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Educating the Next Generation of Structural Engineers

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ABSTRACT

One of the most important attributes of our structural engineering profession is that it is highly creative. This creativity should be exploited endlessly by educators of the next generation of structural engineers because creativity leads to passion, which leads to inspiration, which leads to students learning almost everything they need to know themselves. This is true education for life-long learning, without boundaries. This paper attempts to demonstrate how this form of learning is possible within structural engineering education.

INSPIRATION

Good structural engineering education requires an inspirational learning environment. Students should be inspired to want to learn, rather than be taught, such that they carry with them this motivational benefit throughout their career. Therefore, it is quite imperative that universities employ inspirational structural engineering academics. In general, I believe that this is indeed the case. After all, how can anyone interested in engineering not be enthusiastic about some of the extraordinary structures around us? I feel it is essential that raw structural intuition which exists in a 17-year-old should never be crushed by a codified approach to 'designing' vertical columns and horizontal flooring systems by the time the same person reaches senior year of a civil engineering degree. A way to ensure that intuition is retained is to keep it all fun. Sketching and model making must be high on the agenda.

Within a research-led environment, it is imperative that students are allowed to experiment with structural engineering ideas throughout their degree programme. To do this effectively, it is important to expose students to conceptual design at the earliest stage of their studies. The first week of freshers' year is a good time to start. Developing an innate appreciation of structural behaviour in its broadest sense is in danger of not developing fully if a student is given closed-form elemental sizing 'design' exercises in the early years, followed by a broader design problem in senior year. Conceptual structural design should come first, and the ensuing analytical and sizing issues should lead on in a natural manner as the student comes to understand the educational gaps which need to be plugged in order to realise her/his initial structural ambition.

CREATIVE DESIGN

In order to achieve this natural progression, a profound embedment of creative design projects is required across a curriculum. It is during these frequent design projects that industrial tutoring is of immense benefit. In the joint Department of Architecture and Civil Engineering at the University of Bath in the UK, we are extremely fortunate to have developed dedicated design studio infrastructure for all students and a suitable operating budget to buy in industrial tutoring. Although each design project we run is led by an in-

house academic, almost all design tutoring is conducted by bought-in tutors. Such tutoring is central to our cause, offering a real-world design perspective to our students and reinforcing a culture of creative professionalism, including ethics and integrity. Tutors range from eminent world-leading professionals to recent graduates, and from architects to structural engineers to building physicists to geotechnical engineers. This inter-disciplinary range of industrial tutoring ensures that holistic design is core to success.

As an example, our university recently chose to replace its most intensely used footbridge. We used this opportunity to lead a final-year student project to design the new bridge. The winning entry was to be used as the basis for the replacement bridge. The project led to some extraordinary innovation from our students. It is quite imperative that students feel the freedom to innovate structurally, without constantly considering ‘How am I going to analyse this structure?’. Of course, design feasibility is paramount and we ensure that the structural analysis is sufficient to demonstrate this feasibility. But structural analysis is not an end in itself; rather, it supports the design process and is only one of the tools needed to ensure a successful design.

Students come to realise rather quickly that good structural design is not about sizing members or following codified rules. It is about producing a structural concept which leads to the satisfaction of an holistic set of requirements, including architectural, environmental, building-physics, material, geotechnical, sustainability and construction issues. They also quickly realise that structural analysis is not about understanding matrices or finite-element formulations. It is about appreciating structural behaviour holistically, such that understanding materials, modelling form & connectivity, using simplified structural models and checking any computational output are at the forefront of the learning experience. As engineering is all about problem solving, and intuition plays an enormous part in this, students’ intuition is fuelled continually while they realise that they need to know more technical things in order to solve even more convincingly the design problems which they have been given. Conversely, if projects build up slowly from freshers’ year according to what students already know, they will be hamstrung by this knowledge and will tailor their solutions to the known. This isn’t good enough. Students must be given room to make mistakes without fear of this holding them back in any way. Stretching design projects, embedded throughout a degree programme, allow all of the above to occur in an inspiring atmosphere. Education is about drawing out, not shovelling in.



Figure 1. Fresher’s single-sheet design with accompanying model.



Figure 2. Senior students' design outputs, representing an holistic outlook.

The most illustrious names in our profession worldwide are indeed well known because they are creative. Yes, their analytical skills are top-notch too. But so are those of many others who are not well known. Creativity is the real heart of our profession at its best, and this fact needs to form the basis of our education in structural engineering, in my opinion. All throughout my undergraduate career, I wanted to know how an egg worked, and I wanted to know why we weren't being taught to take advantage of such a brilliant structure. I worry that the very necessary creativity, fun and intuition involved in world-leading structural engineering is sometimes sucked out of engineering degree programmes such that a graduate considers the entire language of structural engineering to be columns, beams and slabs. It remains a central theme to me that intuition, exploitation of materials and creativity lie at the heart of great structural engineering.

USING MATERIALS AS AN INSPIRATION

We introduce our freshers to the extraordinary potential breadth of construction materials available to them. We do this as early as possible, to help drive curiosity associated with structural engineering innovation. The students are each asked to write a 2-page paper on a particular material. The list does not include the generic main four materials. Example materials from such a list include limecrete, super-sulphate-cement concrete, waste-aggregate concrete, re-used steel, stainless steel, cables, nets, recycled aluminium, bamboo, green timber, timber-in-the-round, CLT, glulam, LVL, inside-out timber, timber laths for gridshells, tension membranes, GFRP, ETFE, structural glass, Bath stone, rammed earth, unfired clay bricks, reinforced masonry, gabions, strawbale, hemp, wattle & daub, natural fibres, cardboard, etc. Students are expected to describe the structural properties, present case studies, present a SWOT analysis of the material, and analyse its carbon credentials. The papers are collated, and each student grades each paper in a peer-assessment approach to ensure that each student has read every paper. In this way, the primary learning outcome is an immediate fascination with the breadth and opportunity of structural materials available to them. The secondary learning outcome is an appreciation of the importance of sustainability to structural engineers. Of course, more in-depth coverage of the four main materials follows in later years, as does coverage of some of the other materials listed above.

With material appreciation in mind, the same freshers are then asked to design in groups a conceptually-open structure. In 2013/14, this was an Engineers-Without-Borders-style rural-village water tower. In groups, the students designed the tower (by assuming the use of 10 old timber poles left lying around in a local swamp) and provided method statements, handed

their designs on to another group for checking, and finally handed their designs on to a further group for construction of a model of the tower, which was then tested to destruction under live loading (an incrementally-filled bucket of water). The core learning outcomes in this project are always innovation in thought when resource is scarce, good communication of a design such that someone *else* can build it (this usually throws the students when they realise that they won't be building their own design), and the concept of watching something fail in an unexpected manner, which is buckling predominantly in this water tower project. The first lecture after these tests is on Euler buckling, which suddenly takes on great significance to the students at this stage.

Another example of how we get students to understand the behaviour of structural materials is through a self-run timber laboratory. Students are given access to a specially constructed four-point bending rig (which is housed in public space with easy access) where they each test the strength of small scale timber beams cut from larger beams which they will previously have tested in groups in the main structures laboratory. Through analysis of the cross section and the load at failure, they are asked to calculate the failure stress and the density of the timber. They submit this data on-line and later, during a lecture, the entire data set is described graphically and statistically, alongside the data from the larger beam tests. This gives them an understanding of size effect, mean strengths, characteristic strengths and relationships with density. Their personal ownership of the data aids their engagement with the material presented.

Alongside understanding the construction process and failure modes, students need to appreciate scaling effects. Right at the start of freshers' year, we ask our students to design a small model (around about 100mm (4 inches) in scale) to satisfy various creative requirements. The model is conceptual in nature, and is conducted by joint groups of architecture and civil engineering students. When complete, we ask them to scale up their model 20 fold, such that they need to build something more realistic in size. The students then exhibit their structures on our campus, which attracts all sorts of interested parties. Many of the structures do not survive very long, given their flexible nature, even though the small model appeared to be stable and stiff. Size effects are embedded immediately and profoundly.

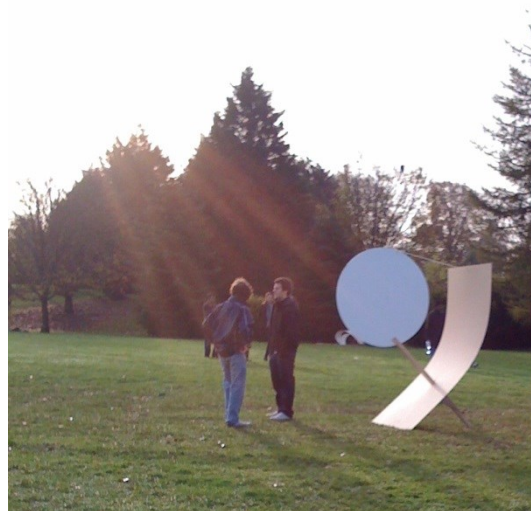


Figure 3. Scaled-up sculptural models demonstrate scaling and size effects.

Students of structural design must also learn how structures can fail. Underfunding of engineering programmes across the HE sector in the UK (Royal Academy of Engineering, 2007) has meant that many universities can no longer afford to make extensive use of ‘build and break’ structures in laboratories. In response to this, we developed a Virtual Concrete Laboratory, which covers the manufacture and testing of 10 major structural concrete tests. Students now watch this video, download the tutorials associated with each test, and dwell on the characteristics of the failures at will. This led to The Concrete Centre approaching us to partner with them and Imperial College to develop this prototype resource into a *global* facility. Structural engineering students across the world can now use this free resource (http://www.concretecentre.com/online_services/webcasts/behaviour_reinforced_concrete.aspx) to see how concrete structures fail, linking theory with reality.

PHYSICAL MODELS

One of the biggest challenges to engineering students is attempting to visualise structural behaviour. Structural behaviour is not about manipulating equations or matrices, but a physical process. It therefore seems obvious that we should be using physical models to help demonstrate this behaviour and, through that, provide an intuitive understanding of behaviour which will lead to feasible structural designs. This use of physical models is, of course, not a new idea in itself, but it is a powerful one which we can use to great advantage. There is a temptation to focus on modern electronic media to present ideas to highly computer literate students. While it has greatly expanded the possibilities for presenting ideas and concepts, as the Expedition Workshed project (www.expeditionworkshed.org) demonstrates exceedingly well, the tactile response that a physical model can give, where forces and moments can be applied and felt, must not be underestimated. An example of this at Bath is the use of flexible models made of thin wooden strips used to support the understanding of the analysis of frames and beams. These are physical representations of analytical problems which the students attempt during the sophomore year. Students can play with these physical models, loading them and observing deflected form which, in turn aids their visualisation of bending moments. Furthermore, concepts of static indeterminacy and compatibility can be explored, by allowing support conditions to be altered, and restoring forces or moments applied. This can all be done with relatively cheap and simple flexible strips of wood. Indeed, the students can be asked to make such models.

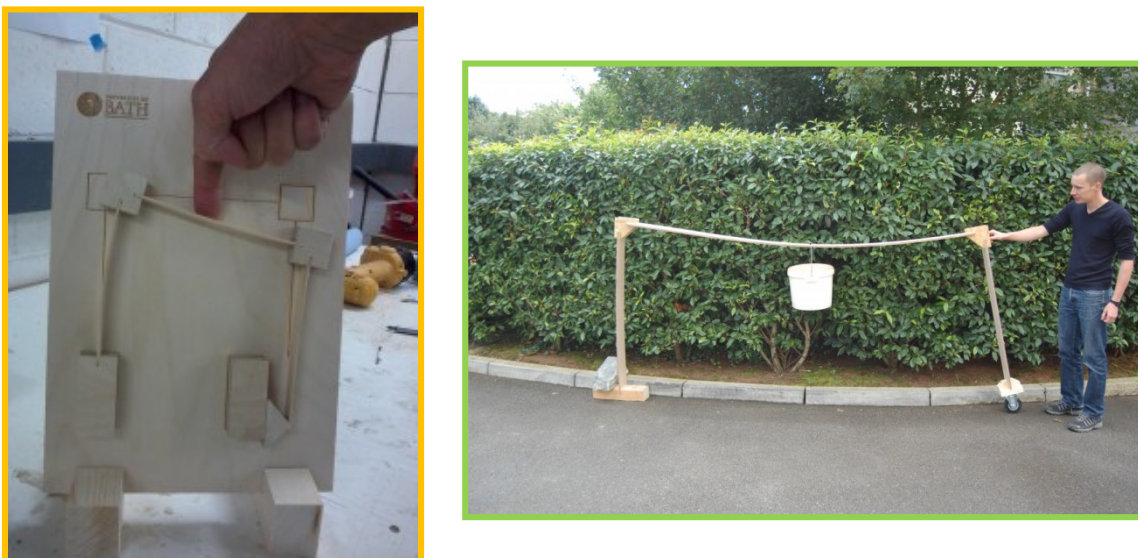


Figure 4. Simple student-made models to demonstrate structural behaviour.

Other models have been developed to help students explore buckling behaviour, prestressing, torsion, bracing, funicular load paths, membrane action and so on. These models are very simple, constructed from steel, timber, plastic, string and elastic bands, with weights to apply loads and household scales to measure forces. These models are available within the department corridors for students to play with whenever they want.

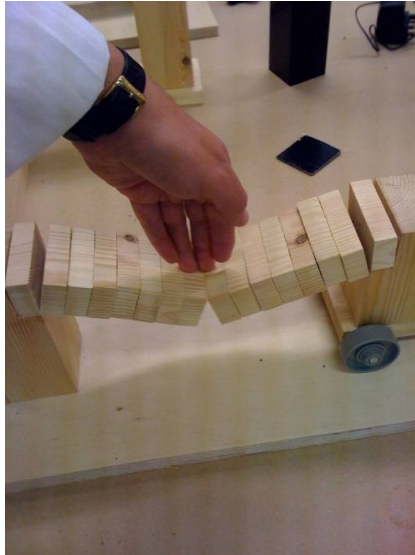


Figure 5. Structural toys available for students.

A small-scale portable shaking table has also been constructed which is used to experiment with the dynamics and stability of structures. Engineering structures are becoming ever more ambitious with taller, longer, more lightweight structures being built all the time. The dynamics of some of these structures is a fundamental driver in the design process and this is an aspect which has become a core part of our course. However, the world of dynamics is often a conceptually challenging one to students. Through use of the shaking table, students can investigate the behaviour of simple elastic systems, observing resonance and mode shapes as well as concepts relating to stability and material choice. This acts as a suitable base for a subsequent earthquake engineering module.

We do not need to limit ourselves to experimenting with small-scale test specimens. Of course, we can, and do, test large-scale structural elements in the laboratory. However, we also have a wealth of buildings and structures all around us which we can use, to obtain a qualitative insight, if not a quantitative understanding of behaviour. For example, as part of the Bridge Engineering course at Bath, we take students over to a footbridge on campus. By loading the bridge with students and using a theodolite to measure the deflection, the students can establish the flexural stiffness of the bridge. This allows the students to estimate the fundamental natural frequency of the bridge. They then, as a group, bounce or jump on the bridge and as simple a device as an iPhone or iPad is used to measure the acceleration response. An App on the iPhone can then be used to calculate the Fourier transform and hence establish the measured natural frequencies. The students clearly enjoy being part of the experiment and, once they realise how simple such investigations can be, they are stimulated to carry out their own investigations into dynamic behaviour using their own mobile devices.

PRECEDENT

University buildings are great opportunities for learning about architecture, structural engineering and building physics. During the first semester of freshers' year, our students are asked to analyse a building of their choice on our campus, and to report their findings on a single A3 sheet. They are asked to draw a structural cross section, to feel the radiators, to feel the windows, to feel the walls, to consider the construction, to discuss the choice of materials, to discuss the acoustics, to discuss the lighting, and to provide a commentary on possible improvements. We see this exercise as important as a simple means to demonstrate a structured approach to the analysis of existing buildings.

In my opinion, most architects probably use precedent study a bit too much. Most structural engineers don't use it enough. It is a simple and effective tool for students of structural engineering to analyse others' work. In their junior year, as part of bridge engineering, our students each choose an existing bridge and write a conference paper on it, to include client requirements, aesthetics, loading, construction, durability, material choice, sizing, maintenance and suggested improvements. Further, at the start of our flagship Sir Basil Spence joint design project in final year (where architecture and civil engineering students work collaboratively on a major building design), we set aside a week at the start for the groups to look at precedents. Learning from others' successes is a trick which I do not believe we exploit as much as we could in structural engineering education. There are some excellent examples of coverage of structural engineering failures in degree programmes at certain universities, and these are immensely important. But, I feel there is a place for analogous provision of structural engineering success stories too, however, and we offer such a module, entitled Architectural Structures. It is our most popular elective.

COMMUNICATION ROUTES

I feel students should feel the need to carry with them a sketchbook, and they should be able to write convincingly and appropriately. They should make structural models of their designs, starting from first year, and they should be encouraged to push and prod them, and to analyse the difficulties they might have experienced in building their model. You cannot do this with a computer screen. And when the design project comes to an end, students should be required to defend their design orally in front of eminent designers.

Students are highly computer literate and are comfortable with accessing material electronically online. However, we must use this material to help support learning, not as a teaching medium in itself. Apart from the profound use of a VLE to supplement learning, Workshed's suite of interactive sites, QSE software and MIT's Interactive Thrust package, we make use of Google Docs to produce multiple-choice quizzes which the students do in their own time on a weekly basis in order to help consolidate the lecture material. These are entirely anonymous and, so, allow students to explore the concepts without the fear or pressure of a formal assessment. However, at the same time the anonymous results are fed back to the lecturer allowing them to see what concepts the students are struggling to understand so that the lecturer can address these issues in a timely manner, before building on the topic further. As another example of using online resources, and as part of our annual student-led Bridge Conference, we have created a map, using Google Maps, which locates the bridges which the students have critiqued. These bridges are across the world. By clicking on the highlighted identifiers on the map, the students can immediately access the conference paper which has been written.

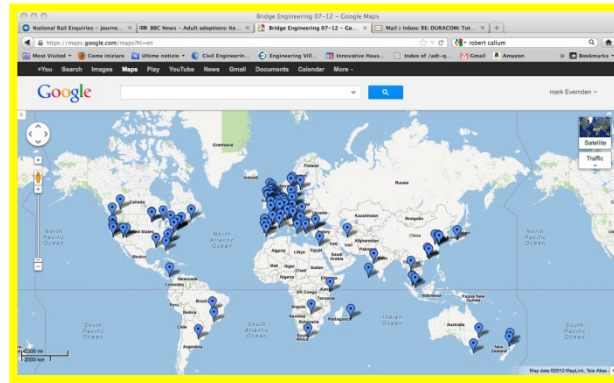


Figure 6. Use of Google Maps to show students’ bridge locations for their papers.

Another way in which we use e-learning is the incorporation of an Audience Response System (ARS) into Structures teaching and assessment. With this system, each student has a wireless ‘clicker’ which they can use to make selections during lectures. ARS can therefore provide channeled responses via the use of multiple-choice questions, using Turning Point slides which run within PowerPoint. Turning Point acts as the interface between the student responses and the PowerPoint display and can be controlled by the lecturer in charge. The major benefit of an ARS over traditional direct questioning is that the system collects responses from *all* participating students, and not just the more vocal members (the use of ARS typically achieves 90 - 100% of class participation), and instantly aggregates and summarises students’ responses for the lecturer. An ARS embodies several key concepts with which the modern student is accustomed, notably the inclusion of ubiquitous technologies, the sense of social networking and interaction, and the instant visual reward for participation. ARS provides the lecturer with a means of engaging the students in a way which fits with the current technological culture.



Figure 7. Oral defence process and the use of clickers.

ARS is used to gauge progression of students in our Structures modules. In a similar way to the on-line multiple choice quizzes described previously, spot tests are carried out during lectures. This is, again, anonymous but allows immediate feedback as to the students’ understanding and thus provides the lecturer with the opportunity to address problems immediately. However, this needs to be used with care since the use of multiple-choice questioning limits the onus on the student to ask their own questions, thereby restricting their

learning experience to the predetermined questions and corrective feedback supplied by the lecturer. Therefore, we do not use ARS as the sole forum for instigating discussion but treat it as one of a number of strategies for identifying levels of understanding.

STRUCTURAL ANALYSIS

So far, this paper has concentrated on structural design education, which I believe should drive the requirements for structural analysis education, not the other way round. The first semester of freshers' year is entirely joint between architecture and civil engineering students at Bath. While all students enter civil engineering with a mathematics background, not all architecture students have A-level mathematics. One of my jobs is to teach this joint first-year class the fundamentals of structural engineering. Because I cannot rely on calculus in the early stages to introduce various basic concepts, as I would lose a chunk of the class, I concentrate on structural behaviour at a more fundamental level, using just algebra, geometry and trigonometry, as appropriate. This apparent handicap turns out to be a fortuitous advantage, as it allows an appropriate mix of 'feel' and mathematics to develop. For instance, I use a simple model of a ribbon stretched between two points (representing zero bending moment at the ends of a simply-supported beam) and then apply uniformly-distributed and concentrated loadings along its length (with the help of various students) to demonstrate the ensuing analogous shapes of bending moment diagrams. This approach extends very successfully into continuous beams or beams with overhangs, and has an immediate resonance with the students.

Six years ago, three of us redesigned the analytical thread of our structural engineering education at Bath. In essence, we pared down the breadth of analytical techniques we teach, we concentrated on ensuring our students understand structural behaviour (deflected shapes, qualitative bending moment diagrams, lines of thrust, etc.) at the expense of some of the more mathematical manipulation which sometimes is expected of students, we looked to ensure that our students can verify computer output using not only hand checks but also the computational tool itself in a sensitivity-analysis approach, and we ensured that our finite-element teaching is aimed at modelling and verification aspects in the main. This exercise was a tremendous success, we believe.

GRADES

However primed in their earlier education, students can, of course, move on from a fixation with accumulation of grades to a real desire for lasting education. This move does not come easily. The difficult, but ultimately essential, approach for long-term success is to ensure that students' education is co-owned by the academic community and by the students themselves. This partnership is extremely powerful. Our students are engaged from the start in our decision-making concerning our taught curricula, and this develops a co-ownership of education amongst the student body. We have full student involvement in teaching enhancement projects, we run focus groups on a range of topics and we have negotiated common expectations on, for instance, assessment and feedback with our students. Importantly, we make considerable efforts to ensure that our students are aware of developments in the Department in relation to both teaching and research. This is not to say that the academic community bows to all requests from our students - far from it. It is a partnership, with all experiences brought on board. In some ways, the combination of staff and students steering the success of their education is much akin to the combination of Civil Engineers and Architects collaborating to achieve outstanding results.

EMBEDDING THE BASICS

For many years, there has been an opinion voiced in the structural engineering industry that the level of understanding of structural behaviour shown by new graduates is dropping. This voice reached a crescendo in the UK two years ago, and the Institution of Structural Engineers decided to do something about it. The Institution of Structural Engineers has over 27,000 members spread across the world, so the legacy of its strategy to improve graduates' understanding of structural behaviour is intended to be global. We have recently launched the Structural Behaviour Examination (SBE), described in more detail later, which aims to provide an international benchmark for the understanding of structural behaviour. There are two aspects to this venture.

The first aspect is the examination itself, which when passed under invigilated conditions will lead to the award of a certificate. When coupled with an Incorporated Engineer qualification, passing of the SBE will allow IEng members to progress to CEng assessment immediately. This package would allow IEng academic qualification holders (Bachelors degree in the UK or Sydney Accord degree outside of the UK) to move to Chartered status via Incorporated status in a relatively fast track process, without the need to submit a Technical Report.

The second aspect of the SBE is formative development of any of our members in structural understanding. Any member of the Institution is now able to download a randomly-generated online test of structural behaviour. By completing this multiple-choice test at one's convenience and as often as one likes (the test will always be different), the understanding of structural behaviour worldwide will improve amongst all members of our Institution. The formative feedback from taking such a test consists of any wrong answers being flagged with reasons given for why they are incorrect. There are presently a little over 200 questions in the database from which these randomly-generated tests are being selected, and numerical values are easily altered from test to test such that additional variety is embedded.

If you have not yet taken this test online, I urge you to do so at www.istructe.org/sbe. Please play as long as you want, and as often as you like. This is why the test is so successful. It allows us to make mistakes in a non-threatening anonymous atmosphere, and to learn deeply from such mistakes and from the reasons given for the mistakes. At my University, we introduced such a system for our students in 2012, and through a related research project on how students learn structural engineering, we discovered that students' understanding of structural behaviour soared from an initial score of around 40% to about 80% after a few attempts using a similar online tool.

The test covers both qualitative (no numbers) and quantitative analysis of trusses, beams and portals. Deflected shapes and approximation of points of contraflexure are the required aspects when indeterminate structures are considered. We have also included plasticity, hanging cables, arches and dynamics in the test. It is crucial that students understand cables and arches as deeply as they understand portals, because profound insight into structural behaviour and appropriate exploitation of materials comes through creative consideration of structural geometry.

It is hoped that universities will embrace the online test, and use it as part of their educational package. Two examples from the test are shown here. In each case, you are asked to choose the correct bending moment diagram (qualitatively for the beam and approximately

quantitatively for the portal). Note that in the UK and many other parts of the world, bending moment diagrams are drawn on the tension side of the element, rather than on the compression side of the element (as in the US). The system adopted in the SBE is that of the British convention.

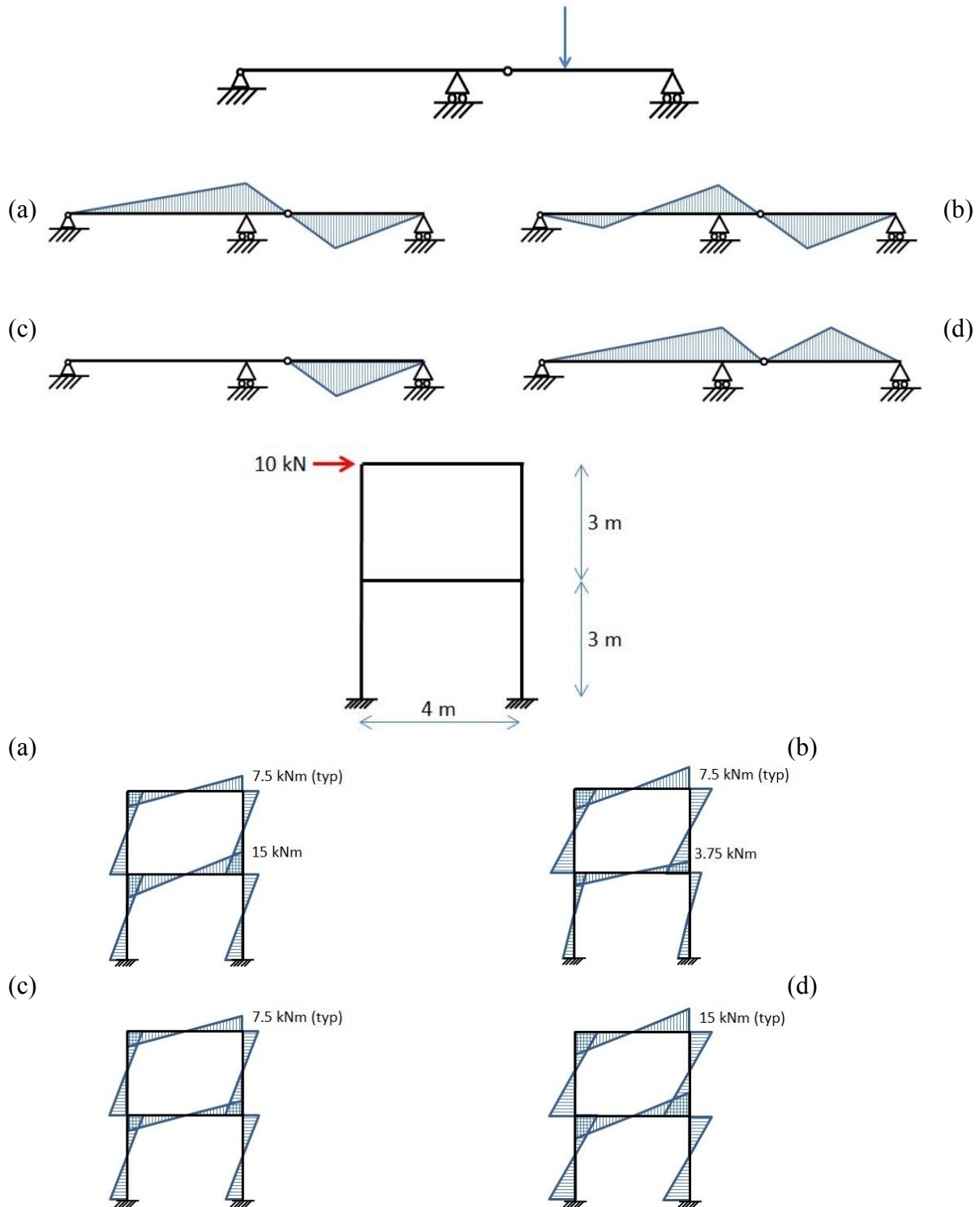


Figure 8. Two examples from the Structural Behaviour Examination ((a) is correct in each case)

CONCLUSIONS

The education of future structural engineers should be fuelled by exploiting the creative side of our profession. Coupled with this, the use of on-line resources which allow students to experiment and make mistakes in a supportive and anonymous atmosphere is one of the keys to deep education. It is the author's belief that the job of structural engineering academics is to inspire graduates to enter the profession of structural engineering. It is not to merely cover the expected curriculum or to suggest to students that an analytical degree programme is a broad-based educational base for any career. This is not good enough, in my opinion.

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