Teaching the concept of free body diagrams

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Abstract: *Free body diagrams (FBD) present a conceptual challenge for Engineering students. These diagrams are the simplest abstraction of the external forces and moments acting on a physical object. Some people "get" FBD's the first time they are shown them while many struggle and continue to produce incorrect diagrams well into their university studies. Having received feedback from lecturers of 3rd year subjects that FBD skills were still below expectations an intervention was implemented in a University of Wollongong first year subject to (a) test students' understanding of FBD's (b) diagnose common misconceptions and errors and (c) reinforce the importance of constructing FBDs that are accurate and complete. This intervention has taken the form of a staged mastery skills test early in the first session of the first year of the engineering degree courses. The quiz is used as a stage gate for the subject and everyone must achieve the mastery skill to pass the subject.*

This paper describes some aspects of the visual learner and the design of FBD questions. Common misconceptions and mistakes are outlined with strategies for teaching the correct approach. Finally some correlations are given between performance in the skills test and subsequent performance in engineering mechanics subjects.

Introduction

Free body diagrams are graphical representations used in mechanics problems involving forces and moments (Rosengrant, Van Heuvelen et al. 2009). There is strong evidence in literature that students of engineering and physics have widely varying abilities in the construction of these diagrams and their effective use in solving mechanics problems. Many engineering students "get" the concept and employ FBD's to study problems, solve them and evaluate the answers. Other learners struggle. This can be because they are not visual learners or they may be operating at a different level to the teacher.

The problem of understanding free body diagrams is not new. One could go back further but Clement's (1982) work coincides with the era when the first author received his Engineering education. That study demonstrated a number of common misconceptions student have when describing what forces act on a body. In one example he asked students to draw the free body diagram of a coin being tossed. A simpler version of this problem is presented in the Foundations of Engineering (ENGG101) class. Students are asked to vote on whether the free body diagrams are different during the upwards motion and the downwards motion. Approximately one third of the class think there is a difference while some are unsure and about half correctly state that there is no difference (in the absence of air resistance). A decade after Clement's paper, Lane wrote his paper "Why cant physicists draw FBD's" (Lane 1993). The problem appears to be intergenerational. At this time, the Force Concepts Inventory (FCI) and Mechanics Baseline

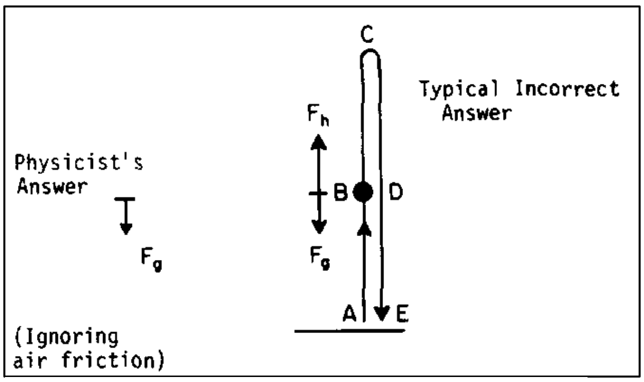

Figure 1 Coin toss example (Clement 1982)

Tests were also introduced to measure students understanding in mechanics (Hestenes and Wells 1992; Hestenes, Wells et al. 1992). These have had a wide take up in diagnostic testing and evaluations.

Another decade later, Sharp and Zachary (2004) linked Van Hiele's geometry learning theory for teaching Engineering Mechanics. This work suggests that geometry and spatial thinking needs to be taught in a specific sequence covering three levels. Level zero considers the visualization of objects, how they look. Sharp and Zachary suggest that lessons need to be designed to give students the opportunity to classify figures according to visual differences – how they look. They use statements such as "does this structure look stable" . Without this skill of visualizing they conclude that students will struggle with analyzing FBD's – Level 1 skill. In level 1 analysis, the students study specific components of the system and can deduce if it is in static equilibrium, or rotating. Finally at Level 2 thinking, students can deduce facts about the object and the forces acting on it. This is when students can use the FBD to develop relationships and predict outcomes. Even at this stage, the students are discouraged from number crunching (an activity they much prefer according to Rosengrant et al (2009). By sequencing, learning activities that address each level, the authors conclude that the students employ diagrams more effectively to understand and solve problems.

Identifying the problem

Evidence from Statics final exam

A detailed analysis of students' responses in an end of session first year statics exam revealed an apparent ceiling in the mark achievable when errors in free body diagrams were evident. Figure 1 plots the mistakes made in free body diagrams against the mark out of 30 achieved in the exam. For this analysis, FBD mistakes were categorized into two simple forms, errors in the forces displayed on the FBD (whether they be directions, locations, or absent altogether) and mistakes made in isolating the free body.

The graph shows very clearly the ceiling mark of around 50% for students who made errors in FBD's. It should be noted here that the data points which show low marks for students who made no errors in the FBD are likely caused by that student not having attempted the relevant questions in the exam, and thus, not demonstrating whether they could do the FBD's or not.

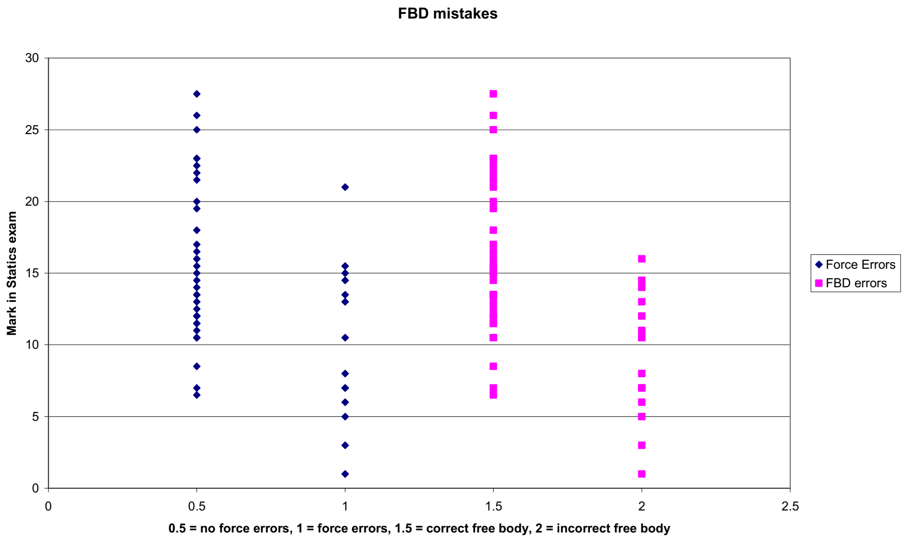

Figure 1 Free Body Diagram mistakes vs statics exam mark.

Curriculum review

As part of the regular curriculum review within the Faculty, a workshop was held to examine and itemise all the mechanics concepts covered in subjects over the first three years of the Civil and Mechanical degree courses. It appeared that all required concepts were adequately addressed although concerns were raised by some about the level of proficiency of in FBDs in students at the end of two years of study. While FBD's were a big part of first year mechanics and second year mechanics of solids, the anecdotal evidence of third year lecturers in structures and machine design was that a proportion of students did not have the skill. It is possible to succeed in subjects by gaining a mark of 50%. As can be seen in Figure 1, it is possible to achieve 50% and still have significant errors in the FBD's.

The outcome of this workshop was that a measure of skill in FBD's was required. Secondly, the importance of FBD's needed to be inculcated at first year and second year level. It has been shown in literature, that where constructing diagrams is fostered and reinforced, students are likely to adopt the use of FBD's in tests even when there are no marks allocated for the diagram (Rosengrant, Van Heuvelen et al. 2009). The instructors involved with the first year subject Foundations of Engineering (ENGG101) were tasked with designing a FBD's activity

Designing the FBD Intervention

Competency attainment is very common in professional training. It is also common in specific disciplines such as medicine. However, in engineering and many other degree programmes, a graduate can leave the university with 50% of the knowledge. When deciding on the FBD intervention and the measurement of competency, we looked at ways in which mastery skills can be taught and evaluated. In order to make sure that every first year engineering student had to demonstrate a basic level of competency with FBD's a set of tutorial exercises were developed along with a stage gate test.

A stage gate is a common construct in project management. In educational terms it means that if you do not get through this gate you do not proceed. Generally, first year students do not experience a stage gate until the end of year exams. This is too late to deliver formative feedback on such a skill as drawing and interpreting FBDs. The subject rules for ENGG101 were modified so that failure to pass the FBD test would result in failing the subject.

When testing a skill, you either have it or you don't. If you cannot ride a bicycle, you just can't. When you learn to ride, it is next to impossible to forget – or so the lore goes. Once you are able to achieve balance and forward momentum, you can improve your cycling skills. This is the same with FBD's. What is needed is a simple test that can demonstrate understanding of the FBD concept appropriate for a first year first session subject. The test must be such that if you do not understand the concept, there is only a small likelihood that you can beat the system and score a pass. The first challenge thus is to create a simple test that traps as many of the misconceptions and errors students have. The second challenge is to engage the students in a novel form of assessment – one where many will not pass the first time round. The test itself becomes part of the learning design.

Implementation of an online Stage Gate Mastery Skills Test for FBD

The test was created within the university's elearning system (Webct/Vista aka Blackboard) and run within timetabled tutorials over a period of some weeks. An online quiz comprising 10 questions; a mix of multiple choice questions and some simple equilibrium calculations was designed. A set of tutorial questions and FBD activities were covered in the early weeks of the subject. A practice quiz was set in week 4 so that students could familiarize themselves with the online system and see sample questions. For the final hour of the week 5 tutorial, students sat the test under supervision. Even though the test was online, students were required to write out their answers and methods in answer books. This was to allow tutors to give formative feedback to those who did not succeed first time.

Students who get 8/10 or better on their first attempt are deemed to have met the skill level. Students who do not meet the required skill level receive one-on-one tuition, and are allowed to re-sit the quiz the following week. As a carrot to encourage some preparation, marks of 8,9 or 10 are possible in this assessment in the first sitting only. In the second sitting, students can only achieve, 6,7 or 8 out of 10. Those who get less than 6 in the second sitting enter a new phase of testing. They sit a subtest of 6 questions the following week but must score 6/6 to pass. Students who do not attain the skill level at any sitting, must have a one to one meeting with their tutor to go over their answers before re-sitting the test. Students can re-sit the phase three test as many times as needed until they pass. The final cut off date is the day before the final exam. To date, every student has achieved the skill level before the cut off. All tests come from the same question repository which comprises some 75 questions with a total of 750 numerical variants.

Question repository

Being mindful of the van Hiele approach, questions were designed to familiarise students with different situations and geometries. FBD's were restricted to complete objects, such as beams and whole trusses. At this stage, the students had not been exposed to dynamics and so all problems were in static equilibrium. Similar problems were presented in different orientations. Many of the numerical questions required students to use the FBD to determine a reaction force and its direction.

For example, when students were asked to deduce something about the left hand reaction of the horizontal beam in Figure 2(a) most were able to recognise that because of the roller support, the reaction must be vertical. For the second case a high proportion picked the wrong answer. When they sat the quiz a second time, the wording of the question might change. For example, for Figure 2(b) the correct answer stated "The reaction is perpendicular to the slope". At the resit, the correct answer was "The reaction has both vertical and horizontal components".

Reaction calculation questions also explored the students' ability to deal with differently oriented structures and forces. Figure 3 shows two reaction problems which are essentially the same structure but with different forces unknown and with one inverted. Again performance in (a) is much better than the answers for (b).

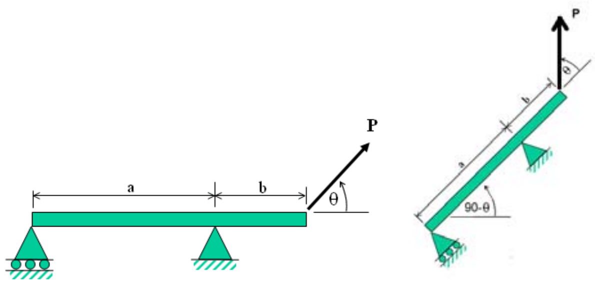

Figure 2 Sample questions (a) Horizontal beam (b) Sloping beam

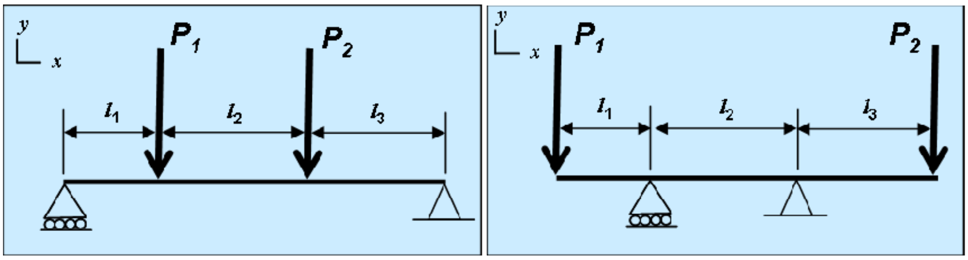

Figure 3 Sample reaction questions (a) Simple question (b) Problem inverted

Outcomes

In this section we will describe the outcomes under three headings. Firstly, student performance in the quiz. This is a combination of an analysis of the difficulty of the quiz and the number of attempts required to pass the assessment. Secondly, we will examine the engagement with the quiz and compare this for 2009 and 2010. Finally, we can see if the quiz had any impact in (a) predicting performance in subsequent mechanics subjects and (b) did the quiz benefit students who took the mechanics subject.

Quiz results

Figure 4 shows the progression of students passing the quiz. There is a marked difference between the first time success rate in 2009 and 2010. Similarly with the second attempt. The main reason for this is that after running the quiz in 2009, the tutorial activities in the lead up were better aligned with assessment. The total number of passes is similar from the third attempt onwards. The final column for 2009 represents those who did the quiz 5 or more times.

In 2010, a small number of students did the quiz more than six times and they are included in the six quiz statistic. It can be seen that almost 80% of the class demonstrated the mastery skill by the second attempt. That meant that tutors could concentrate on the remaining 20% and really understand what their individual problems were. Sometimes it was basic algebra or trigonometry, often it was simply reading the question accurately.

Table 1 gives the number of students in 2010 attempting each question and the number answering correctly. In addition it compares the numbers for the upper quartile and lower quartile. The difference between these is the Discrimination factor which is a measure of the divergence in understanding for that question. A large discrimination factor indicates that there is a bigger gap in understanding between upper and lower quartile students. Here we see that Q2 Simply supported beam with two overhung loads, which is similar to Figure 3(b) has a discrimination factor of 71.72 which is much higher than some of the other questions. A similar question with one of the loads pointing upwards has an even higher discrimination. Another discriminating question is Vertical structure with a factor of 63.54.

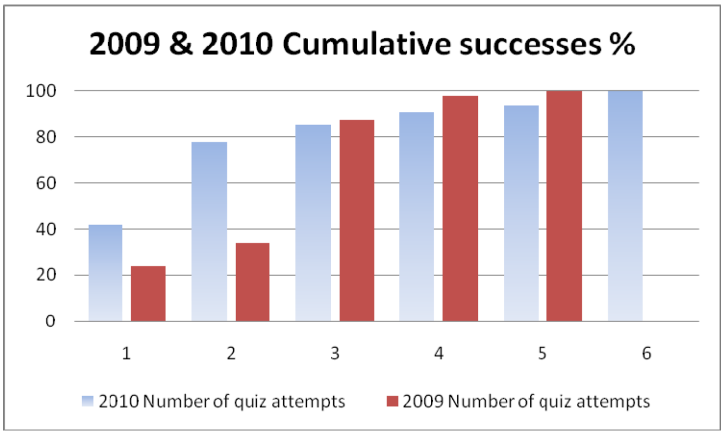

Figure 4 Percentage of class passing

Table 1 Results for the 2010 First attemprt at the FBD Quiz

Question Title	N	% Answering Correctly: All	% Answering Correctly: Upper 25%	% Answering Correctly: Lower 25%	Discrimination	Mean
Specify relevant theory	154	81.17	93.94	59.09	34.85	81.17
Horizontal reaction	166	96.39	100	86.11	13.89	96.39
Free body diagrams11	144	89.58	100	65.52	34.48	89.58
Free body diagrams111	176	93.75	100	84.31	15.69	93.75
Vertical structure	157	70.06	96.88	33.33	63.54	72.93
Question 2 Simply supported beam with mixed loads, Left	106	45.28	81.82	23.08	58.74	50.47
Question 2 Simply supported beam with 2 overhung loads, Left	160	33.75	76.74	5.13	71.62	40.12
Question 2 Simply supported beam with bidirectional loads, Left	95	56.84	92.31	35.71	56.59	61.16
Question 2 Simply supported beam with overhang left up right	119	54.62	90.62	11.54	79.09	59.16
Simply supported beam with vertical load	163	85.89	97.92	55.26	42.65	87.3
Question 2 Simply supported beam with overhung vertical load	320	74.38	96.25	41.25	55	77.12
Question 2 Simply supported beam with 2 overhung loads, Right	160	35.62	83.78	14.63	69.15	42
Resolving Forces	159	89.31	100	73.91	26.09	90.31
Resolving Forces1	161	91.3	100	82.35	17.65	92.17
Free body diagrams for truss11	158	81.65	100	51.16	48.84	81.65
Free body diagrams for truss111	162	80.86	97.67	48.65	49.03	80.86
Sign with cable support1	160	75.62	95.35	60.61	34.74	75.62
Sign with cable support	160	43.12	70.27	25.53	44.74	43.12
Sloping beam	320	59.69	92.5	47.5	45	59.69

This table confirms some students do not readily abstract the meaning of FBD's but rely on surface pattern recognition. They can solve a problem they have seen before but when the same problem is presented in a different orientation, they pick the wrong answer.

The Impact of Stage Gate test

The stage gate approach to testing a skill is a powerful tool. By running it early in the first session it forces many students to confront their lack of understanding. When the test was run in 2009, there was considerable discontent amongst the students. There was a feeling that they had not been adequately prepared for it and hence the lower early pass rate than 2010. Following the review of the 2009 quiz, changes were made for 2010. Some new FBD activities were incorporated in the tutorials in the lead up. A new text book was adopted which contains good instructions on FBD's (Hagen 2009). In addition, the tutors received detailed feedback from the subject coordinator and also the answer books written by the students. Tutors were able to play an active role in helping students prepare for re-sits. Figure 4 demonstrates that the success rate in the early attempts is greatly improved. Student engagement was more positive than the 2009 and tutors noticed more peer coaching in their classes.

Correlation with subsequent performance

Student performance in the 2009 online FBD quiz and their subsequent performance in ENGG152 Engineering Mechanics is compared in Table 2. Of note here is that 102 of the student sample had not done ENGG101 in 2009 and so had not done the FBD quiz. These are indicated as having done the quiz zero times. The average of this group is slightly less than the class average, although this is not statistically significant. The students who succeeded at the quiz at the first or second attempt have a much better performance in ENGG152. Those taking 4 or 5 attempts at the FBD quiz are still struggling.

The contour plot in Figure 5 shows an almost random distribution about the pass Grade P and 3 quiz attempts. The vertical axis is the number of students who have a particular grade and number of attempts at the quiz. There is certainly a big difference between those who only needed two quiz attempts and the rest. Those who have many attempts at the quiz still have a good chance of passing ENGG152.

Table 2 Comparison with ENG152 performance

Number of quiz attempts	Number of students	Average mark in ENGG152	Standard deviation	95% confidence
0	102	59	21.90	4.25
1	62	73	14.50	3.61
2	27	73	13.84	5.22
3	137	57	14.70	2.46
4	27	48	17.27	6.52
5	5	51	8.62	7.56
All students	360	61	18.51	1.91

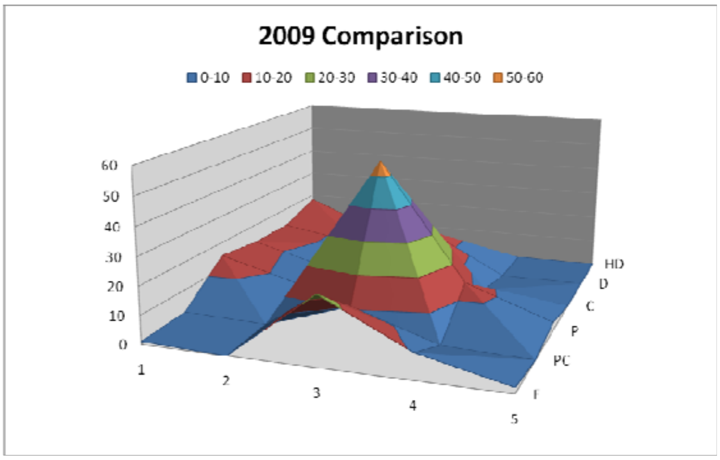

Figure 5 ENG152 grades Number of quiz attempts

Discussion and Conclusion

The 2010 version of the online quiz has run much more smoothly than the first running in 2009. The initial outcomes are better, in that more students passed with fewer attempts. Student satisfaction was much higher in 2010 than 2009 and tutors reported much better morale amongst students in 2010.

The comparisons between performance in the FBD quiz and ENGG152 in 2009 do not demonstrate that the quiz has improved things. The comparison does reinforce the message that those who have mastered the FBD early in their engineering studies do have an advantage when it comes to engineering mechanics. It can be said that those who have done the FBD quiz fair marginally better than those who have not done the quiz (i.e. the zero quiz attempt line in Table 2). However, the grades alone do not allow a full explanation to provide a statistically significant proof.

A clear lesson was learned in 2009, that the students' emotions affect their engagement with the online quiz. When presented with a high probability of failure, even though unlimited re-sits were available, the students reacted negatively. By better gauging the level of difficulty and making the students feel that they have been well prepared for the task has brought about a more positive engagement and a more successful test result.

We await to see how the 2009 cohort perform in second year mechanics of solids and whether their 3rd year lecturers view their mastery of FBD's as any better than previous cohorts.

Other benefits have accrued due to the nature of the online quiz. Students at risk of failing because of a range of difficulties were confronted much earlier in their course. The requirement to pass the quiz has brought more weak students into a positive relationship with their tutors and lecturers. This may turn out to be the most important outcome of the stage gate quiz in first year, first session.

Acknowledgements

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