively large. When loaded in bending, the ruler is perceived as flexible when loaded in the weak direction but may be perceived as (almost or fully) rigid when loaded in the strong direction. Thus, other cross-sectional shapes, with a smaller difference in stiffness between the two directions, might be more appropriate to illustrate the effect these differences have in terms of bending behavior.

To compensate for this, a wooden stick of one meter length with a cross section of 5 x 15 mm can be used, i.e., where the ratio between the cross-sectional dimensions is 3:1, see Figure 5. Such an element can quite easily be bent by hand in both the weak (M_y) and the strong direction (M_z), and the difference in behavior between these two cases is observably different. A cross-sectional aspect ratio of 3:1 yields a bending stiffness (second moment of area) ratio of 9:1, which is quite significant.

Having multiple of these types of elements can provide additional support to the understanding of beam bending, including the concept of more efficient beam cross-sections. In this example, three sets of three sticks are required. To start, the three sticks are laid on top of one another without bonding them together. Bending these results in three independent beam sections where the bending stiffness increase compared to one stick is a factor of 3. However, if the sticks are bonded together into a rectangular section, then it works like a solid section, and the bending stiffness increase is a factor of $3^3 = 27$ (compared to a single stick). The difference in response

³ This case is based on multiple collected examples and the specific example is taken from the Division of Structural Mechanics at the Faculty of Engineering at Lund University.

can be seen in Figure C.7. An even higher increase in bending stiffness can be determined by rearranging and bonding the sticks into an I-shape. This yields a stiffness increase by a factor of 107 (compared to a single stick).

Utilizing the previous tools can support in class discussions about shear stiffness, shear stresses, and the basic assumptions in beam bending theories about plane sections which remain plane (and orthogonal to the beam axis) during deformation. In addition, changing the shape of the cross section can also highlight the importance of cross-sectional shape and design as well as material and structural efficiency.

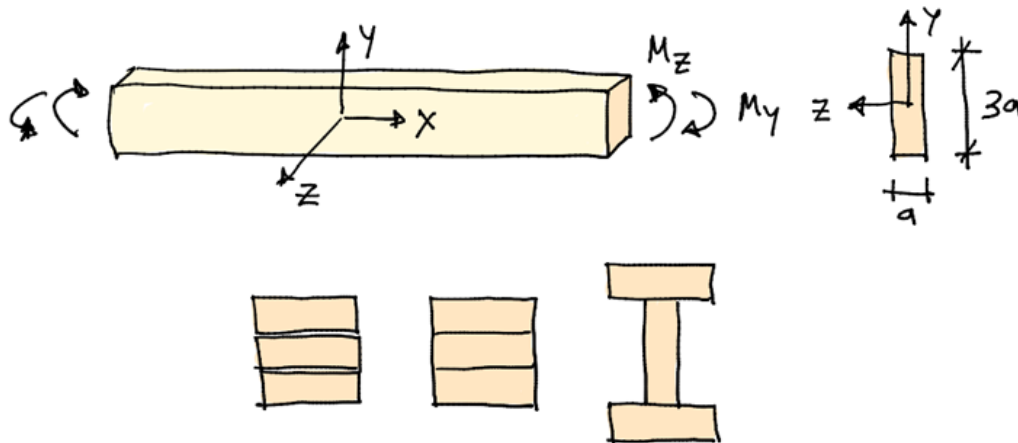


Figure 5. Beams with different cross sections shapes to illustrate bending stiffness.

The second case⁴ of using “everyday objects” to support the conceptual understanding of beam extends the previous by considering the global behavior of beams in bending. Beam bending is in this case illustrated with the support of a readily available plastic wiring duct (or channel) in combination with 3D-printed supports, see Figure 6. The material for the beam can be purchased at most hardware stores and retailers. The remaining parts can be printed with simple 3D printers (the drawing can be made available to anyone who wants to use them by contacting the main author of this report). The following 3D parts have been developed thus far:

- beam supports with free or restrained horizontal deformation as well as the possibility to lock rotation; and
- a holder for positioning various weights on the beam.

One simple way to use this type of tool would be to have a beam section with two or more supports (possibly of different types) and demonstrate the behavior of the beam for different load placements. Observing the variations in deformation of the beam the concept of beam stiffness including the influence of support conditions. If the load is placed eccentrically, then torsional effects could also be included.

⁴ The specific example is taken from Martin Nilsson, Mats Petersson, Erik Andersson and colleagues from the Division of Structural and Fire Engineering at Luleå University of Technology.

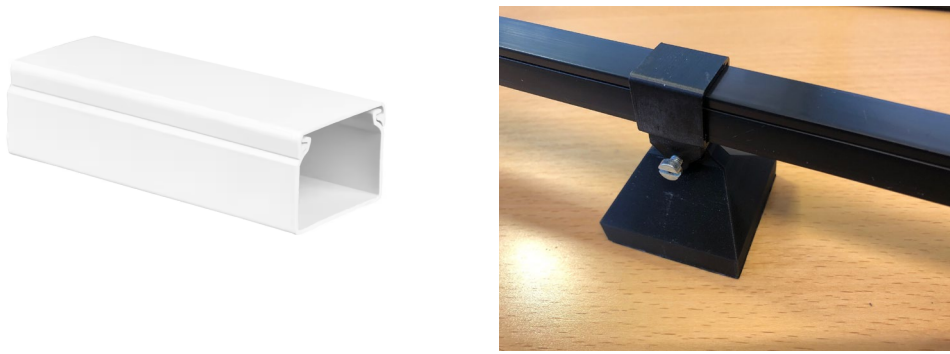


Figure 6. (left) section of a plastic wiring duct and (right) a 3D-printed support

A specific exercise that could be done with these types of beams is shown in Figure 7. Three beams of three different lengths are used, as well as four supports. For the first, longer beam, a point load can be applied in the middle of the beam which has two supports at either end. For the remaining two shorter beams, only one support is used. The students then need to bend the ends of these beams by hand to achieve the same deformation and curvature as the first beam. This will give them a ‘feel’ of the beam section forces (moment and bending) in their hand at that specific point. This is as the beam will naturally want to return to its original form and this resistance is felt by the student’s hand. This process mimics, physically, the process of slicing a beam at a given section to calculate the internal forces. It is thus quite useful in courses basic structural engineering or mechanics concerning the determination of beam section forces.

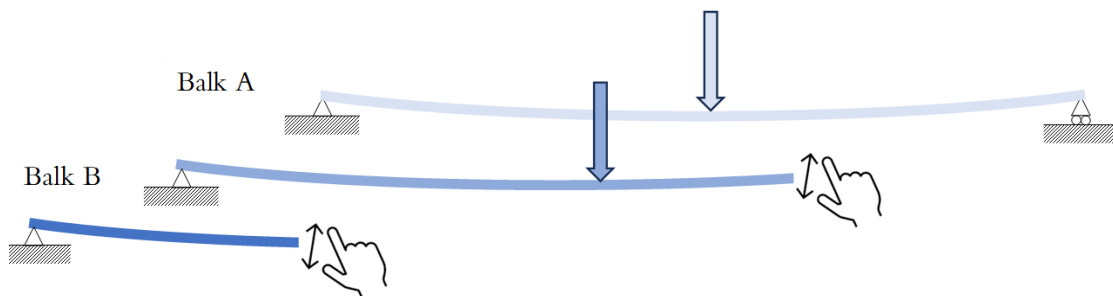


Figure 7. Getting a ‘feel’ for section forces for a beam in bending

4.2.2 Beam torsion

Students often find torsional behavior of beams to be more abstract than bending and there are several examples in Appendices B and C of this report of physical objects used as pedagogic tools to support understanding of torsional concepts. There are thus multiple torsional concepts that could be supported using models. In this section, we will focus on the concept of torsional stiffness and shear center.

The difference in torsional stiffness and torsional warping for **open** thin-walled cross-sections and **closed** thin-walled cross sections can easily be experienced by twisting a paper towel roll (kitchen roll) with and without a slit cut along its length. Foam pipe insulation, as shown in Figure C.4, is another suitable object for such simple but illustrative experiments. These

examples illustrate the high torsional stiffness of closed thin-walled sections, consistent with the theoretical prediction that shear flow develops around the entire perimeter of the section. The tube with a longitudinal slit highlights the role of warping, the very small torsional stiffness associated with thin-walled open sections, and by extension, why open sections are structurally inefficient in torsion-dominated applications.

What appears to be a specifically challenging concept for students regarding torsion is the *shear center* and its relation to the beam response when a load is applied eccentrically over a section. The shear center is the specific point in a beam's cross-section where an applied transverse load produces pure bending without any accompanying torsion. It is mathematically defined as the point at which the lines of action of the resultant forces from the internal shear stresses caused by shear forces V_y and V_z meet (for transverse loading without torsion). Both the general (physical) description and the mathematical definition are complex and require a solid understanding of several other concepts relating to beam theory.

A simple yet very illustrative physical model⁵ can be created which allows students (and teachers) to experience the response of transverse loading of a beam at different positions relative to the shear center. The physical model, shown in Figure 8, is composed of a cardboard tube (e.g., from a discarded paper towel roll) cut into the shape of an open thin-walled cross-section. One end of the tube is glued to a timber board which can be held against a flat surface to give a moment resisting support and cantilever beam situation. A thin plate is attached to the other end of the beam and can be used to apply transverse loading by the push of a finger.

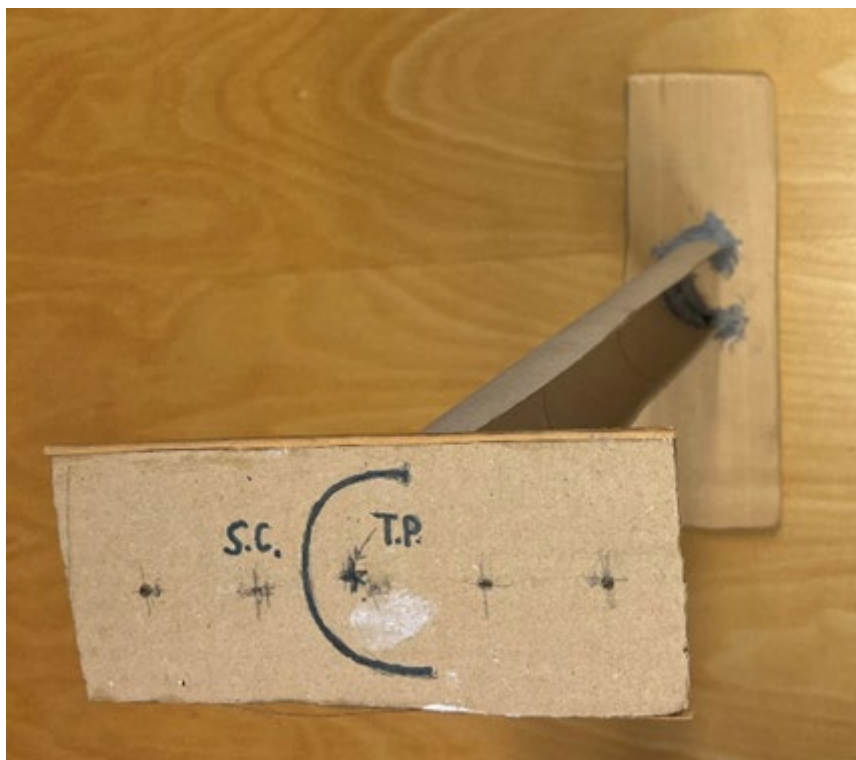


Figure 8. Physical model used to illustrate torsion in beams and the location of the shear center for a thin-walled open section.

The (approximate) positions of center of gravity (CG) and the shear center (SC) of the asymmetric cross-section are marked on the thin plate attached to the free end. Applying

⁵ This specific example was first developed by Prof. Per Johan Gustafsson at the Division of Structural Mechanics at the Faculty of Engineering at Lund University.

transverse loading through the center of gravity results in a clockwise torsional deformation of the beam, as schematically illustrated in Figure 9. Moving the point of load application further to the right gives greater torsion (for the same amount of transverse loading). To find a state of deformation without any torsion, the load location must be such that its line of action passes through the shear center.

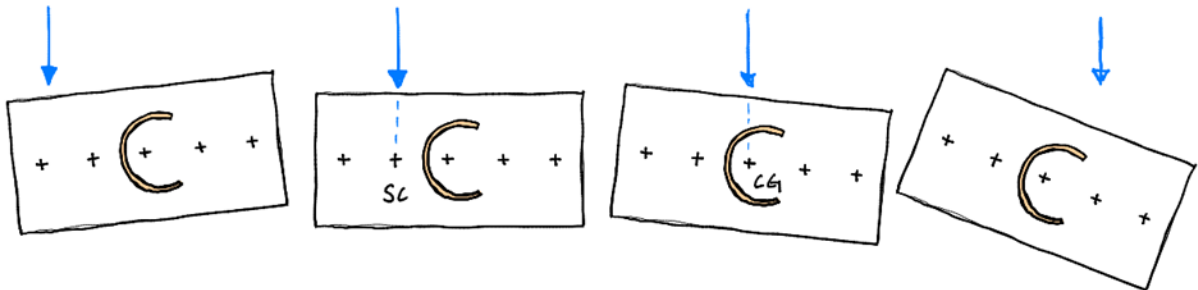


Figure 9. Illustration of torsional deformation for different points of loading with respect to the shear center.

When the students try this model and experience the response at different load positions, the response is often perceived as unintuitive. It seems to add to the general understanding of the position of the shear center for a thin-walled open cross sections and its importance in relation torsion. This experience can reinforce the understanding of the theoretical definition as the point through which transverse loads must pass to avoid torsional effects. This hands-on activity further helps students understand why the shear center of an asymmetric open section does not coincide with its centroid and why this distinction is crucial in structural design.

4.3 Scale models of building frames

Building structures are all around us and something everyone can relate to in some way. For a building to stand up, it must resist the loads to which it is subject. A useful way to think about this is to consider how the forces *flow* through the structure. In the case of horizontal loading, such as wind and earthquake loading, the building structure acts as a system, relying on some form of lateral bracing system. This concept of global stabilization of building structures is a concept in which students are commonly observed to have difficulties in grasping; especially during the first couple of years of a civil engineering program. This observation is based on the project group's collective experiences with courses in basic structural mechanics and structural engineering for second year civil engineering students (with evidence from previously unpublished student surveys). To support conceptual understanding of this concept, some teachers at SBU have adopted scale physical models of building structures to illustrate the need for global stability to horizontal loading, as well as the behavior of typical types of stabilizing systems. Two specific models were mentioned in the collected examples, shown in see Figure 5:

- Home-made building frames using Meccano® frame elements, and
- A commercially available structural kit called Mola® (specifically Structural Kit 2)

In the sections that follow, a description of these types of models is provided as well as their possible implementation in teaching and learning.

4.3.1 Model description

Small scale models of building frames are useful to realistically simulate the behavior of a building structure. The models can be custom built for a specific purpose, although there are

commercially available structural kits which could be used. The models shown in Figure 5 are examples based on teaching experiences of a few of the teachers in the project group⁶. In procuring or creating these types of models, the following structural concepts can be kept in mind:

- Structural mechanism – an unstable building frame which collapses when loaded
- Stabilizing system – bracing with struts, moment-stiff connections, shear walls, etc.

The first concept can be useful as it illustrates what can happen if the stabilizing system is lacking or inadequate. The latter then provides possible solutions to the problem introduced by the first concept. It may also be useful to construct models which illustrate these concepts individually and even distinguish between behavior in two- and three-dimensions. For instance, the custom models in Figure 5 include 2D frame elements as well as 3D structures. It should be mentioned that having a model which illustrates a structural mechanism may be difficult due to it being unstable.

Another important aspect to consider is whether the models are intended to be used interactively by the students. In that case, the models will need to be sufficiently robust or easy to repair. To allow for multiple groups and simultaneous use, multiple models may be needed.

⁶ These specific examples shown are from the Division of Structural Engineering at the Faculty of Engineering at Lund University.

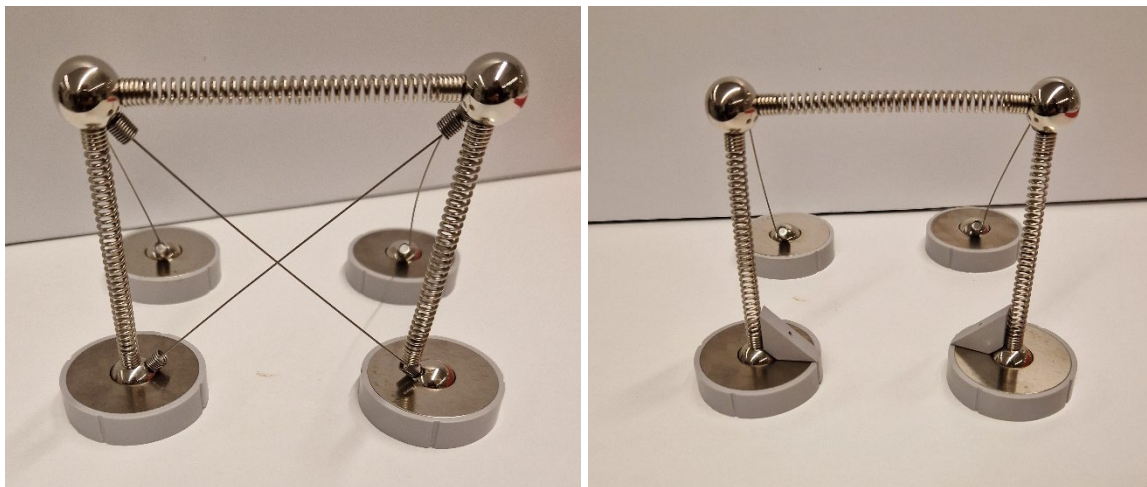
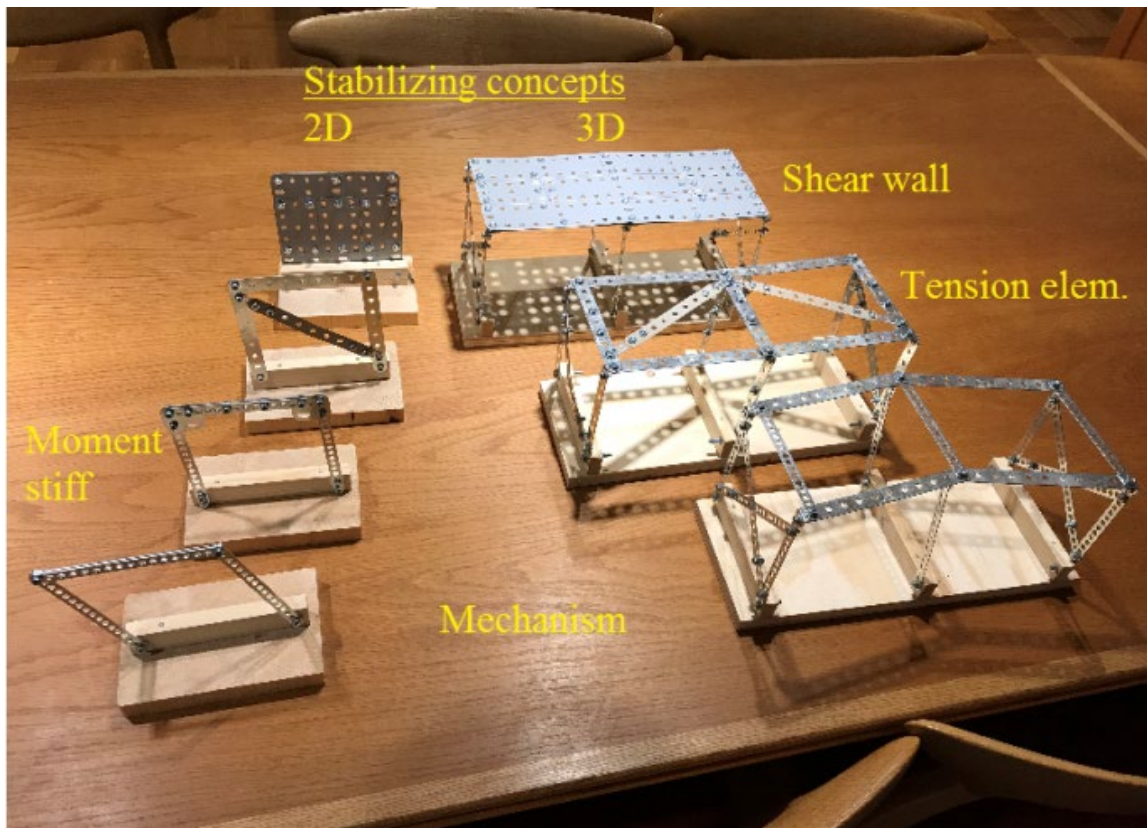


Figure 10. Scale physical models of building frames to support learning related to concepts of global stabilization of building structures – (top) custom built using toy frame elements and (bottom) commercially built

4.3.2 Application in teaching

The models could be incorporated into a course in several different ways, here we will discuss a few of them. One of the simplest uses is to show the students the model during a lecture on the topic and in this way complement the theory being presented with a physical demonstration. Depending on the size of the models, it may be valuable to think about if the students are able to see what is being shown. One approach which has been used previously by teachers is to use a so-called document camera or web-camera to project what is being demonstrated to a bigger screen. The models could also be distributed to the class, but then it is important to consider that this may take the students' attention away from other parts of the lecture.

The previous approach can be improved by integrating some active elements into the lecture to engage students more. For instance, a *think-pair-share* activity could be included where students reflect on the answer to a given question, discuss with a partner and then share with the rest of the class. The question could then relate to what the model shows, or will show; here are some examples:

- Show an unstable model and, before loading it, ask if they think the model is stable.
- After demonstrating the unstable model, ask what could be done to improve this.
- After demonstrating a stabilizing concept with a model, ask how the flow of forces is in the structures.
- After showing the students some stabilizing concepts in two-dimensions, ask how this could be transferred to three dimensions.

Of course, other types of activities such as group discussions and case studies could also be utilized. Furthermore, the models could also be used in other course activities such as exercise classes, workshops or seminars. Having the students themselves interact with the models may be advantageous as it allows them to investigate and identify solutions on their own. This was done in a basic course at Chalmers University of Technology, where the students, in groups, had approximately 45 minutes to build and test building frames using a structural kit. This type of activity has been observed to actively engage students, igniting their interest for the subject and allowing them to be creative; see an example from 2023 in Figure 11.

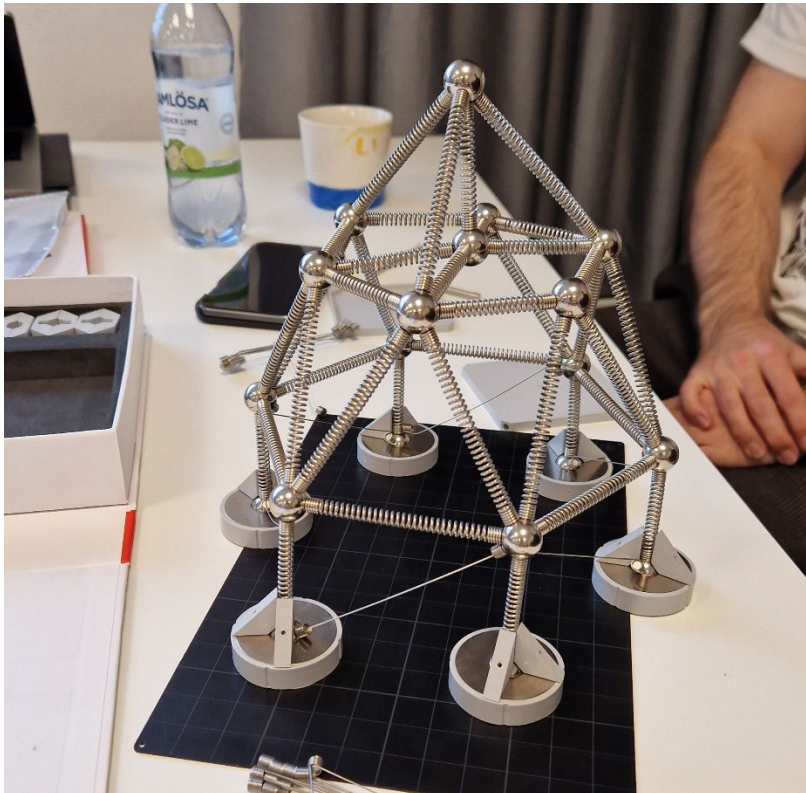


Figure 11. An example of a student-built building frame model from Chalmers in 2023

At the Division of Structural Engineering, Faculty of Engineering, Lund University, custom built scale models were previously used during lectures to second year civil engineering students to physically demonstrate concepts relating to global stability of buildings. However, since 2024, these models have been integrated into a two-hour seminar which include student activity and

multiple tasks incorporating the models as a teaching aid. The active seminar relies on an inductive approach to learning which means that the students observe some physical behaviour and are asked to think about the implications before being given the theoretical solution. A four-stage model for this seminar was developed⁷:

- **P – Problem:** A non-functional scale model is first used to demonstrate the problem
- **A – Activity:** Students are asked to actively reflect on the problem and find a solution
- **S – Solution:** A demonstration of one or several functional scale models is used (often with reference to students’ own solutions)
- **T – Theory:** The theory is introduced with reference back to the previous activities and models

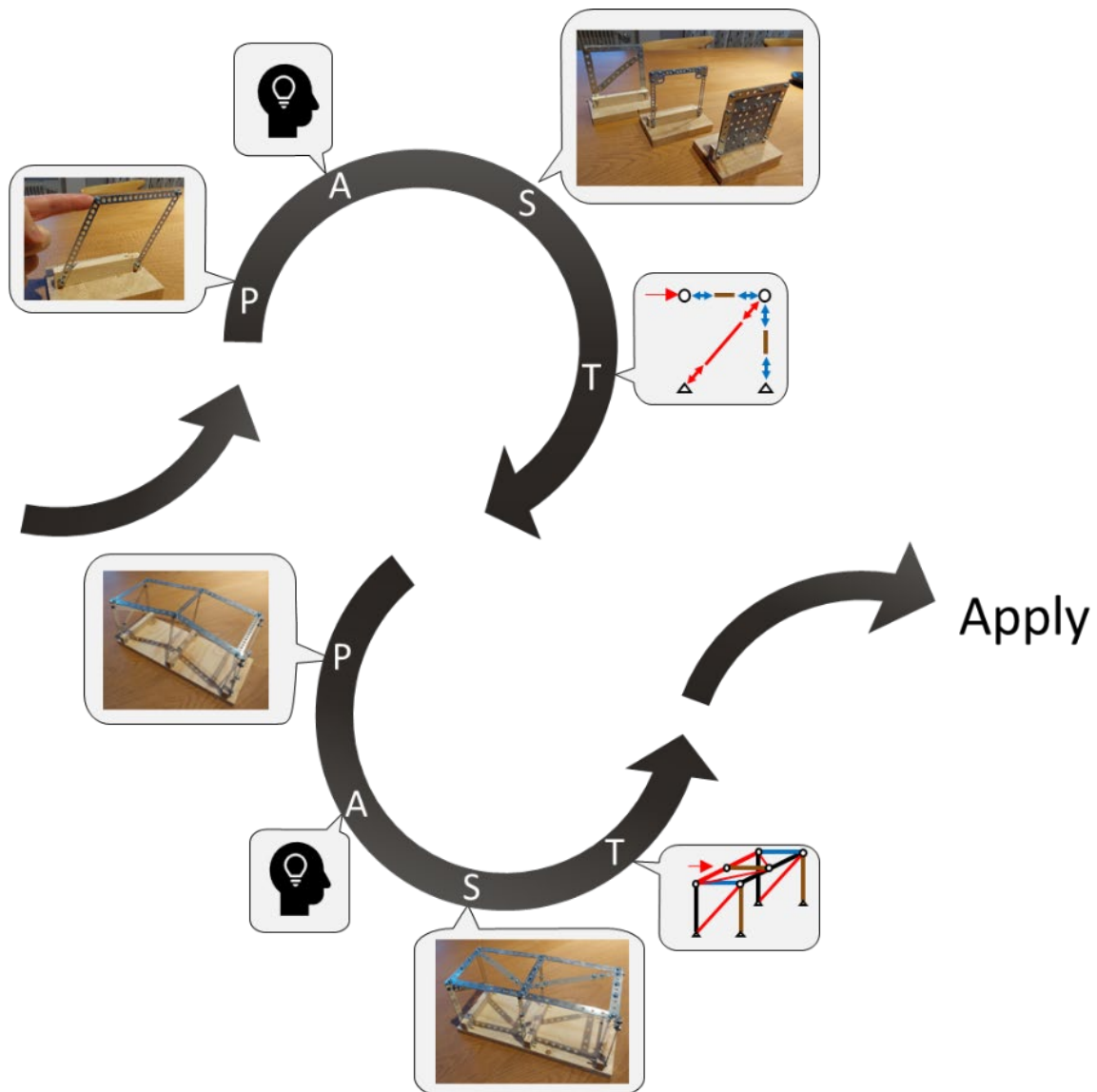


Figure 12. Cyclic process of inductive learning using scale physical models; P - problem (exemplified with model), A - activity (student reflection on problem and feedback), S - solution (demonstrated with model), T - theory (presented with models and in presentation)

⁷ Method developed by Ivar Björnsson & Jonas Niklewski in 2022 during a pedagogic course on active learning

For example, two-dimensional bracing is first introduced by demonstrating an unstable frame with insufficient bracing (P). Students are then given a few minutes to reflect on and discuss how the problem can be solved (A). Next, a solution is given by the teacher in a second demonstration (S). In a final step, the example is generalized and linked to theory through a short presentation (T). The same process is then repeated for the three-dimensional case. It is thus a cyclic process as shown in Figure 12.

Both previous applications of using scale building models to teach global stability of buildings are promising as they utilize active learning approaches, which are known to engage students and improve learning (Freeman et al. 2013), as well as experiential learning theory. The original definition of the latter was given by David Kolb (1984) as

the process whereby knowledge is created through the transformation of experience. Knowledge results from the combination of grasping and transforming experience.

In the case of Lund University, two identical concept-inventory quizzes were used to test students' understanding of stabilizing concepts. The first quiz was given directly after a lecture on the topic, in which no scale models were used, while the second came two weeks later, directly after a seminar which included the use of scale models according to the procedure in Figure 12. In total, 54 students answered the post-lecture quiz, and 51 students answered the post-seminar quiz; everyone who attended the seminar had also attended the lecture. Overall, the student performance on the second quiz was improved, compared to the first quiz. Figure 13 shows the results for a specific question concerning the need for stabilizing buildings which gauges the students' conceptual understanding for the topic in single-story framed structures. This was precisely the topic that the models were aimed at helping students to understand, and the results clearly showed an increase in conceptual understanding after the seminar. The post-seminar results for this question were on average 0.81 out of 1.0 while the post-lecture results were only 0.43 out of 1.0.

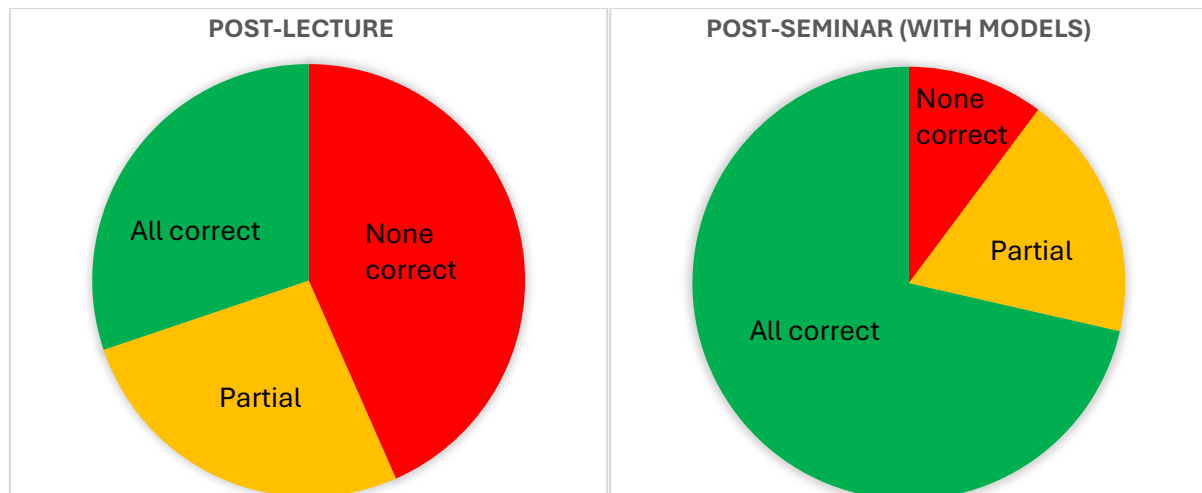


Figure 13. Results to a quiz question concerning how to stabilize single story buildings to wind loading – the question was “where do we need bracing?” and it showed a building structure with wind coming from one direction. The students could select four options (two of which were correct). The graph shows the proportion of students who answered the question completely correct (green), partially correct (orange) or completely incorrect (red).

The previous experiment has been carried out additional times with similar results, although the influence of other factors, such as spacing between the lecture and seminar as well as concurrent project assignments, have also been observed. Thus, the learning potential for using this type of

tool in this teaching situation should be done also by considering the entirety of the course design, including scheduling and assessment tasks.

5 Discussion and conclusions

In this report, we summarize the findings of a project funded by the Swedish Universities of the Built Environment. During 2023, examples of pedagogic tools for supporting understanding of structural engineering concepts were collected from teachers at the Faculty of Engineering at Lund University, Chalmers University of Technology, KTH Royal Institute of Technology, and Luleå University of Technology. The results indicate that pedagogic tools, such as scale physical models or digital applications, are often used to support conceptual understanding. Focus is commonly on structural engineering phenomenon such as the behaviour structures or structural elements to loads. An assessment of the collected tools reveals that many of the tools are readily available and do not require a high amount of effort to use in teaching and learning practice. However, the manner with which the tools can be applied can vary and their effectiveness in supporting the goal of improved conceptual understanding was outside the scope of this project.

To provide some insight into how specific tools can be used, two types of tools were further described. The first concerned the use of ‘everyday’ objects for supporting conceptual understanding of beam theories. Bending stiffness and torsion of beams can be physically demonstrated, observed and experienced by students to provide a compliment to lectures on theory. This can provide a connection between an abstract theoretical concept and something that can be seen, felt and interacted with. A second example concerned small scale models of building frames to support conceptual understanding of global stability of buildings. In this case, a more detailed description of how such models can be incorporated into teaching and learning activities was provided along with the results of a concept quiz investigating the impacts on student learning. The results are positive and indicate an increased understanding for the concept being taught. However, these results should not be seen as an isolated characteristic of the tool but needs to be taken in the context of how this tool was implemented. In this specific case, active learning methods (which are commonly known to improve student learning) were employed in conjunction with using the tool. On the other hand, the activities described were built around the active use of the scale models which could not have easily been achieved without their incorporation.

The results in this report are not surprising given the long history of using models in structural engineering teaching and practice. However, over time the use of these types of models in teaching practice has reduced and appears to be dependent on the interests of the respective teachers. In our investigation, we focused on teachers that actively do this type of teaching while input from others was not included. However, these approaches are considered to have a great potential in an age where digital software, and now generative AI, have become ubiquitous. Even before gen-AI, advanced computational modelling was possible using commercially available software and the ease of use of these tools means that they can be used nearly irrespective of the level of knowledge of the user for how structures behave. In practice, this means that we need to place emphasis on teaching our students how to evaluate the input and output provided to and from these models (much like we want our students to be critical of output from generative AI). Pedagogic tools for supporting understanding of structural engineering phenomenon could be one way to help do this. However, it is important that the incorporation of such tools is done in a reflective manner. Think about how it fits in with the rest of the course, how to engage

students and support them in adopting a deep approach to learning. Hopefully the examples and experience provided can be a springboard for this, and we encourage teachers reading this to share their own experiences with their peers and think of ways how we can support our students in gaining a better conceptual understanding of structural concepts in the courses you teach.

6 References

- Addis B, Kurrer KE & Lorenz W (2020). *Physical Models: Their historical and current use in civil and building engineering design*. John Wiley & Sons.
- Behnejad SA (2016). Benefits of full-scale physical models in civil engineering education. *In 2016 ASEE Annual Conference & Exposition*.
- Björnsson I, Crocetti R, Fröderberg M, & Klasson A (2016). Is advanced modelling always synonymous with increased accuracy? *Structural*, 208 (nov/dec), 1-18.
- Björnsson I (2022) *Opportunities and challenges of digitalization and automation in bridge design: A pre-study*. TVBK-3078, Division of Structural Engineering, Faculty of Engineering, Lund University, Lund.
- Borthwick A, Carpenter J, Clarke B, Falconer R & Wicks J (2013). The importance of understanding computer analyses in civil engineering. *Proceedings of the Institution of Civil Engineers*, 166(CE3): 137-143.
- Dart S & Lim JB (2023). Three-Dimensional printed models for teaching and learning structural engineering concepts: Building intuition by physically connecting theory to real life. *Journal of Civil Engineering Education*, 149(2), 05022004.
- Ferguson ES (1978) The mind's eye: Nonverbal thought in technology. *Leonardo*, 11(2), 131-139.
- Franz J, Ferreira L & Thambiratam DP (1997). Using phenomenography to understand student learning in civil engineering. *International Journal of Engineering Education*, 13(1), 21-29.
- Freeman S, et al. (2013) Active learning increases student performance in science, engineering, and mathematics. *PNAS*, 111(23), 8410-8415
- Hilson B (1993). *Basic structural behaviour: understanding structures from models*. Thomas Telford.
- Ji T, Bell AJ & Ellis BR (2016). *Understanding and using structural concepts*, 2nd ed. CRC Press. (NOTE: first edition is sometime cited which has title *Seeing and Touching Structural Concepts*).
- Ji T & Bell A (2018). Can intuitive interpretation be taught in structural engineering education? *In IV Int. Conference on Structural Engineering Education Structural Engineering Education Without Borders 2018*, June 20-22, Madrid.
- Ji T, Bell A, & Wu Y (2021). The philosophical basis of seeing and touching structural concepts. *European Journal of Engineering Education*, 46(6), 889-907.
- Justo E, Delgado A, Llorente-Cejudo C, Aguilar R & Cabero-Almenara J (2022). The effectiveness of physical and virtual manipulatives on learning and motivation in structural engineering. *Journal of Engineering Education*, 111(4), 813-851.
- Kilpatrick J, Swafford J & Findell B (Eds.). (2001). *Adding + it up: Helping children learn mathematics*. National Academy Press, Washington, DC.

- Klasson A, Björnsson I, Crocetti R & Hansson EF (2018) Slender Roof Structures-Failure Reviews and a Qualitative Survey of Experienced Structural Engineers. *Structures*, 15, 174-183.
- Kolb DA (1984). *Experiential learning: Experience as the source of learning and development*. Prentice Hall, Englewoods Cliffs, NJ.
- MacLeod IA (2016). Time to reflect: a strategy for reducing risk in structural design. *The Structural Engineer*, 94(3): 14-18.
- May IM & Johnson D (2009). *The teaching of structural analysis – a report to the Over Arup Foundations*. <https://www.ovearupfoundation.org/public/data/chalk/file/6/0/Teach-Structural-Analysis.pdf>
- Mills S (2016). Conceptual understanding: a concept analysis. *The Qualitative Report*, 21(3), 546-557.
- Molyneaux T, Setunge S, Gravina R & Xie M (2007). An evaluation of the learning of structural engineering concepts during the first two years of a project-based engineering degree. *European Journal of Engineering Education*, 32(1), 1-8.
- Rittle-Johnson B & Star JR (2007). Does comparing solution methods facilitate conceptual and procedural knowledge? An experimental study on learning to solve equations. *Journal of Educational Psychology*, 99(3), 561–574.
- Rittle-Johnson B, Siegler RS & Alibali MW (2001). Developing conceptual understanding and procedural skills in Mathematic: an iterative process. *Journal of Educational Psychology*, 93(2), 346-362.
- Schaaf RV & Klosky JL (2005). Classroom Demonstrations in Introductory Mechanics. *Journal of Professional Issues in Engineering Education and Practice*, 131(2), 83-89.
- Schmucker DG (1998). Models, Models, Models: The Use Of Physical Models To Enhance The Structural Engineering Experience. *In 1998 Annual Conference* (pp. 3-413).
- Vrontissi M (2015). The physical model in structural studies within architecture education: paradigms of an analytic rationale? *In Proceedings of IASS annual symposia* (Vol. 2015, No. 19, pp. 1-12). International Association for Shell and Spatial Structures (IASS).
- Vrontissi M, Castellón González JJ, D'acunto P, Enrique Monzó L & Schwartz J (2018). Constructing structural concepts by means of physical models. *In Proceedings of IASS Annual Symposia* (Vol. 2018, No. 2, pp. 1-4). International Association for Shell and Spatial Structures (IASS).
- Welch RW & Klosky JL (2007). An online database and user community for physical models in the engineering classroom. *Advances in Engineering Education*, 1(1), 1-25.
- Unterweger H (2005). Simple structural models for the education of structural engineers at Graz University. *Journal of professional issues in engineering education and practice*, 131(4), 227-230.

Appendix A: E-mail to colleagues

English version

Dear colleagues,

We have initiated a project funded by SBU (Sveriges Bygguniversitet) concerning the use of pedagogic tools or aid for supporting students' conceptual understanding in structural engineering. This could be something physical or digital (such as a scale model or app – use links below for specific examples) which is used with the intent of helping students understand a concept (e.g., flow of forces, failure mode, design concept, etc).

During the initial phase of this project, we would like to find persons who are interested in providing their experiences with using pedagogic tools in teaching courses in structural engineering (structural mechanics, structural design, steel structures, etc.). For those who are interested, please provide brief answers to the following:

- In your opinion, how important is conceptual understanding for student learning?
- Which pedagogic tools have you used in your teaching (a bullet point list)?
- For each tool, how does this help students with conceptual understanding (e.g., which concepts)?

Finally, please indicate if you would be willing to be part of the second phase of this project (e.g., for providing more detailed information about selected tools and/or as participants in an interview).

Please provide us with this information latest by **29/9**.

Some examples of pedagogic tools online:

<https://www.istructe.org/resources/case-study/education-building-with-chocrete/>

<https://www.handsonmechanics.org>

<http://epsassets.manchester.ac.uk/structural-concepts/>

<https://casce.princeton.edu/teaching-resources/active-learning>

Hej,

Vi har påbörjat ett projekt finansierat av SBU (Sveriges Bygguniversitet) som handlar om användning av pedagogiska verktyg eller hjälpmedel för att öka studenternas konceptuella förståelse för konstruktionsteknik. Detta skulle kunna vara något fysiskt eller digitalt (som en fysisk modell eller app – använd länkar längre ner för att hitta exempel) som används i syfte att hjälpa elever att förstå ett koncept (till exempel kraftflöde, brottmod, osv).

Under den inledande fasen projektet letar vi efter personer som är intresserade av att bidra med sina egna erfarenheter av pedagogiska verktyg i undervisningen av konstruktionsteknik (konstruktionsmekanik, byggnadsdesign, stålkonstruktioner, mm.). För den som är intresserad så skulle vi vilja ha korta svar på följande:

- I din mening, hur viktigt är konceptuell förståelse för studentens lärande?
- Vilka pedagogiska verktyg har du använt i den egna undervisningen (punktlista)?
- För varje listat verktyg, beskriv kortfattat vad du avser att lära studenterna, till exempel vilket koncept?

Slutligen, vänligen ange om du är villig att vara med under den andra fasen av detta projekt, där vi kommer att välja ut ett antal exempel för mer detaljerad beskrivning (till exempel genom intervju).

Vänligen ge oss denna information senast **29/9**.

Länkar med exempel på pedagogiska verktyg:

<https://www.istructe.org/resources/case-study/education-building-with-concrete/>

<https://www.handsonmechanics.org>

<http://epsassets.manchester.ac.uk/structural-concepts/>

<https://casce.princeton.edu/teaching-resources/active-learning>

Appendix B: All collected examples

Table B.1: All collected examples as originally provided (observe that many are in Swedish).

Videos, increases the understanding of a physical phenomena (for instance progressive collapse, failure mechanisms, etc.)
Photos, increases the understanding of structures, structural elements, details etc. that they later on do design of
Minor tasks during lectures that students can discuss with each other, often the students learn by discussion with each other, and afterwards the correct answer is discussed with the whole class
Quizzes, which students respond to, and after the students have answered the quiz, the answers are discussed for the whole class to increase the understanding of calculations methods and physical phenomena etc.
Plastic straws taped together, to demonstrate the behaviour of wood
A number of examples with photos of real structures, and questions like: what load will be acting load, sketch a structural model, which components are in tension/compression etc. These are used in workshop activities where the students discuss in groups, often with a quiz at the end
A cyber-physical model of a bridge that we use in the course "Konstruktionsteknik". The tool is used in combination with a Quiz, helping students to visualize and understand the right answers in real-time.
Taking a small piece of strands used in prestressed concrete shows the difference between normal reinforcement and this type of reinforcement. They also get an idea about the effective area, which is not the circular cross-section area.
Taking a mold/form of a beam to show how stirrups and reinforcement are placed. They get the idea of concrete cover, which is hard to control.
What I experienced during my undergraduate study was a competition at our university for building bridges with Spaghetti. Not only building Spaghetti bridges, I think students may build other elements with a wooden stick or simple things, which gives some idea to check the stability and other things to improve the load-bearing capacity.
Use of sketches to identify relevant design checks for steel structures (used also during oral exam in which students must do this task)
Photos of physical models can also be used (e.g. styrofoam beams in bending or torsion)
Use of Illustration/sketches of structural behaviour describing structural concepts (stability, etc).
Stadsvandringar, där man går in i byggnader där man kan läsa av byggnadsteknik, lastvägar, osv. Jag hade detta inlag i kursen i konstruktion för brandingenjörer
Vi skulle även kunna ordna permanenta och tillfälliga utställningar med koppling till byggnadsmaterial/konstruktion – efter förebild från arkitektutbildningarna
Temadagar där deltagarna känner på olika material och byggnadstekniker. Jag har till exempel ordnat så kallade murningsdagar. Industrin hjälpte då till med både material och hantverkare
Duplo-beam with tape to illustrate for student how reinforcement (tape) works in concrete beam (duplo pieces) – students observe how tape helps. Students can also interact with model
Meccano models of frames in 2D and 3D to illustrate global stability for buildings – students observe how unstable model (mechanism) can be stabilized (struts, shear wall, moment stiff connections). Students can also interact with model.
A Matlab application demonstrating how concrete column design affects stability (second order effects, etc) – students can see results in real time when parameters change (reinforcement, etc).
Videos of tested beams or similar, sometimes edited (with animations etc) and/or with a load-displacement diagram. This can help the students visualize failure modes, understand the connection between physical and theoretical phenomena, and can be re-watched for clarification.
Using everyday objects to illustrate structural phenomenon. E.g. using paper clips to illustrate fatigue (students count no. of bends till failure), using foam beams to illustrate bending or torsion (as well as warping), using chains with weights to illustrate cable action. The aim is to provide the students with a hands-on experience which, together with their pre-knowledge of the objects, helps them better understand a certain phenomenon (e.g. structural behaviour, practical considerations, uncertainties)
Examples of objects and artifacts used in engineering practice (e.g., beams sections, reinforcement in concrete, formwork, etc.) to get a feel for the material and object (density, scale, etc).
Using purchased physical teaching aids such as the Mola structural kit. This can physically demonstrate how forces are resisted using different types of structural systems such as trusses or cable supported structures

<p>There are some books (and methods) which specifically support learning structural engineering concepts more conceptually. Books aimed at architects for instance. The book 'Understanding structural analysis' by David Brohn is a good example. Some methods which can be useful for conceptual (qualitative understanding) may be the Müller -Breslau method for influence lines.</p>
<p>Use of alternative teaching methods such as flipped classroom (online videos with interactive on-campus seminars) to improve student engagement which supports better learning. Focus in seminars is on difficult (or threshold) concepts and we highlight our aim of the students understanding what these (e.g. students answer questions through online polling tools and we note if there is a need to clarify further).</p>
<p>I have developed some web apps to help students understand basic concepts, like beam bending and moment diagrams. There is no examination or test attached to them. I simply tell my students that they can use them to check their hand-calculations (during exercises and assignments) or just play around and explore. The idea is that they should be able to use them over several courses, to revisit basic concepts when needed.</p>
<p>For physical models I often bring something simple to class. For example, when talking about brittle vs ductile failure I just bend a wooden stick and a (thin) steel section until they snap (or at least one of them). When showing shrinkage of concrete beams I bring three thin sections of a glulam beam. One of them has a thin steel strip attached to it to illustrate reinforcement. The unreinforced ones are first placed in water, one soaked and one floating, to show that only uneven shrinkage (or in this case swelling) lead to curvature. The one with reinforcement is then soaked to show the curvature caused by the reinforcement. The purpose of these "in-class labs" is twofold: to visualize a concept and to activate the students.</p>
<p>I have also used digital models for other purposes. In a course in building systems, I used a model to help the students understand drawings (see fig). In my lectures on bracing, I use a lot of animations from FE-simulations.</p>
<p>The use of physical models to illustrate structural phenomena (Mola Models were mentioned)</p>
<p>A careful choice of relevant literature can be done which present the material in such a way as to support conceptual understanding. Books on structural engineering for architects may, e.g., provide some good examples and figures.</p>
<p>Design task to conceptualize the introduction of models, simplifications and estimation of loading</p>
<p>Illustration during lectures using, e.g., "foam-beams" to illustrate Saint Venant torsion, Bernoulli kinematics, etc., "paper sheets" to illustrate torsional stiffness of open/closed thin walled cross-sections, etc</p>
<p>Tensile test experiments to conceptualize elasticity and yield metallic materials, and model calibration</p>
<p>Software to illustrate load-paths in structures (Point sketch, Comsol)</p>
<p>Step-by-step project from calculations, casting of beams, and testing to failure. Performed in groups of 6 students. Failure modes from calculations are compared with the failure in the lab.</p>
<p>Student competition for predicting shear failure. Comparison with pre-recorded lab test.</p>
<p>Using video clips during lectures to visualize phenomena as shear, buckling etcetera.</p>
<p>Using detailed realistic sketches of structures and structural components.</p>
<p>Bringing material samples to lectures when possible, e.g., wood pieces to explain the influence of fibres, growth rings, and knots.</p>
<p>Using animations, typically created with a FE software, to illustrate local buckling, member buckling, plasticity etcetera.</p>
<p>Showing photos of real structures with components or solutions to explain.</p>
<p>Showing small models or real "elements", i.e. things you can touch and maybe deform/see reaction to e.g. loading.</p>
<p>Loads in arch/line structure: demonstrate/let students try to hold a line (hold 2 ends with both hands) loaded with certain load. If you move hands in horizontal direction, you feel that "loading" changes. You can also use small spring scales to measure this. What to show: geometry will influence loading in line/arch. Also, weights can be attached at several places to show the catenary line for a certain load case (show e.g. chain - i.e. uniform load, or lines with 1/2/3 etc point loads)</p>
<p>Loads in beam and support reactions depending on position of load: small beam placed on 2 scales, move load on beam and observe change in support reaction (scale) --> easier to understand M-/V-diagrams and support reactions later</p>
<p>Foam beam to show stress and strain in beams in bending</p>
<p>Still looking for a good example to visualize shear stresses in a beam with a physical model (maybe several beams bolted with weak bolts/with rubber straps, or rubbery glue)</p>
<p>Shear stresses in beam: use program force pad to show main stress directions. for beam on 2 supports you can e.g. see arch (compression) and line (tension) in the massive beam --> depending on directions, this is bending stresses and shear stresses.</p>
<p>Lego beam with tape to show reinforcement in concrete beam</p>
<p>Small meccano-models or MOLA-models to show stability and stabilization of buildings (frame, diagonalization and shear walls possible). Let students build their own models (trial and error)</p>

Buckling of columns - using ruler to show effect of support conditions on buckling length. but are planning for better examples (better support conditions)
Lab demos or lab tests made by students - see difference between design and reality, understand failure modes etc.
Lateral torsional buckling - using photos of ruler (cantilever beam) that is loaded on top/in shear center/lower edge - effect of loading position on lateral torsional buckling
Fatigue - let students try with a paper clip (gem) bend back and forth - can make some statistics.
Letting students build models of timber bridges to understand their behaviour, test to failure! (architecture students)
"Library" of timber based material examples, to show e.g. the composition (glued parallel or perpendicular). Showing material samples in "right size" is important for students to understand the difference between e.g. glulam and LVL or plywood and CLT.
Timber joints (loaded in shear) - opened up (split) after the testing - to show different failure modes
Simple lego beams to show effect of reinforcement. The students understand that the reinforcement can take a lot of the force in a beam and that it is necessary for a material that does not have any tensile strength
Very simple models in thick paper to show how plates behave. Only to show deformation of plates with different supports
Columns: I often use some simple elements in different materials and of different dimensions to show the behaviour, it can be things that are in the room already or elements that I bring. Here the students can understand both buckling of thin elements and buckling of the whole column, the effect of different type of cross sections, and the effect of boundary conditions
Tested simple beams of timber, steel and reinforced concrete to show the behaviour, primarily in bending but for concrete beams also shear cracking. The students see how different materials behave, the effect of plasticity, the fracture behaviour for different materials and beam types.
CALFEM for MATLAB: Fundamental understanding of the finite element method as well as a toolbox for understanding structural concepts. Toolbox for experimenting with mechanical models.
CALFEM for Python: Fundamental understanding of the finite element method as well as a toolbox for understanding structural concepts. Toolbox for experimenting with mechanical models. Used in conjunction with Jupyter Notebooks it can let students try different scenarios in a teaching setting.
ForcePAD: Basic understanding of flow of forces, optimisation, form finding
CALFEM for MATLAB: Grundläggande förståelse för finita elementmetoden
CALFEM for Python: Grundläggande förståelse för finita elementmetoden
Brobyggande (Bärverksanalys) Olika funktionssätt för bärverk (tryck/drag, böjning), knäckning/instabilitet
Laborationer: Böjning, vridning, knäckning
Enkla "miniatyrbalkar": Tröghetsmoment för olika tvärsnitt med samma area, Vridning och placering av SC, välvning för I-balkar
Letting the students build physical models (models should be to scale, i.e. members' dimensions are correct) Physical models train ability to understand spaces and dimensions and can also reveal unexpected behaviour (stability)
MOLA (structural kits) MOLA Trains understanding of force transfer and stability
Software (ForcePAD etc): Software train the understanding of structural principles (force transfer, mechanisms)
Simple objects that illustrate different phenomena in the classroom: Lego technics: illustrate difference between triangle and rectangle with hinges; Rubber beam with lines that illustrate strain distribution at bending; Ruler or slender wood bar, illustrate buckling; Ruler or slender rectangular wood bar, illustrate different bending stiffness in principal directions, a way to "feel" the difference in moment of inertia and have a hands-on interpretation of this; Classroom ruler: illustrate lateral-torsional buckling at bending in stiff direction compared to bending in weak direction; Classroom pointer: illustrate natural frequency, vary length (stiffness) and mass by applying e.g. orange by tape to illustrate influence of mass and stiffness; Duplo beam reinforced with tape to illustrate composite action of reinforcement and concrete; Carton models of shear wall buildings with two parallel walls, two perpendicular walls and three walls to illustrate mode of action in horizontal stabilisation;
Welding of steel to understand how joints are built
Casting and testing of concrete beams and slabs to understand materials, production, cracking and load-carrying capacity
Building of bridge from timber parts. Competition - which group build the strongest bridge in relation to its weight?
Foam model of beams with varying cross-sections to demonstrate Bernoulli's hypothesis
Model to demonstrate shear and torsion center on cross-section

Appendix C: Images of selected examples

Physical models and teaching aids

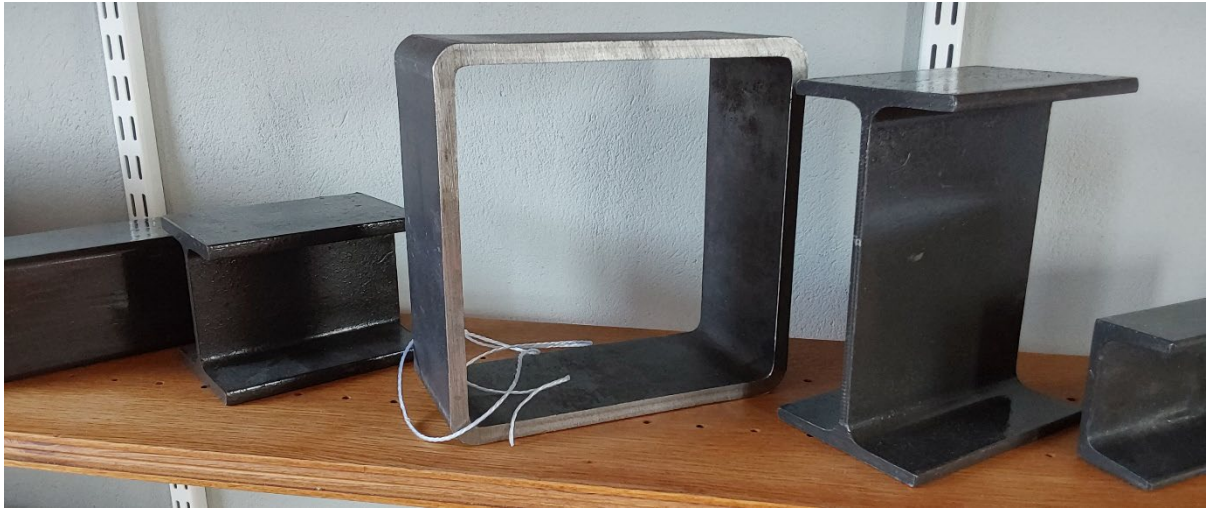


Figure C.1. Steel beam sections (demonstration model)



Figure C.2. Concrete reinforcement and formwork (cut for demonstration purposes)



Figure C.3. A hanging cable showing funicular form for varying load placements (using Mola® kit)



Figure C.4. Foam pipe insulation (top) without and (bottom) with slit to demonstrate warping of open cross sections

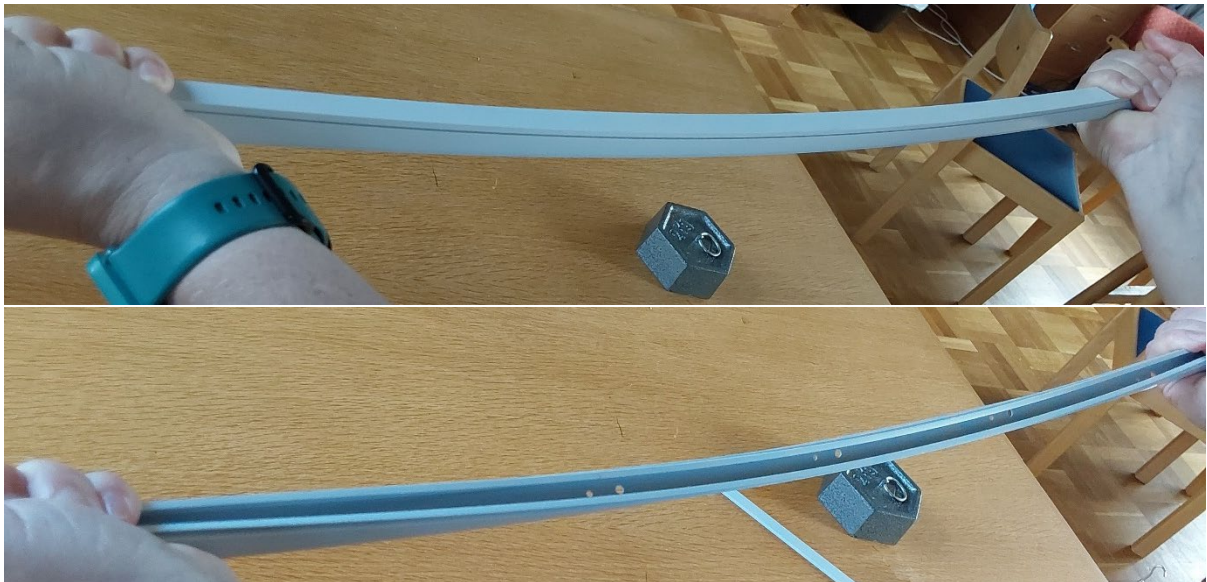


Figure C.5. Bending of cable tray (top) with and (bottom) without cover to illustrate lateral torsional buckling of beams as well as effect of bracing

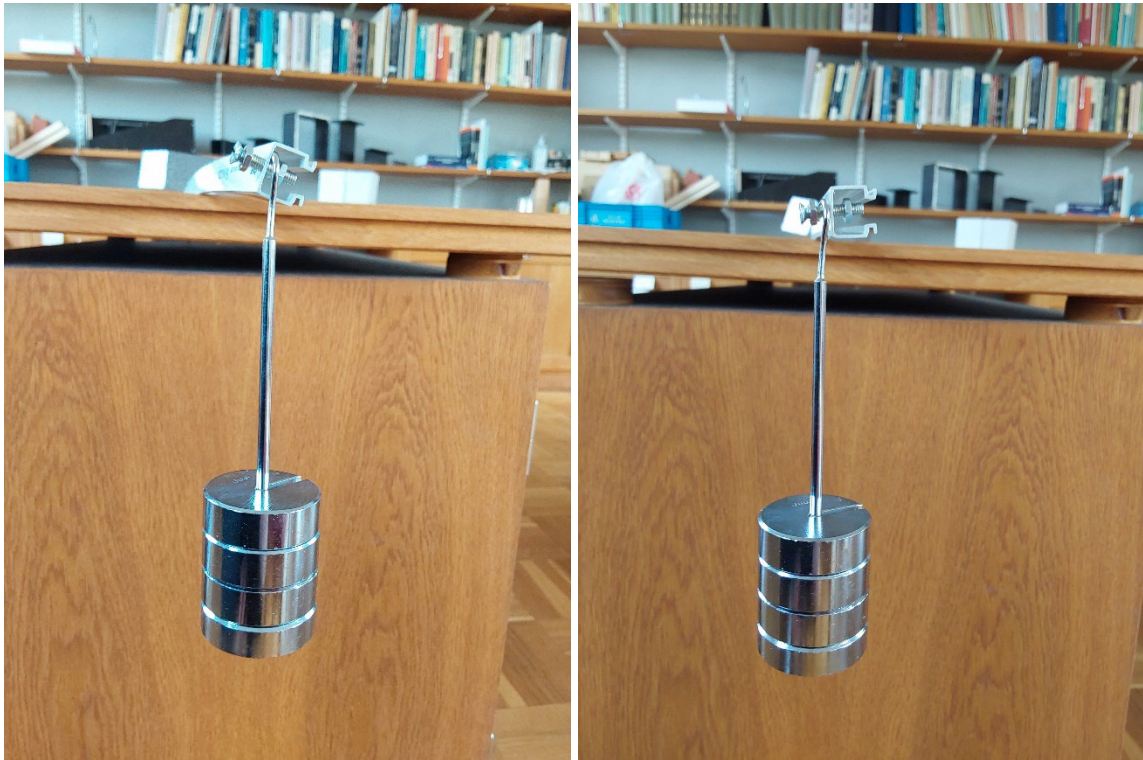


Figure C.6. Cable tray bending with loading point at different locations in sections to illustrate shear center concept

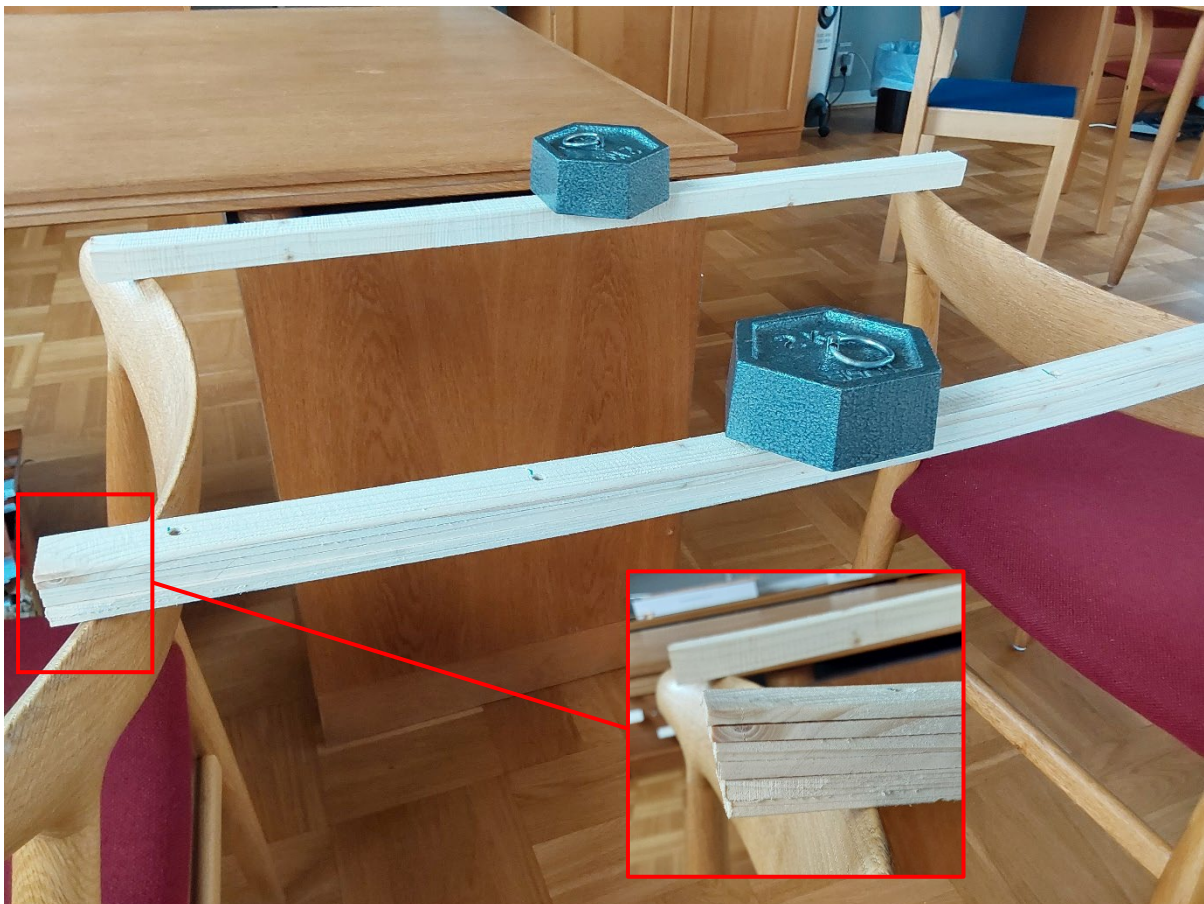


Figure C.7. Timber beams with same cross section but closer beam is composed of laminates not glued to each other. This test illustrates the contribution of shear in the stiffness of the section and helps illustrate horizontal shear flow in a beam.

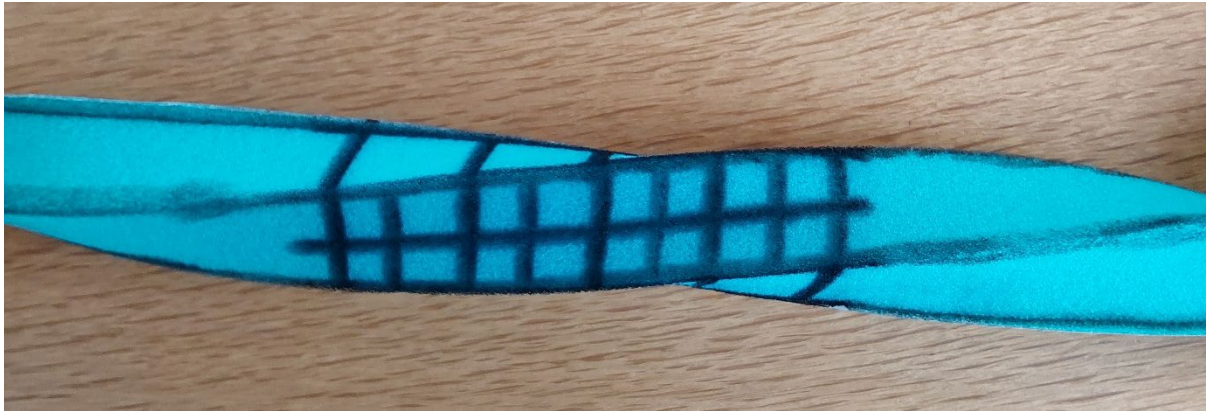


Figure C.8. Uniform torsion of a foam beam. Loading can also be adjusted to illustrate internal torsional moment distribution (e.g., by twisting beam closer to one of the other support).



Figure C.9. A cross section of a burned timber beam showing the residual cross section which can still carry load.

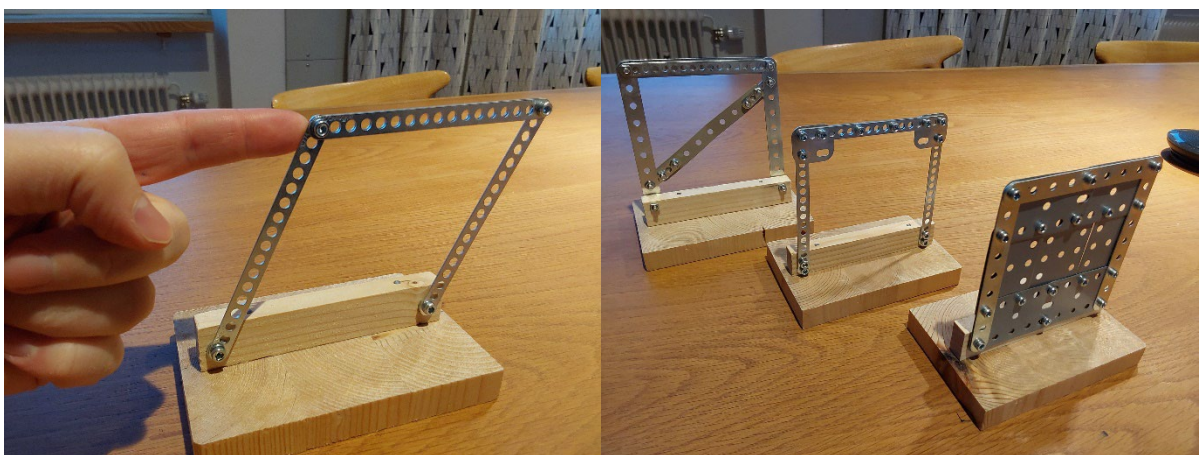


Figure C.10. Custom built building frames (using wood and Meccano® elements) to illustrate the need for stabilizing as well as stabilizing concepts



Figure C.11. Students using structural kit to construct building frame (Mola® kit)



Figure C.12. Bending of a thin timber beam element with variable position of supports and loads. The scale also provide the reaction forces.

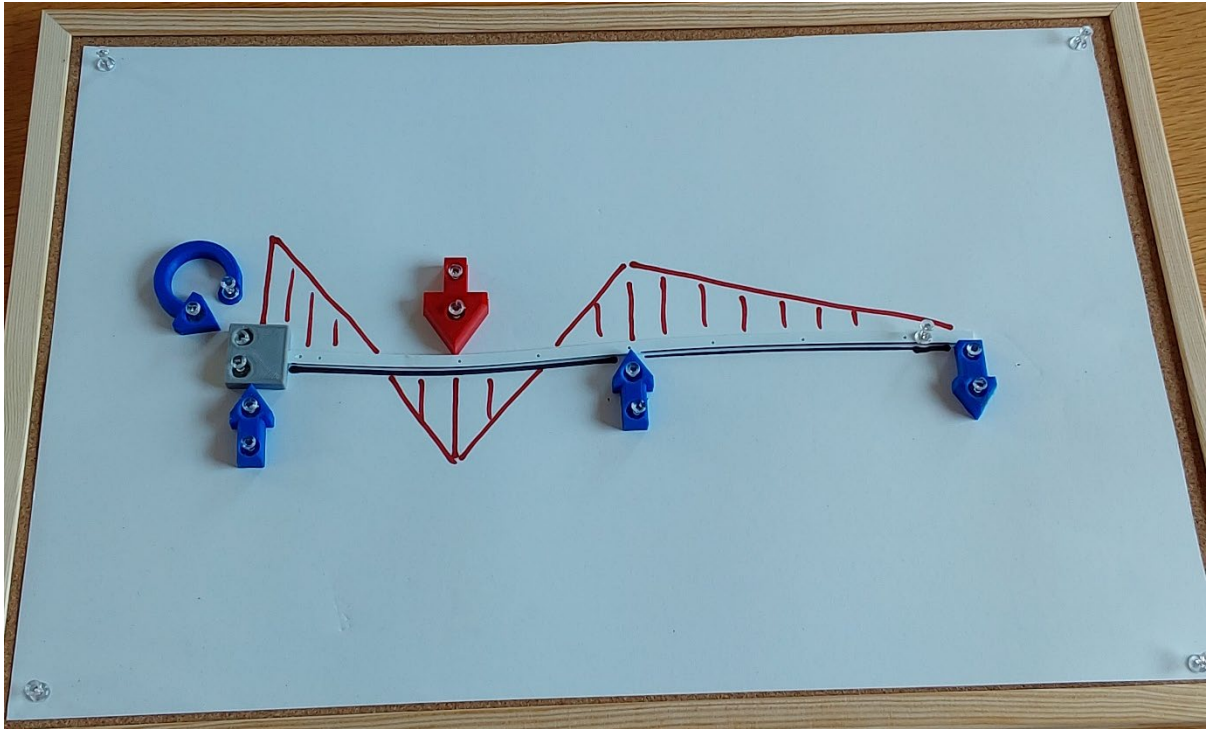


Figure C.13. A commercially available structural model kit to illustrate beam bending and understand internal force distributions (<https://davidbrohm.com/product/structural-model-kit/>)

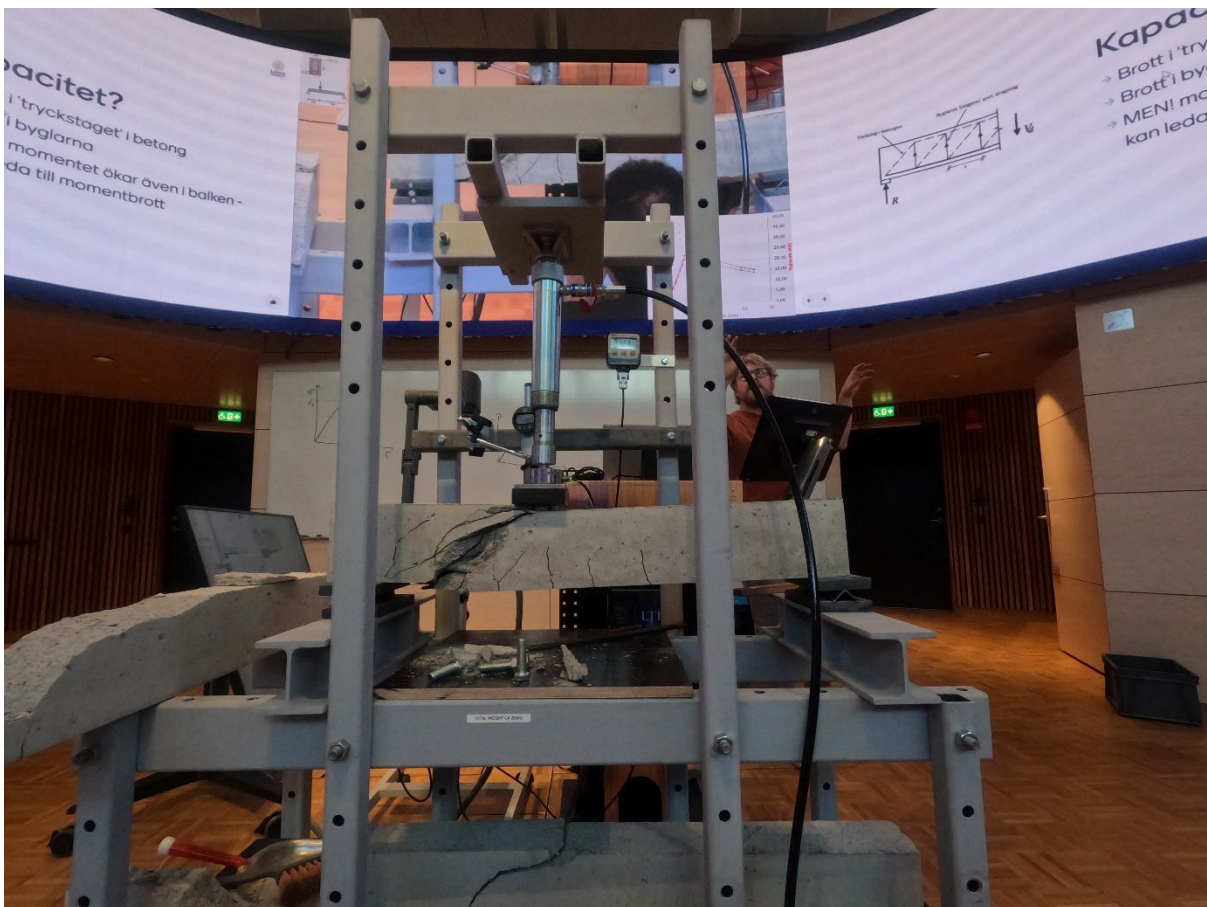


Figure C.14. A mobile mini material testing rig used in class to test a small concrete beam (in this case in shear). Previously tested beams also seen on figure.

Digital models and teaching aids

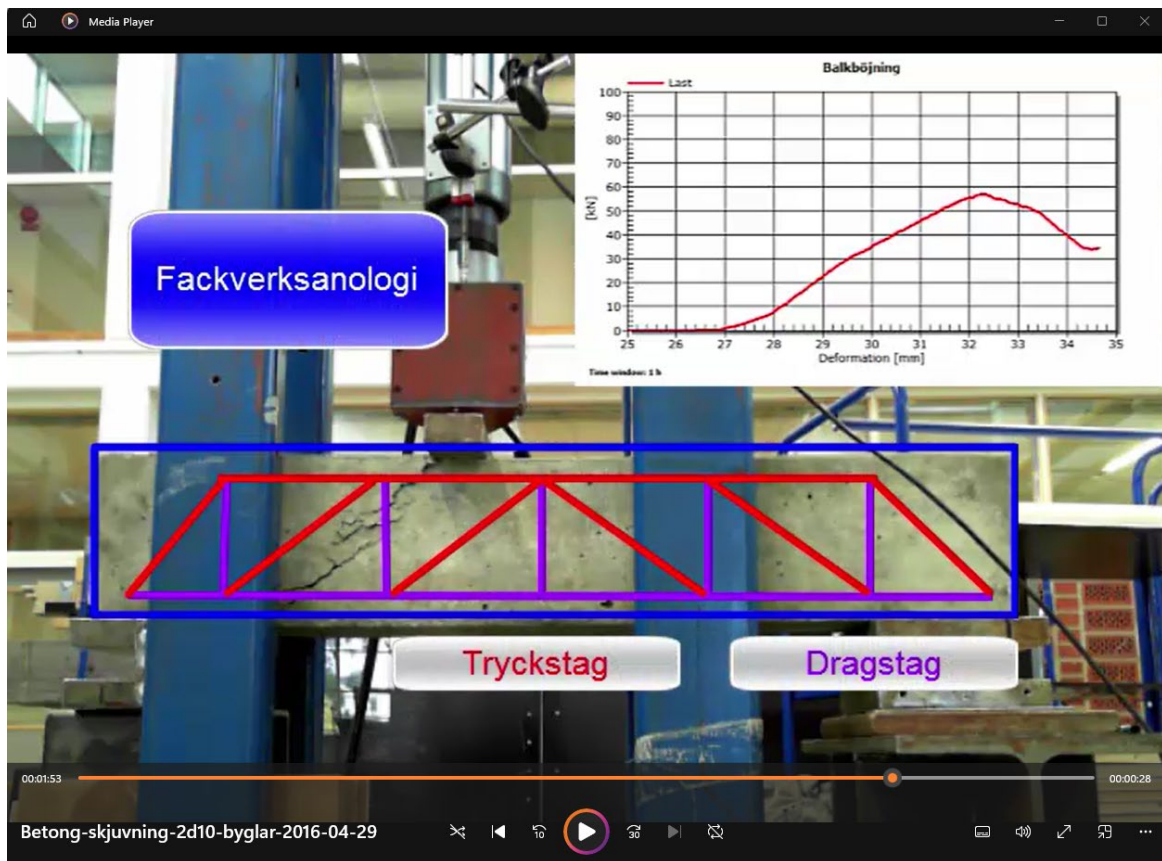


Figure C.15. Screenshot from video of concrete beam with stirrups tested in shear (including animations to illustrate force transfer)

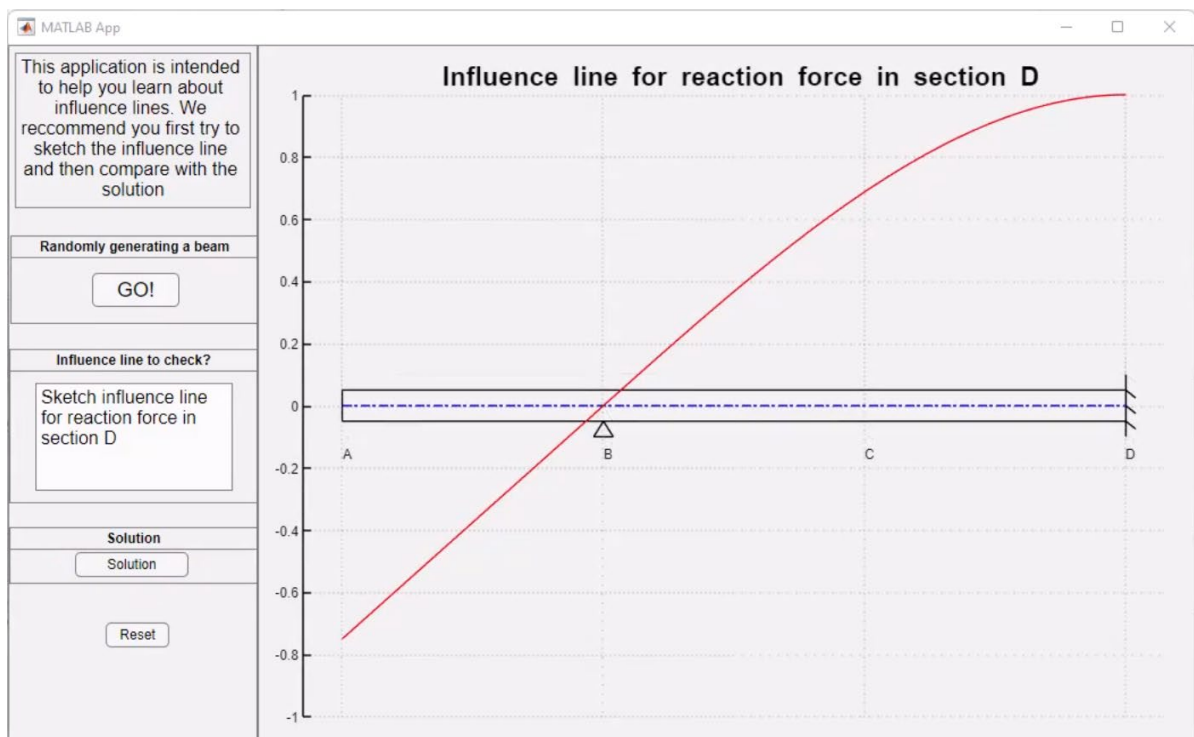


Figure C.16. Screenshot from a MATLAB® application available to students for sketching influence lines (for beams)

Section Geometry

-	h	200	mm	+	-	t _w	5	mm	+
-	b _{r1}	100	mm	+	-	t _{r1}	5	mm	+
-	b _{r2}	100	mm	+	-	t _{r2}	5	mm	+
-	f _{yd}	355	MPa	+					

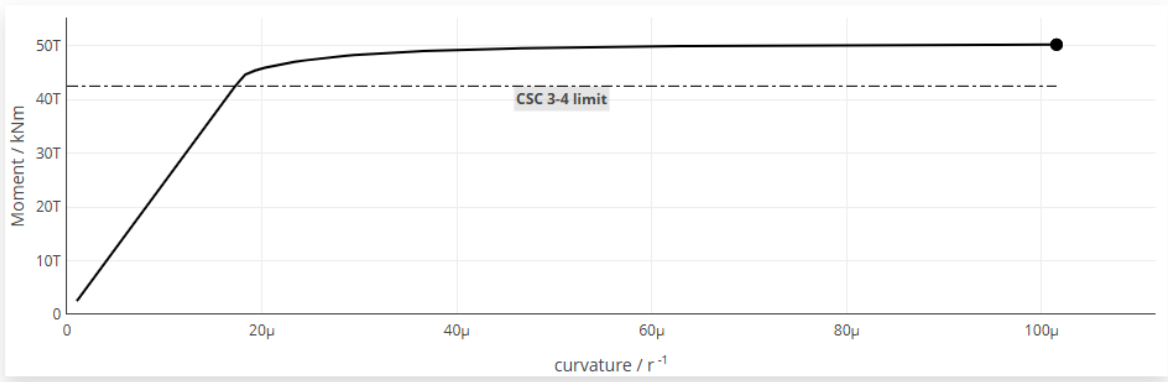
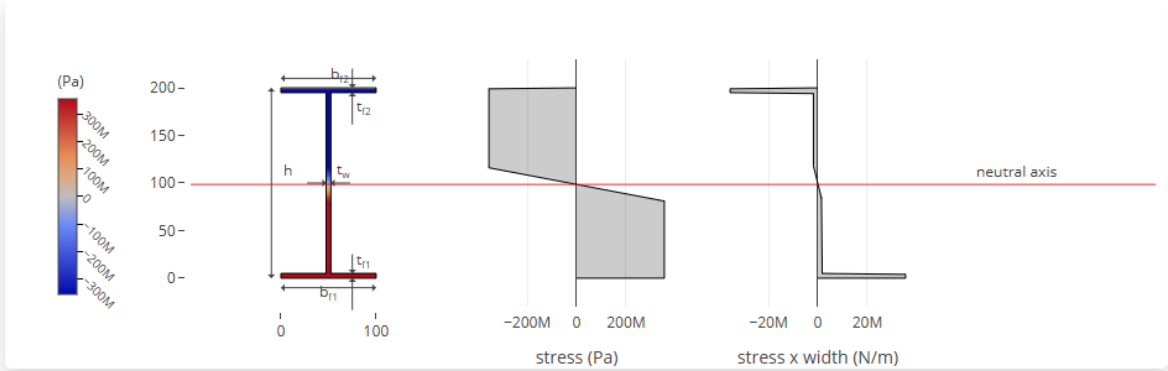


Figure C.17. Screenshot from web application for steel section analysis (<https://jklevski.github.io/SectionBender/>)

Section Geometry

- h	300	mm	+
- b	200	mm	+

Reinforcement

- ϕ_u	12	mm	+
- ϕ_t	12	mm	+
- n	4		+
- n	4		+

Materials

- f_c	20	MPa	+
- f_y	500	MPa	+

Max Concrete Strain (0 - 0.0035)

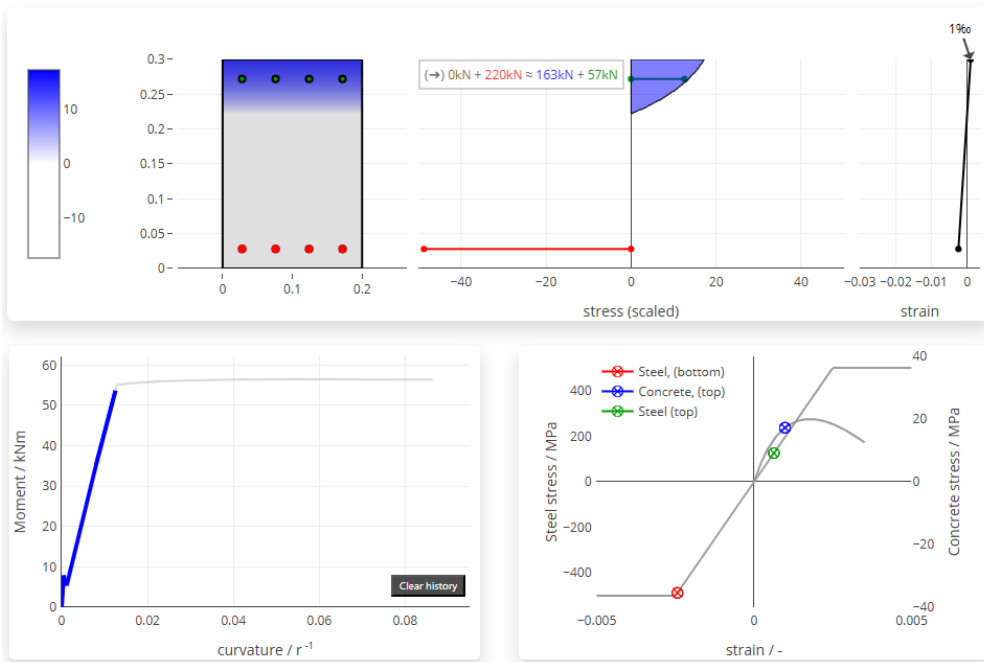


Figure C.18. Screenshot from web application on concrete section analysis (<https://jklewski.github.io/ConcreteBender/>)

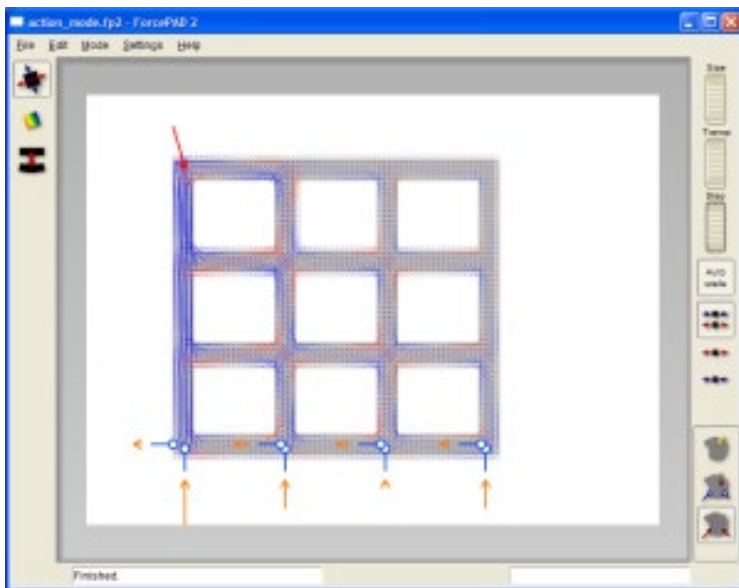


Figure C.19. Screenshot from building mechanics freeware showing flow of forces (<https://forcepad.sourceforge.net/screenshots.htm>)