Emerging technologies for a dynamic learning

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We present our experience in the development and delivery of a project-based learning activity for an undergraduate Dynamics module, aimed at encouraging a participatory and dynamic learning environment. Using emerging technologies such as 3D printing, open-source electronics and freeware, we devise, implement and assess a 'design-manufacture-and-test' assignment. The activity presents the students with an open-ended design problem and guides them through the formulation and construction of their own knowledge base. Throughout this process, students gain awareness of the importance of structural form (as opposed to mere sizing) and engineering creativity. They are encouraged to think about aesthetics, consider the use of new materials of uncertain behaviour under variable loads, take into account fabrication and construction methods early on in the design process, and address the potential limitations of numerical and analytical models. We start this article by describing our experience and its context, continue it by recounting our achievements and proposing some potential modifications. We conclude by highlighting the exciting possibilities of dissemination that lie ahead.

Background

Developing a sound understanding of Mechanics is crucial for the success of structural engineers. A recent report commissioned by the MIT[1] on the current state of engineering education highlights a focus in academic rigor and a deep knowledge of the 'fundamentals'

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[1] Ruth Graham, The Global State of the Art in Engineering Education, New Engineering Education Transformation Massachusetts Institute of Technology, March 2018

as distinctive marks of those institutions emerging as leaders in engineering education. Yet, traditional teaching methods run the risk of inculcating the much-needed know-how at the expense of killing the creativity and enthusiasm of students on the subject. In our experience, this dilemma is particularly poignant in the teaching of Dynamics at the undergraduate level. After spending 2 or 3 years of their graduate education learning Statics, Solid Mechanics or other fundamental engineering modules, students on a traditional UK MEng course come to Dynamics accustomed to simplify and abstract problems to the verge of epistemological naivety. A mature engineer will easily recognise the contingency and limitations of her/his own models and will have little trouble in contextualizing this understanding. From the educators' perspective, we have spent the first 2 years simplifying and compartmentalizing knowledge in the hope that the complexities of engineering practice will be added sometime later. This rarely works out as intended. Used to deal with precisely defined loading, unfamiliar with the effects of temporally evolving actions, and lacking the motivation to anticipate real world eventualities, the student will quickly assume that the purpose of Dynamics is to solve the abstract Equation of Motion in order to obtain some irrelevant numbers for filling the homework sheet. Some will float, some will sink. Many will hate it.

The challenge of instigating the ability to anticipate the dynamic response of structures was highlighted by a recent blind prediction contest on a single bridge pier tested at the UCSD[2] (Figure 2). The contest attracted over 40 submissions from expert teams around the world and yielded a surprisingly large range of wrong estimations. It is true that the very simplicity of the structure bolsters the effect of dynamic nonlinearities. Even so, the results of the blind prediction stressed the pervasiveness of false modelling assumptions and called into question the widespread overreliance on "advanced" modelling techniques. The practical implications of which are nicely encapsulated in Prof Mete Sozen's aphorism: *"If we are going to be wrong, we should be wrong the easy way"*.

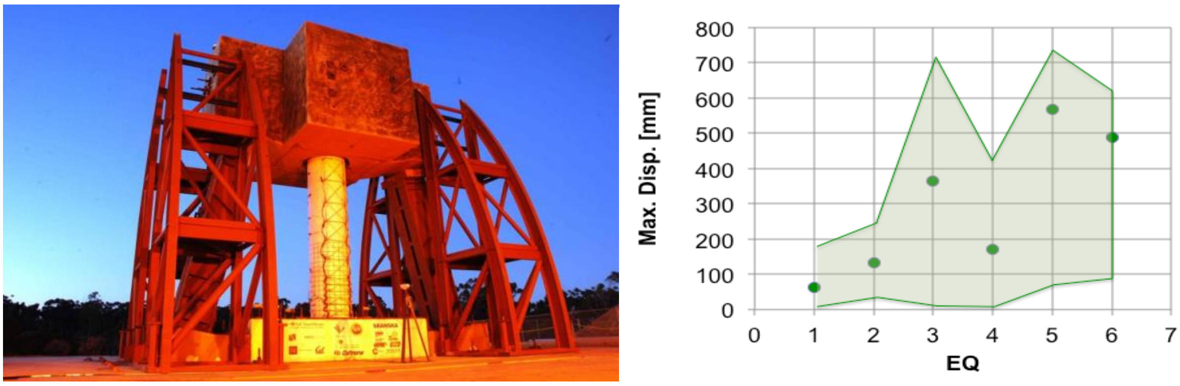

Figure 2. Blind prediction contest on the dynamic response of a full-scale RC bridge pier[2]. The area on the left shows the range of blind predictions and the dots the experimentally observed deformations.

An engineer should, undoubtedly, be able to distinguish the parts of the problem in need of careful attention and precision, from the imponderable aspects of it; and identify which components have the potential for altering, even dramatically, her/his estimations. This

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[2] Vesna Terzic, Matthew J. Schoettler, José I. Restrepo, Stephen A. Mahin, Concrete Column Blind Prediction Contest: Outcomes and Observations, PEER Report No. 2015/01, Pacific Earthquake Engineering Research Center, University of California, Berkeley, March 2015

engineering ability is forged by hours of reflection, field experience, real problem-solving and reflective failure. A student, immersed in the customer-pleasing fast-paced environment of today's neoliberal university, will have had no such luxury of time or opportunity. And this chasm between site and classroom may be deepened if students are routinely taught by scientists instead of engineers[3]. Furthermore, experimentation in structural dynamics, has traditionally required expensive equipment which further hampers its widespread adoption in the classroom. The project we propose and implement below, aims to overcome these limitations, offering the possibility of dynamic design and experimentation in a controlled environment and at a very low direct cost (under £350 in equipment). The activity also stimulates team work, research, reflective failure, risk assessment and multi-dimensional thinking; abilities that are at the heart of good engineering practice. The module to which this activity contributes is lead and delivered by the first author and it runs on the third year of a four-year MEng course. Students taking this module would have passed courses on Creative Design, Mechanics, Structural Mechanics, and Structural Design, among others.

The project

Students were tasked with the design of a model structure to carry a given permanent (gravity) load. Each team (of 8 members) had to deliver detailed digital models of their structure to be 3D-printed, according to their own specifications. The structures were to survive 3 different base-motions (or earthquakes) with pre-defined amplitudes and frequencies of shaking. The structure also had to respect maximum displacement (drift) and acceleration limits, much like those imposed in typical earthquake-resistant design. Very importantly, in order to represent societal and economical demands, the structure was to be efficient (use the least amount of material possible) and aesthetically pleasing. No configuration, span length, or element distribution was imposed on the students, other than the need to provide a number of holes for fixing the structure to the shaking table. Each team had the freedom to explore a structural configuration and form of their own choosing. Besides, a selection of 3D-printing materials was made available to them as well as the possibility of adding supplemental masses if needed. The teams worked independently, but were offered constant one-to-one attention and the possibility to arrange individual discussions whenever needed throughout the design and testing process lasting several weeks.

Several basic knowledge blocks and technical challenges had to be in place before the students were in a position to tackle the assignment. Besides the basic principles of forced harmonically-exited structures, and the fundamentals of the engineering design process, the students were introduced, via recorded lectures (that could be accessed if and when needed), to the principles of 3D-computer drafting. Another session presented them with the basics of 3D printing, and a full lecture was devoted to aspects of experimental testing and measurement. In this respect, the students quickly realised the importance of printing direction and fabrication in the mechanical response of their models, typical dimensional constraints, fabrication precision (or lack of it), requirements for temporary structural

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[3] Devlin Montfort, Shane brown, Dawn Shinew, The Personal Epistemologies of Civil Engineering Faculty, Journal of Engineering Education, July 2014

supports, and experimental errors. In the absence of codified guidance for structural design in fused deposited materials (3D-printed), the students had to think in terms of first principles and fundamental reliability concepts.

The issue of structural aesthetics deserved special attention. A discussion involving the whole class explored the natural apprehension related to the perceived arbitrariness of judging beauty in engineering. To this end, the formal concept of structural art, developed by Prof Billington[4] at Princeton was introduced and relevant bibliography was offered. It was essential that students understood that 'elegance is not ornamentation' and that a good and pleasing design arises from engineering creativity and efficiency and not just from architectural wishing. The cohort unanimously agreed that this aspect of the design deserved an important role in the evaluation.

Figure 3. Various designs were produced and manufactured including column piers, frames, and shell structures. (Note: Holes in the base are for clamping purposes).

A significant constraint to dynamic experimentation, already mentioned above, is the high costs of the actuating and measuring equipment. This aspect is further complicated when advance 'black-box' control software and 'specialized' computer interfaces are employed. We manged to avoid all these complications by employing free open-source electronics and in-house software. To this end, we constructed our own uni-axial shaking table employing an Arduino-controlled servo-mechanical system rolling on two guiding metal shafts and Plexiglas bases (Figure 4). The electronic supplies are not only cheap, but they require minimum levels of prior knowledge and are now of widespread use among young engineers. The table is highly reliable and fully operational for frequencies up to 4-5 Hz with strokes of +- 30 mm. Similarly, low-cost MEMs accelerometers connected to a second Arduino board were employed to measure accelerations at the table and the structure. We also took advantage of open-source

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[4] David P. Billington, The Tower and the Bridge: The New Art of Structural Engineering, 1985

software and freeware like Google Sketch-up for the production of 3D digital models, and Tracker[5] for the collection of displacement histories from post-processed videos taken with mobile devices.

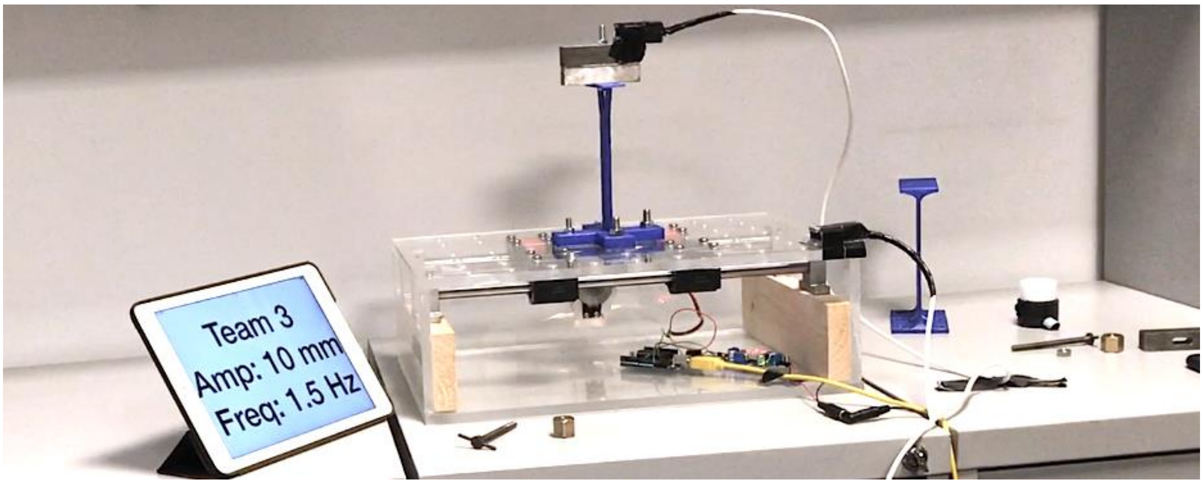

Figure 4. A structure ready to be tested on our Arduino-controlled shaking table.

Student learning process and reception

Each team was encouraged to explore their own group dynamics and design strategy and produced a range of different structural designs. Most of them utilized a divergence-convergence approach with several stages of design optimisation along the way. Although a natural discomfort and predisposition against open-ended questions was expressed during the initial stages of the project: *"I just don't like problems that can be answered in many different ways"*[6], all students achieved an excellent level of satisfaction from the task, including the teams whose structures underperformed. The importance of considering more than one dimension of the problem and the freedom to explore different structural forms was progressively appreciated: *"Our team experienced difficulties when trying to meet all design criteria initially while leaving a certain margin of error for most parameters. It was hence important to decide which parameters were more critical"*. In this respect, the students quickly understood the importance of (3D) drafting as a tool for idea communication and technical discussion: *"Drawing the design was effective in communicating the ideas within our team, and we were able to use our 3D drawing to clarify any misconceptions about the final product".* They also realized rapidly the importance of incorporating an understanding the fabrication (construction) process during the whole design stage and took informed decisions to adapt their design process accordingly: *"To produce the model, understanding the 3D printing technology was extremely important"*. The students were able to defend their own

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[5] Brown Douglas, Christian Wolfgang, Simulating What You See: Combining Computer Modeling With Video Analysis, MPTL 16 – HSCI 2011, Ljubljana 15 -17, 2011

[6] Students comments are taken from course reports, anonymous student surveys, and personal communications

aesthetic choices: *"Having to comply with all criteria, suggests to us that elegance can also be defined by simplicity"*, *"Having to comply with the criteria of efficiency, economy and elegance, we have proposed a minimalistic design"*.

Noteworthy, the contingency of engineering models and the difficulties in translating of-the-shelf formulations to real structural details was well comprehended by most teams: *"We should have accounted for the fact that the actual testing frequency is not exactly equal to the one we input "*, *"…assumptions should always be valid and checked for. Approximating our walls as fixed-fixed column was invalid [due to lack of detailing to ensure it] and influenced our results adversely"*. Very importantly, the students were offered the possibility of reflecting on the performance of their initial design and propose future modifications to it: *"Back analysis is a powerful tool which allows us to properly understand the real behaviour of our structure, and the small discrepancies with the theoretical values"*. Overall, the students enjoyed the experience and expressed good levels of empowerment: *"[This project] is relatively difficult but very rewarding, the group was able to come to a general understanding of the design procedure"*, *"The coursework was very interesting and intellectually stimulating!"*, *"The coursework was very interesting and cool, I enjoyed it a lot"*.

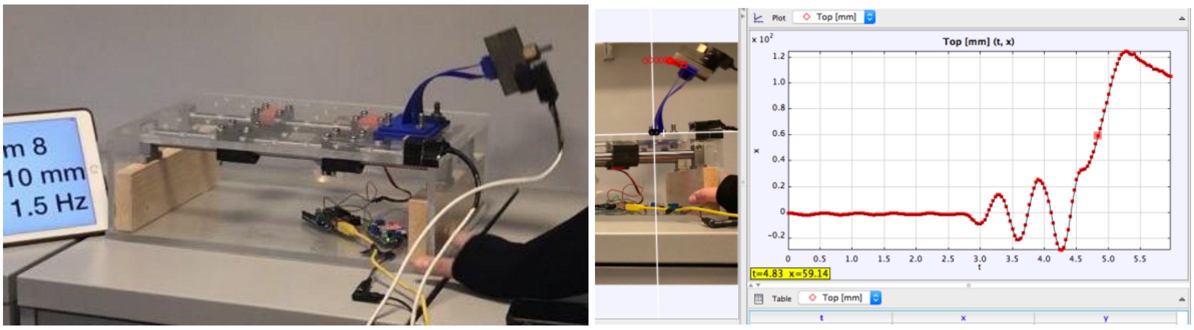

Figure 5. Structure after failure and corresponding displacement history. All videos can be accessed in [7]

Next steps

Sadly, the readiness to think 'advanced' computer models have the right answers without regard for the role of prior assumptions and lack of input information seems to have persisted in one particular team: *"Nowadays, there're more advanced software... For instance A[xxxx]s, which uses Finite Element Analysis to simulate the loading conditions applied to the structure and its dynamic responses, may produce more comprehensive results than from our hand calculations and checks".* This perception was rather circumscribed and in direct tension with the awareness of the approximate nature of modelling: *"We were also able to gain appreciation of the idealised nature of our models and equations"*. This contradicting result may be alleviated by allowing the students to perform their own FE modelling and comparisons in the future. Other modifications for future versions of the project include the

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[7] Link to videos: https://goo.gl/7cJZcA

provision of response modification devices of easy prototyping via additive manufacturing, like tuned, inertial or liquid mass dampers, to expand the experience towards increasingly more complicated dynamic phenomena.

More exiting perhaps, are the endless possibilities of replication opened up by the project. The low-cost, wholly open-source nature of the project encourage international knowledge transfer and collaboration. It frees engineering education from the bounds of a particular classroom. The project has grasped the attention of science and engineering organizations in Latin America and we are currently coordinating a delivery of an updated version of it in the form of an international workshop in Peru. Our vision is to make the design, manufacture, calibration, and operational data of all our in-house low-cost equipment available (at no cost) to the wider engineering community, so anyone, anywhere, can use it to build their own. We are already taking steps to make all designs, list of components, calibration manuals, etc, readily available online [8].

Concluding remarks

The project presented here fulfilled its educational aim since the students performed, generally, at a very high standard. The reflective nature, back analysis, and rapid feedback loops allowed by the innovative aspects of this project (including rapid prototyping) delivered important learning enhancements of a subject that is usually perceived as difficult. Besides, the combined attraction of new technologies like 3D printing and open-electronics, represent an enticing opportunity for reaching young engineers that the engineering education community is encouraged to explore. The experience we have presented here favours a deeper understanding of the challenges associated with engineering design and lateral thinking. It brings to life the theoretical material on the challenging subject of dynamics and allows future engineers to construct their own knowledge base via physical experimentation. Importantly, the open-source and low-cost nature of the project is opening the door for sustained international replications. At the end of the day: ‘Experience is knowledge. All the rest is information.’[9]

Acknowledgments

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[8] http://www.imperial.ac.uk/emerging-structural-technologies/teaching/

[9] Attributed to Albert Einstein