Understanding of structural behaviour

How can academics make the learning and teaching of structural behaviour more effective? What is the role of academics in better preparing graduates to meet industry expectations?

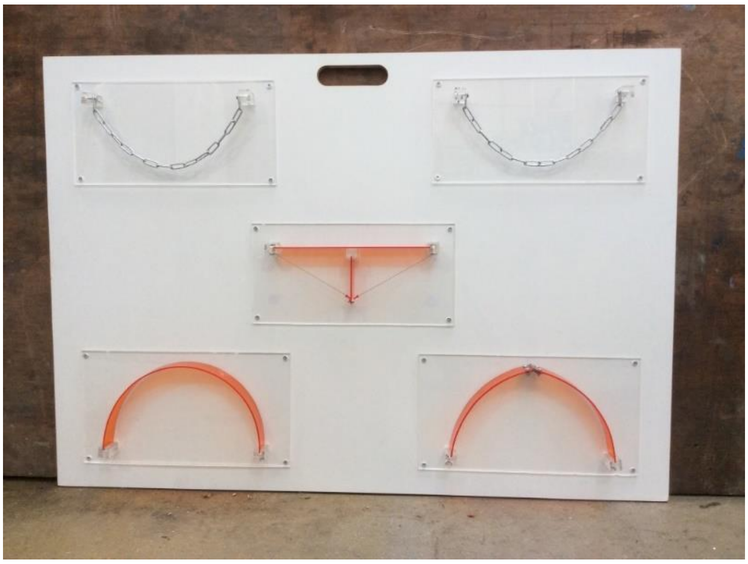
Taking into considerations the limited resources available and the timelines required to implement substantial changes into curricula, this resource sheet looks at ways to improve existing programmes and focuses on 1 aspect of understanding structural behaviour: **Using physical models (e.g. MOLA)**

1. Learning outcomes	To use physical models to correctly predict the behaviour of real structures, ideally through exaggerated movements (in other words, don't make the model too stiff, such that movements / deflections / rotations can't easily be observed).
	To reinforce theory from structural analysis and structural design modules, making often abstract concepts a reality (such as buckling, for example).
	The physical models should be related to the relevant theory, and ideally be compared to both real / actual structures (which could be illustrated using drawings, photos and potentially site visits) and computer analysis models.
	To develop an understanding of load paths, as well as robustness and disproportionate collapse.
	To develop an understanding of the relationship between bending, deflection, rotation and points of contraflexure (for example).
	To provide a good understanding of lateral stability, including (but not limited to) braced and non-braced frames, for example. Also refer to the following publications: IStructE TGN 10: [Technical Guidance Note (Level 1, No. 10): Principles of lateral stability - The Institution of Structural Engineers (istructe.org)] Chapter 9 of IStructE publication 'Conceptual design of buildings': [Conceptual design of buildings - The Institution of Structural Engineers (istructe.org)]

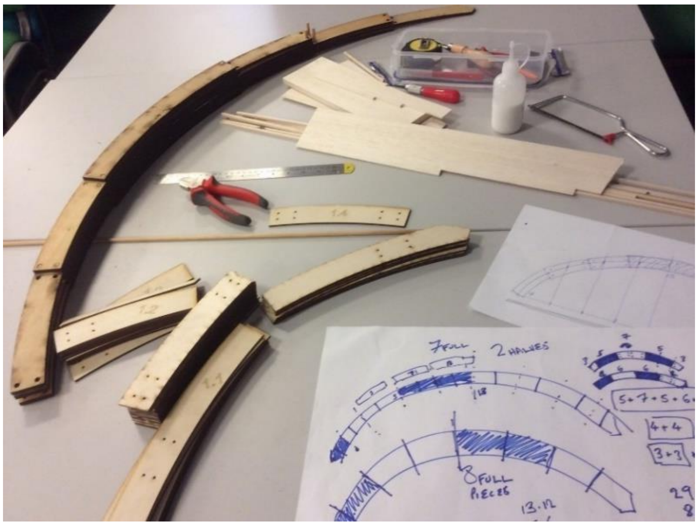
2. Assessment and feedback	Design and build / construct: this method is quantitative, and hence lends itself to being assessed and for providing feedback.
	Working in groups allows peer feedback to be provided.
	Formative feedback can be provided using 'Mentimeter' (or similar apps), in which students can state their predictions. For further details go to: Interactive presentation software - Mentimeter Mentimeter - YouTube
	Short formative quizzes to be done individually during lectures / teaching sessions (ideally anonymised to maximise participation).
	Self-directed group work, assessing a range of models, with a quiz sheet for guidance / prompts etc. Could follow up with a short presentation for groups to present their findings. Tutors could feedback on what students did well, and any common errors or misunderstandings.
	Assessment should test understanding of key concepts and first principles, but should not be a memory test. Could also ask students how / why they gave their answers. Again, Tutors could feedback on what students did well, and any common errors or misunderstandings.
	Use vivas as a way of assessing level of understanding of key concepts and first principles.
	Get students to reflect on what they have learnt.
3. Teaching methods: examples of best practice	Carry out a shaking table test on a timber tower (as done at University of Bristol). Could use other materials, and various types of tower structure (e.g. braced and unbraced frames, different bracing options / configurations etc.)
	Use a pack of playing cards to demonstrate shear?
	Building a water tower model, and assessing how much load 9eater) it can support.
	Take measurements from physical models (e.g. deflection / stress / natural frequency) and compare with theory and computer analysis output.
	Change key parameters of a model (e.g. section sizes, member connections, supports) to see how this affects its structural behaviour.

	Use physical models to test key assumptions about their behaviour, and how accurately these can be replicated in the model.
	Use researched informed teaching to inspire students.
	The following resources, developed by Tianjian Ji and Adrianm Bell from The University of Manchester, make excellent use of physical models (and real structures) to demonstrate key concepts: Microsoft PowerPoint - ucasdis (manchester.ac.uk) Seeing and Touching Structural Concepts (manchester.ac.uk)
	Whilst not falling into the category of physical models, the following resources from Expedition also contain some excellent material: www.expeditionworkshed.org www.expeditionworkshed.org/workshed/push-me-pull-me/
4. Opportunities and challenges	**Opportunities:** Provide sufficient models for students (working in small groups) to build and play with / test the models themselves, as a method of discovery (i.e. as opposed to watching someone else do it at the front of the room). Use models to demonstrate key concepts such as lateral stability, buckling effects and seismic loading for example. Use a range of small scale and large scale models to illustrate different concepts (e.g. some models might include just primary structural elements / members, whilst others might also include secondary members). Relate behaviour of models to relevant theory, and also demonstrate behaviour using lab tests and computer models (where appropriate). MOLA (or similar modelling kits, such as Meccano perhaps) can be used to build braced and non-braced frames (for example). Get students to build their own physical models, potentially using laser cutting equipment and 3D printing facilities on campus. Similarly, get students to build their own physical models using readily available materials, such as elastic bands and chopsticks (for example). This should also help to develop an understanding of the properties of different materials, relating to stress / strain behaviour, ductility, brittle failure etc. Build physical models which relate to structures students see on site visits, or even structures which students get to build on Constructionarium (for example). Building models could be integrated into larger design projects. Adopt a consistent approach to learning and teaching, and ideally use models in a number of modules (and ideally in both analysis and design modules).

	Involve industry in sessions, and potentially to judge /award prizes for the best models. Building / playing with / testing physical models also helps to develop groupwork and communications skills (for example). Get students to reflect on the process.
	Challenges: It's essential to answer the 'so what' question(s), so that students understand what they are doing and why / what the relevant theory and applications are. Avoid the adoption of a 'recipe book' type approach. Focusing on appropriate models for the topic / concept / behaviour being demonstrated. Cost of making or buying physical models, and subsequent time / cost of any setting up and/ or maintenance requirements. Time to make physical models, and storage of physical models. Inertia from teaching staff / time to develop new learning and teaching resources etc. Physical models potentially don't cover uncertainty or more complex issues / structural arrangements. Also, physical models are only an approximation of reality (as are computer models) Not suitable for big groups (say 6 students per group maximum?). Need to ensure exercises are inclusive, as opposed to being dominated by a small number of the students in a group.
5. Strategies for implementation throughout existing curricula	Ideally need to adopt a 'Programme Level Approach', with buy in from all staff involved in the learning and teaching of Structural Analysis and Structural Design. This might include reducing the time spent traditional theory / analysis methods, which are potentially no longer used in practice expect perhaps to check computer analysis output. Need to ensure sufficient funding is available to procure enough model kits (or materials if self-building models) to enable students to work in small groups. Provide sufficient time in the curriculum. Provide suitable workrooms / labs to build models in.

6. Post-meeting notes and additional resources	***Post-workshop thoughts from organisers:*** Overall learning outcome = To use physical models to develop an intuitive feel / understanding for how a range of common structural forms behave when subject to applied gravity and lateral loads / external actions, potentially considering bending moments, shear forces, axial forces, support reactions, over-turning, sliding and serviceability (i.e. deflection and vibration / dynamics) as appropriate. Ideally involve students in the making of the physical models, some examples of which are shown over. Over is one of a series of physical model boards, created by Technicians at the University of Sheffield (TUoS), which were mounted on walls for students to use / play with (in this case showing catenaries, a thrust beam, 2-pinned and 3-pinned arches):  Next is a large scale (7.2m long) cable stayed bridge, designed and fabricated by staff and students at TUoS: 

Laser cutting equipment can be used by staff and students to create a diverse range of small-scale physical models from wood and Perspex sheets:



Re-enacting the famous ‘Forth Rail Bridge’ model can also be a fun and educational exercise (unless of course you get the geometry wrong, in which case it can be hard work!):

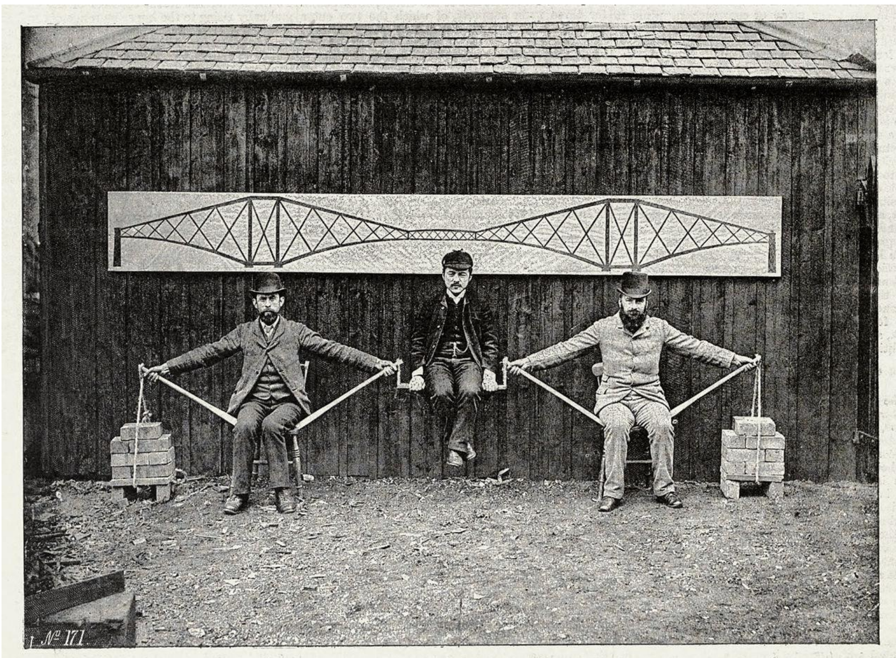
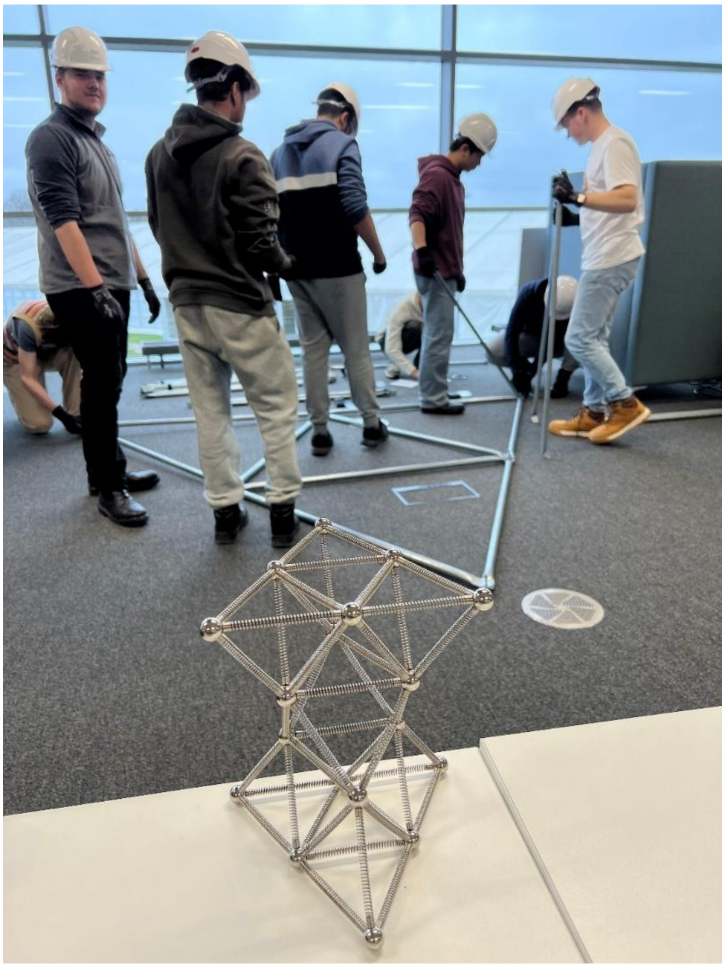


Fig. 5a. Living model illustrating principle of the Forth Bridge.

Next are a range of exercises using physical models provided by the University of Surrey, the first showing the load testing of a cardboard bridge model made by some of their students:

Tabletop ‘Mola’ models are used to understand the geometry / design / construction of full-scale lattice structures (as shown at the bottom of this page):



Here are some full-scale lattice structures, to help students understand triangulation and structural stability:

Tensile membrane structures are used to understand pre-tensioning and structural stability (note that similar small-scale models can be quickly and easily built using timber dowels, cotton thread and tights or similar):

Finally, these models utilise three different connection systems for bamboo structures. From left, hybrid bamboo & tubular steel elements, bamboo triangular elements with duplicated edge members and steel nodular connections: