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Student difficulties in structural distillation tasks

Bruce Field
Monash University, Clayton, Australia
Bruce.field@eng.monash.edu.au

Colin Burvill
University of Melbourne, Melbourne, Australia
colb@mame.mu.oz.au

John Weir
University of Melbourne, Melbourne, Australia
jweir@mame.mu.oz.au

***Abstract**: One of the key tasks to be undertaken when attempting the mathematical analysis of an engineering system is to construct a model of the system. The model would normally contain elements that correspond to established concepts, for which analytical techniques are available. We use the term 'structural distillation' to describe the activity of identifying the established concepts within the 'real' engineering system. Although we might expect an undergraduate engineering course to develop skill in the act of performing structural distillations, either as a step towards predicting the behaviour of actual systems or during preparations to design systems, this does not appear to be the case. In the very fundamental task of constructing free body diagrams, we found that students in two major engineering courses were significantly deficient in the skill, even though their performance in conventional preparatory studies appeared to be satisfactory. We concluded that the nature of the teaching and assessment tasks in those preparatory studies developed a narrow technique for this aspect of structural distillation that was not transferable to a slightly different type of problem in which the structural elements had less defined characteristics or were visually complex.*

***Keywords**: Modelling, structural distillation, misconceptions, visualisation*

Introduction

A fairly typical activity for an experienced engineer might be described thus: an engineering system exists, in hardware, sketch, flowchart, or in the mind, and the immediate task is manipulate the system or its conceptual form so that its embodiment will match the myriad of specifications that have been laid down for the system.

The specifications take numeric forms (Lewis and Samuel, 1989), and relate to characteristics of the solution that can be measured, and usually predicted from the body of knowledge associated with the task scenario. This body of knowledge may be very broad, and include disciplines such as economics, psychology, sociology, law, aesthetics and the natural sciences. Within the concept are alternatives: dimensions, materials and components that separately influence one or more of the specifications in a matrix of interactions (Alexander, 1963). The engineer's task is therefore complex (Lewis *et a*l, 2000), and various strategies are applied to work efficiently towards a final solution.

Crucial to progress towards a solution is an ability to predict the effects of various decisions: is it more, or less likely that the constraints imposed by the specifications will be satisfied? The ability to predict the effects with a degree of certainty requires the use of abstract models, whose validities have been confirmed (or whose predictive accuracy is well known). The engineer must therefore translate the hardware or concept into the jargon of the appropriate abstract models, select data for those models, and then manipulate the enhanced models if they are to predict the degree of match with the specifications.

We call the process of transforming the concept into its models that of 'structural distillation' (Samuel and Weir, 1999).

However, models are imperfect – or more accurately, models are likely to be 'correct' for idealised concepts that are similar to, but not the same as the concept under consideration. The engineer might have a choice between various alternative models that may be more, or less likely to predict accurately in their non-ideal application. The engineer has access to safety factors, their own experience and perhaps intuition (Field, 1994) to resolve these issues.

We are interested in the mechanism by which an engineer gains the skill needed to distil system concepts. A young undergraduate is not likely to possess the ability as a natural skill. How does their training develop their abilities? This paper reports our investigations at two Australian Universities, where we found that one of the most fundamental of modelling skills used in mechanical engineering, that of constructing free body diagrams, was not well developed through conventional courses in statics.

Study Programmes

The research reported in this paper drew upon tests with two groups of level 2 undergraduate students. The first group, at the University of Melbourne (UoM), were enrolled in the level 2 subjects "Engineering design and materials" and "Mechatronics design and laboratory". The second group, at Monash University (MU), were enrolled in the level 2 subject "Design process".

The principles of static equilibrium were contained in very different level 1 studies at the respective universities. At the UoM, the principles were presented as a large portion of a dedicated subject "Engineering mechanics and materials" delivered by staff from the Department of Mechanical and Manufacturing Engineering. The subject was one of four that constituted a full workload during the first semester. The recommended text was the widely used "Engineering Mechanics: Statics" (Meriam and Kraige, 1998), and the subject covered 2-D and 3-D equilibrium, in vectorial and graphical modes. Figure 1 shows sample problems from this subject.

At MU, statics forms a small part of an introductory unit "Civil Engineering" (delivered by staff from the Department of Civil Engineering) which is one of six units that constitute a semester of full time study. The elements of statics are primarily 2-D, and are applied to classical civil engineering forms: beams and trusses. There is no exposure to forces in mechanisms, and the modes of solution are principally through the use of orthogonal components. Figure 2 shows typical problems in statics from this unit. The mechanics portion of a study in Physics at MU contains some elements of FBDs. Figure 3 shows two examination problems from this unit.

A common characteristic of the problem types from both universities is the presence (or strongly implied presence) of external loading, with defined directions and loads (including the cases of gravity loads). The positions of equilibrating forces, or the presence of the equilibrating moments are also quite unambiguous in most instances. Consequently, all the problems covered at both universities have unique, numerical (or algebraic) solutions. This is not unlike problems set in the early levels for most of the other engineering sciences at the two universities.

Draw free body diagrams for each of the structures shown below

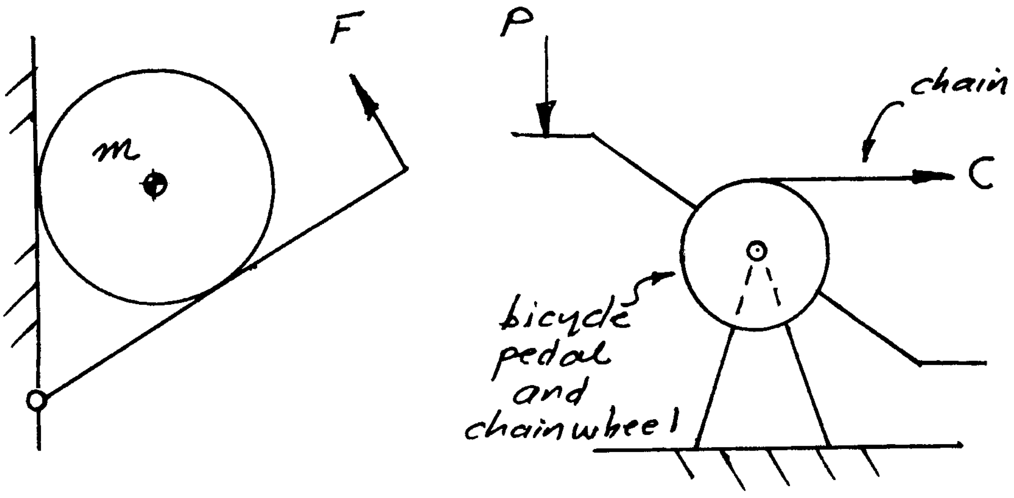
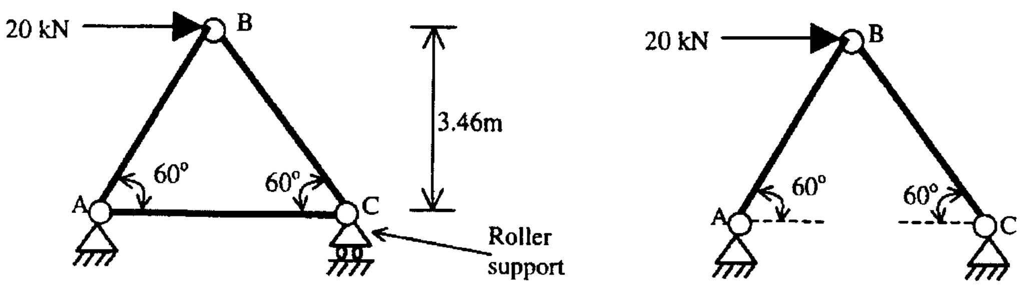


Figure 1: Statics problems used in Mechanical Engineering at the University of Melbourne

(b) Calculate the **support reactions** and forces in the **members** of both trusses subject to a horizontal force of 20 kN. Length of all members = 4m. Indicate whether the members are in tension or compression. (80%)



(a) 3-member truss

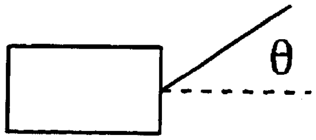
(b) 2-member truss

Figure 2: Statics problems used in Civil Engineering at Monash University

The level 2 engineering design studies at the two universities encompass the design of mechanical elements, principally to resist failure, and mainly to avoid excessive stress or deflection. Consequently, an appreciation of the forces imposed on mechanical elements is a prerequisite for the satisfactory design of such elements. However, when design problems are presented in a practical context, it is not uncommon for the task to be defined in words (such as the statement of a need), for which the magnitude, location, and other aspects of loads are variables in the task, to be found, assumed or calculated. Therefore the equilibrium models presented to students in design problems are likely to be relatively incomplete compared with those set in classic studies of statics, mechanics and physics.

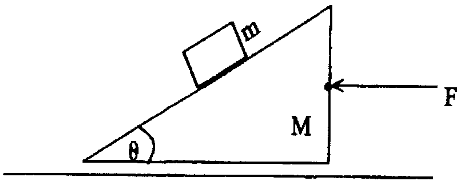
The uniformly poor performance of undergraduate students in the construction of FBDs in level 2 design subjects at both universities, even following the apparently large difference in attention paid to the skill at each university led the authors to investigate the likely causes for the shortcomings.

A 200-N box, which is being pulled with a rope at an angle θ relative to the horizontal, moves horizontally at a constant velocity. The tension in the rope is 35 N and the force of kinetic friction on the box is 20N



(a) Draw a free-body diagram for the box. Label each arrow with the name of the force.

A small block of mass m rests on the sloping side of a triangular block on mass M, and the triangular block itself is in contact with a horizontal table, as shown in the diagram. All surfaces may be assumed frictionless. A horizontal force F is applied to the block of mass M, and its magnitude is such that the block of mass m does <u>not</u> move on the incline.



On the diagram above, mark and label appropriately the two forces acting on the block of mass m.

Using two directions at right angles, write the equations of motion for the block of mass m.

Figure 3: Mechanics problems used in Physics at Monash University

Research Methodology

Similar testing environments were created at each of the two universities, where short 'tests' worth one or two percentage points (to motivate students to seek a correct solution) were conducted during regular weekly lectures. There were seven different tests used in the first half of 2002.

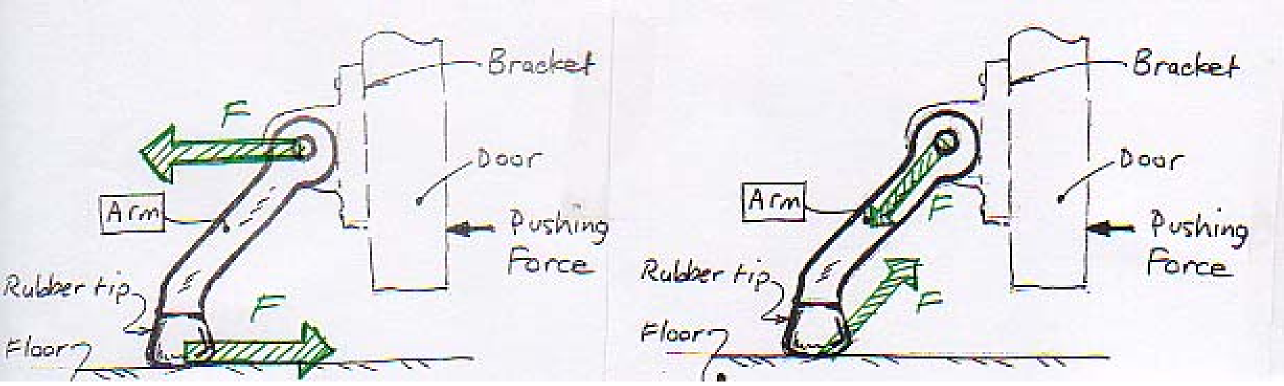
The majority of the tests contained drawings to represent real, familiar artifacts (a doorstop, a spanner, etc.) but which were devoid of the forces or moments that normally act upon those artifacts. Students were to place the forces and/or moments on those images to represent the equilibrium arrangement: no magnitudes of any forces or moments were required. Some other tests represented abstract structures or mechanisms that contained forces (symbolic or numerical), and students were required to find forces at other points in the device.

In all cases, students were only allowed five to ten minutes to reach a solution. They were informed that this small amount of time should have been sufficient to reach each solution (and this was normally confirmed after each test when they were presented with correct solutions).

There were approximately 120 students at MU and 180 at UoM in 2002. Following each test, the papers were assessed by the first author, and those students obtaining a correct solution were awarded their one or two percentage points. It is notable that no test yielded a success rate above 5% at either university. The test papers were grouped into categories of similar or identical solutions, and the most common solutions were identified.

Outcomes

The first problem depicted a doorstop in its functional mode (Fig 4). The task required students to place force arrows on the diagram (or a separate image of the arm portion) to represent the equilibrium of the arm. Single forces acting at any one point were required. The most common solution, offered by 20% of the students at MU, and 15% of those at UoM (Figure 4a) shows a pair of forces that could satisfy the requirement for a zero nett force, but which clearly fails to satisfy the requirement for zero nett moment. The second most common solution at MU (10% of the students) was similar to Figure 4a, but also included a vertical force at the point of contact with the floor. This solution violates both force and moment conditions for equilibrium, and, significantly, violates the requirement to depict a single force acting at any one point. The same problem presented to the 2003 undergraduate cohort yielded the most common solution shown in Figure 4b, with 28% of the MU students and 20% of the UoM students presenting a solution in which the force at the pin is depicted as passing along the centreline of the arm. On this occasion the UoM undergraduates were more successful, with 10% of the group creating the correct solution.

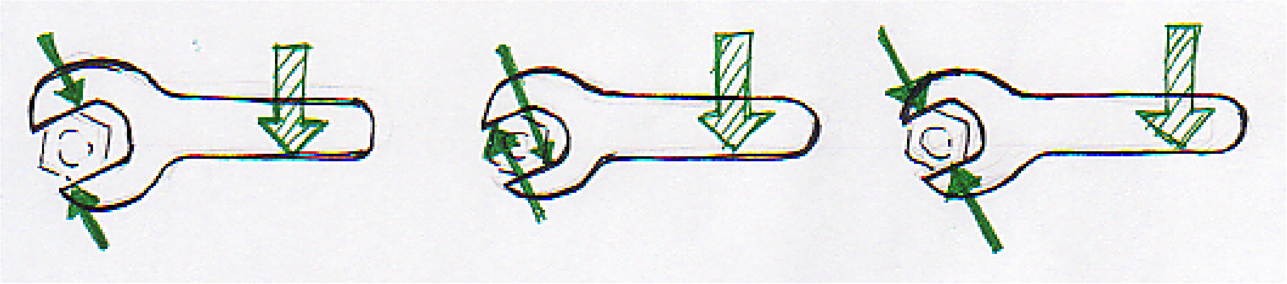


(a) (b)

Figure 4: Common incorrect solutions to a FBD problem depicting a doorstop

A second problem involving the same doorstop image was presented a few weeks later. In this problem, the task was to represent the forces on the bracket. This was a three-force equilibrium task, with the special feature that two of the forces arise from the surface contact between the bracket, its retaining screws (which were described as being loose) and the door. Again only a few percent of the students at each university constructed a satisfactory solution, with most depicting a door reaction force horizontally through the pivot pin.

The problem which asked for the placement of forces on a spanner was also poorly solved. Apart from the non-concurrency of forces and non-zero sum of the forces, many students at both universities created solutions like Figure 5a and 5b. In 5a the contact forces were depicted as acting onto the nut, and in 5b the forces were placed onto the incorrect corner. A large number of students also created solutions like that in Figure 5c (with point or distributed forces), representing a clamp.



(a) (b) (c)

Figure 5: Common incorrect solutions to a FBD problem depicting a spanner

Discussion

None of the seven problems attempted by level 2 students in 2002 involved the application of principles that they had not studied in 2001, during subjects that were prerequisites for level 2 design studies. However, the vast majority of the students at both universities were uniformly incapable of achieving correct solutions to the problems under the conditions that were imposed. While the students at UoM performed a few percent better than the students at MU, the differences were not significant. The authors have considered four plausible reasons for the poor performances.

1. For problems in which no, or only some of the loads were depicted, students required additional insight to locate points of application of the forces, and then to align those forces appropriately. These constituted new, untaught and untested skills. The insight required was largely visual and in some cases (such as with the spanner) required a kinetic mental image of function. Visual capabilities are also required to avoid the misleading clues presented by structural elements that are not aligned with the loads (such as the 'bent' doorstop arm which has encouraged the placement of forces along the 'neutral axis' of the arm in Figure 4b). The authors have for some time been concerned that the general demise in visual/graphic skill in undergraduates may have been partly responsible for a decline in other skills (Field et al, 2001). The results of the experiment are consistent with this hypothesis. Other researchers have noted the tendency for novice engineers to seek more concrete spatial representations during problem solving when compared to their seniors (Ahmed et al (2003), Gobert (1999)), suggesting that shortcomings in visual skill may diminish in later years of an engineer’s career. However, the engineers’ education may well be impaired by this factor.

2. The tendency for many lecturers to present the analysis of equilibrium problems solely by computational methods encourages the use of force components, rather than whole forces. The introductory studies at the UoM are presented in parallel with vectorial techniques (including the use of orthogonal unit vectors), and at MU with algebraic components to be used when analysing trusses via the 'method of sections' (force polygons are not discussed) and in Physics. Consequently, forces are 'seen' by their components, and in particular in their 'active' components. As a result, solutions like that in figure 4a show the force components that stop the door from closing, and in Figure 5a the forces are those that do the ‘work’: from the hand to the spanner and the spanner to the nut. The very common tendency for students to depict force *components* at a point (like the version of Figure 4a referred to earlier), even though they were instructed not to do so may also mean that they see the components as separate forces (apparently friction and normal reaction are seen as two distinct forces rather than as the components of a single contact force). However, although students universally agreed that they were well aware of the principles that determined equilibrium in 2-D mechanisms, the majority of their solutions, whether using components or whole forces, could not represent equilibrium conditions. Their earlier understanding could not be *transferred* to the new problems. This type of difficulty has long been recognized by educational psychologists (White and Gunstone, 1981).

3. The problems were presented as five-minute tasks, whereas in the past, whole problems in equilibrium were met as substantial activities (taking some 30 minutes or so) in examinations and tests. This change may have forced students to adopt different strategies, when they realised that their previously successful approach may not lead them to a timely solution. It seems likely that the methodological approach of setting up component forces, making separate summations of forces and moments and solving simultaneous equations (without requiring any substantial insight) was now seen as inappropriate, and students may have fallen back onto their intuitive understanding of equilibrium. Therefore their solutions may represent their first thoughts on the solution (which could well become modified if they had been given more time), which shows that student understanding of the principles of equilibrium are either not well understood, or are perceived as a very complex set of rules: too complex to handle in the five-minutes available to them. Perhaps many students have formed misconceptions that are normally masked by the self-correcting mathematics that uncover many of their inconsistencies (such as when they subsequently find that the forces on the flats of a spanner, Figure 5a, are negative). The authors have observed this phenomenon during their study of engineering intuition where students appeared to select diametrally opposite solutions from non-computational choices (Field et al, 2001). In these instances the incorrect choice appeared (visually and psychologically) to be more attractive than the correct solution.

4. At least five months (and in some cases ten months) had elapsed since the students had formally studied equilibrium during their level 1 subjects. We are aware of the great difficulty that students appear to have in applying learning from one subject to another, even from one subject to a following subject of the same name! The 'compartmentalisation' of knowledge and the subsequent mental barriers to accessing that knowledge appear to inhibit the effective application of prerequisite skills. It is also possible that the techniques used in teaching and assessing skills and knowledge do not ensure that concepts are properly understood. Students admit to using past examination papers to help them study for the present examination (one of the problems

in Figure 3 actually appeared in two examination papers two years apart) and appear to look for patterns in solutions that they can memorise and recall, rather than the fundamentals that they can understand and apply. Consequently, those pattern-recognition strategies may only exist in short term memory, and be unavailable in the following years. This phenomenon was also reported by Field et al (1989) during their attempt to use *mastery learning* to re-emphasise first-level topics in a second-level study: many students required three attempts at mastery learning tasks before they could create correct solutions. The observations are instances of surface learning, whereas teachers generally aim for deep learning outcomes (Ramsden, 1992).

Conclusion

Students at UoM had formally studied the graphical and algebraic methods of solving statically determinate problems involving FBDs in the year prior to the experiment. The types of problem in that study involved representations of objects that could have been interpreted as ‘real’, but were always line representations, and usually partial representations, in that they showed only the portion of the mechanical system that was of interest. Points of application of forces were always shown or implied, while lines of action of the forces were either shown, or implied, or were dependent on other forces. The study, taught by mechanical engineers, was similar to equivalent courses and subjects at other universities, where the nature of problems set by the teacher always led to single ‘correct’ solutions.

However, during the experiment, it was found that very few (<5%) of the students could apply this knowledge to realistic representations of simple objects where points of application, and directions of forces were not pre-defined, even where there were unique solutions.

Similar students at MU did not have the benefit of an extensive earlier study in which they might have learned how to construct FBDs. Their preparation was largely algebraic, learned from within a structural analysis unit taught by, and for civil engineers, or from a study in Physics.

These students performed slightly worse than the students at UoM but the difference was not significant. Neither university had prepared their students for the apparently simple and similar tasks in the experimental protocol.

For most of the experimental tasks, students independently created identical incorrect solutions. Because the solutions were graphical concept diagrams, and not numerical or graphical scale diagrams, they were not inherently self-checkable. Students seemed unable to systematically confirm that their solution matched the known conditions of equilibrium. They could get the solutions partly correct, thereby satisfying some conditions (zero nett force was commonly implied) but appeared ‘blind’ to other conditions.

Since there were no forces or moments supplied in most tasks, and no points of application defined in most instances, students did not have a starting point for their strategy: unlike their earlier studies where some of this information had been supplied. Evidently, this ‘new’ type of problem, for which they had had little preparation (no preparation at MU) was difficult, and students adopted a simplified strategy where they focussed their effort on portions of the problem (partial equilibrium) and seemed comfortable in accepting, or overlooking other portions.

This behaviour is similar to the behaviour that we reported at ICED2001 (Field *et al*, 2001). In that study, student intuition was seen to be deficient, conflicting characteristics of a problem were resolved incorrectly apparently because of the students' inability to 'see' abstract forms. In both that study, and the present study, novice engineers have been unable to cope adequately with the perceived complexity of the task. In both cases, they were not able to develop a strategy for tackling these types of problem (the styles of problem were completely new to them), and without a strategy, the starting point, and subsequently, the finishing point, were somewhat arbitrary.

We acknowledge that experienced engineers do not suffer the same difficulties, but at yet it is not clear when, or how the necessary skills in structural distillation are developed. The work reported in this paper might serve as the beginning of a longitudinal study as the novices become more experienced over the following three years of their engineering courses.

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