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Keywords

body, online, free, concept, understanding, students, assessing, diagrams, tests

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ASSESSING STUDENTS UNDERSTANDING OF THE CONCEPT OF FREE BODY DIAGRAMS USING ONLINE TESTS

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Abstract

There are many threshold concepts for students to grasp in Engineering Mechanics. Research has shown that one of the critical concepts that must be understood is the Free Body Diagram (FBD). This paper describes an approach to check students' mastery of simple Free Body Diagrams and to address errors and misconceptions they may have. An online FBD quiz has been designed and implemented in a first year Engineering subject. Teaching material and follow-up support is targeted for students who struggle with the concept until mastery is achieved. These have been based on the theory of threshold concepts and the force concept inventory. The FBD quiz is found to be a good predictor of future performance in subsequent Engineering Mechanics subjects. An analysis of student performance in the FBD quiz has identified the questions that best test the conceptual understanding.

Keywords: Free body diagram, FBD, online testing, threshold concept.

1 INTRODUCTION

One method of teaching concepts is to study the nature of students' misconceptions and the systematic errors they make. Based on this knowledge the curriculum is designed to employ corrective strategies. Many Engineering students learn in a constructivist manner where they try to create meaning in what they see and experience. They do this construction from what has gone before. Anomalies are sorted out through experimentation until a new and more elaborate meaning is established. Difficulties arise when one holds a misconception which seems to explain a phenomenon or when one misses the true concept underlying the phenomenon. The authors have implemented an online test with remedial instruction for teaching Free Body Diagrams. This is based on Bruner's theory of concept attainment through a systematised adaptation of instruction to counteract the identified errors and misconceptions [1].

1.1 Threshold concepts

There are many concepts in Engineering that students must come to terms with if they are to succeed in their undergraduate studies. There are core concepts which must be understood before progressing to the next level of understanding of the subject. These are building blocks which need to be understood but do not lead to a different view about the material. Examples of such concepts may be mathematical procedures used to determine a solution to an engineering problem. Meyer and Land [2] characterised "*threshold concepts*" as ones that have a *transformative* effect on the learners' understanding and views of the material. They further suggest that once the threshold has been crossed, the effect is probably *irreversible* and impossible to unlearn. Many such threshold concepts are *integrative*, in that they open ones eyes to links between different topics or subject matter that was previously unseen. A final characteristic of the threshold concept that affects many engineering students is that it is often *troublesome*. The truth of the concept may disturb a previously held belief. Misconceptions based on everyday experiences tend to make many Engineering Mechanics threshold concepts troublesome or problematic. For example, we can perceive the velocity of an object by observation. However, it is difficult to observe acceleration. Many students have confusion about phenomena associated with acceleration and velocity e.g erroneously thinking that high velocity is necessarily associated with high acceleration.

Many authors have described problematic concepts in basic Physics and Engineering Mechanics. Hestenes' work in the early 1990's introduced the Force Concept Inventory and a mechanics baseline test for first year university students[3-4]. This work established a taxonomy of misconceptions people commonly hold about the concept of force and its effects. This is a superset of the concepts involved with static equilibrium. One member of the Force Concept Inventory is termed "*concatenation of* *influences*" or the ability to combine forces correctly [5]. A method to avoid errors with this is to draw the correct Free Body Diagram.

Male and Baillie [6] have constructed a list of engineering threshold concepts using Meyer and Land's characteristics. One concept identified in their work is relevant here: "*moment equilibrium in statically determinate systems"*. This is a subset of the concatenation of influences and is particularly troublesome for many engineering students.

The nature of the threshold concept is that when it is mastered, it transforms the student's understanding. Like riding a bicycle, once the skill has been achieved, it is hard to forget it. Facility with the concept will improve with practice just like one can become a better cyclist. Not understanding the concept is a complete barrier to mastery of content that relies upon it.

1.2 Free body diagrams

In order to solve many combined force problems, a graphical representation of the system showing the spatial relationship between all forces and moments is constructed. Free body diagrams (FBD) are the abstraction of the external forces and moments acting on a physical object. The effects of all external connections are replaced by the forces and moments that those connections or supports can impart [7-8]. A simple FBD is shown in Fig. 1. The diagram is usually hand drawn as part of the solution in an engineering mechanics problem. In this FBD, the table beneath the ball is replaced by the upwards force that the table exerts on the ball. A frame of reference showing x and y axes is included. In this case the weight of the ball is W and the reaction force from the table is F_y. If the system is at rest and in equilibrium, one can deduce that the forces, W and F_y, are equal but opposite. More elaborate force systems and diagrams are included later in this paper.

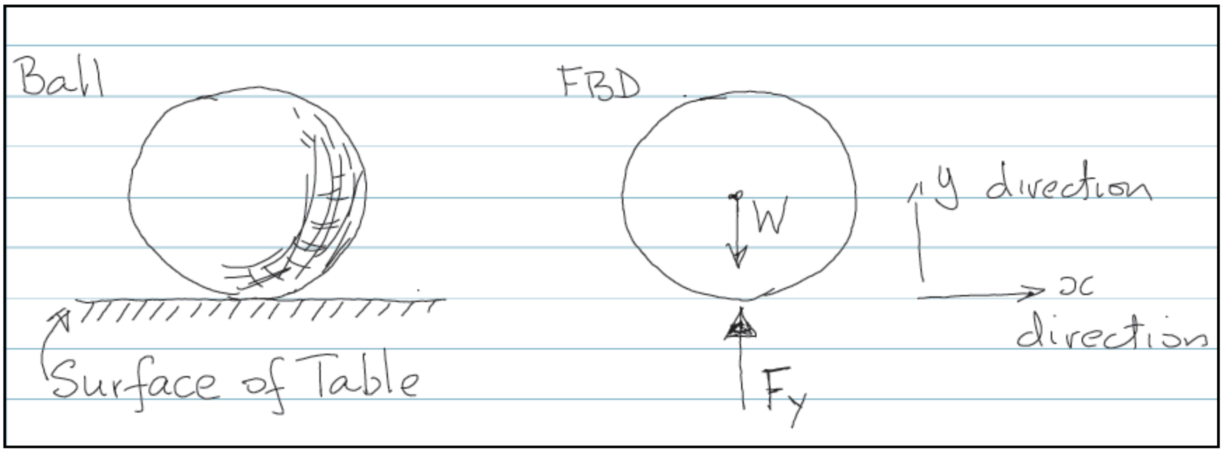

Figure 1 Hand drawn FBD of a Ball on a Table

1.3 Problem identification

From section 1.1, one can see that there are aspects of the free body diagram included in a number of previously reported threshold concepts. Indeed, the FBD itself is a concept that meets the criteria to be considered as a threshold concept.

A study of engineering students' performance in a mechanics statics examination confirmed that those students who made errors in the free body diagram or omitted drawing one, performed markedly worse than those who drew correct diagrams but made other mistakes. Virtually the whole group with incorrect FBDs failed the test [7].

During a 2008 curriculum review of Engineering Degree programmes at the University of Wollongong, Australia, it was reported by instructors of 3rd and 4th year Engineering Design subjects that their students were producing incorrect free body diagrams even though this topic was taught in earlier years. Given the irreversible nature of the threshold concept, this indicated that many students were never fully grasping how to construct free body diagrams. From this review, the teaching of FBDs was changed and an intervention was designed and implemented in a First Year core Engineering subject. The aim was to better teach students how to draw FBDs and to reinforce the importance of this concept for solving an Engineering Design problem.

1.4 Context and the curriculum

The First Year subject, ENGG101 Foundations of Engineering, covers the introduction to statics and dynamics through two intensive hands-on enquiry based learning activities [9]. The first activity which takes place over a six week period involves the design and building of balsa wood beams. It is within this activity that FBD's are introduced. Following an analysis of the First Year Engineering curriculum, it was discovered that the treatment of FBD's was very brief. The existing mechanics text books treated FBD as assumed prior knowledge.

The text book was dropped in 2009 and in 2010 a new text book, Introduction to Engineering Analysis by Kurt Hagen [10], was adopted. This book includes a good introduction to FBDs. The lecture on free body diagrams was re-written, new tutorial activities were designed and an online FBD quiz was created.

ENGG101 occurs in the first semester of first year and is core for all Engineering degree programs. It is followed in second semester by a more traditional Engineering Mechanics subject ENGG152 which covers both statics and dynamics. The textbook for ENGG152 is Hibbeler's Engineering Mechanics: Statics [11]. In first semester of second year, the students take ENGG251 Mechanics of Solids which follows Gere and Goodno's textbook [12]. The possible sequences for students to take these subjects are shown in Fig 2. The majority of students follow the sequence ENGG101-ENGG152-ENG251. However, some students begin their studies in mid year and so do ENG152 first and then take ENGG101 in parallel with ENGG251.

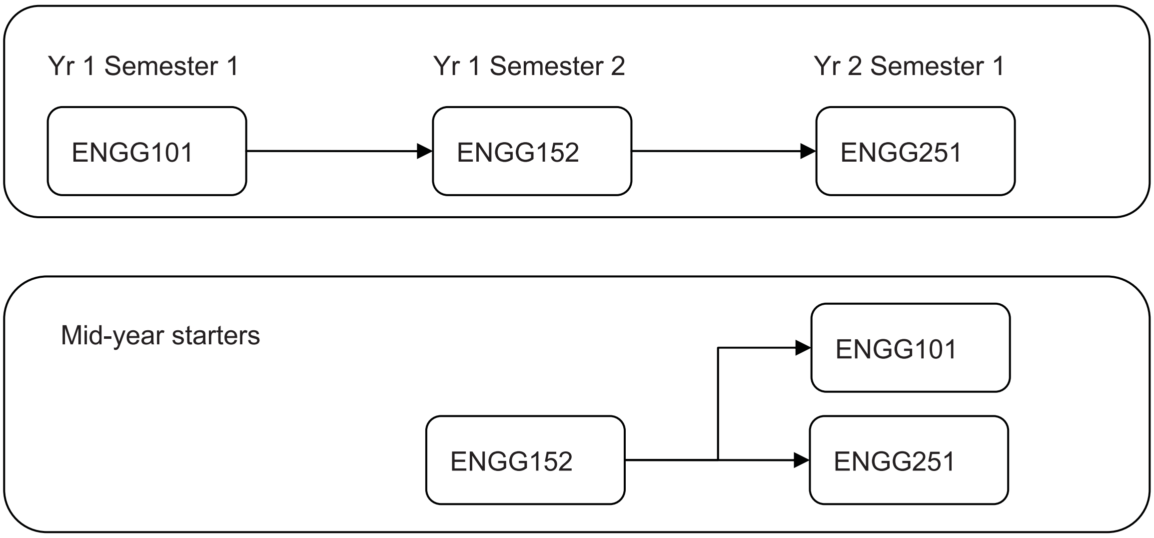

Figure 2 Subject sequences

2 ONLINE FBD QUIZ DESIGN

The online FBD quiz is taken by students as part of ENGG101. It is run as a stage gate assessment meaning that students must pass the test and demonstrate the minimum mastery skill to progress in the subject. This requirement reinforces the importance of FBD's in the curriculum and quickly identifies those students who need extra help with the topic. Students retake the quiz as many times as necessary. It concentrates on whole system statics and equilibrium.

2.1 Questioning concepts

Since this quiz occurs very early in the degree program and since the exposure to FBDs is limited, the questions are simple in nature. The type of question is also limited by the capabilities of the online learning management system. The questions are designed to identify students who struggle with FBDs and not hold up those who have an acceptable grasp of them. The quiz is not intended to be an all encompassing FBD test, rather it is a stage 1 initial test.

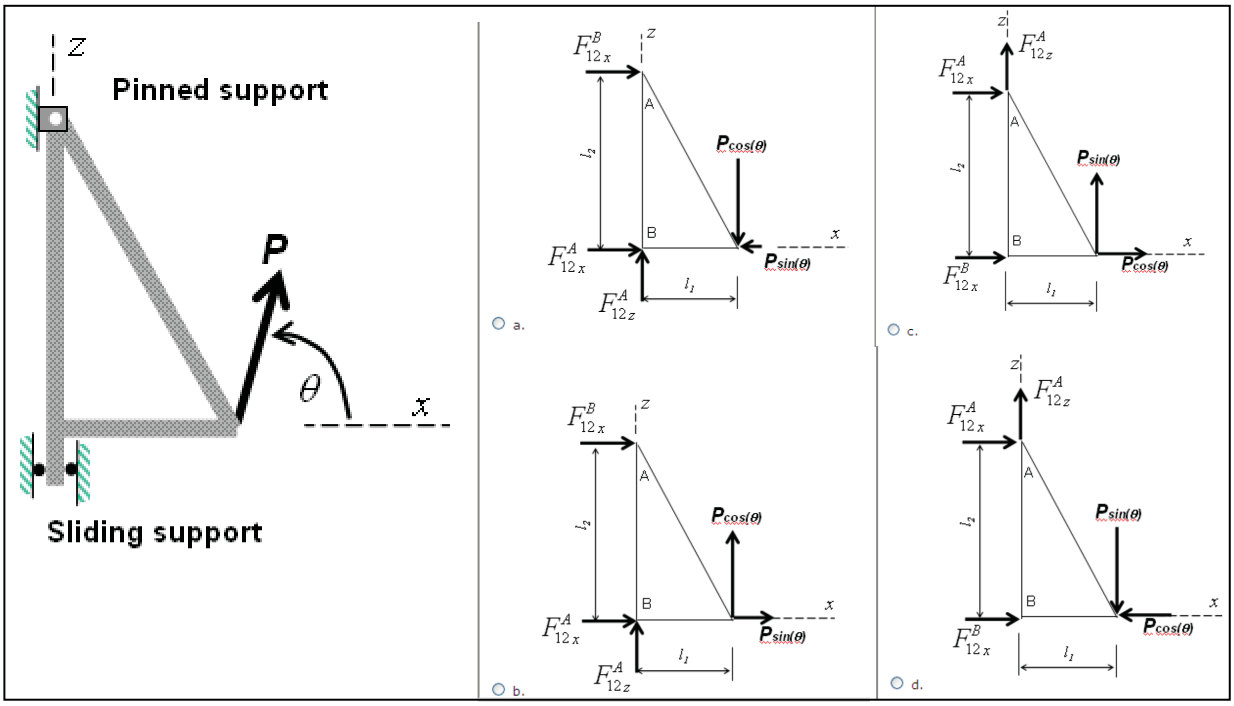

Figure 3 Truss Multiple choice question

The initial two questions relate to force resolution and basic trigonometry rather than FBDs. This is to verify the assumed prior knowledge. These are followed by sketches of beam and truss structures (Fig.3) and students are asked to select the correct FBD from four options. Students are required to calculate reactions for horizontal simply supported beams and then a vertical structure. Horizontal beams with overhangs (Fig. 4(b)) test the ability to calculate the moment equilibrium correctly. Some questions present correct answers which appear to be counter intuitive. The same question is presented in different orientations and students are required to reason about the forces without doing any calculations (Figs 5 a & b).

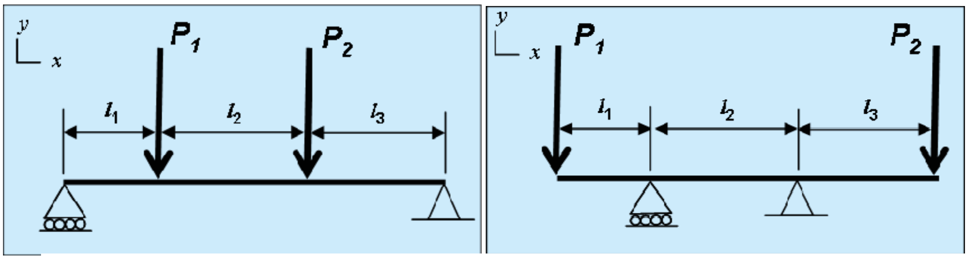

Figure 4 (a) Simply supported beam (b) Beam with overhangs

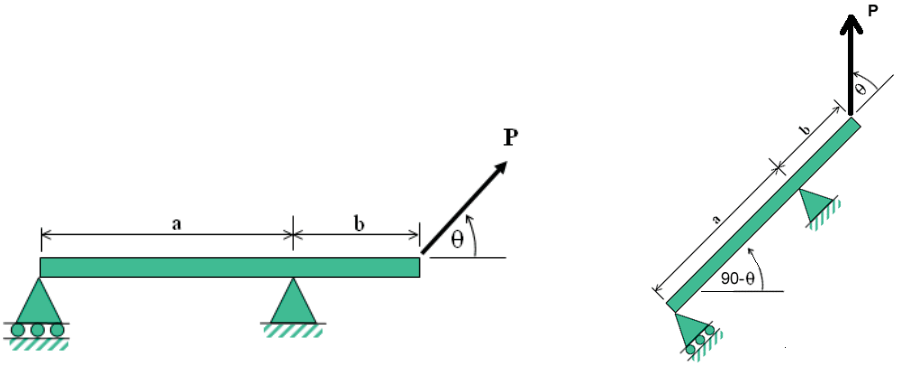

Figure 5 Sample questions (a) Horizontal beam (b) Sloping beam

2.2 Quiz implementation

The staging of the quiz is such that students are allowed multiple attempts, until they achieve the standard required. There is a lecture and tutorial activity on FBDs, linked to their beam design project in the 3rd week of the subject. A practice online quiz is held during the 4th week to familiarise the students with the quiz interface and the topics covered. The Online FBD quiz is run during the 5th week. It contains 10 questions from a databank. Students attend one of the computer laboratories and access the quiz under examination conditions. As they answer the questions, some of which require calculations and drawing FBD's, the students are required to show all their workings in a paper script and then input their answers to the online quiz. The computer marks their work and the paper script is handed to the tutor who will give immediate feedback on errors before the student leaves the quiz room.

To demonstrate the mastery skill, students are required to achieve at least 8/10 in the first sitting of the quiz. So if they achieve 8, 9 or 10/10 that will be their mark for the assessment. The quiz assessment is worth 10% of the overall mark or the subject. If they get 7 or less, they must attend a second running of the quiz the following week. This will be after their next tutorial when the tutor will give more feedback on the common errors. At this second sitting, the quiz is reduced to 8 questions. The two easiest questions are removed. To demonstrate the mastery skill this time, students must get at least 6/8. Thus, if they achieve 6, 7 or 8, that will be their mark for the assessment. Students who score below 6 are required to sit the quiz once more. At this stage, the quiz is reduced to 6 questions and students must score 6/6 to pass. Students who have not demonstrated the minimum mastery skill receive additional tutoring and can take the quiz as many times as needed until they get 6/6. Once they achieve this level, their mark for the assessment is 6/10.

The online FBD quiz has been implemented in WebCT Vista [13] for the years 2009-2012. From 2013 the University will be using a Moodle [14] based learning management system. The question types used in the quiz are calculations based on parametric formulae and multiple choice. Questions are organised in 10 categories, each dealing with a single aspect of recognising correct FBDs or using and FBD to obtain a force. There are a number of questions in the databank for each category. For each calculation type question there are 25 variations.

When a student takes the quiz for the first time they receive one question from each category. Within the category, the question is chosen by the computer, at random. For multiple choice questions, the order of the answers is changed each time the question is used.

For security, the learning management system restricts access to the quiz to the allocated times. The quiz has a password which is announced at the start of the quiz and access can be limited to IP addresses within the computer laboratory.

3 ONLINE FBD QUIZ RESULTS

When the online FBD quiz was run for the first time in 2009, the ENGG101 subject coordinators were not sure where to set the pass mark. It was quickly realised that the original idea of a pass mark of 9/10 was not going to work as competent students were often making more than one mistake which was not related to an understanding of FBDs. The pass mark was set at 8/10 and it can be seen from Fig 3 that just over 20% of the class passed on the first attempt. Another 30% of the cohort passed at the second attempt after which there was a gradual success rate.

This initial high “failure” rate caused much anxiety amongst the students and was de-motivating. Students reported that they felt underprepared for the test. They also complained that format of delivery was too restrictive. Initially questions were delivered one by one and had to answered in sequence and the system did not allow students to revisit questions.

The first point was addressed in the tutorial design and by the introduction of the new text book in 2010. That book had not been published in time for the 2009 class. The delivery of questions was changed so that all questions were delivered at once and students could decide which one to answer first. They could also change their answers before submitting the entire quiz for marking at the end. It was a surprise, but this latter change had the biggest impact on the student attitude and also on initial pass rates. Students in 2010 and 2011 did not display any of the de-motivation seen in 2009.

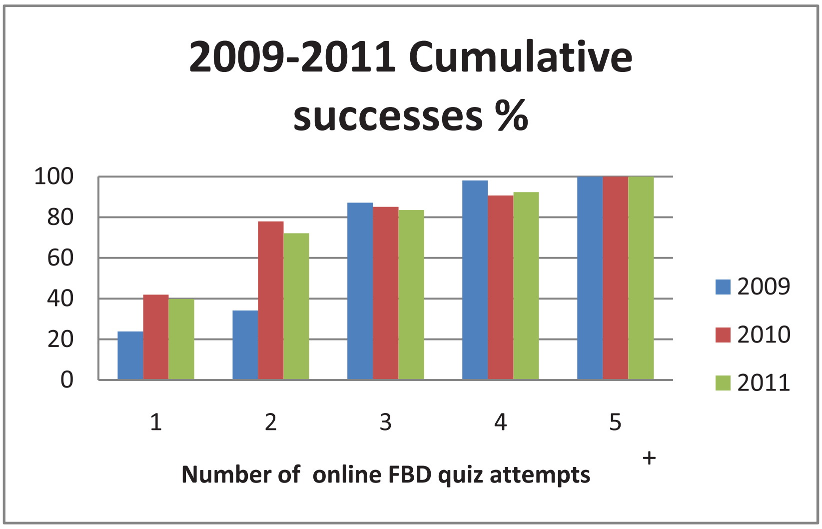

Figure 6 Online FBD Quiz Success rates

3.1 Pass rates 2009-2011

Fig. 6 shows the percentage of students who achieved the minimum skills level after each running of the test. It can be seen that the 2009 results for 1 and 2 attempts are well below the later years. In 2010 and 2011 approximately 40% of the class succeeded at the first attempt. Feedback from tutors suggests that this figure is about right. After 2 attempts, the portion of the class still in need of FBD tutoring is only 20-25%. About 10% of the class take 5 or more attempts. This group of students struggle with other subjects and have a high risk of failing later mechanics subjects. Every student who engages with the online quiz activity passes it eventually.

3.2 Discriminating questions

One of the aims of the online FBD quiz is to have questions that separate students who understand the concept from those who do not. Questions should be easy for those who have a good grasp of FBDs and should be difficult for those who do not. Table 1 shows the numbers answering each question in the 2011 first attempt. It gives the percentage of those who answered correctly and also shows the Discrimination percentage. The Discrimination percentage is the difference between the top quartile and bottom quartile answering a question correctly. A high value for the discrimination value indicates that that question is successful in identifying those who have missed the concept. When this number is viewed in conjunction with the overall score for that question one can identify which concepts are giving most trouble to the bottom quartile and which are problematic for most of the class.

Referring to the upper part of Table 1, it can be seen that the simply supported beam with mixed loads and overhangs is dividing the class. The beam in Figure 4(a) is the sixth most discriminating question while the beam in Figure 4(b) is the second. 4(b) is simply 4(a) inverted. Although the sloping beam is showing the lowest discrimination value at the bottom of the table, it is somewhat problematic for the whole class. The question with the lowest overall score is the Sign with a Cable support shown in Fig 7. The question asked for the FBD for the cable indicated by the number 3. The correct answer in the quiz was counter-intuitive. A second version of this question with a straightforward answer did not present the same problems for students.

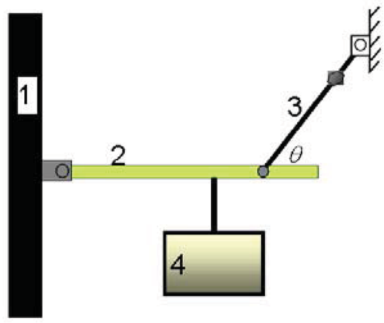

Figure 7 Sign with a cable support

Table 1 Results for 2011 First attempt at Online FBD Quiz

Question Title	N	% Answering Correctly: Whole Group	% Answering Correctly: Upper 25%	% Answering Correctly: Lower 25%	Discrimination
Simply supported beam with mixed loads, Left	108	55.56	89.19	3.57	85.62
Simply supported beam with 2 overhung loads, Left	191	38.22	88.37	5.36	83.01
Simply supported beam with bidirectional loads, Left	116	56.9	94.74	19.35	75.38
Simply supported beam with 2 overhung loads, Right	155	49.03	79.55	12.9	66.64
2 Simply supported beam with overhung vertical load	346	58.96	87.36	21.84	65.52
Simply supported beam with vertical load	167	79.64	97.67	37.84	59.84
Vertical structure	179	70.39	95.45	38	57.45
Free body diagrams for truss11	185	72.43	97.67	41.67	56.01
Simply supported beam with overhang left up right	122	59.84	83.87	28.57	55.3
Specify relevant theory	158	68.99	93.94	39.53	54.4
Free body diagrams11	183	83.06	100	50	50
Free body diagrams for truss111	161	78.26	95.45	46.15	49.3
Sign with cable support	171	38.01	65.62	17.65	47.98
Sign with cable support1	175	74.29	98.18	55.56	42.63
Free body diagrams111	163	82.82	94.44	57.78	36.67
Horizontal reaction	188	88.83	100	63.64	36.36
Resolving Forces1	176	86.93	100	68.89	31.11
Resolving Forces	170	88.82	100	71.43	28.57
Sloping beam	346	59.83	80.46	58.62	21.84

4 ONLINE FBD QUIZ AS A PREDICTOR OF FUTURE PERFORMANCE

Student performance in the Online FBD quizzes and their subsequent grades in ENGG152 and ENGG251 have been recorded. Three years of results for ENG152 are shown in Table 2 and Fig. 8. One factor that is worth looking at is whether the subject ENGG101 and the Online FBD quiz have any positive effect. A second aspect is to investigate if there are any long term predictions that can be made from the student results in the Online FBD quiz. The 2011 results for ENGG251 are presented in Figure 9.

4.1 ENGG152 performance

Table 2 includes some 218 students who have not studied ENGG101 or taken the FBD quiz prior to studying ENGG152. These students may have transferred from other universities, articulated from colleges or joined in mid-year of 2011. They represent approximately 10% of the combined population. Their average mark in ENGG152 is 56.8% with a confidence of 2.9%. The average of all students is 59.4%. The average mark for those students who took the FBD quiz can be calculated as 60.1%. This means that there is a small but significant improvement in performance for those students who underwent the Online FBD quiz.

Looking at those student who showed early mastery of the simple FBDs (passing in 1 or two attempts), we can see that their subsequent performance in ENGG152 is markedly better than those who took 3 or more attempts. The average mark in ENGG152 for those who took 5 or more attempts at the ENGG101 Online FBD quiz is less than a pass grade.

Figure 8 presents the number of students obtaining each grade High Distinction (85% or more) down to Fail (less than 50%). The surface dips to zero for the number of students who took 5+ attempts and those who obtained a high distinction in ENGG152. This is seen towards the front of the graph. Towards the back of the surface, we see the distribution of grades for those who passed the FBD quiz at the first attempt. We can see that passing the quiz is no guarantee of subsequent success as just over 20 of these students failed ENGG152. However, the general trend is maintained. Those who passed the quiz with fewest attempts do better in ENGG152 than those who struggled.

This means, that while there is a small overall benefit in doing ENGG101 and the FBD quiz, the quiz does not fully address the difficulties that some students have.

Table 2 ENGG152 performance versus FBD Quiz 2009-2011

Attempts at FBD	Number of	Average ENGG152	Standard deviation	95% confidence
0	218	56.8	22	2.9
1	301	68.1	16.4	1.9
2	224	61.3	16.3	2.1
3	234	54.2	18.7	2.4
4	71	49.9	15.3	3.6
5+	46	47.2	16.2	4.7
	1094	59.4	19.2	1.1

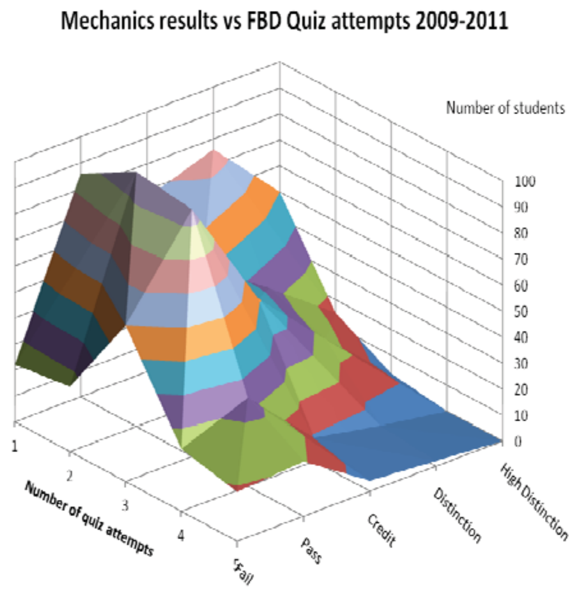

Figure 8 ENGG152 vs FBD 2009-2011

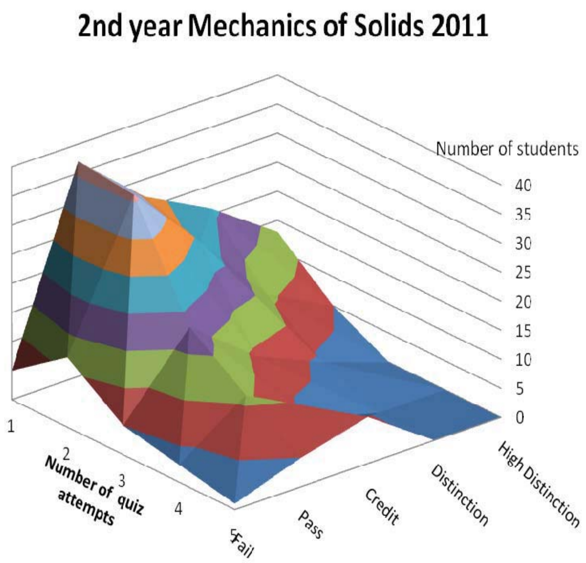

Figure 9 ENGG251 vs FBD 2011

4.2 ENGG251 performance

Fig. 9 shows a slightly better outcome for those students who have made it thus far, having taken 4 or more attempts at the FBD quiz. Here we see much fewer failures and while there are no Distinction or High Distinction grades for these students, many are achieving Passes and Credits. The proportion of these students failing ENGG251 is only marginally higher than for the class as a whole.

There is a similar story to ENGG152 for the students who took only 1 or 2 attempts at the FBD quiz. Their mastery of FBDs continues to lead them to better performances in ENGG251. Those who passed the FBD quiz on the first attempt are twice more likely to obtain High Distinction than those who took two attempts. Those who took 3 or more attempts did not score any HD grades in ENGG251.

5 CONCLUSIONS

The results presented here demonstrate that we have successfully developed an online FBD quiz that detects student who *get* this concept and those who have difficulties with it. Questions which present problems in different orientations to simple horizontal are good discriminators of FBD understanding.

While all students eventually succeed at the FBD quiz, receiving extra tuition along the way, it is not a universal panacea for down stream subjects. Some students who take many attempts to succeed at the FBD quiz pass ENGG152 and even obtain credit grades at ENGG251. However, approximately half continue to struggle on the pass/fail boundary.

Given that it is possible to design tests to check students understanding of the concepts of FBDs it might be desirable to create new higher level FBD quizzes to check understanding in more complicated scenarios.

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