# Teaching Numerical Problem-Solving Methods to Undergraduate Engineering Students Using Specially Designed Finite Element Codes

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## ABSTRACT

Computer-Aided Engineering is an essential solution in many engineering problems in today's industry. Modules looking into this area in the engineering courses aim to further enhance both the theoretical and practical appreciation of the numerical problem-solving methods. In such modules, students are expected to appreciate how mathematics, numerical analysis and computational technology are combined to model and simulate the behaviour of physical systems. However, when it comes to teaching, there is a significant difference between how the background theory looks and what students experience as they work with a commercial software package as they cannot see what is going on in the background of software packages and how the outputs have been achieved. In this work, the authors have proposed a method to help students comprehend how the theory is related to software packages. This is done by providing students with specially designed Finite Element codes asking them to investigate, and tailor the codes for some basic but real-life applications. The method starts with 2D problems for elementary Finite Elements, and through a few steps helps students extend the codes to 3D cases to enable them to solve real-life applications by the FE codes they have tailored themselves. This approach enables engineering students make meaningful links between the background math and the target numerical problem-solving methods. According to student surveys taken over three academic years, 85% of students believe "User FE-codes helped understand how theory translates to problem-solving tools and FE software". There was also significant enhancement in student performance on the associated assessments.

## INTRODUCTION

Engineering simulation is an essential solution in many engineering problems in today's industry as it reduces the cost of design and product development or optimises the current engineering systems. Computer-Aided Engineering (CAE) introduces the mathematical and numerical methods to simulate the engineering problems by utilising state of the art engineering tools as well as commercial software packages.

Modules looking into this area in the engineering courses like Mechanical, Manufacturing, and Civil aim to further enhance both the theoretical and practical appreciation of the Finite Element Analysis (FEA), and the Computational Fluid Dynamics (CFD) to achieve the engineering of a product, structure or a system. Both the FEA and CFD theories are very mathematics intensive, and they need good knowledge of matrix algebra, mechanics, theory of elasticity, and computer programming.

Such modules introduce methods to validate engineering simulation through physical correlation which needs a deep engineering judgement on the outputs of software packages. Students are often expected to appreciate how the background mathematics, numerical analysis methods, and computational technologies are combined to model and simulate the behaviour of physical systems. They should also develop their understanding of the importance and relevance of modelling engineering systems before embarking on detailed designs and modelling processes developed with software packages.

However, when it comes to teaching numerical problem-solving methods, both instructors and students find a significant difference between the background theory and what students experience working with a commercial FEA or CFD software package. As users, students cannot see what is going on in the background of software packages and how the outputs have been achieved. This makes students struggle to find a link between what they are taught in the modules and what they do for real-life problems via software packages. Thus, there is a missing link which is needed to connect the knowledge transferred in the classroom to the application of numerical problem-solving methods in real-life applications.

## LITERATURE REVIEW

Inclusion of teaching FEA in the undergraduate level is getting ever increasing interest in engineering courses. (Plevris and Markeset, 2018) discussed the importance of a sound engineering knowledge about FEA theory to obtain correct and reliable results for designing real-world structures. (Sracic, 2016) proposed an approach for teaching FEA using familiar undergraduate mechanics and mathematics concepts, such as principles of energy and equilibrium. This is in addition to the practical use of computerl software to analyse the same problems solved by hand-calculations. (Smith and Davis, 2015) presented an FEA course plan that makes a good balance between the theory and practical software usage. (Bishay, 2020) proposes teaching FEA using the approach of building a useful code with the students step by step. He found it very effective in helping students understand the process of solving FEA problems. He used mini-projects to allow students to generate their own assignments including the description of the problem which promote critical thinking. He concluded that the mini-projects can replace big coursework to achieve specific goals. (Watson et al., 2015) also integrated FEA active learning modules in the engineering curriculum to provide an effective learning resource that reinforces fundamental course concepts without requiring knowledge of the difficult mathematics underlying FEA.

## AIM AND OBJECTIVES

In this work, inspired by (Bishay, 2020), the authors have tried to fill the gap between the underpinning theory and the FEA software usage by providing students with specially designed Finite Element codes. The FE codes were written in MATLAB and included instructions to be further developed by students. The students were asked to carefully investigate the codes, and tailor them for some basic but real-life applications like bridges, cranes, and power towers. It was expected that, the investigation of the provided FE codes helps students understand how simple structures are simulated in computer programmes, and how the underpinning physical phenomena are used to mathematically formulate such structures. Another objective was that the instructions included in the codes help students learn how they can extend or tailor FE codes and how such codes can be debugged. The aim of the study was to familiarise students with a simplified version of what is going on in the background of FE software packages, equip them with the knowledge to justify software simulation results, also to develop their self-confidence for writing/amending FE codes to simulate real-life engineering problems.

## METHODOLOGICAL APPROACH

The method starts with 2D problems to introduce elementary Finite Elements (like bar element, 3-noded bar element, beam element, and CST element). In this step, students can simulate 2D cranes, bridges, trusses, etc. which helps them understand the numerical formulation of such engineering problems in simplified/reduced dimensions. This helps students avoid the complications of assembling and solving equations in three dimensions. Once they gain some knowledge and experience, through a few steps, they are instructed to extend the provided codes to 3D cases to enable them to solve real-life applications by means of the FE codes they have tailored themselves. At this stage, they can simulate 3D truss bridges, power towers, etc. This approach has been implemented in two undergraduate modules across two different apprenticeship degree programmes at the university of

Warwick. The modules are Advanced Structural Analysis (Module I), and CAE & Physical Correlation (Module II).

## KEY FINDINGS

Results of the proposed approach to teaching numerical problem-solving methods to undergraduate engineering students are evaluated by means of the student surveys as well as the module assessment results. The first survey was taken in Module I where the proposed approach was first implemented. This survey directly targeted the students' opinion on the coursework which was designed based on the proposed approach. Results of the survey are shown in table I.

*Table 1. Student feedback on the module I coursework*

| | **Question** | **Agreed (%)** |
|---|---|---|
| **1** | The coursework helped further comprehension of the content | 100 |
| **2** | Working with user FE codes (MATLAB scripts) helped understand how the theory translates to applied problem-solving tools like commercial FE software | 85 |
| **3** | The coursework widened my knowledge of numerical problem-solving techniques | 91 |

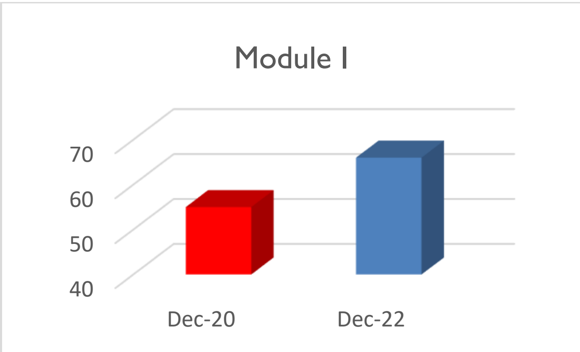
Later, the same approach was implemented in Module II, too. Summary of the student surveys on both modules taken in 2022-23 academic year are reported in table II. The effectiveness of the utilised approach can be evaluated by comparing the survey results before and after implementation of the approach.

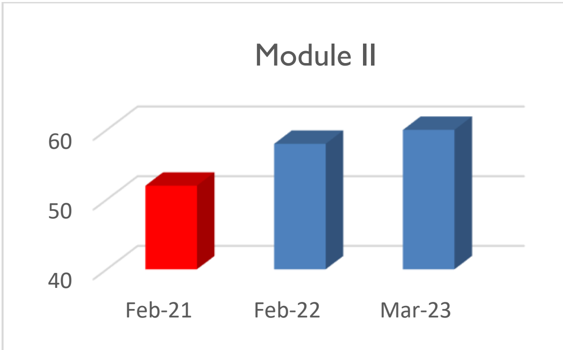
*Table 2. Summary of student feedback on the two modules the approach has been applied to*

| | | **Module I** | | **Module II** | |
|---|---|---|---|---|---|
| | Question | Before (%) | After (%) | Before (%) | After (%) |
| **1** | This module was intellectually stimulating | 62 | 72 | 67 | 100 |
| **2** | Staff have made the subject interesting | 70 | 91 | 66 | 68 |
| **3** | The module has provided opportunities to explore ideas or concepts in depth | 45 | 76 | 33 | 76 |
| **4** | The module has provided me with opportunities to bring information and ideas together from different topics | 35 | 70 | 66 | 66 |

Finally, the average coursework marks across modules I and II over three academic years (2020-2023) from five cohorts are reported in Figure I to compare the marks before and after implementation of the FE-codes assisted teaching of numerical problem-solving methods.

*Figure I. Average coursework marks for modules I and II, before (red) and after (blue) implementation of the FE-codes assisted teaching.*




## DISCUSSION

Table I shows that the students have found the new FE-codes assisted teaching of numerical methods very helpful. The participation rate was 55% (24 students out of 44) which is acceptable compared to other modules across the degree apprenticeship programmes. All participants believed that the coursework (which was designed based on the FE-codes assisted teaching) helped further comprehension of the module content. Also, most of them (85%), believed working with the provided FE codes helped understand how the theory translates to applied problem-solving tools like commercial FE software. This is exactly the gap that both students and instructors have been suffering from. Moreover, 91% believed the coursework widened their knowledge of numerical problem-solving techniques which is so beneficial in an engineering course.

Table II shows that the new method has made the topic more interesting as well as intellectually stimulating to the students. This is the case for both modules. There was also significant enhancement in providing opportunities to explore ideas or concepts in depth. This is also one of the existing challenges in modules addressing numerical methods as students often struggle to understand concepts in depth. Moreover, in Module I, there was a significant improvement in providing opportunities to bring information and ideas together from different topics.

Figure I shows the average coursework marks for the two modules investigated on five cohorts. It is seen that the student performance on FEA-related projects/tasks has significantly improved after implementing the FE-codes assisted teaching of numerical problem-solving methods. In Module I, the average coursework mark increased from 55 in 2020 to 66 in 2022. In Module II, the average mark increased from 52 in 2021 to 58 and 60 in 2022 and 2023, respectively (all marks out of 100).

## CONCLUSIONS & RECOMMENDATIONS

It is concluded that, filling the gap between the underpinning theory of the finite element method and the FE software packages by providing engineering students with specially designed FE codes, enables them to make meaningful links between the background math and the target numerical problem-solving methods. All students participated in the surveys believed that coursework designed based on the specially designed FE codes not only made the module more interesting but also helped further comprehension of such modules content. There was also significant enhancement in providing opportunities to explore ideas or concepts in depth where this has been one of the existing challenges in modules addressing numerical methods as students often struggle to understand concepts in depth.

The student performance on FEA-related projects/tasks was significantly improved after implementing the FE-codes assisted teaching of numerical problem-solving methods. It seems that the proposed approach helps students find a link between what they are taught in the modules and what they do for real-life problems via software packages.

## REFERENCES

Bishay, P. L. 2020. Teaching the finite element method fundamentals to undergraduate students through truss builder and truss analyzer computational tools and student-generated assignments mini-projects. *Computer Applications in Engineering Education,* 28**,** 1007-1027.

Plevris, V. & Markeset, G. 2018. Educational Challenges in Computer-based Finite Element Analysis and Design of Structures. *Journal of Computer Science,* 14.

Smith, N. & Davis, J. L. Connecting Theory and Software: Experience with an Undergraduate Finite Element Course. 2015.

Sracic, M. W. An Approach to Teaching the Finite Element Method That Uses Best Practice Techniques From Industry. ASME 2016 International Mechanical Engineering Congress and Exposition, 2016. V005T06A002.

Watson, K. A., Brown, A. & Liu, J. 2015. Finite element analysis active learning modules embedded throughout a curriculum: Implementation and assessment of results based on student GPA. *ASEE Annual Conference and Exposition, Conference Proceedings,* 122.