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DOING ENGINEERING DESIGN: REFLECTIONS ON THE ACTIVE LEARNING EXPERIENCE

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ABSTRACT
A structural design exercise has provided students with an effective experience of designing to meet a specific need. The brief is that students design a structure to support a 30N load midway between two tables placed a metre apart, using only balsa wood, A4 copying paper and balsa cement. It is run as a competitive exercise, with the lightest structure that holds the load gaining maximum marks – a clear, unambiguous and objective criterion that gives students immediate feedback.
The first part of the paper concentrates on the experience of running the exercise over the years, of how the students have coped with the open-ended nature and demonstrates the variety of solutions that have been presented.
The second part of the paper is reflective, and concerns the student learning experiences and how this develops their design abilities, their experience of the real world and their self-motivation as learners.

Keywords: Active learning, structural design, open-ended design exercises

1 INTRODUCTION

How do you provide engineering students with practical design work that has adequate links to their other studies and yet is sufficiently open-ended so that they can pose multiple solutions? Baume [1] makes it clear that education must place an emphasis on active processes of doing, design in this case, and the exercise needs to cover conceptual and embodiment design work as described by Pahl and Beitz [2], and to meet a particular brief.
Active learning is not a new phenomenon. But it is something that seems to be necessary to develop student skills, particularly if what they are studying has a vocational context, such as design. Design students do design because they want to become designers. Active learning brings benefits that are not easily defined in terms of learning outcomes: what is not written but is learned is probably just as important, including tacit learning outcomes which are impossible to write in any case [3] [4].
Schön [5] argues that reflection happens both *in-action* (improvisation on the spot) and *on-action* (consideration of the process after the event). The learning experience described in this paper primarily encourages *reflection-in-action*; the active process, for example, of iteratively building and testing structures, reducing weight with each iteration. The exercise also however includes the opportunity for *reflection-on-action* after the testing event through a report and reflection.

2 THE EXERCISE

This design exercise, proven over several years, not only gives students an initial shock, but provides them with an effective design experience to meet a specific need. It runs as a competitive exercise, with a few clear objective criteria giving students immediate feedback. It has been used on several courses at different levels, with different learning objectives, from first year BSc design students developing structural understanding to masters engineering students who may have had analytical first degrees and who may not have carried out a design project before.
The brief is that students design and make a structure to support 30N midway between two tables placed a metre apart. The materials students may use are generally limited to balsa wood, A4 copying paper and balsa cement, although newspaper and adhesive tape have been specified. If a structure fails to take the load it receives no marks: the heaviest successful structure receives a bare pass mark, and the lightest structure that successfully carries the load gets full marks. Those in between receive a mark according to their weight relative to the lightest and heaviest in that group. This means marks are objective and easy to calculate: students discover their marks by carrying out the test on the specific

date. There is no measure of the load the structure takes before collapse, no calculation of how many components or joints there are in the structure, notional build cost or structural beauty.

The newspaper and adhesive tape version results in students treating the problem in a light-hearted manner, whilst the balsa wood version results in serious engineering work that is capable of trial and error solution but which is also amenable to analysis.

There have been a number of variations over the years; caveats have developed as students have found ways of not exactly cheating, but finding loopholes in the brief in order to gain the best competitive advantage. The first time this occurs it is allowed because it demonstrates a creative process at work, but the second time it needs to be prevented so not all students find the loophole.

These added rules are that the tables may only support the structure on the top and front surfaces (those facing each other), tables must be treated as being immovable, structures may not be wrapped round the table, and rear edges of the tables may not support the structure. The loopholes have resulted in students inverting tables so they were higher, designing hooked tension structures on the rear of the tables, and using another table upside down to loop the structure round its legs.

An additional feature is that a report now has to be written. This may also be used as an exercise in developing written skills early in the course in a relatively small piece of work. The report structure is now determined; this is designed to assist students in developing effective design methodologies, but does not always work if students do not read the outline beforehand. The report structure is:

1. Topic investigation and definition: research
2. Conceptual design
3. Embodiment and detail design
4. Construction processes
5. Testing and modification
6. Drawings and illustrations of the tested structure
7. A personal reflection

Assessment of a report is necessarily subjective, even if having sections cuts down on subjectivity.

Three hints have been added over the years. The first is that some things have been deliberately left out and they have to find them themselves. The second is to use report sections to guide their work on the assignment, and the third is to direct them to a local shop that stocks balsa wood (and labels each piece with its weight).

At undergraduate level 4 on Product and Engineering Product Design BSc degrees, the lecture course accompanying the project provides an introduction to structural design from a practical point of view, encouraging understanding of compression, tension, and shear in beams, and resolution of forces. For example, students tensile test strips of copy paper, and are frequently astounded at how thin a strip will support a 30N load, but also at how much weight paper alone can add to their structures.

3 RESULTS OF THE EXERCISE

The balsa wood version of the exercise is repeated most frequently as the design processes are taken more seriously and engineering students may realise that it is advantageous to use numerical reasoning at conceptual and detail stages.

Students are deliberately not told how balsa wood is sold by the local supplier. Students discover that the normal length is 36" – 914 mm – and less than the metre span that they have to construct. The revelation that the structure requires joints sometimes leads to requests to change the brief so they can span a lesser gap. Naturally, these requests fall on deaf ears: that goalpost is immovable. More enterprising individuals locate suppliers that offer longer sections – but that demands planning.

The exercise is a *structure* and not a *bridge* although students repeatedly call it such. Although a bridge spans a gap, it has other characteristics: in particular, it carries something across the gap, i.e. a dynamic load, which this structure doesn't. Use of the term *bridge* is misleading and limits students to a subset of the structural forms available. Use of the term, however, leads them to seek design inspiration through analysis of existing bridges.

3.1 Topic investigation and definition

Students are supposed to find out about balsa wood, structural forms and to see what background information they can find. Some students who don't have English as their first language sometimes think *definition* means writing down dictionary definitions. This can be quite useful, particularly when the definitions are strange, but not sufficient as investigation. Whilst there are quite a few internet sites describing student balsa wood bridge or structure building competitions, there doesn't seem to be one specifically for the one metre span. Many others have structure weight limits or smaller spans and the assessment tends to be on the load to fracture. A roadway may be required, although what it has to carry isn't always clear – pictures of failed bridges seem to have been loaded with a point load even though they have a roadway [6].

3.2 Conceptual design

Students are encouraged to measure the density of the balsa that they have purchased, and thus predict the mass of their structure from the volume of wood used prior to building it. It is our experience that some students have more success at this than others.

The obvious design concept is a beam. These can be commendably light: below 20 grams is possible. Some students decide that 914mm width takes the load and forget about integrating the ends. Figure 1 shows two beam structures – the left one shows this and also what happens when the weight criterion is ignored, perhaps in the knowledge that any successful structure passes.

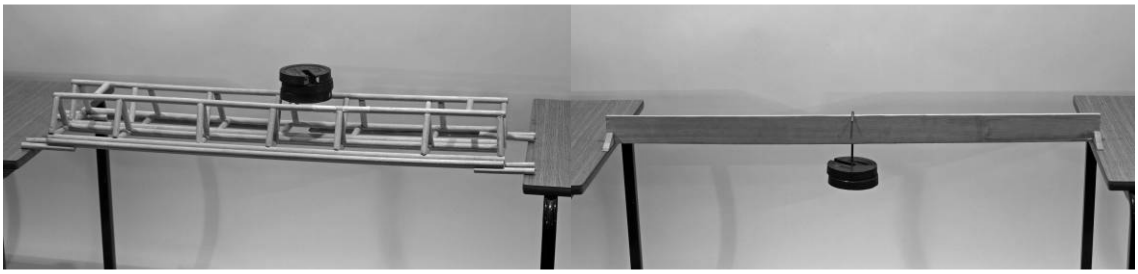

Figure 1. Beam concepts – heavy and light versions

If the bridge idea is forgotten, the next concept that works is a compression structure. This has two or three variations: the first is to use the corners of the tables to take side loading, and the second is to use ties across the bottom. Figure 2 demonstrates this approach.

Figure 2. Compression structures using the tables or tension members to take side load

The competition winners consistently seem to be those structures that hang the load from the centre of a sling and employ the cross member in compression. Figure 3 shows examples of these. The structure on the right has the addition of a tension member to prevent buckling and is similar to the current holder of the record: the 30N weight is being held by a structure that only weighs 12 grams.

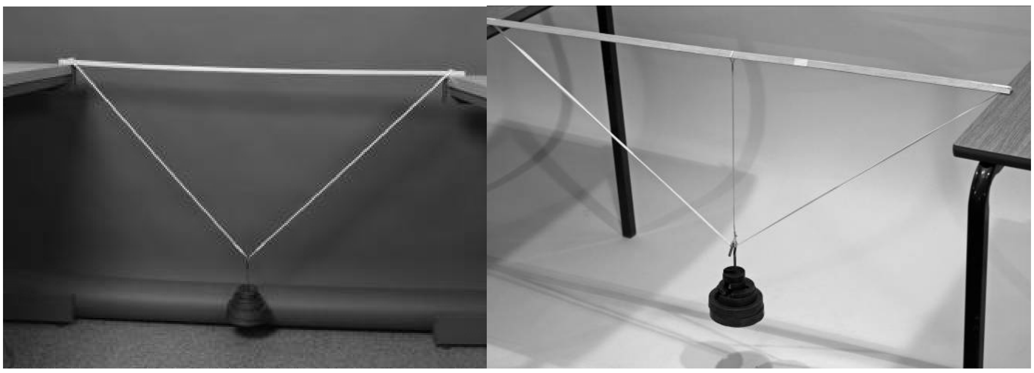

Figure 3. Structures with the load slung beneath a compression strut

One problem experienced with design for a minimal factor of safety is the propensity of balsa to be affected by the atmosphere of the room in which it is placed. There have been several occasions in which a very light structure failed in the official test though it had been tested successfully in the workshop the previous day. This may be attributed to the moisture content of the environment, or to spurious claims made by the students about their testing procedures.

To date, the lightest structure that has supported the 30N load weighed 11 grams – quite a remarkable achievement. This was one of the compressive member and sling configurations.

3.3 Detail design

It is true that the better the concept, the better the product (or, in this case, structure) is likely to be. However, there is another saying that the devil is in the detail, and good detail design is essential. A relatively poor concept with good detail can result in good performance in this assignment. Structures repeatedly fail in ways students have failed to calculate and that have been completely ignored in their thinking. This is one of the benefits of their making and testing models. Care and attention in manufacture of the model are also critical. Students who scored well have learned the value of using jigs in their construction method to ensure consistency. Aesthetic beauty was intentionally excluded as an assessment criterion, but often well-considered and carefully constructed truss arrangements have displayed an inherent elegance, often from Product Design students who are weaker on engineering principles but have highly developed aesthetic sensibilities.

Instabilities never envisaged start to occur with structures because a perfectly symmetrical structure may have been envisaged when they were analysed: for instance, local torsional effects become important on the beam structures, particularly when the weights are hung slightly sideways as they need to be in the right hand structure in Figure 1. In this instance the beam is a hollow composite that resists torsion well and which has ended up reasonably light (see Figure 4, right). Buckling tends to be the major cause of failure for compression structures: weights need careful balancing on structures like those in figure 2 and students need to find ways to avoid that problem. The record-breaking structure has avoided buckling by including a vertical tension member and by careful design of the strut so it has a tendency to buckle upwards. The member is forked where the weight attaches so it passes either side of the hook on the weight (Figure 4, centre).

Another detail discovered by students is that balsa wood is better than paper in tension as well as compression, so lighter structures result from all-balsa construction. Some students discover the precision from the use of laser cutting techniques, as seen in the left hand structure in Figure 2 (see detail on the left in Figure 4), although they often neglect to consider that the grain of the balsa is no longer aligned to many internal cross members.

One of the most interesting structures was created by a part-time student who produced a solid-looking box. He argued that an unwritten requirement was that the structure had to be carried on public transport during the rush hour, so it was important to protect it and hence the box. But it was too short: or so it seemed. A two-part compression structure emerged, using the tables at the lower ends for side load support and the weights as part of the structure at the top. Careful design of all parts resulted in an extremely light structure that won that year’s event.

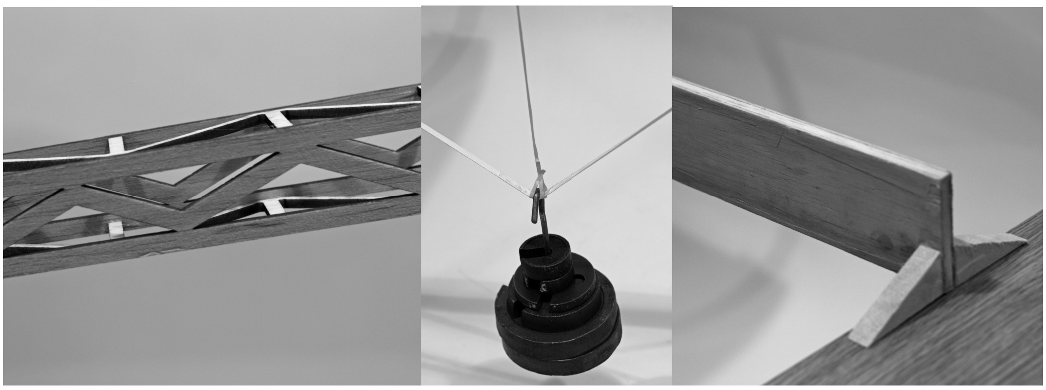

Figure 4. Detail design considerations: laser cutting, forked tension member, hollow box section to avoid torsional effects.

3.4 Testing

As with many design and make student projects, there is often a tendency for students to leave the manufacture of their structure until the week of the submission. With this in mind, it has been beneficial to schedule a class workshop session early in the project to kick-start the build process. In addition, a draft test session in the weeks preceding the submission date encourages students to benefit from a pre-assessment diagnostic run through without the stress of having to do it for marks. This serves two purposes; for those students who have not progressed far with the build by that point, it can provide a valuable element of peer pressure as they observe their more proactive colleagues. For those who do take advantage of the opportunity, it shows what needs modification, offers the opportunity for tutorial feedback, and spurs them to develop corrective action. With a practical project it is relatively easy to see what is going on structurally, and this can be one of the most valuable parts of the exercise. It should be noted that the students tend to greatly enjoy the test sessions; it is not unknown for other academics in the building to request that the volume of cheering be contained. It is advantageous to stage the session in an area which affords a good view of the test to the entire cohort, if necessary using a camera and projector.

4 REFLECTION ON THE EXERCISE

4.1 Personal experience

Both authors were first faced with a similar design exercise as students and had to develop their own design solutions to it. One was given newspaper and self-adhesive tape variation, with no report requirement. This is still remembered as a useful design exercise, even though it was over 30 years ago. The first task was to develop a successful way to manufacture reliable compression members from newspaper, with a secondary task to develop the form for the load-bearing structure. Thin members can be manufactured using welding rod as a mandrel. It was some time before the sling method was recognised as the way to achieve the lightest structure, and that the sling should be as close as possible to the floor to minimise compression in the upper member. The top member initially started life as a single strut but developed into a fabricated member with three compressive pieces prevented from buckling by being further apart in the middle than at the ends and by being wrapped with tape at the centre. The test was successful, but the strut appeared to have been loaded beyond the first buckling mode and exhibited an S-shaped deflection. There was the usual panic before the test when it was realized that the test tables were slightly lower than those used to develop the structure. But it still passed, and the weight was 46 grams. It would probably have been almost as effective if the structure had failed: it forced one to use a set of unconventional materials in effective ways and to use ingenuity and iterative processes to arrive at a functional solution. The exercise was more about the chase and getting a competitive result that beat the others. It was noticeable that those who worked off-campus in isolation tended not to do so well: grape-vine information tended to flow quite fast around the student group about what worked and what didn't, and this was almost as valuable as the trial and error process.

4.2 Feedback and reflection

The testing procedure, particularly when coupled with a verbal critique from the tutor, has proven to be a highly effective method of providing students with immediate feedback on their endeavours. The addition of the written report allows students to document their design process, and in some cases to compensate for marks lost when a structure has failed under the test load. Whilst the original objective was for the report to be used as a design tool, it often tends to be written retrospectively.

In recent versions of the exercise a reflective student feedback is part of the written assignment. Some students have difficulties in making this a statement of effective learning, simply stating whether the structure held the load, what it weighed and that it was successful. Others include significant insights about the process of learning by doing. For several students, even some at postgraduate level, this seems to have been the first time that they have tackled an open-ended design problem. For them it is a new experience not to be told exactly how to do something: they have always been given specific instructions before.

For other students, this opportunity to say what they have learnt results in sets of eye-opening comments. It's an exercise that works. It gives students an all-at-sea experience to start with: it gives them quite a bit of information from websites and other sources but not really enough to provide all the answers, and it has the opportunity to use a combination of analytical techniques at both conceptual and detail level, if they want to use them or are able to draw upon them. Whatever and however those analytical techniques are included, they never substitute for the reality of the variability of materials and the necessity to actually construct and test a real structure. Some students simply say that they wouldn't have missed it for the world. This is, of course, what we like to hear.

5 CONCLUSIONS

The assignment continues to frustrate, annoy and delight students, which is perhaps as it should be. Seldom do they have a neutral attitude towards it. It is clear that for some students they are learning something that is probably what Ray Land calls a Threshold Concept [7] which seems to be initially troublesome but which they find enjoyable once they have crossed the threshold and achieved the outcome of a successful structure. As this is an experiential concept it is difficult to put into words exactly what it is they have learnt through doing the exercise, but they are certainly considerably better equipped for subsequent independent work after succeeding with it. Although in theory students may plagiarise structures, it is quite difficult to produce a structure without learning anything about the task in hand. Websites on designing balsa structures don't yet seem to have found this particular variety, and even if they did, students would still learn a significant amount through attempting to copy.

5.1 Further developments

The written report part of the assignment might be used profitably as a writing exercise that is developed as a diagnostic tool. A number of MSc students have not really been in the position of writing significant pieces of work in English, and the University is considering ways of developing written skills with small pieces of work at an early stage of their course and providing extra tuition and support as they do this [8].

The assignment is already used as an introduction to two-dimensional drafting packages. A further possibility is to develop it as an introduction to solid modelling programs and link it with finite element analysis packages. Enterprising students have already done this when tackling the exercise.

REFERENCES

[1] Baume, D., *Writing and using good learning outcomes*. 2010, Leeds: Leeds Metropolitan University.

[2] Pahl, G. and W. Beitz, Engineering Design. 1984: Design Council.

[3] Swansborough, S., D. Turner, and K. Lynch. Active Learning approaches to develop skills for sustainability. 2007 [cited 4 March 2011]; Available from: http://www2.glos.ac.uk/offload/ceal/resources/B2.pdf.

[4] Horvath, J. and R. Sternberg, Tacit Knowledge in Professional Practice: Researcher and Practitioner Perspectives. 1999, Mahwah, NJ: Lawrence Erlbaum Associates.

[5] Schön, D., The Reflective Practitioner: How professionals think in action. 1991, Aldershot: Ashgate.

[6] Wikipedia. Balsa wood bridge. [cited 4 March 2011]; Available from: http://en.wikipedia.org/wiki/Balsa_wood_bridge.

[7] Meyer, J. and R. Land, Threshold Concepts and Troublesome Knowledge – Linkages to Ways of Thinking and Practising, in Improving Student Learning – Ten Years On, C. Rust, Editor. 2003, OCSLD: Oxford.

[8] Bergstrom, C. The Status of Writing in the University. Higher Education Academy English Subject Centre Online Newsletter 2004 February 2004 [cited 4 March 2011]; Available from: http://www.english.heacademy.ac.uk/explore/publications/newsletters/newsissue6/bergstrom.htm