ExpeditionWorkshed: Engineering education for the 21st century

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Summary

The Expedition Workshed (www.expeditionworkshed.org) is an internet based application that carries a wide range of high quality, free-to-use material that will help in the education of engineers. This paper explores the current challenges facing those involved in the education of civil and structural engineers. It goes on to describe how the Workshed sets out to help address those challenges. Among other things the role of interactive online structural models is described along with the development of a new structural modelling application "Catastrophe". The paper concludes with some observations about the success of the initiative to date, as well as setting out the next steps that we plan to take.

Keywords: *structural engineering; civil engineering; teaching resources; new media; education*

1. Introduction

The "Art of Engineering" evolves over time to meet the emerging challenges faced by human society. Similarly the "Art of Educating Engineers" evolves over time to deal with the changing character and needs of: engineering practice; society; students; academics; educational institutions; and teaching technology. As such we should expect evolutionary and sometimes revolutionary change. Moreover, such change will generate winners and losers, both among ideas as well as the people and institutions involved.

We are currently in a period of relatively rapid change in engineering education and this paper starts with a brief overview of the key factors driving this change. We then describe the principles and ideas behind the design of the Workshed. The rest of the paper describes the key content and shows how new media and computational methods combine with established design and educational ideas are all important in the formation of the Workshed.

2. Current issues in engineering education

We have been closely involved with the education of engineers since the late 1990's through teaching, participation in Industrial Liaison Boards and 5 years membership of the Joint Board of Moderators. During this period we have seen significant and rapid changes in Higher Education for Civil & Structural Engineers. Fundamental drivers of change have included: increased student numbers; increased importance of research; and the different character and makeup of the student population, both in terms of their academic formation and attitudes to learning. These drivers have presented very significant challenges to the institutions responsible for engineering education.

For example, academics often observe that the maths and physics standard of students now is materially lower than in the past. Academics also observe that the average student is much less likely to have much physical experience of building kit radios or airplanes, taking motorbikes apart, building bivouacs with the scouts or guides and so on. This makes it more difficult for them to do the courses, which in many cases were designed for the students of decades ago. At the same time many Academics observe that modern students are typically more computer literate and possess better oral and visual presentational skills than their predecessors, as well as being rather more focussed on exam grades and employability.

The traditional educational model, based as it is on lectures, tutorials, laboratories and projects, struggles to cope with the increased student numbers because the staff and space resources available have not generally grown to match the increase in numbers. It is important also to recognise that the traditional model was by no means perfect and many have argued that there are better ways of teaching engineering. Increases in the numbers and type of students simply serve to amplify the deficiencies of the traditional educational model.

Finally, the focus on research in HE means that modern engineering academics are much less likely than their predecessors to have significant experience in practice. This makes it harder (but not impossible) for them to teach design and construction skills, for example.

We are not alone in making such observations on the teaching of structural engineering. Similar conclusions have been drawn by the structural engineering community through various reports and conferences, including: the Arup Foundation commissioned report *The Teaching of Structural Analysis*[1]; David Brohn's report to the IStructE *Qualitative Analysis of Structural Behaviour* [2]; The Civil Engineering Employers Training Group survey in 2008 [3]; and the inaugural IStructE Annual Academics' Conference in September 2009 [4],[5]. One outcome of this activity has been the current IStructE project under the leadership of Dr Graham Owens, Past President of the Institution of Structural Engineers. The paper *Transforming undergraduate engineering education in the 21st Century*, [6] outlines the first stages of this project.

For us and many others the challenge of educating engineers is not solely the responsibility of university departments but is the responsibility of the community of engineering professionals. In that context the Expedition Workshed is one initiative, within a movement across our profession, towards educational improvement.

3. Workshed – Principles

The Expedition Workshed is an internet based application that contains a wide range of high quality, free-to-use material that will help in the education of engineers. The material includes interactive online structural models, structural games, high definition professionally produced videos of material tests, significant projects and inspirational engineers; and downloadable make & do projects. Importantly the Workshed is imagined as a space where many from industry and academe can contribute and get appropriate recognition for their input.

The concept of the Workshed is based on the following ideas and beliefs:

1) The most efficient way for modern academics to spend their teaching time is interacting directly with students, not preparing support material, organising lab sessions or marking.
2) Modern academics do not in general want to be replaced by online learning systems but do welcome high quality resources that they can use to support their efforts.
3) Modern academics are particularly interested in resources that they cannot easily generate or access, for example: high quality video material, project histories and case studies or information about industry leaders.
4) Modern students are used to working and learning through interactive and online media and specifically they are very familiar with online gaming and social networking activities.
5) Modern students have high expectations in terms of production quality of audio visual material.
6) Resource constraints mean that students only spend a small time in laboratories and do not have the chance to experience many of the physical phenomena and materials that they will encounter in practice.
7) Visual observation can be an extremely effective means of developing an understanding of physical phenomena, material characteristics and structural behaviour. This is particularly true of dynamic phenomena.
8) Repetition, interaction and patient practice are fundamental to the development of deep understanding and mastery.
9) A broad general knowledge including of engineering precedent is fundamental to the development and exercise of key engineering activities such as conceptual design.
10) The sustainability of any educational initiative will depend on the existence of an affordable funding model.

11) The internet, modern computational techniques and the reduced cost of modern AV production mean that a web based application could provide an excellent platform for resources to help in the education of engineers.

Workshed content is divided into sections with content style individually tailored to suit the relevant teaching goals. It is not intended as a stand-alone resource, rather to supplement and support classroom teaching.

In developing the portal, we have focussed on incorporating the principles of good design. Specifically we have tried to provide a high quality, user-friendly interface that encourages interactive use of the resource. We believe that this will encourage uptake among users and improve the effectiveness of the learning experience.

There is a widespread apprehension among many experienced engineers about the over-dependence on computational modelling of young engineers, who may not have a proper understanding of underlying engineering principles and phenomena. [7]. As such, Workshed has focussed on resources that help develop qualitative understanding of core engineering principles. The following sections describe some of the content developed to date.

4. Qualitative Interactive Structural Models on the Workshed

Developing an understanding of how structural systems function is an integral part of the education of civil and structural engineers. David Brohn's book *Understanding Structural Analysis*[8], uses sketching to develop students' ability to assess structural systems qualitatively and was the inspiration for a series of interactive structural models demonstrating the behaviour of beams, frames, arches, nets and solids.

Firstly, we develop the linkage between real structures and their schematic representation by starting with renders of real structures showing encastre or pinned connections for example. The user then clicks a button to reveal the schematic model.

The user then interacts with the structural model by pushing and pulling it with the mouse. A series of buttons allow the user to toggle different qualitative outcomes on or off, namely: deformation, reactions, bending moment and shear and axial forces. All of these outcomes change in real time as the user changes the load. Professor Iain MacLeod, Strathclyde University, has commented that *"One of the main issues in the teaching of structural mechanics is to develop an understanding of structural behaviour. This is the arena in which the Workshed will operate and I believe that its potential to improve the quality of learning is high."*

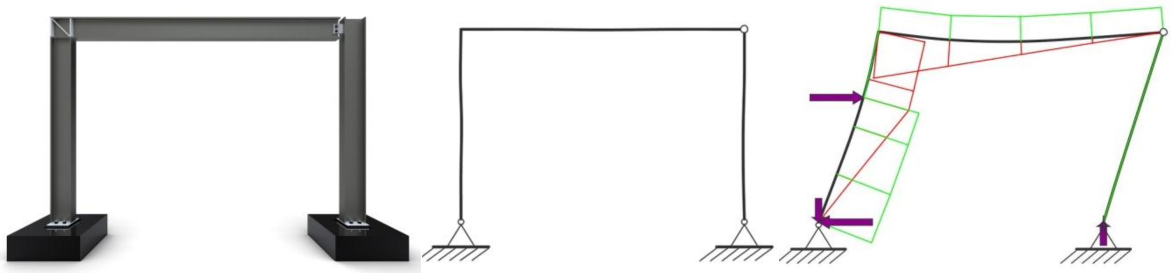

Fig. 1: a) 'Real-life' structure, b) Analysis model,c) User manipulation demonstrating the effect applying a force has on deflection, bending moment and reactions: Have a go here.

5. Materials

Understanding the behaviour of different material and different material combinations is fundamental to the practice of engineering. Workshed's growing materials section is intended to help engineers develop a comprehensive qualitative understanding of a wide range of materials.

It is interesting that many engineers spend much of their time designing systems to avoid failures that they have never seen happen. In part this is because it is simply impractical to cover the huge range of potential materials and failure modes in the limited laboratory time available during an undergraduate degree. For this reason our initial focus has been on providing video clips demonstrating the various failure mechanisms for a range of different materials.

There is nothing particularly new about the idea of filming materials being tested to destruction. Unfortunately, most of the material available online is of relatively poor quality in terms of modern production standards. Moreover the range of material easily available is surprisingly limited.

To produce effective video clip of this type requires proper framing, lighting and camera speed. Working with UCL we used professional lighting equipment and special high-speed digital cameras to shoot bolts, concrete, and glass failing. The use of high speed cameras allows us to view details invisible to the naked eye which is particularly important in brittle failure. The intention is for these clips to be as memorable as the iconic shadow graph image of the shock waves produced by a travelling bullet that many of us remember.

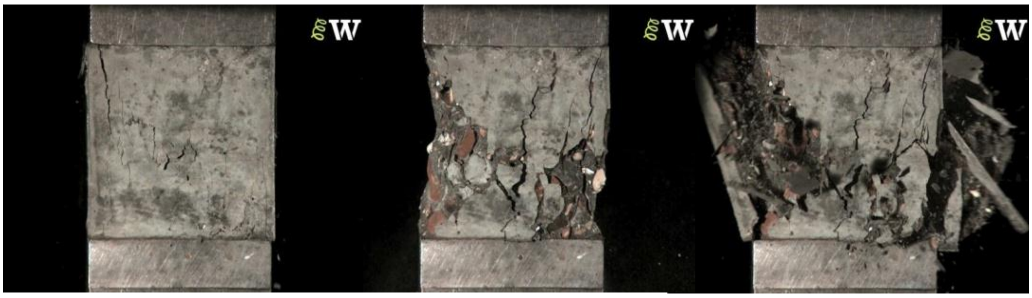

Fig. 2a-c: Stills from a video demonstrating the different stages of concrete undergoing compression failure.

Watch this clip and others here.

Subject to funding being available we plan to film a the impact of fire on structural elements at Edinburgh University and key hydraulic phenomena in the labs at Birmingham University.

6. Project and People Videos

The study of precedent and the opportunity to hear from eminent and successful engineers are important to the education and inspiration of young engineers. As such we have started to compile a library of video clips and images about major and significant projects and engineers. Archive footage is being reformatted into succinct, video clips that include the memorable anecdotes as well as facts and figures. Over time the plan is to build an extensive, and evolving library of material. So far the Institution of Civil Engineers has provided us with huge amounts of information from their archive. Arup, the Building Centre and others have also provided valuable contributions. The success of this part of the Workshed will depend on those from industry being prepared to provide information about their projects and people.

7. Gaming and learning about Complex Structures

Based on discussions with engineering students and academics we believe that there is a significant opportunity to improve the qualitative understanding of structures through online gaming. In effect this would be a modern analogue for the way that people learnt engineering principles through games like Meccano. Properly done this may also provide a useful way to engage with children at school.

The Finite Element Method (FEM) is the main algorithmic technique taught for structural simulation. Although FEM is a very efficient and accurate technique, it is not easily used for online and interactive models, particularly of large and complex structures. This means that to develop online interactive structural models that can be used to explore complex structures or for interactive games we need to develop an alternative to the traditional FEM based tools.

This section describes the work carried out by Gennaro in collaboration with Daniel Piker (Space Symmetry Structures) in this area and specifically in developing the computational application, "Catastrophe" that offers non-experts the possibility of gaining a qualitative understanding of the behaviour of simple and complex structural topologies, for both static and dynamic systems.

7.1. Applied Mechanics based on particle systems

Computational mechanics based on particle systems have been extensively used in computer graphics to simulate phenomena such as explosions, fluid dynamics and materials such as fur and grass. Analytical methods based on particle systems have also been used for the design of tension structures such as those built with cable or fabrics [9] and more generally for the static solution of structures exhibiting material and geometrical non-linearity [10]. Amongst the most used techniques the Force Density Method and Dynamic Relaxation have been utilised for the design of full-scale structures such as the Munich Olympic Stadium by Frei Otto, and more recently the British Museum Great Court Roof, Foster and Partners with Buro Happold.

These algorithmic techniques, implemented in commercially available software, are based on splitting the material continuum into a set of concentrated masses (particles) linked by elements defining how forces propagate through the system. The system oscillates around the equilibrium position due to the presence of out of balance forces, which become null once equilibrium is found through an iterative process (it can be thought of as a discrete integration of their motion). Information regarding position, velocity and acceleration of each node is computed for each iteration and convergence is usually achieved by adding artificial viscous or kinetic damping.

Dynamic Relaxation is widely accepted in the design of tension structures and sophisticated implementation of load transfer, including axial, bending, torsion and instability,[11] as well as high order integration techniques can achieve a high level of accuracy.

7.2. The "Catastrophe" solver

Catastrophe is based on a mass-spring system where particles are linked by linear elements that only have axial stiffness. The main reasons for such simplification are that; the application is designed as a qualitative teaching aid tool with computational efficiency (fast convergence), interactivity and internet access being more important than numerical accuracy. Even so, mass-spring systems have been proven to simulate complex phenomena with a striking resemblance to reality, [12] [13].

An integration algorithm using the velocity Verlet Scheme matched these requirements. The scheme uses finite difference method to approximate the solution of ordinary differential equations. Each particle can be described as an object having mass, position and velocity. The motion of each particle is governed by Newtonian law, ***f=ma***, whose integration according to the velocity Verlet scheme leads to:

$$p(t+\Delta t) = p(t)+\mathbf{v}(t)\Delta t+1/2\mathbf{a}(t)\Delta t^2 \quad (1)$$

$$\mathbf{v}(t+\Delta t/2) = \mathbf{v}(t)+1/2\mathbf{a}(t)\Delta t \quad (2)$$

$$\mathbf{a}(t+\Delta t) = \mathbf{f}(t+\Delta t)/m \quad (3)$$

$$\mathbf{v}(t+\Delta t) = \mathbf{v}(t+\Delta t/2)+1/2\mathbf{a}(t+\Delta t)\Delta t \quad (4)$$

The vectors **p**, **v**, **a** represent position, velocity and acceleration while **f** and **m** are forces and masses for each particle. The Verlet scheme's significant difference from an Euler integration is that, at each time step, velocity is computed twice, the first time being updated at the half time step. The difference, although subtle, has proven to give to the scheme a much higher stability and accuracy.

A force vector, **f**, represents the forces acting on particles at each time step and is computed as the sum of components including gravity and imposed forces. As a result of the applied loads, each particle is subjected to internal forces propagating the system through the elements that connect them. The simplest case is to consider these elements having only axial stiffness and subjected to viscous drag so that the force transferred to its ends (a & b) are:

$$\mathbf{f_a} = -\left[k_s(\mathrm{Dist}(a,b)-r)+k_d\frac{\Delta\mathbf{v}(a,b)\cdot\mathrm{Dist}(a,b)}{|\mathrm{Dist}(a,b)|}\right]\cdot\frac{\mathrm{Dist}(a,b)}{|\mathrm{Dist}(a,b)|}, \quad \mathbf{f_b} = -\mathbf{f_a} \quad (5)$$

The first part of eq. (5) represents Hooke's law of elasticity where k_s is the stiffness constant of the spring set as EA/r, E being Young's modulus, A the cross sectional area and r the original unstressed rest length. This generates a force proportional to the extent of deformation of the element. The second part of eq. (5) applies viscous drag, introduced to achieve convergence over iterations. An additional force, added for faster convergence, is kinetic damping, which is negatively proportional to particle velocity thus gradually reducing vibrational motion. Collision detection is implemented to simulate the presence of a "floor" preventing elements from falling due to local/global instability or fracture (Fig. 3).The solver is able to deal with both dynamic and rigid assemblies as well as structures where rigid and soft elements interact, such as those represented in the schematic models of the London Eye and Infinity Bridge.

Fig. 3: Sequence demonstrating structural instability induced by random removal of elements.

7.3. Catastrophe user interface

The application runs in two main modes, *Draw & Sketch* and *Play*. In *Draw & Sketch* mode users are able to draw a structural model from scratch using nodes and elements. Constraints can be added/removed at any node and the model can be altered at all times. Forces including gravity and point loads can be applied at any node. Figure 4 shows a hanging chain modeled directly in Catastrophe using a poly-line with constrained ends. By applying gravity the chain relaxes into its equilibrium position. Adding additional weight at the centre alters the state of stress (red symbolizes tension, blue compression) in the system.

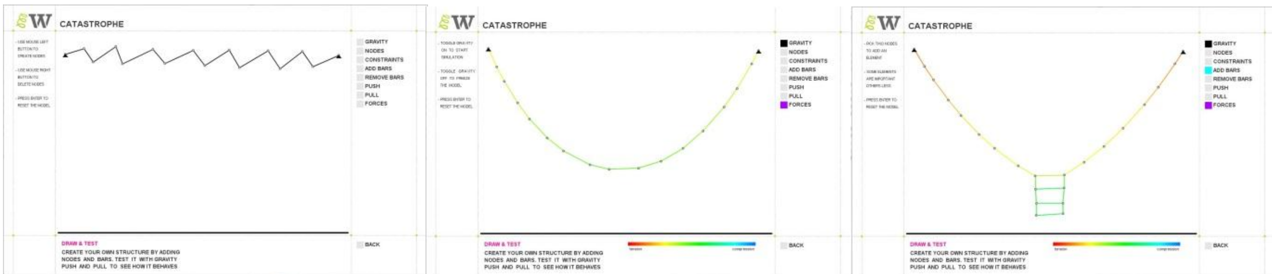

Fig. 4: 'Draw and Sketch' mode of Catastrophe illustrating the effect of applying forces.

In *Play* mode the user is presented with a series of challenges designed around model representations of famous buildings. Initially designed as a student oriented game, both to be showcased at the Big Bang Science Fair 2011 and to prove concept feasibility, Catastrophe challenges users to remove as many elements as possible without the structure collapsing. Through play, users develop an understanding of which elements are critical to system stability (Fig. 5) thanks to the real time feedback of the model's state of stress. Additional features can be activated such as identifying the fracture of highly stressed elements (denoted by yellow flashes).

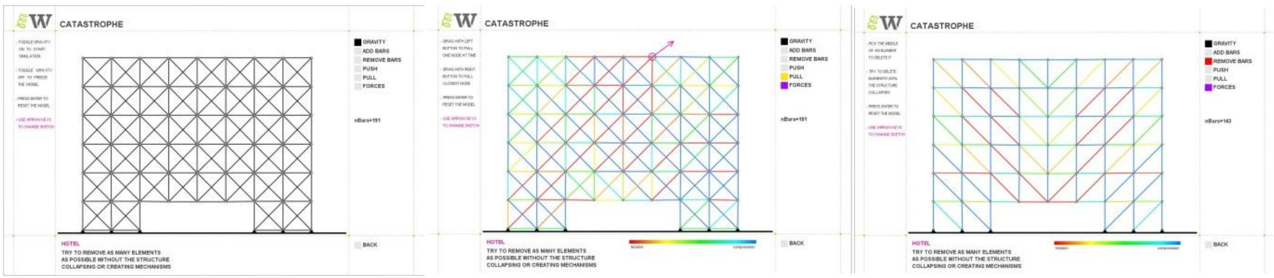

Fig. 5: a) initial geometry, b) point load applied at node, c) set of diagonal bracing removed

Models can be built and tested in real time under different loading scenarios while receiving immediate feedback on their state of stress. Fracture of highly stressed elements can be enabled (the yellow circle highlight elements fracture), fig. 6.

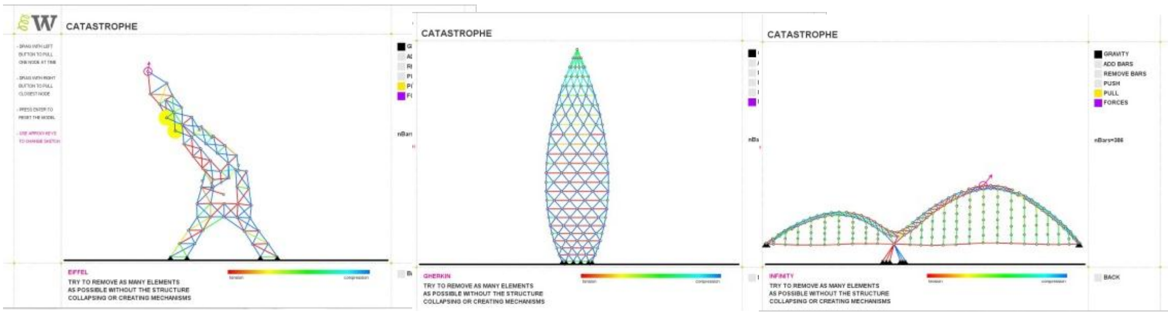

Figure 6 (a) Eiffel tower, (b) the Gherkin, (c) Infinity Bridge

It is also possible to model pre-stress by assigning elements with a rest-length shorter than their initial length. This makes it possible to interrogate structures stable only in states of self-stress. Figure 7 illustrates the consequences of removing cables on tension and compression elements.

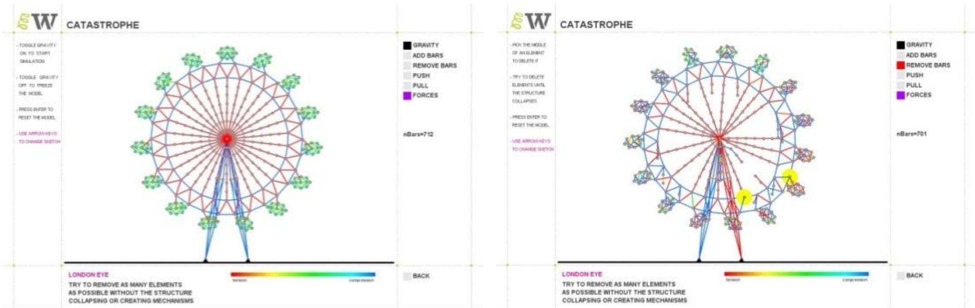

Fig. 7: London Eye model with pre-stressed cables, b) result of removing cables

7.4. Virtual experiments

Catastrophe proved the viability of physical engines based on particle systems coupled with user-interaction to produce real-time interactive, realistic structural simulations. It also demonstrated the potential teaching capability of online applications for developing qualitative understanding of advanced structural concepts. Using these techniques as a basis, the plan is to broaden the scope of the models. Applications addressing the visual representation of bending, shear and torsional load transfer, as well as buckling instability are already under development. There is also the possibility of a 3D extension and a Dynamic Relaxation version of the solver, which will enrich user experience and enable more sophisticated form-finding exercises.

8. Next Steps for Workshed

In line with modern on-line practice Workshed is intended to be highly collaborative and designed to evolve as demands change. There are active forums for academics and other stakeholders that can be accessed via www.thinkup.org. Here requests for new content can be made and the best way to address teaching needs discussed. Students can also engage with the development of Workshed by voicing their opinions on the Expedition Workshed facebook group.

The success of the Workshed will depend on its content and to produce that content will require some level of financial commitment from industry and the public sector. Early indications are good that this will be forthcoming. For example, beyond the significant initial investment made by Expedition, the Institution of Civil Engineers, the Building Centre and Arup have kindly supplied video content. Funding has been secured from HE-STEM to develop tutorials to accompany the interactive structural models and the Institution of Structural Engineers Education Panel for the development of an accompanying teacher's portal. Many universities are contributing significant resources to its development most notably UCL, Bath, Brunel and Strathclyde. We do not know precisely where the next steps will take us, but it feels like an interesting and productive journey.

9. Conclusions

The Expedition Workshed sets out to help in the education of civil and structural engineers through a cross industry collaboration and making use of new media, modern computational methods and best practice pedagogical techniques.

Probably the most significant teaching innovation in the Workshed to date is in the area of online structural models. The development of the Catastrophe application appears to offer tremendous potential both in teaching and gaming. The videos of material performance should also prove to be of huge value across the UK and beyond.

Feedback to date indicates that Workshed does have the potential to be transformational to engineering education. As of April 2011, less than six months after its launch, the Workshed is being used in over twenty UK universities and is already garnering an international following. It was showcased on the Institution of Structural Engineers stand at the Big Bang Science Fair in March 2011 and has been featured in The Structural Engineer. Sir Duncan Michael, FREng, Past Chairman of Arup, has the following to say about the Workshed: *"In education what you learn is a necessary but insufficient choice. You also need to choose how you learn, to be necessary and sufficient. In today's culture of speed and imagery, the Workshed material may prove an excellent match to the students' abilities for learning."*

10. Acknowledgments

So many people have contributed to Workshed that it is not possible to individually identify them all, and our humble apologies to those that we have missed but special thanks go to: Iain MacLoed and colleagues at Strathclyde University; Graham Owen and the IStructE; Paul Greening and his colleagues at UCL; Tim Ibell and colleagues at Bath University; Lawrence Coates and colleagues at Birmingham Uniuversity; Richard Haryott and colleagues at Arup; Mike Cook and colleagues at Buro Happold; The Building Centre; David Brohn; Mike Chrimes and his team at the ICE; Andersen Inge and Trevor Flynn; all at Expedition, MustRD and the Useful Simple Trust.

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