ENGINEERING ANALYSIS: A PRE-REQUISITE FOR DESIGN

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1 Introduction

The design element of an engineering curriculum in a higher education degree course is often found to shape the structure and content of the whole course. That is, all other elements ranging from mathematics, applied science to finance and management are devised to provide the engineering student with sufficient knowledge to support the requirements of the design process. The definition and the description of the design process have been given considerable attention in the literature. For example Pugh (1991) discussed the design process in depth and presented what was to become an established view on the multitude of the diverse elements that exist and the skills that are required to be mastered. This diversity is often found to be rather troublesome for engineering teachers and the developers of engineering course curricula due to the different types of subject matter and the provision of effective teaching and learning environments.

Figure 1  Typical Design Process (From Childs,1998, based on Pugh(1991))

In this paper one particular stage of the design process is discussed from an educational perspective and concerns the requirements of technical design analysis, i.e. the ability to
formulate mathematical equations based on the laws of physics to predict the performance of the design. Fig 1 shows a typical process representation (Childs, 1998) and shows how analysis fits into the overall process.

It is acknowledged that the extent and sophistication of the design analysis required is problem dependent and may not be a critical issue in the design process. However, in many design problems the performance of the product or the optimisation of the design requires skills in technical analysis. Most engineering teachers who are involved in design teaching find that students have great difficulty in applying engineering physics to a design problem. This situation is astonishing given that at least half of most engineering courses can readily be identified with engineering science and mathematics, the basic tools of technical analysis. Part of the problem lies in the inherent difficulty associated with these subjects, but is also related to how they are taught and how they are integrated into a teaching curriculum. It is often the situation that the design class is the first opportunity for the student to investigate the integration of mathematics and engineering science in an open-ended design problem. Unfortunately this often ends in failure with either minimal analysis being carried out or the majority of the time being devoted to technical analysis as an end in itself instead of being a tool within the design process.

A review of the literature and engineering curricula from many other universities indicated little attention has been given to these issues. This is surprising since, a requirement for teaching engineering analysis in a design context had been identified by the ASEE in the 1950’s, (Nicolai, 1998) but rarely implemented in any formal way. However, Tavakoli and Mariappan, (Tavakoli and Mariappan, 2000) highlighted a need and attempted to address the problem of teaching analysis in an integrated design, analysis and manufacturing class and claimed successful outcomes. In the study presented here, it has been assumed that one of the main reasons students have difficulty with analysis is due to insufficient effort being devoted to the integration of the engineering physics classes and the design application classes. Thus, it is suggested that a gap exists in most engineering curricula and it requires to be filled with a design based analysis approach. This paper presents an attempt to re-shape the curriculum in the Mechanical Engineering department at Strathclyde University by providing a focus for a number of classes that were previously identified as applied numerical methods/computational techniques. The focus of the new classes was to be the skills and subject content that underpin design analysis methods. This paper discusses these developments and proposes that consideration should be given for a separate design analysis element within the engineering syllabus. This paper discusses how this requirement was implemented at Strathclyde University and what it has evolved to over the 5 years that it has been running. The learning objectives of the class are discussed in detail, the syllabus is presented and a typical case study is discussed. In addition, the objectives of the class have also influenced the redesign of the physical layout of the teaching environment and this is discussed along with the reasoning behind the changes.

2 Review of Teaching Difficulties

Mechanical engineering students in the third year of a five-year course were presented with a design and build project consisting of the creation of a monowheel cycle. A photograph of a typical design is shown on Figure 2. The general brief was to take the basic concept of a large single wheel and design it to be driven by a recumbent rider inside the wheel. The students were to work over a period of 12 weeks with an allocation of about 5 hours a week with 3
hours in the week supervised by academic teaching staff and where necessary, technician staff. The students had previously been given lectures on project management, planning, design methodologies, team building, etc and previous engineering science lectures had equipped them with sufficient knowledge in dynamics, strength of materials and materials engineering. The student’s progress was monitored during the period and all students maintained progress logbooks. Students worked in groups of four and each member was allocated a specific role with identified tasks to be completed each week. Academic staff attempted to monitor the progress of each group and guide them to a satisfactory completion. At the end of the period most groups had designed and constructed a cycle and one of the assembled bikes is shown in Figure 2. The post construction assessment of the designs showed that most of the bikes were excessively heavy and impossible to control or were too flexible for reliable operation. In either case there was a failure by the student to account properly for strength to weight issues.

![Students Monowheel Design](image)

**Figure 2 Students Monowheel Design**

The student’s designs were assessed using a number of methods including, oral presentation, a design report and group interviews. These were used to determine the student’s technical understanding of the problem and effectiveness in a group-working environment. The assessment exercise indicated that while most groups worked effectively; generating ideas, pursuing data searches and producing detailed designs, very few students had a clear idea of how to undertake an analysis to determine the performance issues mentioned previously. In addition, it was generally found that most designs were completed with very little engineering physics being applied. In this design problem there were a large number of possible methods to construct the wheel and therefore no prescribed set of equations to determine the wheel’s structural strength were provided. The students were expected to develop or procure appropriate analysis equations. This exercise highlighted a range of procedural weaknesses which included:

- Failure of the students to apply a technical solution strategy
- Difficulties in the application of engineering physics
- Difficulties in the integration of engineering physics, mathematics and the implementation to provide design based solutions.

These issues were combined with a general lack of knowledge of what benefits design analysis can provide and when it is practicable to pursue it. Given that the general role of design analysis is to ensure the performance or to enhance the performance of a design, it is...
essential that students appreciate its importance. At Strathclyde University, in common with many other institutions, the objective of fundamental classes is to teach the basic understanding of the applied sciences as required by an engineering degree. This is usually performed in classes separated from design and, within Mechanical Engineering, is usually carried out in classes subdivided into dynamics, thermodynamics, strength of material, control, fluid mechanics, etc. There are good educational reasons for doing this but unfortunately this encourages students to categorise the physics and prevents the student from identifying a unified approach to technical problem solving.

To resolve these issues it is proposed that design analysis should be seen as a unique and separate requirement for an engineering curriculum. The issues identified were regarded as being too complex to resolve within introductory engineering physics classes and possibly too time consuming to incorporate into a design class. The resolution of this difficulty was by focussing on an integration theme and resulted in a number of new classes, which were commonly referred to as Engineering Analysis which attempted to teach analysis skills in a more fundamental way.

3 Imbedding Engineering Design Analysis in an Engineering Syllabus

Definition of Engineering Design Analysis
For the purposes of this paper, engineering analysis is defined as the integrated application of engineering physics and mathematical techniques to predict performance related features of an engineering problem. In addition, the use of modern mathematical software such as Mathcad, Maple or MatLAB is also included within the definition to provide a platform to efficiently solve design problems. We also see it as a requirement that students should be able to formulate or appreciate the equations that are being applied to a design problem. It is therefore important to note that design analysis problems require to be well matched to the student’s mathematical ability and that design analysis problems should be classified in terms of a mathematical form that allows for appropriate allocation. Three classes were developed covering the first three years of the five year engineering course at Strathclyde University and these are identified as Engineering Analysis I, II, and III. The three classes develop the analysis skills required for design analysis and lead towards a senior year application class provided in year 4 called Computer Aided Engineering Design. The rationale behind the approach is described by discussing the year 2 syllabus in the Engineering Analysis II class. Two features of this class will be discussed. The syllabus is presented first. Secondly, a classroom based on a studio environment has been constructed for the teaching of computer based design classes and this will be described, indicating the benefits of a more teaching and learning friendly environment.

Teaching of an Engineering Analysis Class
The direction of the engineering analysis classes follows a classical mathematical modelling approach. A representation of this is shown in Figure 3 below. An important observation concerning the teaching of general design analysis is the difficulty students have in applying the skills they have previously studied in the engineering science classes. Because of the historical development of these subjects and the often specialised leaning of the academics involved, it is often the case that specific analysis techniques are taught in each of the areas of Dynamics, Structures, Thermodynamics and Fluid Mechanics and prevents the generality of the techniques to be missed. The compartmentalisation of these topics allows a focussed approach and aids learning within each subject but produces significant problems when the student tries to apply the techniques outwith the confines of the specific topic, as found in
design classes where multidisciplinary problems are common. The basis of the class is that good design analysis skills are based upon a general understanding of three main steps: problem formulation, solution and implementation of results.

The **Problem Formulation stage** concerns how the physical problem will be modelled and a set of mathematical equations to predict some characteristic of the nature or performance of the system can be determined. The main emphasis in the teaching is to highlight how the laws of physics and mathematical techniques are used together to represent the problem. The emphasis here is that for engineering problems many levels of modelling are possible and therefore different levels of approximation possible. What level of approximation is required depends on the importance given to the outcome of the analysis. Students find great difficulty with this aspect because for the first time they are faced with the consequences of the approximation that is implicit within the mathematical model.

**Figure 3 Engineering Analysis II Structure**

The **Solution stage** poses less problems in both teaching and learning since it falls into a traditional syllabus common in maths or numerical methods classes and mainly consists of specific techniques to solve the equations that have been formulated in stage 1. Here we emphasise the need to be able to apply the techniques using hand calculation and through implementation in appropriate software. Our particular choice is the MathCAD software due
to its ease of use, generality and the ability to generate readable documents that can be submitted as coursework by the student. The **Results stage** is used as a means to emphasise the engineering nature of the analysis output, ie the analysis is not an end in itself but simply part of the design process. How to interpret the output and use it effectively within the constraints of its uncertainty requires separate consideration in the teaching of design analysis.

**Syllabus**

The syllabus developed for the class Engineering Analysis II consists of the topics shown in Table 1. The topics are presented in terms of their fundamental nature and therefore stress their general relevance. The class attempts to teach several features of the skills required to tackle design analysis problems. Viz, Formulation, numerical solution methods and their application to design analysis problems relevant to Mechanical Engineering.

<table>
<thead>
<tr>
<th>Engineering Analysis II</th>
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<tbody>
<tr>
<td>1 Concepts in Technical Problem Solving</td>
<td>2 hours</td>
</tr>
<tr>
<td>2 Revision of Basic Tools: The Taylor Series and Linear Algebra, Matrices</td>
<td>1 hour</td>
</tr>
<tr>
<td>3 Formulation of Systems of Linear Equations and Solution Methods for Linear Equations</td>
<td>6 hours</td>
</tr>
<tr>
<td>4 Formulation of Integrals and Numerical Integration Techniques</td>
<td>4 hours</td>
</tr>
<tr>
<td>5 Ordinary differential Equations</td>
<td>8 hours</td>
</tr>
<tr>
<td>6 Formulation of Non-linear Systems of Equations and Non-Linear Equation Solving</td>
<td>3 hours</td>
</tr>
<tr>
<td>7 Basic Tools: Curve Fitting</td>
<td>1 hour</td>
</tr>
<tr>
<td>8 Engineering Applications from Thermodynamics, Fluid Mechanics, Dynamics and Structure Use of MathCAD to solve problems</td>
<td>12 hours</td>
</tr>
</tbody>
</table>

**Table 1 Engineering Analysis II class syllabus**

Over the 5 years this course has been developing, a number of variations in delivery approaches have been attempted including

(i) **Concurrent Approach**: all three main features were dealt with together ie formulation, solution and application were taught in small modules for each topic either in a classroom or computer lab environment.

(ii) **Sequential Approach**: The numerical methods and formulation were taught in a classroom environment and the design applications were taught in a computer lab environment. For this approach the class was taught over a 24 week period. The first 12 weeks used 24 hours to teach the formulation and numerical methods and the second 12 weeks used 12 hours to teach engineering applications using a number of case studies.
It was found that the concurrent approach was not as effective at ensuring a good understanding of the techniques. The combination of concepts, techniques, and applications were thought to be too much for the students to absorb. The teaching of numerical methods both by hand calculation and by use of MathCAD at the same time seem to induce a lack of motivation to learn and apply the techniques by hand since the software is more effective at solving the problems. The sequential approach introduced a temporary separation of the teaching of formulation and solution from the application case studies. By focussing on general techniques for formulation and solution within a mechanical engineering context allowed a working ‘tool box’ to be developed for the student. This knowledge could then be applied within the same class but in a separate module to design analysis based problems.

Teaching Environment
The teaching of the formulation techniques and numerical methods was carried out effectively in a lecturing environment. However, the teaching of the applications of design analysis where the use of PC’s were required was more troublesome. The delivery of the class in early years was confounded by the use of a general use University PC lab. These consisted of a large number of PC’s on standard tables and arranged in rows. This arrangement did not provide any working space for non-computing work nor did it allow the ability to address the class properly. In an attempt to provide a classroom that was more conducive to teaching of design based problems an investigation into room designs was initiated. The desire was to develop a room that provided for more interaction between students and between teaching staff and students in a computer based set up. The outcome was the building of a teaching room adapted from the designs developed from the Rensselaer Polytechnic Institute Studio Concept (Glinkowski et al., 1997). The teaching room that was built is shown in Figure 4 and has the following features.

![Figure 4 Studio Teaching Room](image-url)

- It provides working space for computing and non computing tasks
- It allows small group work
- It allows for teacher centred discussions
- Each working position has access for single student/ teacher discussions

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The room has been a significant improvement on previous arrangements and allows improved interaction between students and staff. Students and staff prefer this environment over others and has led to the original rooms being used for general student use only rather than teaching.

**Example of a Design Analysis Case Studies**

The case studies used to teach the design analysis process are crucial to meeting the objectives of the class. They require to be constructed so to integrate the main elements of the class. The main features of the case studies to allow the engineering design issues to be explored are

(i) They require a formulation element, ie identify or construct the equations that are required.

(ii) Implementation of a solution process.

(iii) The problems require to be open ended, ie should be loosely specified so that a variety of solutions are possible.

(iv) Elements of conflict should be introduced, ie to meet the design objectives the student has to balance a number of requirements.

(v) Objectives should be set so that design performance should be emphasised. This allows the important features of optimisation in the design process to be explored.

(vi) The reporting of design calculations as part of design documentation should be included.

An example of a truss design is used in the initial parts of the class and is shown in Figure 5. The knowledge of statics was taught in the previous year and the particular formulation requirements introduced in part 1 of the Engineering Analysis II class. The example asks the student to design a truss to support a load but leaves the overall truss shape to the student, (ie is open ended). The equilibrium equations to calculate the loads in the truss require to be formulated, transformed into matrix form and solved in MathCAD. A buckling constraint is introduced to generate a conflict between load and length and finally the student is required to think about an optimum solution to the problem. The student is left to define what an optimum is in this case and how to determine it.

The difficulty most students find in this problem relate to the choices and possible variations that can be encountered. At this point in their education, the students have had limited opportunity to apply their technical knowledge in an open ended way. Thus significant resistance is met and the students feel that the problem is ill defined. However, the exercise is usually attempted successfully by the majority of the class.
Truss Design

A framework of pin jointed members has to be designed to support a plug introduced into the reservoir wall to prevent leakage and further progression of a crack along the wall. The plug is cylindrical, has a diameter of 0.35 m and is supported by a single pin joint. The frame is anchored to the ground using a pin joint and a roller joint, as shown in the Figure.

You are to comply with the following requirements

(i) Design a **statically determinant** structure to meet these requirements.

(ii) The limiting load determined by the buckling load in compressive members and can be calculated by

\[ P = k \frac{\pi^2 EI}{L^2} \]

I is the Moment of Area of the member, E is the elastic modulus and L is the length of the member. k being a correction factor for imperfections in the member (I=10x10^4 mm^4 E= 70 kN/mm^2 k=0.6)

(iii) Consider obtaining an optimal solution of the problem

![Figure 5 Example of Design Analysis II Case Study](image)

4 Conclusions

It has been argued that engineering based courses encounter difficulties in the teaching of design analysis techniques and it has been suggested that most curricula would benefit from the inclusion of specific classes that focus on the teaching of design analysis. The classes are by nature an integration of various elements; mathematics, engineering science, numerical methods, computational tools, etc. The proposed classes would be developed with the main objective of showing how these different elements are integrated within a design theme.

5 References


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Dr Marcus Wheel was appointed to a lectureship in Mechanical Engineering at the University of Strathclyde in 1993 after having obtained his PhD from the Department of Mechanical Engineering, Imperial College. At Strathclyde University Dr Wheel has taught a range of subjects including introductory mechanics, computer based engineering analysis and computational fluid dynamics. His research interests include the impact behaviour and crashworthiness of novel automotive structural components and the development and exploitation of computational mechanics procedure for analysing fluid structure interaction and multi-physics problems.