

Use of interactive tools in seismic engineering and structural stability to facilitate learning and foster engagement: application to high-school outreach and university courses

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ABSTRACT

The theories of structural stability and dynamics of structures in a sense provide the backbone of structural engineering education and underpin advanced design approaches. Some of the challenges students face in these classes stem from the required knowledge synthesis, requisite level of mathematical treatment, and difficulties in visualizing structural behavior. In this paper, we present teaching modules wherein interactive tools are integrated with mathematical treatment to address these challenges. The modules have been used since 2019 at various educational levels including outreach activities as well as in master's level courses at EPFL. Survey data is also presented suggesting strong benefits of using such tools. For example, results suggest that using the hands-on activity kit in combination with shake table testing undeniably makes the modules fun. Moreover, students report that using the activity kit helped them better understand how buildings 'stand up' with mean scores of 4.2 and 3.8 out of 5 for the high-school and graduate students, respectively. Overall, it is found that when students experiment with the hands-on interactive approach they get interested in the subject and they have a better understanding or relate better to advanced concepts. All teaching materials presented in the paper are made openly available.

KEYWORDS

structural engineering, dynamics and stability of structures, interactive tools, surveys, outreach, active learning, project-based learning

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Introduction and Objectives

Shaking of the ground can have devastating consequences on communities as shown by the extent of damage to the Kahramanmaras, Turkey urban center (Figure 1a) following the February 6, 2023 earthquakes. According to the latest estimates, around 51 thousand people lost their lives in that sequence of events with more than 37 thousand structures destroyed and 3.3 million individuals displaced (Türkiye, ReliefWeb 2024). This recent example clearly demonstrates the societal responsibility of structural engineers, and many other stakeholders, in creating an urban environment that continues to function despite extreme loads.

Proper education of structural engineers as well as the public is a key component in this process. In that sense, this paper presents teaching modules on earthquake risk and structural stability which can be used for both outreach as well as university education. A key component of the modules is the use of hands-on experimentation to help with the learning process. For instance, shown in Figure 1b is demonstration of the city-scale response to an earthquake load using structural activity kits and a small-scale shake table. Such a demonstration can help students more tangibly feel the severity of the problem they are studying to tackle and thus provide a strong learning motivation.

As a further motivation for the hands-on approach in university setting, we use structural stability and dynamics as an example of capstone classes in structural engineering curricula. These classes build upon applied mechanics and structural analysis methods to treat concepts that underpin advanced engineering design approaches. As such, they are both important and challenging to grasp for various reasons. For example, besides the challenges stemming from required knowledge synthesis, in our experience university students often struggle with the required level of mathematical treatment, which can obfuscate the intuitiveness of the underlying concepts. Moreover, being able to effectively visualize the structural behavior is helpful for building intuition and understanding, yet this can be challenging depending on the educational background and the learning style of the student (Felder, Richard M and Silverman, Linda K 1988; Felder, Richard M and Brent, Rebecca 2016). This is the aspect where in our experience the hands-on experimentation with interactive tools can be particularly effective.



Figure 1 : Regional response to earthquake load: a) destruction in the urban center following the 2023 Kahramanmaras, Turkey earthquake (Abraham et al. 2023), b) demonstration of the city-scale response using the activity kit models and a small-scale shake table.

For instance, a key yet challenging concept to comprehend in structural stability is the buckling behavior of columns under compressive axial loads. Structural activity kits, such as MOLA (“Mola

Structural Model: A New Way to Learn About Structures,” n.d.), can be used to assist students to build intuition about the underlying behavior that control buckling before getting into the formal mathematical treatment of the problem. Shown in Figure 2 are the elements of the activity kit which allow constructing small-scale physical models of buildings as discussed subsequently. To begin with, the short and long springs can be used to model beam-columns of the building, i.e., vertical load-bearing elements. When exposed to certain amount of load along the length of the member (indicated with the red arrow in Figure 2b) columns can exhibit almost instantaneous loss of load-carrying capacity due to instability. This instability, termed global buckling of the steel column, is shown in Figure 2b using a full-scale laboratory experiment. While the theory describing this behavior is treated in advanced nonlinear analysis classes, the behavior is straightforward to demonstrate using the activity kit. As shown in Figure 2c, simply pressing the spring vertically with a finger allows students to induce buckling. Moreover, by changing the boundary conditions using the stiffeners (shown in Figure 2a) or by contrasting the behavior between the long and short springs, students can experiment with different amounts of load required for instability to occur. As such, in few minutes students can gain intuition into one of the important mechanisms controlling collapse of structures.

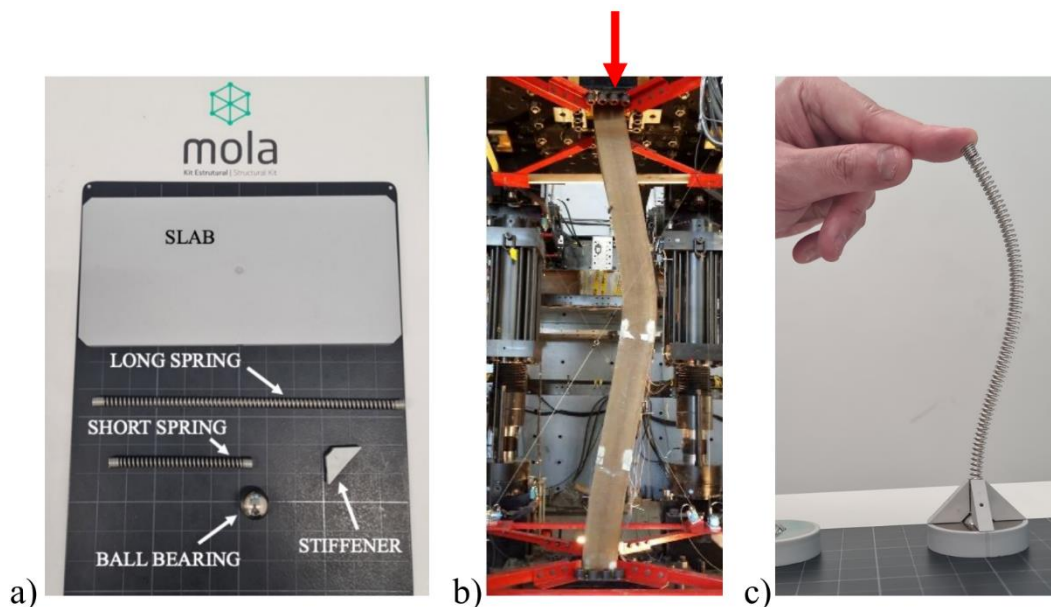


Figure 2 : Global buckling of a steel column under vertical load: a) building blocks of the MOLA (“Mola Structural Model: A New Way to Learn About Structures,” n.d.) structural activity kit, b) laboratory experiment (image courtesy of Prof. Robert Tremblay, École Polytechnique Montréal), c) small-scale model demonstration of buckling using the activity kit.

The overall objective of this paper is to provide useful and actionable insights and learning modules to instructors of structural engineering at university level or educators dealing with promotion of science to attract high-school students to civil engineering university study programs. The first specific objective is to share teaching approaches, class materials, and workshop resources we found to be effective in this domain. These teaching modules, as discussed in the following sections, cover the same core concepts of structural dynamics wherein we use the MOLA activity kit and a shake table for demonstration purposes. However, the level of treatment and the language we use to make groups of different backgrounds relate to the key concepts are different. The modules have been used over the last five years in Civil Engineering at EPFL, Switzerland for outreach activities to introduce high-school students to seismic effects and earthquake engineering but also as part of master’s level courses.

The second objective is to present the results of cross-sectional, self-report student surveys that suggest the effectiveness of the developed materials and approaches. In particular, the general observations are that with the same teaching ingredients, groups of different backgrounds (e.g., high school versus university students) react favorably in a like manner while learning by doing is effective regardless of age, background and focus on studies. All data and teaching materials presented in the paper are made openly available. In addition, some of the challenges encountered in developing and implementing the modules are discussed along with suggestions on how the modules can be expanded and scaled.

Literature review

Various advantages of the university outreach programs have already been discussed at length including increasing the interest of elementary school students in engineering and enabling students to see the intertwined nature of science, technology, engineering and mathematics (STEM) fields with the surrounding world. Moreover, successful outreach programs can also clear up the misconceptions suggesting sedentary nature of work, lack of room for creative endeavors, and prospective students' self-doubts related to not possessing adequate levels of intelligence required to study engineering disciplines and have a fruitful career in STEM (Anthony et al. 2016; Tan, Genalo, and Verner 2010; Jeffers, Safferman, and Safferman 2004; Watters and Diezmann 2013; National Academy of Engineering 2008; National Academy of Sciences, National Academy of Engineering, and Institute of Medicine 2011; National Research Council 2011). These outreach activities can be in many formats – typically as in-person or online workshops involving activity kits or computer software (Jeffers, Safferman, and Safferman 2004; Mosley et al. 2010; DiLisi, McMillin, and Virostek 2011) – with a common component being hands-on, active learning through prediction, experimentation, observation, and design while fostering self-regulated learning (Biernacki, n.d.; Barak 2012). All these benefits related to knowledge retention and engagement can get further amplified in the university settings where different formats and best practices can be implemented either as full semester project-based learning courses and independent studies, or as more active components incorporated into otherwise lecture-oriented classes (Eckerdal, Berglund, and Thuné 2023; Kolmos et al. 2023; Kunberger 2013).

Related to the structural engineering education, past work reported on successful application of virtual reality, physical models and the use of computer and laboratory models (Vahdatikhaki et al. 2023; McCrum 2017; O'Dwyer, Logan-Phelan, and O'Neill 2007; Mahendran 1996; Gavin 2011) as effective tools for laboratory work preparation, for reinforcing key concepts, and for the understanding of the iterative design process as well as the interdisciplinary interactions between the engineers and architects. In addition, experience from past studies suggests that gaining robust knowledge of structural engineering theory before engaging in fully project-based learning classes is beneficial as the existing gaps in requisite knowledge are otherwise challenging to address in such settings (Molyneaux et al. 2007). At the same time, shifting the course emphasis from lecture-based to project-based learning, i.e., emphasizing skills over concepts, results in reduced content coverage but increased student ability to independently acquire a breadth of knowledge (Kunberger 2013). Some of the successful and long-standing examples of project-based learning outreach activities in the structural/civil engineering domain at the university education level include the EERI Seismic Design Competition ("2024 Seismic Design Competition – Student Leadership Council," n.d.), the ASCE Concrete Canoe Competition ("ASCE Concrete Canoe Competition," n.d.), and the U.S. Department of Energy Solar Decathlon ("Solar Decathlon: About Solar Decathlon," n.d.). All these events are multi-semester endeavors aimed at promoting the concepts of resilience and sustainability in the design and operation of the built environment.

Overall, the consensus is that project-based learning adds meaningful value to the learning experience. However, a key challenge to successful implementation of such didactic approaches in science and engineering education is to achieve a balance between the learning of theory and the learning of practice (Aufschnaiter and Aufschnaiter 2007; Eckerdal et al. 2007; Holmes et al. 2017; Séré 2002). This may be evident in what is referred to as the “mathematics problem” (Munns 2017) where mathematics is typically decontextualized from engineering education thus leading the students to learn procedures rather than the underlying concepts. In turn, this can create problems in more advanced classes such as structural dynamics or stability where mathematical roadblocks can detract students from understanding intuitiveness of theoretical concepts to focusing on rote and procedural learning. In our experience, as described subsequently, building the intuition of the problem and the appreciation of the tools to tackle the underlying questions can foster the learning engagement. Moreover, we subscribe to the view that frequent switches between theory- and active-learning actions drive the learning process forward as was previously reported for some engineering disciplines (Eckerdal, Berglund, and Thuné 2023).

Teaching modules and materials

Experiences from using the following three different teaching modules are described in this paper: (1) a university outreach workshop for high-school students related to earthquake hazard and risk, (2) a hands-on workshop and a capstone class project as part of the graduate course on dynamics of structures, and (3) structural stability and earthquake engineering master’s level independent study semester project. The modules have been developed and tested as part of the educational activities of the the Resilient Steel Structures Laboratory (RESSLab) at EPFL (“Resilient Steel Structures Laboratory (RESSLab)” 2024). The target audience as well as the learning outcomes for each of the modules are provided in Table 1. Also given are the numbers of participants we had in each module over the course of the study.

Table 1. Target audience and learning outcomes for each of the modules

Module	Target Audience	Learning outcomes	# participants
Outreach workshop	high-school students	<ul style="list-style-type: none"> Learn about building materials and structural members Understand why earthquakes are damaging to buildings Gain intuition into response of structures to earthquakes 	124
Workshop & capstone project	graduate students taking dynamics of structures	<ul style="list-style-type: none"> Understand the dynamics of different structural designs through hands-on experimentation Apply theoretical knowledge to simulate the behaviour of the small scale experimental model 	26
Independent study semester project	graduate students	<ul style="list-style-type: none"> Apply sensors to capture building response to dynamic loads Experimentally test more complex structural systems and behaviour including instabilities and torsion Numerically simulate the measured behaviour, understand the effects of modeling assumptions 	30

The core of each module is the same in that the contents cover the principles of structural dynamics and introduce the students to some of the fundamental concepts and challenges in earthquake engineering. All modules consist of the teaching materials – e.g., the lecture slides, problem set for the interactive activity with the mola kit, project problem for the dynamics class – which are shared in a public repository (<https://zenodo.org/uploads/14165930>). Crucially, to assist students in building the intuition about the underlying deterioration mechanisms that control stability and seismic collapse

performance of structures, the MOLA structural activity kit is used in combination with the shake table for interactive demonstration purposes.

For instance, a very important failure mechanism occurring during earthquakes can be effectively demonstrated using the activity kit. Specifically, if certain deficiencies are present in the structural system (Federal Emergency Management Agency 2018), a so called “soft story” collapse mechanism can occur, as shown in Figure 3a. In essence, if under the same lateral load one of the stories in the building deforms much more compared to other stories, i.e., if that story is “softer” or less stiff than other stories, then the building can undergo sidesway collapse where the whole building topples onto that weak story.

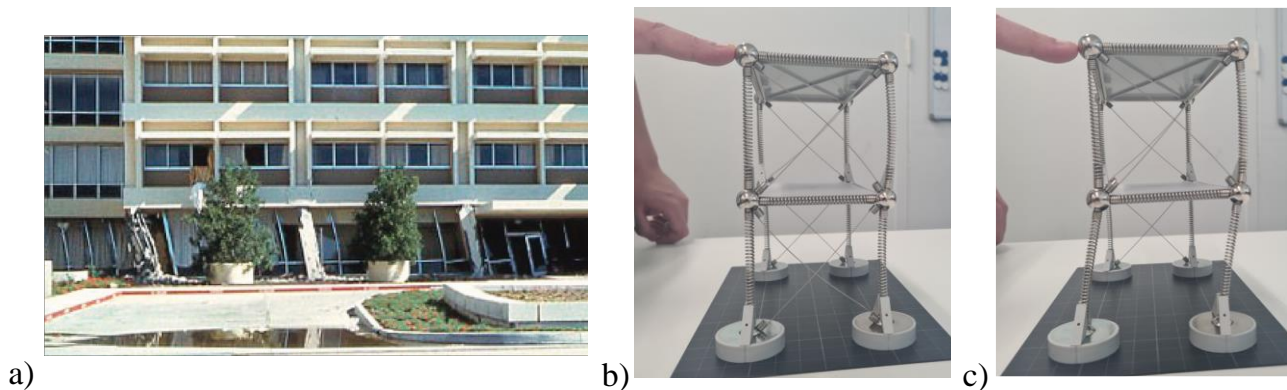


Figure 3 : Building collapse due to a “soft story”: a) Olive View hospital, San Fernando earthquake, 1971, showing extreme lateral deformation of the columns in the first story (Federal Emergency Management Agency 2007), b) small lateral deformation of a braced frame model, c) soft story collapse of the braced frame model due to removal of the braces.

Like in the case of flexural buckling shown in Figure 2, theoretically understanding and numerically simulating the sidesway collapse is an advanced graduate class topic (Lignos et al. 2019). Nevertheless, the soft-story mechanism can be showcased using the activity kit to allow students of wide educational levels to build insight into the problem in a straightforward manner. For example, shown in Figure 3b is a braced frame created using the activity kit and subject to a horizontal load (finger pushing the frame from the side). The thin elements arranged in an x-shaped pattern are called braces. These elements provide additional lateral stiffness to the frame structural system consisting of columns and beams around braces. Referring to Figure 3c, if the braces are removed from one of the stories – for instance, the bottommost story to make space for a garage, the structural system becomes much weaker in that story and undergoes collapse under the load which would not cause collapse if the braces were present. By experimenting with different brace configurations and placement of stiffeners, the students can feel their way into the intuition about the structural behavior.

The specific details of each of the modules are described in the following sections. As mentioned, there are three modules all dealing with dynamics of structures and stability while being aimed at different audiences – starting with high-school students and moving to undergraduate and master level university students. The learning objectives for the outreach module are to introduce the students to key concepts in structural engineering pertaining to seismic hazard and risk. On the other hand, the learning objective for the university level modules are to enhance the in-depth treatment of the same subject with the hands-on component and practical project tasks that emphasize integration of learning of theory with experimentation.

While there is thematic overlap between the modules, each modality has unique characteristics stemming from the differences in module length, depth and breadth of the covered material, as well as

educational background and level of participating students. In other words, the level of treatment and the language we use to make groups of different backgrounds relate to the key concepts are different. At the same time, a common thread between the modules is the emphasis on self-guided and independent active learning in a team setting.

University outreach workshop on seismic hazard and risk

The university outreach workshop, in a nutshell, is a one and a half to two-hour long module aimed at introducing high school students to structural engineering and exposing them to key concepts related to seismic hazard and risk. The workshops have been administered twice per year since 2018 as part of the EPFL outreach to high school students across Switzerland. The outreach is organized by the EPFL Education Outreach Department (“Education Outreach Department (SPE)” 2023) and is aimed at students considering university studies the following year.

Beyond attracting students to high-quality university programs, the timeliness and pertinence of the workshop topic stem from the fact that, on average, every person in Switzerland will experience in their lifetime at least one earthquake causing serious damage (Federal Office for Civil Protection (FOCP), n.d.). Moreover, of all natural hazards in Switzerland, earthquakes have the greatest damage potential and earthquakes are among the greatest risks facing Switzerland, along with pandemics and power shortages (Wiemer et al. 2023). Yet, there is a discrepancy between the actual earthquake risk and the perception of the risk by the population (Federal Office for Civil Protection (FOCP), n.d.; Wiemer et al. 2023). This observation is also supported by responses to questions administered to the high school students at the beginning of the workshops, as shown in Figure 4. Specifically, about 78% of the 124 respondents do not really think about earthquakes (Figure 4a). Moreover, most of them (~50%) do not expect earthquakes to affect their lives while only about 15% of the respondents see earthquakes as potential disruptors of their lives at some point (Figure 4b). The number of responses in this and subsequent figures is indicated with ‘n_resp’; referring to Figure 4b there were a total of 124 students that responded to the question, but it is noted that not all students responded to all the questions. More details on the survey are provided in the following section.

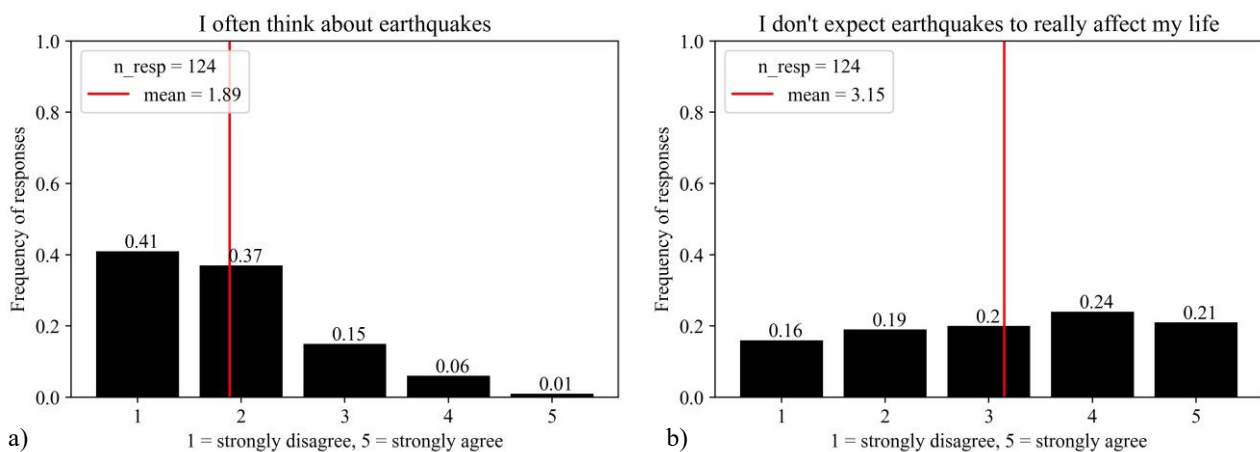


Figure 4 : Self-report of a) interest in earthquakes, and b) perception of earthquake risk amongst high-school students in Switzerland.

The workshop begins with a ~20-minute overview session covering the commonly used structural materials – i.e., reinforced concrete, wood, and steel – with the corresponding example structures, the different types of load-bearing structural elements, as well as the different types of loads. Throughout

the session the students are encouraged not to take any written notes, but rather to “sit comfortably and enjoy the pictures” as well as to freely ask any questions. Our anecdotal observation is that this helps with engagement and removing the barriers that may exist due to the age difference between the students and the instructors.

In addition, we find the use of analogies to be very effective in this context. An example of an analogy emphasizing the fact that iron and steel are very different materials is shown in Figure 5a. Using a pop-culture reference that pits ‘Superman’ (i.e., the Man of Steel) against ‘Iron Man’ makes it much more likely that all the students will remember for a very long time the fact that there indeed is a difference between iron and steel compared to simply stating the fact that “steel is an iron alloy with low carbon content, which exhibits the desirable property of ductility”. There are other examples of analogies and effective communication in the materials shared with this paper (<https://zenodo.org/uploads/14165930>) which according to student self-report help the material be properly tailored to the audience. For instance, about 97% of the respondents found that material is presented in an understandable way, as shown in Figure 5b.

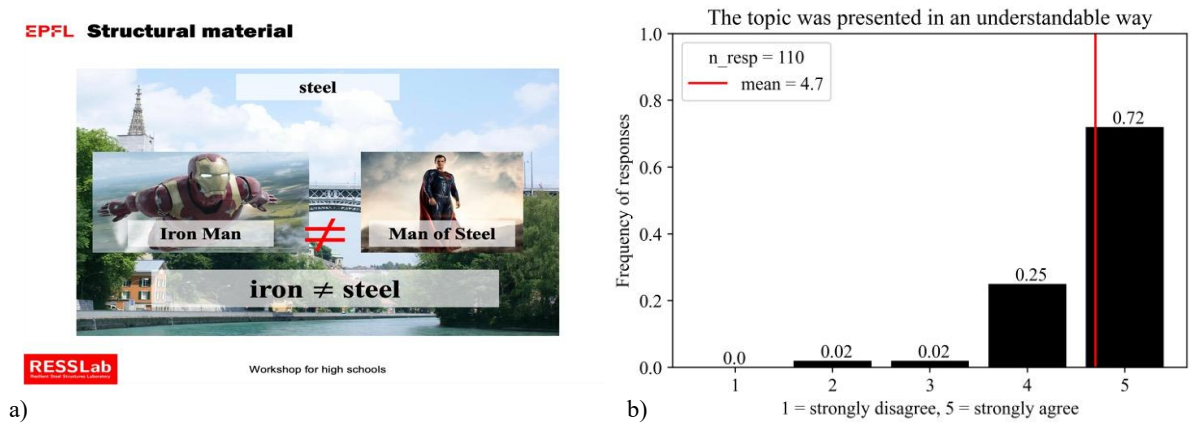


Figure 5 : Edutainment in outreach: a) example of an analogy emphasizing that steel and iron are very different structural materials; b) self-report of students related to properly tailored workshop content for the audience.

Following the theoretical overview session, the outreach workshop switches to a hands-on practical component. The students are handed out the activity kit consisting of the instructions and the MOLA structural kit (“Mola Structural Model: A New Way to Learn About Structures,” n.d.). The instructions contain basic guidance for two competition-type problems. In the first problem, the students are tasked to assemble a structure to withstand gravity loads. The only constraint in the instructions pertains to the maximum number and type of structural members that can be used as well as that the structure needs to have two stories and the roof slab. Students work in self-organized teams (Figure 6a) while the points are assigned based on the vertical load their structure can withstand before collapse (Figure 6b). Students are encouraged to quickly test multiple designs and only the highest score is kept.

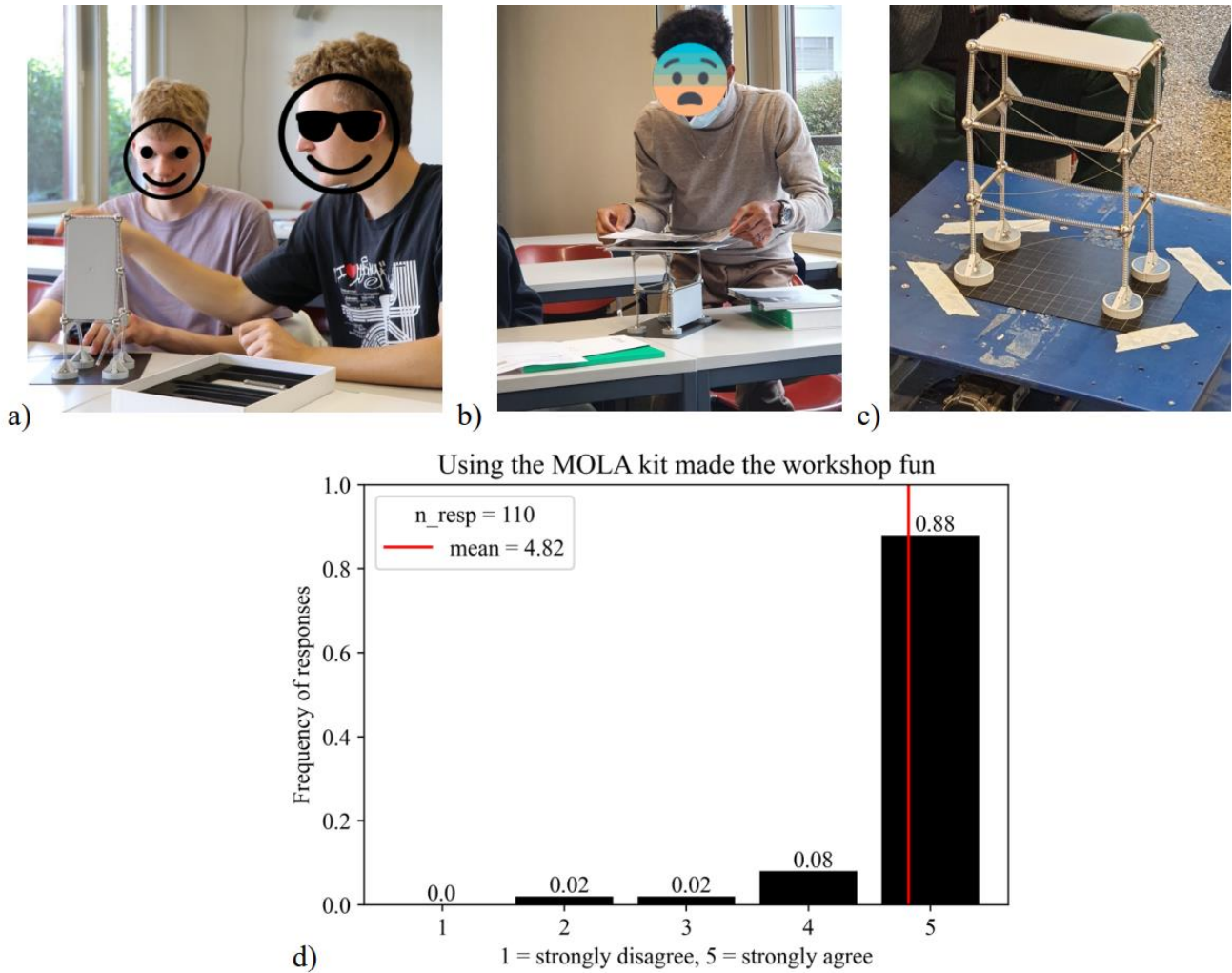


Figure 6 : Outreach workshop in progress: a) students assembling a small-scale structural model; b) student loading the structure with the vertical load (challenge I); c) earthquake test of a student team’s structure on the shake table (challenge II); d) student self-report related to the use of the structural activity kit.

Motivating the students to iterate quickly between different designs promotes the frequent switches between the theory- and practice-oriented actions as suggested to be effective in (Eckerdal, Berglund, and Thuné 2023). For instance, developing the initial design for the first structure requires considering some of the theoretical concepts covered during the session, such as deciding on the types of fixities for the supports and whether to use braces or walls. Students then typically experiment with the structural kit to get a better intuitive sense of the structural behavior on the component level, e.g., examining the influence of the base fixity on the lateral stability of a single column (as shown in the Figure 2c). In turn, students then assemble their initial design and observe the deformations while gradually loading the structure to collapse. This allows the teams to discuss the effectiveness of different design decisions – e.g., whether to put the wall vertically or horizontally – and propose the design changes for the second and subsequent trials. The loading of the structures with the vertical loads is performed by the teaching team which allows for an opportunity to point out some issues with the designs via comments such as “Notice that this column is ‘working’ much more than other columns, i.e., it is more deformed” or “Why do you think the structure is so wobbly?” However, the discussions and actions on how to address the issue are primarily left for the student team to propose and implement.

The second construction challenge involves building a three-story structure to withstand earthquake loads imposed by a shake table (Figure 6c). The primary difference to the first problem is that the ground shaking induces high lateral loads as opposed to vertical-only gravity loads. The students build the structural models and can iteratively test them on the shake table under increasing levels of earthquake shaking. The points in this case are assigned based on the shaking intensity the structure withstands before collapse, where the larger shaking intensity affords more points. The team with the largest sum of the points from the two challenges win the competition. An example of a similar but multi-university activity is the EERI Seismic Design Competition (“2024 Seismic Design Competition – Student Leadership Council,” n.d.) where civil engineering and architecture undergraduate students have the opportunity of designing and constructing a cost-effective frame building out of balsa wood to resist seismic loading imposed by a shake table. The results of our survey (Figure 6d) suggest that using the shake table and the structural kit is pivotal for the success of the outreach workshop as judged by the ‘fun’ factor.

There are two anecdotal observations worth mentioning here. One is that the students find it most engaging if the structures are tested using real recorded earthquakes – as opposed to, for instance, using a sinusoidal excitation – and in a “city scale” scenario (Figure 1). Testing the structures in this way enables one of the key considerations related to seismic risk and resilience studies to be effectively demonstrated. Specifically, while people tend to think about buildings as separate entities, the fact is that no building “lives in isolation” in our urban fabrics. That is, a poor performance or collapse of one building also affects its surroundings. Moreover, under a common case that only a handful or so of construction companies develop buildings in any given region, poor construction practices tend to result with increased correlation of poor building performance. Both points can be seen in Figure 1 demonstrated in real world and using a small-scale shake table.

Moreover, testing multiple structures simultaneously creates the added suspense for the students stemming from direct comparison with the other teams as well as the instructors – the collapsed rubble of white sugar cubes seen in Figure 1b was the structure built by the teaching team to additionally demonstrate the generally poor seismic performance of unreinforced masonry buildings. This building was the first to collapse, which was motivational for the students as they did better than the teaching team. Finally, testing multiple structures at the same time makes the workshop more time efficient.

The second anecdotal observation is that any violations of the “building standard” (i.e., the rules and constraints provided in the instructions) are best left to be pointed out by the student teams rather than the teaching team. Points could be deducted on this basis, but in our experience making a humorous reprimand acknowledging the violations of the rules while pointing out that the objective is to learn while having fun works the best. As shown in Figure 7, a snapshot of the written student responses from the official EPFL survey supports the previous claims.

EPFL What did you like most?

Original comments from the students, as collected from the form:

It was a lot of fun

It was e very good module! It was very funny and exciting but you could also learn something.

It was my favourite module

It was very good.

Really nice way of presenting the things. Reall sympathic people.

The best course and activity of the week

The explanations were brought to us in a funny, interesting and clear way. It was a nice module and a great teacher.

The two Professors were awesome

Wow



Figure 7: Comments from the high-school students on the official EPFL outreach evaluation survey for the 2023 EPFL Summer School. (Figure courtesy of Maya Fruehauf Hovius, EPFL Education Outreach Department)

Project-based learning components in the graduate class on dynamics of structures and semester projects

A hands-on workshop with essentially the same format as the undergraduate outreach one can also be used as part of a graduate course on dynamics of structures. However, given that the students possess the requisite technical background, the workshop can be administered in a more compact 45-minute format in which the bulk of the time (~40 minutes) is devoted to the hands-on experimentation rather than theoretical concepts. Moreover, using the sinusoidal excitation in addition to recorded ground motions in this case is useful for didactic purposes to effectively demonstrate and visualize the structural modes, as shown in Figure 8 for the case of a 3-story moment-resisting frame (MRF) structure. This is a key concept in structural dynamics, which can be hard to grasp and appreciate “on paper” but is readily understood when seen first-hand, particularly at the city-scale where different structures are directly comparable.

As such, this workshop in our case is a project-based learning component in an otherwise lecture-oriented class. Furthermore, it also serves as a basis for the subsequent capstone class project wherein the objective is to study the dynamic properties and response of a 2-story building in the direction where the MRF is employed. Specifically, (teams of) students first compute the dynamic properties of the model and then numerically analyze its behavior and compare the results to actual experimental measurements. This requires students to synthesize the knowledge from this class along with the prerequisite knowledge from structural analysis classes they took previously.

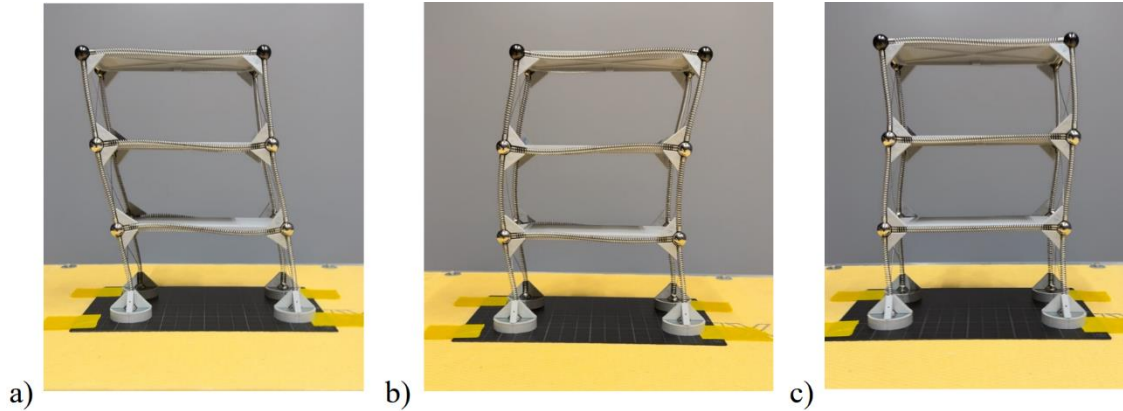


Figure 8: First three structural modes of a 3-story MRF structure built using the MOLA structural activity kit. The corresponding videos of the displacements of the structure under sinusoidal excitations are provided online with other teaching materials (<https://zenodo.org/uploads/14165930>).

The fact that the students are performing an in-depth analysis of the same structure they constructed during the workshop makes the problem much more relatable. Moreover, the task is much more engaging as there is a sense that they are working on a “real” problem and data which would not have been the case had they not done the hands-on workshop before. In fact, as shown in Figure 9, most students (~70%, Figure 9a) really liked the class project and an even greater number of them (~76%, Figure 9b) would recommend the class to a friend. Furthermore, similar to the high school outreach program, students report that using the structural activity kit really makes the workshop engaging and fun (Figure 9c). This same idea from the capstone project can also be extended to a semester-long individual study, wherein the students not only construct the structures to investigate some aspects of dynamic response or instabilities, but also perform all the supporting measurements in addition to developing the numerical models and implement the requisite numerical analysis procedures.

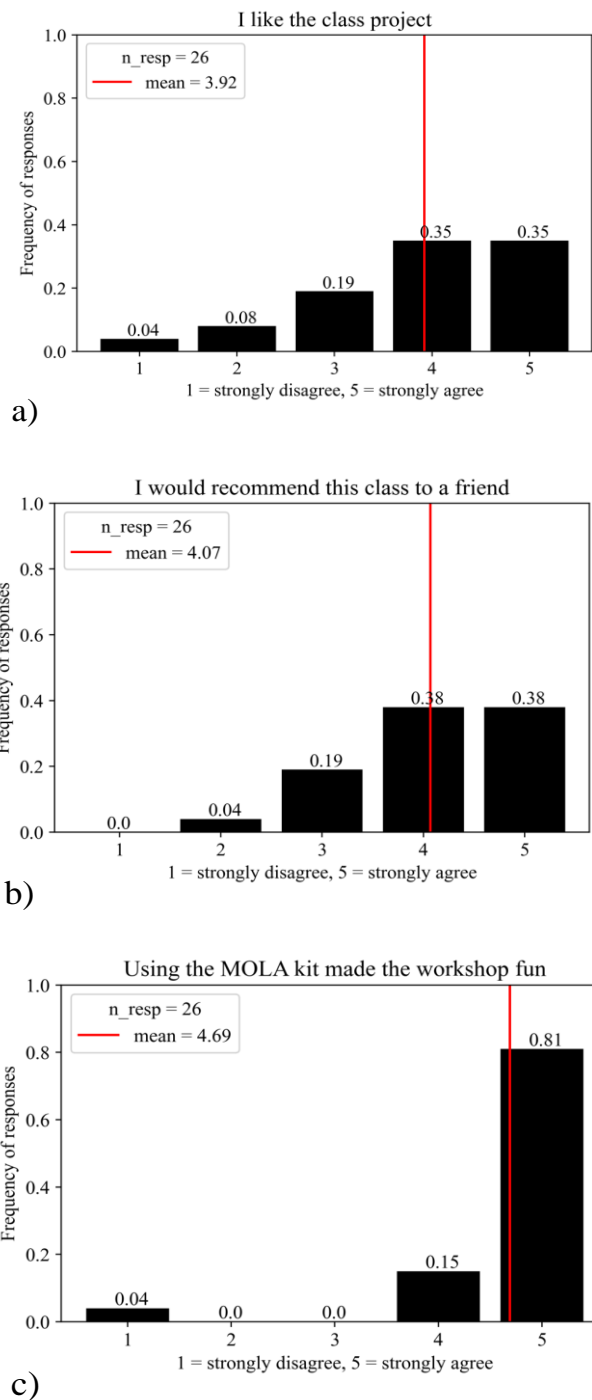


Figure 9 : Structural dynamics class and capstone project evaluation.

Before presenting the core results of the surveys in the following section, we make a few notes on the analogies and communication we find to be effective when teaching structural dynamics and earthquake engineering. In particular, we find the analogy with music to be effective when introducing and explaining the concepts related to single-degree-of-freedom (SDF) oscillators and the associated theory of structural modes. In essence, each SDF system only responds to dynamic excitations of a certain frequency. In other words, the analogy is based on the anthropomorphized SDF which likes to dance only to a specific type of music.

To introduce this notion, shown in Figure 10a is a poll slide wherein the students are asked to choose their favorite singer out of the few options. In that instance Queen had the highest number of votes while Justin Bieber had the least. Given this info (as well as the assurance to the students that this is indeed pertinent to the class), the subsequent discussions proceed as follows. The students are asked to assume that people who voted for Queen only like their songs, while the people that voted for Justin Bieber only like his songs. Under these assumptions, regardless of how loud one plays “Bohemian Rhapsody”, the fans of Justin Bieber simply will not dance to that song. The opposite is also true – an exclusive fan of Queen simply cannot dance to whatever Justin Bieber hit may be playing on the radio.

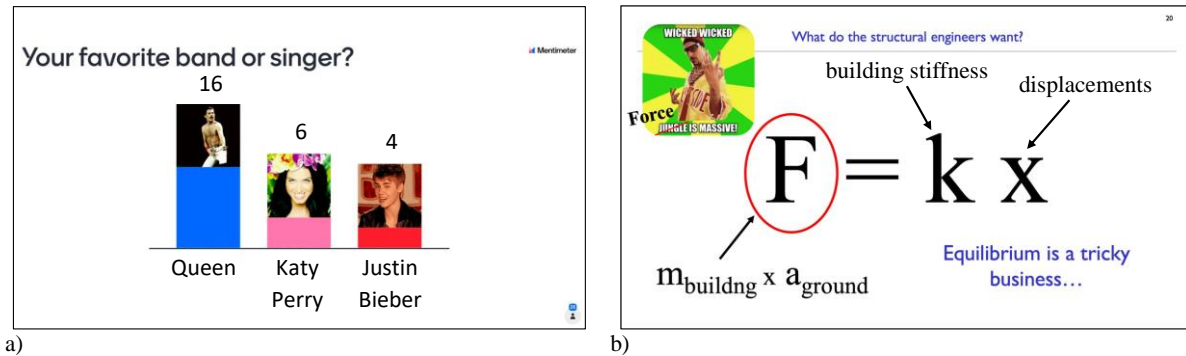


Figure 10 : Useful memes in structural dynamics: a) music analogy to structural modes, b) the challenges of achieving equilibrium.

The analogy to the SDFs here is that if the dynamic excitation does not contain the frequency to which the SDF reacts, then the SDF does not respond to that excitation regardless of its amplitude. If the dynamic excitation happens to be an earthquake record, then the volume of the song can be analogous to the magnitude of the earthquake (or, more technically, to the spectral amplitudes of the ground motion). In other words, regardless of the magnitude of the causal earthquake, unless the resulting ground motion contains certain frequencies associated with a set of SDFs, such SDF systems simply will not respond to the shaking of the ground. Moreover, the analogy further extends to the case of multi-degree-of-freedom (MDF) structures which are susceptible to excitations at a range of frequencies. An effective demonstration of this can be a video showing a 3-story model building “dancing” to a song of a different band in each of its modes. For the modal response videos provided online with this paper, one could use “Cutthroat” by Imagine Dragons for the first mode, “Master of puppets” by Metallica for the second mode, and the noise of a hammer drill for the third mode.

Another useful meme explaining one core issue in earthquake engineering, i.e., that ground motion shaking imposes very large forces on the structures, is shown in Figure 10b. In particular, the internal forces in the structure, indicated with \mathbf{F} , are linked to the mass of the building and the ground acceleration via the Newton’s second law. To appreciate the amplitude of the forces, it suffices to recognize that because the mass of the building is large, then even relatively small ground accelerations will cause significant loads that the structure needs to resist let alone in the case when the acceleration of the ground is large. For example, the largest ground acceleration recorded during the 2011 Tohoku, Japan earthquake equals 2.82g (Goto and Morikawa 2012). In essence, the effect of that ground motion is as if the structure, for instance a tall building, is rotated so that it is hanging sideways while amplifying the gravity by a factor of ~ 3 . This example effectively demonstrates to students the challenges of achieving equilibrium and designing buildings in earthquake-prone regions. Loosely stated, the challenge is to design a structure with sufficient stiffness, \mathbf{k} , to resist the imposed loads while the associated displacements, \mathbf{x} , are not extreme.

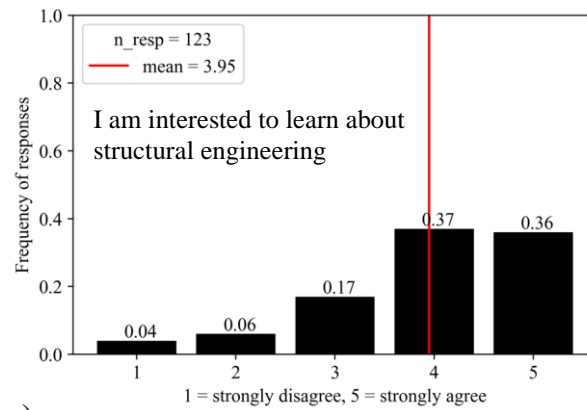
These examples demonstrate the core idea of the developed teaching modules: concepts of stability, statics, and structural dynamics are taught across different levels of education – the presented set of teaching modules were designed in order to facilitate the learning process and help students relate and link various concepts including the ones that they think they do not know while the opposite is in fact true (as in the case of linking the Newton's second law to the earthquake resistance of a structure). As supported by the survey results presented in the following section, when this approach is applied to groups of different ages and educational levels (i.e., high school versus university) the students are similarly motivated to learn while active learning helps students relate and resolve challenging concepts.

Survey results

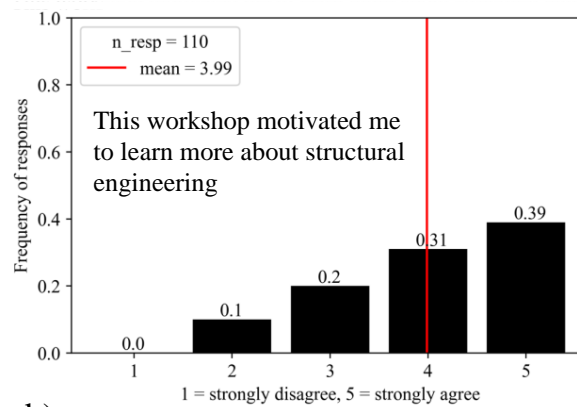
The primary objectives of the surveys reported in this paper were (1) to gauge the interest of participants in learning about structural engineering before and after the workshops, and (2) to examine the utility of using interactive tools in structural engineering education to foster engagement and facilitate learning. In addition, there were two groups of students that were of interest. The first group consists of students from high schools across Switzerland, which participated in the outreach workshop when considering prospective universities for enrolment in the subsequent academic year. This group had none or very limited formal exposure to structural engineering theory and practice. In contrast, the second group consists of master's level students in the structural engineering program at EPFL, Switzerland. As such, the graduate students had a strong educational background in structural engineering. However, the surveys were administered while all the students were enrolled in the structural dynamics class for the first time. In that sense, they were aimed at measuring the effectiveness of project-based learning components promoting active learning in otherwise lecture-based class as mentioned previously.

These cross-sectional surveys were administered during the 2023 calendar year and involved a total of one hundred and twenty-four high school students and twenty-six graduate students. However, all the students did not answer all the questions and hence the number of responses (n_{resp}) reported in the figures varies. The student responses to survey questions were anonymous, i.e., the individual responses cannot be linked to any of the students and were collected via the Mentimeter application ("Mentimeter: Interactive Presentation Software,"). Both groups consisted of both male and female students but the statistics on the demographics were not collected. There were no control groups (e.g., conducting workshops without the hands-on component) and so far, there was no follow-up with the students to measure any aspects pertaining to knowledge retention over time. At the same time, some of the questions do involve a longitudinal component as they contrast the students' perceptions before and after the workshop or class.

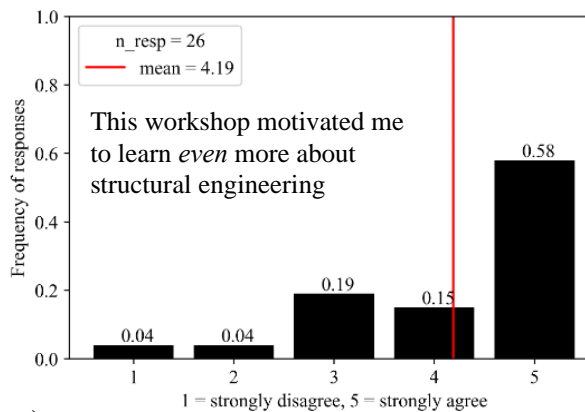
Shown in Figure 11 is the self-reported interest of both high school and graduate students to learn about structural engineering. Specifically, Figures 11a and 11b contrast the interest of high school students to learn about structural engineering before and after the outreach workshop. While the number of responses is not the same for the two questions, the figures do show a slight tendency of the increased interest in learning about structural engineering following the workshop. In particular, the mean of the response shifted from 3.95 to 3.99, wherein 5 is the largest possible value. Additionally, the interest increased both amongst the least and the most interested students. Referring to Figures 11a and 11b, the percentage of respondents who rate their interest with the lowest grade decreased from 4% to 0%. At the same time, the percentage of respondents who rate their interest with the highest grade increased from 36% to 39%. As such, the shifts at the tail ends of the distribution were towards increased interest of students to learn more about structural engineering. The summary of the results is also shown in Table 2.



a)



b)



c)

Figure 11 : Contrasting the self-reported interest of students to learn about structural engineering: a) *high school* students before the workshop, b) *high school* students after the workshop, c) *graduate* students after the workshop.

Table 2. Mean values of the survey responses by high-school students

Survey question	High-school students	
	before	after
Interest in learning about structural engineering	3.95	3.99
Understanding of how buildings “stand up”, ie. carry loads	2.72	4.21

These trends in the results are generally positive particularly when also examining the responses of graduate students after the workshop. As shown in Figure 11c, around 73% of the students were motivated to learn even more about structural engineering following the hands-on activity. Note that these are students in their fourth year of university studies, hence such a rekindling of interest in learning despite already possessing significant requisite technical background is a positive result.

The survey results examining the utility of using interactive tools in structural engineering education to foster engagement (as shown previously in Figures 6 and 9) and facilitate learning also show positive trends. For instance, there is a stark difference between self-reported assessment of understanding before and after the workshops, as shown in Figures 12 and 13. Specifically, a left-skewed distribution with a mean of 2.72 before the outreach workshop (Figure 12a) shifts to a right-skewed distribution with a mean of 4.21 after the workshop (Figure 12b) with a total of 84% of the high school students reporting a grade of 4 or higher that the hands-on activity helped them better understand the technical concepts. Furthermore, around 62% of graduate students report the same assessment (Figure 13b) while a total of 96% of the students report they learned a lot during the structural dynamics class (Figure 13a).

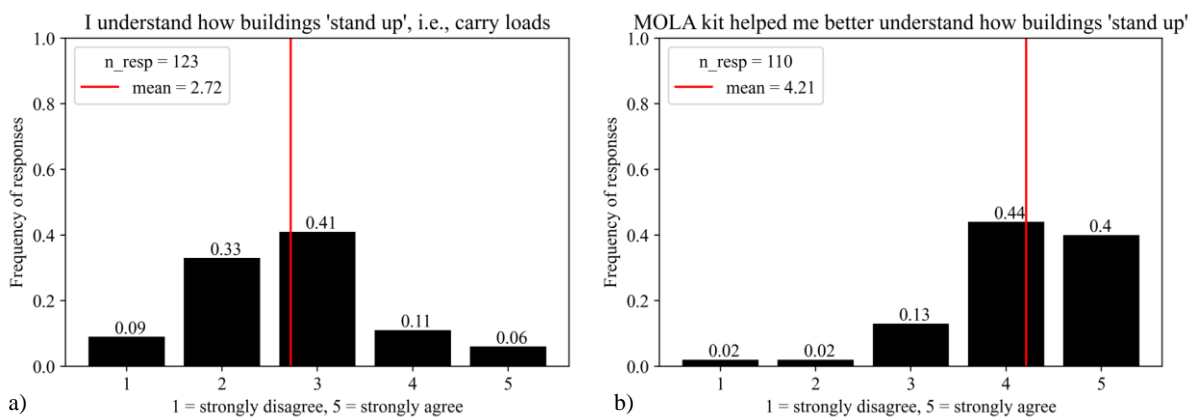


Figure 12 : Self-report of high school students on using interactive tools to facilitate learning: a) perceived knowledge before the workshop, b) influence of the hands-on activity on understanding after the workshop.

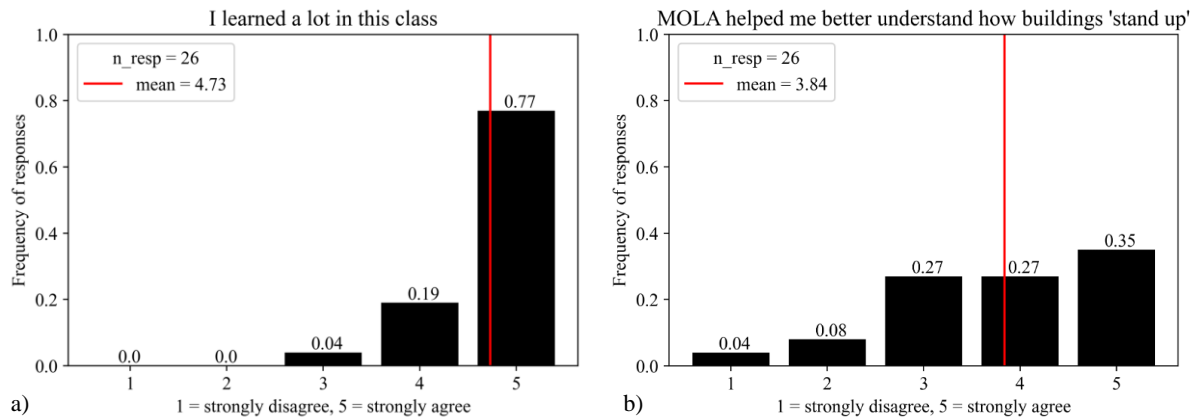


Figure 13 : Self-report of graduate students on using interactive tools to facilitate learning: a) general benefit from the entire class, b) influence of the hands-on activity on understanding structural engineering concepts.

Discussion

It should be emphasized that the limitation of this study is that no control group exists. In other words, we did not administer the same modules without the hands-on experimental component to be able to contrast the two cases. Similarly, no control groups were used to explicitly test the effectiveness of analogies and memes included in the presentation modules. However, since almost all students report that using the MOLA kit was fun (see Figures 6d and 9c) and that it helped even the advanced graduate students to better understand the theoretical concepts (see Figure 13), it is certainly plausible that the hands-on experimentation was the key contributor to the quality of the modules. To provide some additional explanation why the proposed teaching interventions are effective we consider the different learning styles of students drawn to engineering disciplines.

The Felder-Silverman model (Felder, Richard M and Silverman, Linda K 1988; Felder, Richard M and Brent, Rebecca 2016) differentiates the following learning styles, i.e., types of learners: (1) active and reflective, (2) sensing and intuitive, (3) visual and verbal, and (4) sequential and global. In brief, active learners understand best through active use of information (e.g., discussing, applying or explaining it) while reflective learners prefer to first think things through independently. The sensing type of a learner prefers facts, data and experimentation while intuitive learners prefer theories. Visual learners learn best from what they see – such as graphs, videos, or demonstrations – while verbal learners get most benefit from written and spoken explanations. Finally, sequential learners learn best through a progression of linear steps while global learners prefer the big picture to grasp the concepts.

In this sense, using the hands-on activity kit for experimentation adds the observable phenomena and a live demonstration to the workshop. According to (Felder, Richard M and Silverman, Linda K 1988), this type of an activity helps both the sensing learners and visual learners by providing a balance of concrete information and more abstract concepts; it also helps active learners through the direct use of information and demonstrations. This is advantageous because most of the students that gravitate towards engineering disciplines fall into these learning style categories (Felder, Richard M and Silverman, Linda K 1988).

Furthermore, working in teams during the workshop or the class project allows for a combination of active experimentation coupled with reflective observation to understand the theory (Kolb, D. A. 1984) which helps both the active and the reflective learners. Moreover, the competition format used in the

workshop adds an incentive for active participation and learning of the students so that they outperform other groups. In the similar vein, using the workshop as part of a graduate class is an excellent way to motivate the subsequent capstone project. This is because the students are solving a problem that they directly relate to which is a motivation to learn the required theoretical concepts and methods. All learning styles benefit from a motivation to learn. Finally, memes and analogies in the lectures can be effective as they are visual learning aids that also relate to the concrete student experience (in this case through a pop-culture references).

In closing we also provide some comments related to the scalability and application of the modules as our hope is that the community adapts the developed materials in their work. In the modules we used a professional structural activity kit and a shake table. If these are unavailable, an alternative would be to build the structures out of straws or balsa wood while using marshmallows as the connecting elements. Using such do-it-yourself (DIY) kits can be particularly fun in high-school or elementary school settings, although it adds time for the preparation of the activity. If a professional shake table is not available the DIY approach is also an option with a lot of ideas available online (e.g., see the following link: <https://pbskids.org/designsquad/build/seismic-shake-up/>). In that case, however, imposing loads in a repeatable manner will be a challenge because a human instead of a computer-controlled actuator would be shaking the table. This challenge can be addressed, for instance, by simultaneously testing structures of all or most of the competing teams. As mentioned previously, simultaneously testing the structures also helps reduce the length of the workshop with the added benefit of continuously engaging the students through anticipation of how their buildings will perform.

In terms of implementation, a teacher with a background in physics should be able to lead the modules in the elementary school and high-school settings. At the university level, the instructors should have a strong background in structural engineering – postdocs and PhD students can typically lead the workshops while master's level students can provide support. Furthermore, the presented capstone projects as part of graduate curricula can be expanded in several ways. For instance, a bridge structure could be considered where two shake tables are used to impose different loads at the two supports. Moreover, an independent project where the students first analyze a specified design of a structure and then subsequently propose strengthening solutions could be pursued.

Conclusions

This paper presented the teaching modules related to university outreach and graduate classes that use interactive tools to foster engagement and facilitate project-based learning in the structural engineering domain. These modules have been used over the last five years for outreach as well as master's level courses at EPFL, Switzerland. The results of cross-sectional, self-report surveys were also presented suggesting the effectiveness of the developed materials and approaches.

The main observation from the survey results is that using the hands-on approach with the structural activity kit undeniably helps with the learning experience. Specifically, most of the students report that the workshop helped them better understand how buildings 'stand up' compared to, in case of high school students, not understanding this before the workshop. Moreover, a significant portion of both high school and graduate students reported the motivation to learn more about the structural engineering following the workshop.

Given the overall objective of this paper is to provide useful and actionable insights and learning modules to instructors and scientists teaching structural engineering at university level as well as dealing with promotion of science to attract high-school students to civil engineering university study programs, all data and teaching materials presented in the paper are made openly available. It is our

hope the community finds some of the presented ideas and best practices useful to adopt and adapt for their work.

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Declaration of Interest

None.

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