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Title: Evaluation of creative problem solving abilities in undergraduate structural engineers through interdisciplinary problem based learning

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Abstract

For a structural engineer, effective communication and interaction with architects cannot be underestimated as a key skill to success throughout their professional career. Structural engineers and architects have to share a common language and understanding of each other in order to achieve the most desirable architectural and structural designs. This interaction and engagement develops during their professional career but needs to be nurtured during their undergraduate studies. The objective of this paper is to present the strategies employed to engage higher order thinking in structural engineering students in order to help them solve complex problem based learning (PBL) design scenarios presented by architecture students. The strategies employed were applied in the experimental setting of an undergraduate module in structural engineering at Queen’s University Belfast in the United Kingdom. The strategies employed were: active learning to engage with content knowledge, the use of physical conceptual structural models to reinforce key concepts and finally, reinforcing the need for hand sketching of ideas to promote higher order problem solving. The strategies employed were evaluated through student survey, student feedback and module facilitator (this author) reflection. The strategies were qualitatively perceived by the tutor and quantitatively evaluated by students in a cross-sectional study to help interaction with the architecture students, aid interdisciplinary learning and help students creatively solve problems (through higher order thinking). The students clearly enjoyed this module and in particular interacting with structural engineering tutors and students from another discipline.

Keywords: Active learning; critical thinking; problem based learning; interdisciplinary

1.0 Introduction

Structural engineers and architects work closely together throughout their entire careers. However, only a small number of universities in the United Kingdom explicitly offer Master in Engineering (MEng) degrees in Structural Engineering with Architecture. One of the fundamental learning outcomes of such degrees is to develop creative engineering problem solving abilities within an architectural context.

The ability to be an innovative engineer has been identified by professional engineering accreditation boards around the world as a key to success and therefore should be nurtured during undergraduate education (e.g. the Accreditation Board for Engineering and Technology (ABET 2015) in the United States, the Institution of Structural Engineers (IStructE 2015) in the United Kingdom and the Institution of Civil Engineers (ICE 2015) in the United Kingdom). Innovative thinking can be developed by undergraduate engineering students through creative problem solving in problem based learning (PBL) exercises.

As stated by Gavin (2011), many epistemological studies related to PBL in civil engineering support the application of PBL in undergraduate degree programmes. However, few studies

provide an illustration as to how to practically implement PBL in an undergraduate degree. In the case of the discipline of structural engineering, few if any studies provide practical ways to implement interdisciplinary PBL with architecture students. Structural engineers and architects spend the majority of their professional careers working together, so it is necessary for their relationship and mutual understanding to be developed during their education. The research question exists: how do structural engineering students perceive their skills and ability to solve complex problems in an interdisciplinary PBL project? This paper describes a case study of three strategies to aid interaction and engage higher-order interdisciplinary problem solving between undergraduate architecture and structural engineering students in a PBL module. The three approaches are as follows: the use of active learning to engage with content knowledge, the use of physical conceptual structural models to reinforce key concepts and finally, reinforcing the need for hand sketching of ideas to promote higher order problem solving. These strategies were adopted during an interdisciplinary PBL design project aimed at achieving higher order thinking to enable creative structural engineering problem solving. Student surveys, student feedback and module facilitator (tutor) reflection were used to assess whether and to what extent the students positively engaged with the architecture students in the PBL scenario and used higher order thinking to creatively solve complex problems. The success of the employed strategies was evaluated through qualitative reflective module facilitator assessment and quantitative analysis of student surveys and feedback. This paper provides practical teaching approaches to help undergraduate structural engineering students achieve their own innovative PBL design solutions through creative problem solving.

2.0 Background

2.1 Problem based learning

In third level education over the past twenty years, there has been a gradual move away from programme delivery solely through traditional lecture based “chalk and talk” learning towards integration of PBL modules in degree programmes. In a study by Bernold (2005) into engineering education, the author found that engineering education has to reform itself to allow creative students to succeed. In the study, Bernold (2005) quotes a 2001 survey finding that 87% of United States professors still lecture passively to students who sit and copy down material never to be used again. However, there has been a move towards more interactive learning in different disciplines of engineering education: civil (Bielefeldt 2013), mechanical (Frank, Lavy, and Elata 2003); electronics (Cirstea, 2003); chemical (Cline and Powers 1997) biomedical (LaPlaca, Newstetter, and Yoganathan 2001) and a common first year programmes sharing multiple engineering disciplines (Hall, Palmer, and Bennett 2012).

PBL was first adopted in medical teaching at McMaster University, Canada by Barrows and Tamblyn (1980). The two basic postulates of Barrows and Tamblyn (1980) were, firstly that learning through problem solving is much more effective than learning a large body of useable knowledge and secondly that problem-solving skills were more important for physicians than memory skills. PBL has since spread to other disciplines and has been well received in civil engineering. Within a civil engineering context, Barker (1986) describes PBL as a way of counteracting the conditioning of general education and helps students to produce unique solutions. As stated by Chandrasekaran et al. (2013) PBL is well developed and implemented in most engineering schools around the world now. However, interdisciplinary PBL at undergraduate level in engineering is less well developed. In civil engineering education, PBL is often referred to as project based learning because of the engineering projects have a longer time duration than problems, are usually run in parallel with lectures and learning is directed by the project (Mills and Treagust 2003). However, in this paper it is referred to as problem based learning.

Issues in PBL in engineering education exist that need to be addressed to successfully achieve the learning outcomes. Hosseinzadeh (2012) taught PBL in electrical power systems engineering and had concerns over the breadth of content to be covered without compromising subject specialised technical content. Frank, Lavy, and Elata (2003) observed that students needed to be trained in teamwork in order for the PBL exercise to be effective. Hall, Palmer, and Bennett (2012) taught PBL in a common first year module for civil, mechanical, electrical/electronic and biomedical engineering pathways. Hall, Palmer, and Bennett (2012) found most of the common issues in group projects affect PBL such as: high time demand in project work, issues with students not pulling their weight and a need for preparation of the students for teamwork. These issues have been addressed during the planning of this PBL module but are also discussed with the students in the introductory lectures.

2.2 Problem based learning and structural engineering undergraduate degree requirements

The Institution of Structural Engineers, one of the accrediting bodies for engineering degrees in the United Kingdom, reported on the requirements for undergraduate degrees in 2012 (Owens 2012). In the report, Owens (2012) identified the interpretation of structural drawings, sketching of structures and load paths as abilities that graduates should have. Importantly, graduates should also qualitatively understand the overall stability of structures. The choice of structural material and evaluation of potential skeletal structural solutions are also key abilities highlighted by Owens (2012). Equipping the structural engineering students with the ability to perform the above mentioned requirements form part of the learning objectives of the module. The PBL exercise the structural engineering students were presented with was a new market hall located in a small town in Northern Ireland. The architecture students were tasked with creating a building design based on their site analysis and precedent study of similar buildings. The architecture students are in their second year (Stage 2) of a three year undergraduate Bachelor in Architecture degree. Improving the structural engineering student's engagement with the architectural design process and improving their ability to impact the creative process of building design with the architecture students will help in part to achieve the abilities highlighted by Owens (2012). The fundamental task of a teacher and fundamental aim of the strategies adopted in this paper are similar to those outlined by Shuell (1986) i.e. to get students to engage in learning activities to achieve the desired learning outcomes. The ability to perform the tasks identified by Owens (2012) could appear to be specific to the discipline of structural engineering, however they essentially equate to being able to convey complex problems and solutions to others and understand the fundamental theory and concepts of the discipline and how to apply it. The ability to understand theory and then solve complex problems is necessary for any undergraduate studying any discipline of engineering. Therefore, the PBL exercise needs to align learning outcomes with the skills the students will need for success in the future as structural engineers.

2.3 Skills for success

Professional engineering societies such as the Institution of Structural Engineers (IStructE 2015), Institution of Civil Engineers (ICE 2015), and advocacy groups such as Think-up (Think-up 2015), Expedition Workshed (Expedition Workshed 2015) and Science, Technology, Engineering and Maths (STEM) (STEM 2015), exist to promote education in engineering. These groups have their own take on what skills are needed for graduates to succeed, however, Beers (2012) sums up well the skills needed for success by STEM practitioners throughout their career in the 21st century world. Beers (2012) states that some key principles to enable students to conceptually store, retrieve and use information in new ways are as follows:

1. Connecting the content knowledge to real-world applications and problem situations that enable students to see how what they are learning connects with their lives and the world around them
2. Emphasising deep understanding of the learning by focusing on projects and problems that require students to use the content knowledge in new ways
3. Engaging students in solving complex problems that require higher order thinking
4. Helping students make connections between subjects, concepts and ideas and with others, including those outside of the classroom

It is important as an educator to keep the industry context within PBL modules and ensure the skills for success are at the core of the learning outcomes. These skills for success are applicable to any discipline of engineering.

2.4 Use of technology for visualisation

It is worth mentioning new technologies in civil engineering as on the face of it, promoting hand sketching and physical model making may seem outdated. In particular, the implementation of technology into the civil engineering profession such as Building Information Modelling (BIM), the use of aerial drones for assessment/surveying and the use of virtual reality for visualisation has increased recently. It is clear that the classroom needs to keep pace with these technological developments whilst not undermining the content knowledge and understanding required to be an engineer. BIM, within a construction sector context, is a model-based process for planning, designing, constructing and managing the construction of buildings and infrastructure projects. Pikas, Sacks, and Hazzan (2013) have shown that BIM helped students visualise products and processes in capstone engineering courses. Importantly though, Pikas, Sacks, and Hazzan (2013) showed that for structural analysis and rapid generation and evaluation of plan alternatives BIM was not sufficient in achieving expected student competencies. The authors recommend these be taught elsewhere in the curriculum. In this module, students are required to engage with architecture students and quickly solve/resolve problems using a common language. As BIM does not aid rapid generation and evaluation of plan alternatives it is not suitable for use in this module.

Virtual Reality (VR) (McCabe and McPolin 2015) and Augmented Reality (AR) (Izzary et al (2013); Chi et al. (2013); Bendzahan and Kamat (2013)) have been applied to both of the architecture and engineering construction industries in recent years due to the reduction in cost of the technologies. The current major drawback, within a teaching context, is that VR and AR have to significantly reduce in price before they will become a widespread teaching tool. Within PBL scenarios, both VR and AR will have a role to play in the future with respect to discussing design alternatives and solving problems. Computer aids that help visualisation of engineering structures are ever improving; however the skill of quickly and accurately sketching complex ideas remains a key skill to success for a practicing engineer. If you are on a building site and have to sketch out a structural detail to a contractor, VR and AR are still not relevant. In a similar manner to BIM, VR and AR are not applied in this module as they do not allow students to rapidly generate and evaluate plan alternatives.

Other reasons for not using technologies such as BIM, VR and AR are that they insufficiently develop student’s basic competencies and there is a lack of time to develop the student’s abilities. For all of the reasons mentioned above, BIM, VR and AR are not deemed appropriate for use in this module.

2.5 Achieving creative problem solving in problem based learning

As pointed out in Section 2.3, engaging students in solving complex problems that require higher order thinking is a key skill for success. Therefore, in higher education, it is important for students to become critical and innovative thinkers in tackling problems they have not previously encountered. A structural engineering tutor’s role is to guide design and not instruct design. This allows students to think about solutions to problems rather than be instructed as to an expected solution. Sometimes engineering design can suffer due to curricula being full of other subjects with there being no more space for design (Bernold 2005; Russell and Stouffer 2005). The PBL nature of the module described in this paper addresses such a concern present in civil engineering higher education.

As noted by Aparicio and Ruiz-Teran (2007), civil engineering students are required to have a number of critical skills by employers such as: teamwork, innovative thinking, communication, critical thinking and engineering design capabilities. Higher education institutions are under pressure to produce graduates with such abilities. Employers have observed that recent graduates find it difficult to form creative solutions to problems they have just been encountered with (Aparicio and Ruiz-Teran 2007). Interdisciplinary PBL is an environment that provides engineering students with exposure to other professions and ways of thinking, namely; the discipline of architecture in this paper. Johnson (1999) also points out that PBL needs to be complex enough to provide engineering design scenarios where there is no one right answer. In the module described in this paper, the interaction between the structural engineering and architecture students forms part of the learning outcomes and its success forms part of the assessment through a submission of a Journal in Week 5 (see Table 1) that details their interactions with the architecture students.

The learning processes involved in PBL are addressed in order to enhance creative thinking and engagement between engineering and architecture students. Woods (1977) considers PBL a five step process:

1. Define
2. Think about it
3. Plan
4. Carry out the plan
5. Look back

However, these steps can differ for expert or novice problem solvers (Adams 2010). It is important to understand that the students have novice cognitive abilities and subsequently need to have some level of understanding to apply their subject specific content knowledge and allow them to be creative problem solving. Sternberg (2003) refers to these students as ‘pseudoexperts’. The students need to be able to draw on their content knowledge in order to demonstrate cognitive skills that allow them to apply, analyse, synthesise and evaluate problems (DeHaan 2009; Crowe, Dirks, and Wenderoth 2008). Litzinger et al. (2011) discuss the strategies identified by Entwistle and Peterson (2004) to promote approaches to learning that result in deep understanding of concepts and principles. This can be achieved by relating ideas to previous experiences and knowledge, searching for patterns and underlying principles, examining evidence and relating it to your conclusions, and cautiously and critically examining logic and argument (Litzinger et al. 2011). It is important to note that the engineering students have not collaborated or worked with architecture students in their degree prior to this module. Therefore, the skills required for creative problem solving need to be addressed prior to and during their interaction with the architecture students in this module.

As stated by DeHaan (2009), there are two distinct modes of thought associated with the creative process: associative and analytical (Neisser 1963; Sloman 1996). The associative mode of thinking is more intuitive and defocused. In the analytical mode, thought is evaluative. As stated by DeHaan (2009), the analytical mode of creativity is relevant to the higher end of Bloom's taxonomy (Bloom 1956) e.g. analysis, synthesis and evaluation. The analytical mode is associated with 'critical thinking' and most relevant to the interaction between architecture and structural engineering students. The question arises as to how to engage this analytical mode of creativity in structural engineering students? The methodology in the next section will set out the strategies employed to achieve this.

3.0 Methodology

To provide context to the experimental setting of this paper, the Stage 3 undergraduate structural engineering students study a module called Architectural Design Studies. The timetable for this single semester module is shown in Table 1. The module is taught as an elective module in the Bachelor of Engineering (BEng) and MEng Civil Engineering degree pathway and is compulsory in the MEng Structural Engineering with Architecture degree pathway at Queen's University Belfast, United Kingdom. The module was taught in the 2013/14 academic year and there were a total of sixteen students registered for the module in which this paper relates to.

A student evaluation questionnaire was completed in Week 5 after completion of the engineering students' engagement with the architecture students. The cross-sectional quantitative survey queried the students rating of the introductory lectures and structural/architectural tutorials. A total of 15 out of the 16 students were surveyed (94% of the class). The students were asked to rate their opinion on the questions from 1 to 5 where: 5 = very good and 1 = very poor.

At the end of each module (Week 11 in Table 1) on all civil engineering degree modules within the School both module and lecturer evaluations take place. The surveys were anonymous and performed by administrative staff as part of quality assurance. A total of thirteen students were present at the module evaluation (81% of the class). Only the relevant module evaluation responses have been presented here as the remainder of the questions relate to assessment, feedback and attendance. None of the lecturer evaluations are presented. This cross-sectional quantitative survey queried the student's experience of the module and how their expectations were met in terms of teaching, assessment and ability to analyse a problem and create a solution with the architecture students.

3.1 Layout of module

In the introductory lectures, prior to the structural engineering students starting their PBL with the architecture students it was necessary to create a learning environment in which students re-engaged with their structural engineering content knowledge from their previous two years undergraduate education. The students have a breadth of knowledge starting this module, but it was important to focus them on the appropriate content and prevent them suffering from information overload. Getting the students to re-engage would provide the students with the necessary skills to fully engage in the PBL interaction between both disciplines during the architectural/engineering design studios. Indeed, Gavin (2011) noted that PBL in engineering is hierarchical in which missing concepts may result in a failure to learn. Therefore, as stated by Hadgcraft (1997), students who are well prepared in civil engineering PBL get more out of the process.

[Table 1 located here]

In the first week of the semester, an introductory lecture on steel and timber structural design was delivered to the structural engineering students only. The first lecture in Week 1 sets out the structural engineering students expectations of the module and interactions with the architecture students. Student’s expectations in terms of time demands are explicitly set out by the tutor in this lecture. An emphasis was also placed on the importance of teamwork. It was also important to provide reassurance in terms of their abilities and what they had previously learned. Pseudoexperts can feel overwhelmed by a large volume of unexpected information, such as can be experienced in interdisciplinary PBL. Therefore, simple design guides, definitions of terminology and concepts they would find useful e.g. moment resisting frame, braced frame, portal frame, were provided in conjunction with an active learning exercise. It is necessary to provide students with ample support and encouragement to draw out their confidence in their own understanding.

In Week 2, a lecture was delivered jointly to both the structural engineering and architecture students as shown in Table 1. In the same week, the engineering students were partnered with at least two architecture students to form a design team. For two weeks prior to this, the architecture students were separately developing their own architectural design of a building structure. For the following three weeks (Weeks 2-4), the engineering students work as structural engineering ‘design consultants’ to the architecture students. The engineering students are required to perform a preliminary structural design of the architecture student’s projects.

Within the design tutorials and workshops from Weeks 2 to Week 4 the structural engineering tutors in this module would be tasked with achieving a preliminary structural design amongst the structural engineering students. However, it is not just a matter of applying previously learned procedures; the students need to adapt their content knowledge to new problems in a creative way. Importantly, during the introductory lecture in Week 1 the engineering students were explicitly informed that the process required creativity and that the engineering and architecture tutors would help to guide them through it.

Providing useful terminology for pseudoexperts is not enough by itself to achieve creative problem solving. Helping students to engage with content knowledge is also necessary as it provides them with the skills to solve more complex structural design problems during their interaction with the architecture students in this module. In order to solve these complex problems, higher order thinking is required. A worksheet was specifically designed and then introduced in Week 1 during the lecture (refer to Table 1) to promote active learning and reinforce key structural engineering concepts using simple small scale physical structural models. Engineers think, design and communicate through their hand sketches (UCL Drawing Gym 2016). The need to sketch complex structural engineering ideas was also promoted in order to equip the students with the tools to achieve higher order thinking and solve the complex problems they would encounter. The ability to solve the complex engineering problems would allow the students to engage more in the creative engineering and architectural design process with the architecture students and not be afraid of the unknown problems they were presented with. To reinforce and allow evaluation of these key skills, the students were informed that they had to submit a Journal in Week 5 that detailed their interaction with the architecture students in their group. Their description of their discussions, their hand sketches and details of how they influenced the design were all assessed in the Journal.

From Week 5 onwards the engineering students carry out detailed structural calculations of their project and finally create structural drawings as part of the final submission in Week 11. In Weeks 6 and 9, brief lectures take place before the design tutorials to clarify submission details. With such open-ended PBL projects, it is important to clarify to the students exactly what is expected of them in terms of submissions and how they will be evaluated. There are two ‘facilitators’ (tutors) for this PBL module, both with extensive practical structural engineering design experience. Both tutors provided guidance for the students during all of the architectural and structural design issues they had.

The following sections set out the strategies employed to achieve creative problem solving through higher order thinking and ensure the module learning outcomes were achieved.

3.2 Introductory lectures

The introductory lectures in Weeks 1 & 2 (see Table 1) covered key learning content such as: loading, structural forms, lateral stability, structural types, structural steel beam design and structural timber beam design. The content was reasonably familiar to students but was presented during the lecture in order to refresh the student’s content knowledge from their previous two years undergraduate study or from any industrial summer structural design experience they might have had. Only steel and timber framed structural solutions were encouraged because the engineering students had not been exposed to reinforced concrete or masonry design previously in their curriculum. To prevent the students from feeling under pressure to learn a new way of design it was decided to keep the structural materials familiar so that the main focus would be creating architectural/structural concepts and designs. Framed structures were encouraged as to allow the engineering students easily preliminarily structurally size beams and columns rather than walls. The introductory lectures were vital in setting student expectation, preventing information overload and focussing the students on the appropriate content.

3.3 Active learning to engage with content knowledge

At the beginning of the introductory lecture a ‘Rethinking Structures…’ worksheet was distributed to the class and the students were requested to complete the worksheet. The worksheet is detailed in Figure 1. Upon completion of the worksheet the delivery of the Introductory Lecture was completed and the students were asked to revisit their answers on the worksheet based on what they had learned in the lecture. An open discussion amongst the engineering students and the lecturer took place to discuss the answers they gave and why they were correct or not. The students openly and actively participated in the discussion session. This form of active learning uses a worksheet to engage students in the learning process. As stated by Prince (2004) such active learning is designed to get the students to think about what they are doing through meaningful learning activities. As an extension to the content covered in the worksheet, additional simple structural design ‘rules of thumb’, for example approximate span to depth ratios for truss depth sizing, were also provided. These would be useful when the students had to help the architecture students with their designs such as approximating the structural size of beams and columns. The structural engineering students would have the ability to approximately size structural elements without performing detailed structural element design calculations.

[Figure 1 located here]

The worksheet was designed to help the students in the ‘Definition’ and ‘Think about it’ steps of PBL as defined by Woods (1977). The worksheet tasks gave the students the opportunity to practice cognitive skills in a safe environment i.e. not being assessed. For example, Question 2 on the worksheet (see Figure 1) aimed to improve their cognitive ability to comprehend, apply and analyse a load path in a structure that they have not seen before. Question 4 also gets the structural engineering students to comprehend, apply and analyse the forces required for lateral stability in building structures. The concepts were reinforced by the structural models described in the next section. For example, the structural model in Figure 2(a) provides the answer to Question 4 in the worksheet. The students can then re-use the concepts addressed in the worksheet when working with the architecture students to solve analyse and synthesis more complex structural engineering problems.

[Figure 2 located here]

3.4 Structural models

The introductory lecture in Week 1 was targeted at getting the structural engineering students to connect to the content knowledge. One approach adopted to improve this connection was to reinforce key engineering concepts through simple small scale physical models as shown in Figure 2. The use of simple structural models to motivate and engage structural engineering students has been championed by Ji and Bell (2014). Models were passed around the class, two of which are shown in Figure 2, whilst concepts of lateral stability were discussed simultaneously in the lecture. As stated by Ji and Bell (2014), models are ideal for concepts that cannot be easily understood from diagrams or text. Simple structural models were purposely chosen to illustrate concepts of lateral stability in buildings that could not easily be understood from lecture notes or images.

3.5 Importance of sketching

In Week 2, a 30 minute lecture was delivered jointly to both the architecture and structural engineering students. During this lecture, emphasis was placed on the communication of ideas through sketching as this is vital in comprehending a problem to allow a solution to be analysed and synthesised. Figure 3 demonstrates an example of and the importance of sketching in the initial conversations between architects and engineers in a real-world project. The sketches presented in the lecture notes were obtained directly from a real-world project by Hunt (2003). Figure 3(a) shows details of the case study (Sainsbury's Centre, Norwich, United Kingdom) presented during the lecture. Figure 3(b) shows a small sample of the initial sketches between the practicing structural engineer and architect on this case study project. Figure 3(c) shows an alternative solution to Figure 3(b) for the same project. Finally, Figure 3(d) is presented to the structural engineering students so that they can see photographs of the exterior and interior of the finished project. This allows the structural engineering students to see how the hand sketching of solutions has helped achieve a final solution in a real-world project. In the lecture three other projects are presented to the students to exemplify the importance of hand sketching. As a further incentive to reinforce the importance of sketching, the students' hand sketches demonstrating their discussion of structural concepts with the architecture students during the PBL project also form part of their module assessment in the Journal submitted in Week 5.

[Figure 3 located here]

An example of the hand sketches produced by some of the engineering students during the Weeks 2-4 are shown in Figure 4. Figure 4(a) is one students sketches from a project, Figures 4(b) & (c) are a second student's sketches from a second project and Figure 4(d) is a third student's sketches from a third project. These sketches are taken from some of the students Journal submissions. Sketching between architects and engineers allows the articulation of ideas and concepts that would be too complex to describe verbally. It can be seen from these sketches that comprehension of their PBL project is needed in order to generate various solutions. The sketches form a common language between the architecture and engineering students. Hand sketching is more fundamental form of communication than BIM, VR or AR and is therefore much more appropriate in aiding engagement between two disciplines.

[Figure 4 located here]

3.6 Tutorials – tutor guidance

During the tutorials in Weeks 2-4, the tutors promote the processes in PBL: define, think about it, plan, carry out and reflect. The students receive immediate and formative feedback on their solutions and level of understanding by the tutors. The tutors also ask the students questions that engage them with their content knowledge and refer back to the simple design rules from Lecture 1. As such, the tutor's role is to guide students to reflect on their content knowledge rather than present 'correct answers'. The guidance occurs during the tutorial sessions and is one of the key characteristics for improving conceptual learning through interactive engagement (Hake 1998) and help to develop the student's expertise. Frank, Lavy, and Elata (2003) also champion student interaction with tutors in instructing the student as to how to learn and how to construct knowledge. Tutors also play an important role in motivating the students. Jones et al., (2013) showed that facilitating and mentoring strategies for tutors such as, specific questioning and the use of role modelling, are successful in empowering self-direction in students and improving engagement in PBL exercises.

4.0 Results

4.1 Qualitative reflective observational evaluation of problem based learning solutions

In order to provide some context to the types of PBL solutions, the structural/architectural designs for three different PBL projects are shown in Figure 5. The architectural designs were presented to a panel of both academic and professional structural engineers and architects at the end of Week 4. Figures 5(a) & (b) show the architectural drawings and architectural model for two separate projects. Structural engineering input can be seen in Figure 5(b) as the structural frame is evident in the model. Figure 5(c) presents the architectural model and Figure 5(d) presents the structural model from the same PBL project. From a structural engineering aspect, it is clear in Figure 5 that the architectural designs have been strongly influenced by structural engineering judgement and the solution the structural engineering student has created. This demonstrates that the structural engineering student in these examples engaged in the architectural design process by creating a clear structural engineering solution.

[Figure 5 located here]

4.2 Qualitative and qualitative evaluation from student survey and feedback

4.2.1 Student survey in Week 5

The results of the introductory lecture portion of the questionnaire shown in Table 2 indicate that the students had a positive experience of the introductory lectures (4.3/5) and that these lectures helped them to think again about structural engineering (4.5/5). In particular, the students rated well the introductory lectures to positively align their expectations of the module (4.5/5). The small scale physical structural models were probably a bit simplistic and this is reflected in their rating of 4/5 in aiding their understanding of structural form.

[Table 2 located here]

As can be seen in Table 3, the students rated the experience of the architectural tutorials in Weeks 2-4 as good (3.8/5). The support provided by the engineering staff during the architectural tutorials scored particularly highly (4.7/5) as shown in Table 3. However, the architectural tutors did not score as well. The students rated their own understanding of the development of structural forms quite highly (4.2/5). The rating for how well the students gauged their ability to analyse a problem and create a solution with the architecture students (3.9/5) was a good response given the architecture projects are complex, not well defined and the architecture students frequently changed their scheme each week.

[Table 3 located here]

A comments section was also provided at the end of the questionnaire. In terms of the comments received from the students, the top responses in order of popularity were “really enjoyed the module” so far (27%), “great having a project like real life” (13%), “frustrated by the architects changing their designs” (13%) and “interesting working with architecture students to see how engineer affects design” (13%). These responses were on a whole very positive and indicate good engagement with the creative design process.

In general, we observed that the strategy of engaging in content knowledge, the use of structural models and emphasising sketching played a significant role in helping students make connections between concepts and ideas discussed in the first two lectures that they could use when engaging with the architecture students. From a teacher’s reflective and observational point of view, the students had most of the necessary tools and knowledge to comprehend the complex design problems facing them and most of the students were more than able to synthesise and evaluate untaught design concepts. The students were able to engage with the architecture student's ideas and concepts using the creative analytical mode of thinking described by DeHaan (2009).

4.2.2 Module evaluation in Week 11

The students had a very positive perception of the module content and structure as shown in Table 4. Particularly pleasing to see from the evaluations in Table 4 was that the students found the module intellectually stimulating and challenging with a score of 4.8/5 and that the module met their expectations (4.5/5). The students felt the learning resources were adequate (4.5/5) and rated the organisation of the module highly (4.8/5).

[Table 4 located here]

Nine of the thirteen students in attendance during the module evaluation replied with hand written comments to the following question: "*Please identify any good practice on the module that could be adopted on other modules*?" Their comments were as follows:

- Integrating practical work with the architects
- Clear structure
- Most like real life practice. Enjoyable for the most part
- The conversation with architects
- Contact with other related discipline
- Group work was well organised on the engineering side – Projects were challenging and helpful

Other comments not directly relevant in evaluating creative problem solving were: readily available lecturers, regular tutorials, tutorials and quick feedback. From the survey comments, it is evident that the interaction with the architecture students was a positive experience for the students as the following points of good practice were identified: integrating practical work with the architects, most like real life practice, the conversation with architects and contact with other related discipline. These were comments that the students decided to make and therefore point to the students having the skills to creatively problem solve and interact with another discipline in what are complex projects with open ended design questions.

Six of the thirteen students replied with hand written comments to the following question: "*Can you identify any improvements that you would make to the module*?" Their comments were as follows:

- Consultation with architects was difficult
- More useful online documents
- Better architectural lecturers (who understand structures)
- No
- The amount of work is high, especially towards the end
- First crit was a little too architecture focussed

In general, the comments about improving the module were not too negative. Two of the improvement points were about the architecture staff that took part in the module and therefore are not within the control of the module co-ordinator to change. Only one of the comments related to the interaction and engagement with their architecture group members "Consultation with architects was difficult". Stating that something was difficult does not explicitly state it was a bad experience, but may be leaning towards that. The comment about the amount of work being high is relatively accurate, however it is stated to the students at the start of the module that this PBL module reflects the workload you would expect on a real-world project i.e. heavily end loaded. There is also no examination in this module, so the workload is expected to be higher.

5.0 Summary and conclusions

This paper presented three strategies to engage higher order thinking in structural engineering students in order to help them to solve a complex architectural problem based learning project. The strategies employed were: active learning to engage with content knowledge, the use of physical conceptual structural models to reinforce key concepts and finally reinforcing the need for hand sketching of ideas to engage higher order thinking to creatively solve complex engineering problems. These strategies were adopted in a structural engineering module that aims to improve engagement between the structural engineering students and architecture students in a problem based learning scenario similar to a ‘real world’ building project.

The success of these strategies was assessed through teacher reflection, student surveys and student feedback. The strategies were qualitatively perceived by the tutor and quantitatively evaluated by students in a cross-sectional study to help interaction with the architecture students, aid interdisciplinary learning and help students creatively solve problems. In particular, the active learning to engage in content knowledge that took place during the introductory lectures was rated very highly by the students as they reported that the lectures helped them to think again about structural engineering (91%), helped them to positively align their expectations of the module (88%) and provide them with the tools to work with the architecture students (87%). The physical models were rated at 80% by the students, and on reflection they may have been slightly simplistic. A qualitative assessment of the hand sketches developed by the students with their architects demonstrated higher-order creative problem solving and interdisciplinary learning had taken place Altogether, the students rated their own abilities to analyse a problem and create a solution with the architecture students as very good (78%). This is an excellent overall response from the students given the architecture projects are complex, not well defined and the architecture students frequently changed their scheme each week.

The recommendations to any undergraduate engineering PBL module co-ordinators either in structural engineering or not, are to firstly use active learning to allow the students to fully engage in content knowledge prior to starting an interdisciplinary PBL project. Secondly, the use of physical scaled models allows the engineering students to understand concepts that are difficult to explain in words or images. In other engineering disciplines alternative small scale physical models could also be employed to reinforce key concepts that the students will be using in the interdisciplinary PBL module. Active learning and exposure to physical models prior to starting an interdisciplinary PBL allows the students, who are pseudo experts, to draw on their content knowledge and provide them with the knowledge and confidence to succeed. The final recommendation would be to promote the use of hand sketching to generate ideas, communicate designs, understand complex ideas and react quickly during discussions with project members from another discipline. This helps the students to achieve higher order thinking and creatively solve complex interdisciplinary PBL problems. Making hand sketching part of the module assessment also helps to promote its use to help students creatively solve complex problems.

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