The Teaching of Structural Analysis

A Report to The Ove Arup Foundation

by Professor Ian M May and Dr David Johnson

The Ove Arup Foundation

THE TEACHING OF STRUCTURAL ANALYSIS

David Johnson and Ian M. May

FOREWORD

Ian May and David Johnson approached The Ove Arup Foundation to seek our support for this paper. We were attracted by the proposal because we were already providing funds for a separate paper outlining research into the teaching of design to engineering undergraduates, and structural analysis is one of the essential building blocks for good design in engineering and architecture.

In particular, it gave us the opportunity to encourage the authors to give some thought to how structural analysis could be taught in such a way as to encourage students to develop a 'feel' for how structures actually behave, and in so doing to create simplicity and elegance of thought and outcome. Our suggestions were very warmly received and taken up by the authors, and we hope their paper will help both teachers and students to exploit the opportunities that modern analytical techniques provide, including the power of computing, and not themselves to become a servant of them.

Richard Haryott
Chairman, The Ove Arup Foundation
October 2008

PREFACE

As academics whose careers started in the 1970's, we have seen a number of changes in the area of Structural Analysis – in particular, the universal use of software packages that not only speed up the analyses that once were carried out by hand but also allow analysis of a complexity that was impossible by hand. There have also been significant changes in higher education, including the increase in the participation rate, the broadening out of engineering courses and changes in the pre-university education system. All these aspects have brought a number of challenges to the teaching of structural analysis.

There have been regular papers on the teaching of structural analysis, but usually several important questions remained unanswered, such as: what was being taught in University Departments; what did the profession require of its new graduates; and what teaching and learning approaches were currently considered most effective by students and staff?. We therefore set out to try to address these questions. We also wanted to look at the impact of computer aided learning, how the use of computer software and the associated problems with verification and validation were being dealt with and to make some suggestions as to what should be taught.

Obviously, to carry out this work, we required some assistance and this was provided by the Arup Foundation, who have an enviable reputation in supporting investigations into Engineering Education. In particular, the discussions with members of the Foundation about the contents in final report were extremely enlightening. We are extremely grateful for their support and assistance.

We are also grateful to all those colleagues who assisted by answering our questionnaires and discussing the teaching and use of structural analysis.

Finally, we consider this report to be a snapshot; there is no doubt that things will change in the future bringing yet further challenges to the teaching of Structural Analysis

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ABSTRACT

This report describes the results of an investigation into the teaching of structural analysis in Universities within the United Kingdom. A brief outline of the current state of teaching together with the requirements of industry is given. The results of an extensive survey into what topics within structural analysis are taught, together with what resources are used are given. This is supported with a survey of what structural analysis skills industry requires of its engineers, particularly graduates. A discussion of the surveys is given, which highlights a number of areas of concern to academics, together with recommendations as to what the authors believe should be taught.

INTRODUCTION

When the authors presented a paper on the teaching of structural analysis (May et al., 2003), to members of the Institution of Structural Engineers it became fairly obvious that no-one was particularly clear as to what was being taught on university courses in Theory of Structures courses and what industry expected from graduates. The objective of this report is to describe efforts to address the above by carrying out and analysing the results of questionnaires and face to face interviews with academics, practising engineers and students, the results of which are given later in this report.

Much has changed in the last thirty years in the requirements for structural analysis due to the introduction of computer software. One of the skills required of the analyst in the past was the ability to simplify complex structural systems so that they could be analysed by hand. This meant that an analyst would have a number of methods which might be applied to a particular problem – the choice of which method to use was important in that the incorrect choice could mean that the solution was impossible by hand because of, for example, the large number of equations to solve. Structures courses and examinations reflected this in that often the first part of any exercise was a choice of the suitable technique. Substantial effort was put into determining degrees of freedom and redundancy in order to assist in the choice of the method. Most analyses were linear elastic, the exception being ultimate load analyses using plastic analysis and yield line theory.

Today the analyst has an array of powerful computer programs that can analyse most structural problems that an engineer is likely to face. This can include complex geometry, multi-member frames, buckling, dynamics, non-linear materials, etc. The problem for the analyst has changed – it is now a case of deciding how detailed an analysis is required. In addition there are two further problems: the first is to determine a suitable model and the second, assuming that the software being used is error free, to check or validate the results. That the latter is the cause of some concern can be gleaned from reading articles in the Structural Engineer, for example, (MacLeod, 2006), (Mann and May, 2006).

One further aspect of structural analysis that is considered to be of particular importance is the relationship between the results of an analysis and the stress state within the real structure. This has been the subject of a number of recent papers, (for example (Heyman, 1996), (Heyman, 2005), (Mann, 2005), (Burland, 2006).

Heyman and Burland both discuss Hambly's paradox in order to assist in identifying why design calculations do not reflect real behaviour. Hambly considered two stools each with a centrally placed loading of W, the first stool had 3 and the second 4 symmetrically placed legs. The question was then posed as to what force should the legs be designed for. The three legged stool is statically determinate so the design force is W/3. The four legged stool is not determinate so the assumption made about the boundary conditions becomes important. Assuming that one of the legs is not in contact with the ground, due possibly to a slight difference in the length of the legs or a variation in the ground, then from consideration of equilibrium the force in the diagonally opposite leg will be zero and the forces inn the other two legs will be W/2. An elastic analysis assuming perfect contact would have led to forces of W/4. The problem can be taken further in that if the legs are assumed to have a maximum load capacity W/4, adequate ductility and not to buckle then as the stool is loaded the two loaded legs will carry load and then yield and continue to deform plastically until all four legs are in contact with the ground at which stage these legs will now carry the additional load, until all legs carry W/4. The problem with the design of the stool arises if the legs are manufactured of a brittle material or the legs are likely to buckle – the four legged stool then, counter-intuitively, becomes less economic!

Heyman uses a number of examples, including an elastically designed propped cantilever in which a relatively small settlement causes a significant change in the maximum moment in the member. This example is taken a stage further to show the advantages of plastic design for strength – again demonstrating the role of ductility. As a second example, a rectangular portal frame, is used as a warning about the use of plasticity theory for structures which include members that are prone to buckling. A series of analyses of the structure for the same loading show that the end moments on the column can change from double curvature to single curvature depending on the assumptions, all of which are realistic, made about, in particular the boundary conditions.

These examples illustrate the effect of the assumptions on the analysis and the limitations of elastic analysis when dealing with ductile materials. They also demonstrate that when dealing with members that are prone to buckling or brittle materials there is a need for careful consideration of the sensitivity of the behaviour of the structure due to, for example, boundary conditions. Discussions of this type of structural behaviour need to form part of the teaching within structural analysis. Teaching material for this aspect tends not to be covered in most structures text books which still tend to be orientated towards giving the correct solution for a particular problem.

Having discussed the changes in the approach to structural analysis, it is necessary to consider how these impinge on industry and academia. In industry the requirement is to produce accurate analyses in order to both check and aid the development of a design proposal or, increasingly, to assess an existing structure – this is becoming an increasing requirement and often requires analytical skills of a higher degree than that required when producing new designs. Indeed the current spend on maintenance repair and renewal in Europe is approximately equal to that on new construction, and likely to increase.

The advantages of computer assistance include speed and accuracy, thus, if used correctly, leading to fewer errors. An additional advantage, because of the speed, may be the opportunity to carry out sensitivity studies. The disadvantages may be that the analyst has software that is not suitable for carrying out the required analysis or that is capable and is being used to carry out analyses beyond the analyst's experience and knowledge. Additionally, a false sense of security may occur resulting in inadequate checks on the validity of the chosen model and the results. A further advantage is the ability to analyse structures that would have been too complex to analyse by hand, for example the Eden project (Jones et al., 2001) and the structures, including the Water Cube, Beijing, described by Carfrae, (Carfrae, 2007).

The effects on academia of the changes in the approach to structural analysis have meant that there has been a shift from teaching numerous techniques for the analysis of indeterminate structures and, more recently, the theory behind computer based methods, to the educated use of software. The teaching of the basic theory, for example the analysis of statically determinate structures, equilibrium and compatibility has remained much the same.

An opportunity exists for the use of computers to aid learning but it appears to the authors that little advantage is being taken of this aid at present other than the use of a computer program to analyse a problem for which a solution already exists and then comparing computer and analytical solutions.

Academia – and particularly engineering courses - face additional problems due to the background that students arrive with at university. Particular problems occur with the mathematics and physics that students have covered prior to university. Whilst the changes in the syllabi may have benefited society as a whole they have caused problems for engineering – these problems are described in great detail in the report of the Engineering Council, (Engineering Council, 2000). Briefly they identified that many students applying for engineering course were not as well equipped in mathematics, particularly mechanics, as they would have been 15 years earlier. It has therefore been necessary to take this into account in the design of engineering courses.

There are a number of further changes that structures courses – along with other components of the syllabus – have had to come to terms with. The broadening of the course content over the past thirty years to include aspects of management, health and safety, environmental issues and sustainability has meant that the time spent on structures has had to reduce. It could be argued that it has been possible to compensate for some of this reduction in time by the reduction of the number of techniques having to be taught. However, there are a number of newer techniques that the graduate should have been introduced to, for example finite element methods, and, increasingly, the requirement of some basic structural dynamics in view of the type of structures now being designed and built.

A further cause for concern arises from the experience of David Brohn, who has employed an identical graduate diagnostic test, (Brohn and Cowan, 1977) of bending moment sketching ability for over 30 years now and finds that the results (always poor) have actually declined in recent years. An average score is around 25%. Presuming that bending moment sketching is a valued skill, and some sort of measure of the understanding of structural behaviour, then something is surely amiss in the teaching and/or learning of structural analysis.

It was in the light of the above that, in order to understand better the teaching of structures at present, the authors therefore set out to

- Obtain a reliable picture of current syllabus contents and teaching practices in structural analysis.

- Discuss with practising engineers the structural analysis knowledge and abilities graduates should have.

- Survey attitudes to proposed changes in the teaching of structural analysis.

- Suggest changes in syllabus content and teaching practices

Whilst the brief for this project was to look at the teaching of structural analysis only it is the authors view that this needs some integration with structural design.

However, it needs to be reiterated that structural analysis is not only part of design but also becomes of prime importance when carrying out structural assessments.

The sections that follow describe the surveys carried out, discuss the results and make recommendations of changes that could be beneficial in the teaching of structural analysis.

SURVEY ANALYSIS

Background

A survey of academic (Appendix 1) and industrial (Appendix 2) opinion was undertaken and twenty-five responses were received for each category. The academic responses covered the full range of university departments, both geographically (Aberdeen – Exeter) and in date of institutional foundation (Oxford – Bolton). A somewhat more detailed assessment of the time devoted to varying structural analysis topics was provided by a typical department (Nottingham University) and verified by discussions with colleagues at the universities of Leeds, Loughborough, Manchester, Sheffield and University College London. Student opinion proved somewhat more elusive to survey and the results presented are based on a survey (Appendix 3) of a total of seventy students at Birmingham, Queen's University Belfast, Heriot-Watt, Liverpool, Nottingham and Nottingham Trent Universities.

Importance of analysis capabilities for "structural understanding" and practice

Survey results

Table 1 : Importance of analysis capabilities for "structural understanding" (0-5 high)

Academic		Industry	
Hand determinate	5.00	Hand determinate	5.00
Buckling	4.50	Theory of Elasticity	4.63
Plastic analysis	4.33	Buckling	4.45
Hand indeterminate	4.04	Plastic analysis	4.18
Torsion	3.90	Hand indeterminate	3.90
Theory of Elasticity	3.73	Torsion	3.80
Dynamics	3.50	Finite Elements	3.52
Plates & Shells	3.32	Dynamics	3.32
Matrix analysis	3.13	Matrix analysis	3.18
Finite Elements	3.00	Plates & Shells	3.00

Table 1 shows the average assessments of the importance for structural understanding of the range of topics commonly included in structural analysis courses. Possibly the most striking feature of the table is the agreement between academics and practitioners. The only significant discrepancy is in respect of "Theory of Elasticity" which may well have been interpreted as "Strength of Materials" by the practitioners as opposed to the assumption of "Plane Stress/Plane Strain Analysis" that was the intended interpretation and would probably have been the understanding of the academics. The over-riding importance of sound capabilities in respect of statical analysis and a clear appreciation of the principles of bucking and plastic analysis were further emphasised in the subsequent qualitative responses.

Table 2: Importance of analysis capabilities for "practice" (0-5 high)

Academic		**Industry**		**Student**	
Hand determinate	4.88	Hand determinate	4.86	Buckling	4.07
Buckling	4.42	Buckling	4.54	Hand determinate	3.96
Plastic analysis	3.83	Plastic analysis	3.91	Hand indeterminate	3.93
Finite Elements	3.61	Theory of Elasticity	3.71	Finite Elements	3.48
Torsion	3.33	Torsion	3.40	Dynamics	3.47
Dynamics	3.32	Finite Elements	3.38	Theory of Elasticity	3.42
Theory of Elasticity	3.19	Dynamics	3.20	Torsion	3.37
Hand indeterminate	3.13	Hand indeterminate	3.22	Plastic analysis	3.35
Plates & Shells	2.80	Matrix analysis	2.94	Plates & Shells	3.00
Matrix analysis	2.71	Plates & Shells	2.77	Matrix analysis	2.83

Table 2 shows the relative assessments of analysis topics in relation to their perceived importance for "practice". The agreement between academics and industrialists contrasts somewhat with the student preferences, which might well derive from the students' lack of practical experience, but which does indicate that the importance of different topics in relation to practice might be more vigorously emphasised to students. There is a strong correlation between the academic/industrial assessments of relative importance for practice (Table 1) and understanding (Table 2) with the exception of hand analysis of indeterminate structures. This is valued for understanding (probably in the form of moment distribution, for example) but, given the universal employment of analysis software, is no doubt seen as having much less relevance to practice.

Table 3: Inclusion in core course and time devoted to topics (MEng courses only)

Topic	**Included in courses (%)**	**Topic**	**Time (%)**
Buckling	100	Buckling	8
Hand determinate	100	Hand determinate	25
Hand indeterminate	100	Hand indeterminate	19
Matrix analysis	100	Matrix analysis	8
Plastic analysis	100	Plastic analysis	8
Theory of Elasticity	79	Theory of Elasticity	3
Torsion	79	Torsion	4
Dynamics	68	Dynamics	7
Finite Elements	58	Finite Elements	15
Plates & Shells	37	Plates & Shells	4

Reassuringly, the topics that are considered of most importance for structural understanding and practice are included as core material in all the MEng courses surveyed (Table 3). Matrix analysis may perhaps be considered an anomaly in the sense that its universal inclusion contrasts strongly with its lowly perception in relation to usefulness for either structural understanding or practice. Most analysts would, however, no doubt contend that a basic familiarity with matrix analysis is essential, since it forms the basis of all structural software. Its inclusion in courses is therefore not likely to be contentious, but the time devoted to matrix analysis and some other topics that are not highly rated in respect of relevance to structural understanding and practice might be worth questioning. For example, as shown in Table 3, a typical structural analysis programme can devote almost as much time to the hand analysis of indeterminate structures as to the consideration of determinate systems and more than twice as much time as is spent on buckling theory.

Table 4: Perceived student difficulty of topics (0-5 high)

Topic	Difficulty
Finite Elements	3.85
Plates & Shells	3.55
Matrix analysis	3.42
Dynamics	3.41
Theory of Elasticity	3.21
Hand indeterminate	3.13
Torsion	3.00
Buckling	2.96
Plastic analysis	2.91
Hand determinate	2.22

The inverse correlation of the degree of difficulty perceived by students (Table 4) in relation to the perceived importance of the topics (Table 1 and Table 2) is encouraging in that it suggests that high standards in these topics should be readily obtainable.

Summary and suggestions

- The hand analysis of statical systems, knowledge of buckling phenomena and an appreciation of plastic theory are the qualities most prized in relation to both an acquisition of structural understanding and for relevance to practice.

- Students appear to be unaware of the relative importance of topics to practice and more might be done to emphasise this aspect. An example might be the importance of determinacy in relation to possible redistribution effects when structures are loaded beyond their elastic limit.

- The proportion of time devoted to the hand analysis of indeterminate structures is large compared to the relevance ratings of the topic, while the time devoted to bucking is relatively small. This is probably due to the extent of the appropriate mathematical theory that applies to the two topics. However it may be that the time spent on indeterminate structure theory/solution techniques could be reduced and that devoted to buckling could be enhanced (possibly through case study material, model construction/testing, laboratory investigation or similar practically oriented learning strategies).

- Students following only the core analysis programme of a typical MEng course are more likely than not to have no background in plate and shell theory.

- Students consider the topics rated most effective for understanding and practice to be the easiest.

Importance of skills/competencies for "structural understanding" and practice

Table 5: Importance of skills and competencies for "structural understanding" (0-5 high)

Academic		Industry	
Conceptual design/Approx. analysis	4.82	Conceptual design/Approx. analysis	4.85
Patterns of behaviour	4.43	Patterns of behaviour	4.52
Laboratory skills & investigations	3.96	Case/project studies	4.00
Case/project studies	3.83	Study failures/historical structures	3.81
Use of physical models	3.79	Laboratory skills & investigations	3.83
Computer analysis skills	3.39	Computer analysis skills	3.34
Study failures/historical structures	3.38	Use of physical models	3.42

Table 6: Importance of skills and competencies for practice (0-5 high)

Academic		Industry	
Conceptual design/Approx. analysis	4.91	Conceptual design/Approx. analysis	4.95
Patterns of behaviour	4.38	Patterns of behaviour	4.57
Computer analysis skills	4.26	Computer analysis skills	4.28
Case/project studies	3.82	Study failures/historical structures	3.76
Study failures/historical structures	3.24	Case/project studies	3.31
Laboratory skills & investigations	2.70	Laboratory skills & investigations	2.76
Use of Models	2.58	Use of Models	2.61

Table 5 and Table 6 indicate the importance attached to various skills and competencies in respect of relevance to structural understanding and practice. Again the agreement between the academics and industrialists is striking and demonstrates a consensus that conceptual design, approximate analysis abilities and familiarity with standard patterns of structural behaviour are the most highly prized competencies for both structural understanding and relevance to practice. "Hands-on" activities such as the use of models and laboratory skills/investigations are less favoured, while computer analysis skills are considered valuable for practice but relatively unhelpful for the promotion of understanding. On the other hand, when the students rated the effectiveness of a variety of learning approaches (Table 7) "hands-on" type approaches rated highly with laboratory tests and investigations and the use of models being valued for the promotion of understanding. Students, however, agree with the academics and practitioners that computer based approaches, whether based on the use of CAL, internet or structural software, are of limited use for the promotion of structural understanding.

Table 7: Student assessment of the usefulness of different learning approaches for "structural understanding" (0-5 high)

Learning approach	
Problem solving classes	4.14
Qualitative Work	3.98
Use of models	3.91
Laboratory tests & investigations	3.75
Lectures	3.74
Use of textbooks	3.42
Liaison with fellow students	3.38
Case studies	3.31
Study of failures	3.12
CAL	3.08
Computer analyses	3.05
Liaison with non-students	3.03
Study of historical structures	2.57
Use of internet	2.29

Summary and suggestions

- Conceptual design, approximate analysis abilities and familiarity with standard patterns of structural behaviour are the most highly valued abilities for both structural understanding and relevance to practice. It is, however, unlikely that either substantial time or effort is devoted to the development of these attributes, and, more particularly, their assessment, within current university programmes.

- Laboratory skills and investigations are thought valuable for the development of structural understanding by both academics and students.

- Computer skills are considered important for practice but not helpful in the development of understanding.

Student views on structural analysis learning

Relationship of structural analysis to other topics studied

Table 8 indicates that students consider structural analysis to be highly relevant to practice but difficult and not of outstanding intrinsic interest. Students should therefore be motivated by the presumed practical relevance and require teaching and learning approaches that mitigate the perceived difficulty of the topic and inspire interest in it.

Table 8: Structural analysis rating (0-5 high) relative to other topics studied

Property	Rating
Relevance to practice	4.01
Difficulty	4.00
Interest	3.68

Usefulness/interest of different learning approaches

Table 9: Rating of learning approaches in respect of assessment success and interest (0-5 high)

Assessment success		Interest	
Problem solving classes	4.38	Use of models	4.00
Lectures	4.02	Study of historical structures	3.63
Qualitative Work	4.00	Case studies	3.61
Textbooks	3.62	Study of failures	3.40
Liaison with fellow students	3.53	Laboratory tests & investigations	3.33
Laboratory tests & investigations	3.27	Problem solving classes	3.16
Case studies	2.99	Lectures	3.06
Liaison with non-students	2.97	Qualitative Work	3.04
Use of models	2.78	Use of internet	2.85
CAL	2.73	Computer analyses	2.82
Study of failures	2.63	Liaison with fellow students	2.75
Computer analyses	2.59	CAL	2.57
Use of internet	2.27	Liaison with non-students	2.49
Study of historical structures	2.14	Use of textbooks	2.40

Table 9 indicates a tendency to an inverse relationship between the assistance found from various learning approaches in enhancing success in assessments and the interest generated by them. Much naturally depends on the teaching and learning styles adopted in the institutions surveyed and the “Qualitative Work” results, for example, might be a case of a local effect, given its extremely high rating for assessment success and relatively low rating for interest.

The findings of Table 9 were reinforced by student responses to a request for the best features of their analysis courses. This produced typical responses of *"Anything practical!"*; *"Design, make and break was top-notch, laboratories, worked example classes"*; *"Examples and relationship to practice";* or *"Practical laboratory work; self discovery"*. One very much hands-on approach that has been developed in recent years is the "Constructarium" that Imperial College has pioneered at the Bircham Newton centre (Imperial College, 2006).

The general inverse relationship between learning approaches that promote assessment success (and hence, presumably, mitigate the difficulties of the topic) and those that motivate students) poses a dilemma in terms of educational strategy. Most courses currently emphasise the learning approaches that most strongly align with assessment success, there being, perhaps a tendency to regard the interest strong approaches as additional, "luxury" items. An assessment strategy that was weighted towards the "hands-on" activities that student find motivational would face the logistical and expense problems of ensuring equitable assessment, high staff involvement and ensuring that a full range of analytical/theoretical material is covered. These concerns did in fact lead to the abandonment of a Problem Based Learning approach to engineering education that was experimentally trialled at the University of Manchester some years ago. Although never implemented in Civil Engineering, the approach is still employed by some courses at the university (University of Manchester, 2006). In Denmark, however, the University of Aalborg was set up in 1974 specifically to promote Project Based Learning and has been operating on this basis ever since (Kjersdam and Enemark, 1994).

Summary and suggestions

- Students appreciate the importance and relevance to practice of structural analysis but find the topic difficult and interest needs to be further stimulated.

- Learning approaches (problem classes and lectures for example) that favour currently employed modes of assessment do not rate highly in terms of student motivation. More weighting might be given to approaches that generate interest (models and case studies, for example) and innovative ways of motivating students need to be explored.

- In common with the promotion of student understanding, computer based learning approaches (internet, CAL, computer analyses) rate poorly for either assistance with assessments or for interest value.

Learning aids

Textbooks

Table 10: Recommended texts for different aspects of analysis

Text		Citations	No. texts
Statically determinate structures			19
Hulse & Cain	Structural Mechanics	4	
Seward	Understanding Structures	4	
Bhatt & Nelson	Structures	3	
Hibbeler	Statics & Mechanics of Materials	3	
Megson	Structural & Stress Analysis	3	
Statically indeterminate structures			14
Coates, Coutie & Kong	Structural Analysis	7	
Ghali & Neville	Structural Analysis	4	
Williams & Todd	Structures: Theory & Analysis	4	
Bhatt & Nelson	Structures	3	
Finite elements			12
Williams & Todd	Structures: Theory & Analysis	3	
Approximate analysis			4
Brohn	Understanding Structural Analysis	2	
Hambly	Structural Analysis by Example	2	

The texts cited more than twice (once in the case of approximate analysis) as being recommended to structural analysis students are shown in Table 10. A striking feature is the large number of texts (full lists in Appendix 4) recommended for all categories apart from approximate analysis and that no single text dominates any category, although, somewhat surprisingly, the text that received the most citations of all (Coates, Coutie & Kong) must be rather dated since the last edition appeared in 1988. Obviously texts are chosen to reflect the orientation of courses and the personal preferences of teachers but there is perhaps an implication that there is a lack of outstanding texts. This may be particularly the case in respect of "approximate analysis" texts where only three books were cited and the two most favoured (Brohn and Hambly) are quite different in character.

Students, if anything, were less enthusiastic about the use of textbooks than academics. When asked to cite an analysis text that had been found particularly useful, few did so. The citations that were made tended to refer to reference books such as *The Steel Designer's Manual* or Fiona Cobb's *Structural Engineer's Pocket Handbook*. There were also a number of replies along the lines of "*used very few*", the overall implication being that students preferred to work from the lecturer's course specific notes, producing comments such as "*haven't used any, I always rely on the lecture notes and tutorial questions, and still score highly*". One department did clearly use a course text and this produced at least one favourable comment saying that the text had "*very good examples but the book is expensive*". However, most students gave the impression of agreeing with comments such as "*There are very few textbooks which explain structural analysis in easy-to understand terms. Most assume that we have a sound knowledge of structural analysis already*" Students therefore relied on "*Lecture notes and good luck*". For one of the authors, the final word on the matter goes to the student who replied *"The only book I have found useful is 'Linear Structural Analysis' by David Johnson"* (Johnson, 2004).

Summary and suggestions

- A wide range of analysis textbooks are recommended, there being no clear favourite in any of the three categories surveyed.,
- There is little enthusiasm for the use of textbooks, especially from students. As indicated in Table 9, students consider textbooks to be the least interesting learning approach, although they can be found moderately useful for success in assessments (by reference to worked examples?).
- In a number of cases, local loyalty plays a part with a text authored by a past or present university member being recommended at the institution. It may be, therefore, that a text prepared by a group of academics from a range of institutions and offering, in particular, a wider range of problems for student solution might be more successful than current texts.
- Few texts on "approximate analysis" are recommended.

Computer Aided Learning (CAL)

Table 11 : Citations for use of CAL packages

CAL package	Citations
CALCRETE	8
STEELCAL	3
DEFLECT	1
DrBeam	1

Four CAL packages were cited as being available for students at different institutions, but, as shown in Table 11, only CALCRETE was at all reasonably widely utilised. In no case was it stated that CAL was formally integrated into a course. Indeed, in a number of instances it was specifically made clear that while CAL material was available its use was left entirely to student discretion. Contact details of the cited packages and selected others are provided in Appendix 5.

Summary and suggestions

- Despite the large budgets that have sometimes been devoted to the production of CAL material, there is very little enthusiasm for its formal adoption within courses.

Academic views on the nature of analysis courses

Innovative/distinctive features

The pressure analysis courses currently experience from competing topics was graphically illustrated by one response in this category which considered that the distinctive feature of the course was that *"we still teach it at all levels"*. More generally, the claims made in this category tended to mirror the ethos of particular institutions, so that engineering science based courses, such as Aberdeen and Exeter, tended to emphasise the benefits of cross-discipline working and "older" institutions, such as Cambridge and Glasgow, tended to "*concentrate on* *theory*" or were "*deliberately analytical*". Others cited a commitment to the integration of design and analysis and a number had features stemming from their research expertise, such as dynamics at Oxford or cable nets at Warwick. Overall, Birmingham probably accurately represented the practice of the majority in aiming to provide a *"combination of formal, qualitative, analytical and practical studies".*

Integration of analysis and design

A full spectrum of practices was reported, from Aberdeen where analysis and design are *"fully integrated"* to Cambridge where there is *"very little – emphasise ability to analyse is not ability to design".* The majority of respondents cited some integration of analysis and design, commonly in the later stages of the course and often through the medium of design projects. Many expressed aspirations towards more integration, since integration was typically considered to be *"desirable from educational, motivational and pass-rate perspectives".* A number of respondents cited time constraints as limiting the amount of integration that was possible but, perhaps surprisingly, none mentioned limitations due to available academic expertise.

Summary and suggestions

- The distinctive features and the amount of integration of analysis and design that is achieved in course are both extremely variable and, if anything, perhaps tend to reflect institutional ethos rather than assessed educational objectives.

- No one department stands out as being particularly innovative in its analysis teaching. Maybe the topic does not encourage or need a radical approach.

- Many would hope to integrate design and analysis more, especially in the later stages of the course, if time and time-tabling constraints allowed.

Student views on the nature of analysis courses

Problems in learning analysis and ways to overcome these

A minority of students took a mechanistic view of their analysis course and cited, for instance, the main problem to be "*exams*" and that the most promising solution was "*doing examples, less focus on theory... leave that to the maths people".* Complaints that the subject involved *"long derivations, hard to follow"* were also typical. These occasional backwoodsmen apart, however, it was surprising to find students broadly in agreement with academics and industrialists in considering that the main problems are "*understanding why/how structures work and getting that clear in your head before starting the analysis"* and *"...understanding …concepts such as BM/SF…stems from student's inability to physically appreciate such principles".* Solutions cited included "*lab experiments/Design, Make, Break help"; "worked examples are clearest way";* and "*seeing how things work in a real situation".* Individual students obviously found particular approaches best suited their personal mental framework and one student, for instance, commented that *"main problem for me is understanding how various structures act under different loading conditions. The use of computer analysis is the best way of overcoming this…".*

Integration of analysis and design

Although limited to the six institutions surveyed, students generally exhibited more enthusiasm for enhanced integration of analysis and design than the academics. Most favoured increased integration and this was expressed most forcefully by the comments "*more would help understanding and also increase enjoyment*" and "*the more advanced structures course has little emphasis on design and this can sometimes make it difficult to see the point of studying such topics*".

Summary and suggestions

- Students appreciate that the main problems in coming to terms with analysis lie in developing an "*understanding of material and structural element behaviour*". Increased efforts to increase understanding should therefore meet with the approval of the majority of students; although an examination focussed, mechanistically minded minority exists.

- A range of student experience is probably desirable, given that cited helpful approaches varied considerably.

- Students generally favour increased integration of analysis and design.

Academic use of structural analysis software

Since a major spur for the survey, and the investigation more generally, was to explore the impact of the availability of analysis software on teaching practice, the views of both academic and industrial survey respondents were sought in respect of practices and implications associated with the universal usage of structural software.

One of the main aspects of any modelling is the ability of the analyst to be able to carry out verification and validation of the model, the method of analysis, the analysis tools and the results. In this report the definitions given in Guidelines for the use of computers in engineering calculations (IStructE, 2002) which defines 'verification' as the consideration of whether the model has been correctly implemented and "validation" as consideration of whether the model is capable of satisfying the requirements have been adopted.

Software employed

Academic institutions commonly cited the use of more than one analysis software system so that there were a total of 40 citations from the 25 academic replies. Multiple replies commonly resulted from the use of one package for frame analysis and one for finite element (continuum) analysis. The software packages that received three or more citations are shown in Table 12. A further 10 systems received one or two citations. Both staff and students reported relatively trouble free operation of the various packages. The learning time for the more extensive finite element packages is obviously longer, and produced student comments such as "*Found it difficult to begin with…got easier as use.. increased*". This type of experience has prompted the use of frame specific software in the early stages of some programmes.

Table 12: Software used as cited by academic respondents (40 total citations)

Elastic analysis software	Citations
QSE	8
Oasys	5
Ansys	4
LUSAS	3
MASTAN	3

Software usage

Analysis software is overwhelmingly used for undertaking sample analyses and in conjunction with design projects. A limited number of departments expect some programming to be undertaken and others specifically undertake computer modelling; case studies (Johnson, 1989); or computer investigations (Rafiq and Easterbrook, 2005).

Verification of software results

Verification of results is generally undertaken by a mixture of equilibrium checks, approximate hand calculations and qualitative assessment of deflected shapes and stress resultant distributions. The respondent from Exeter emphasised that all verification needs to follow the Napoleonic code prescription of *"guilty until proved innocent"*. No reference was made to the use of more formal validation and verification schemes that have been promoted in recent years (MacLeod, 2005 and IStructE, 2002).

Summary and suggestions

- Universities operate a wide range of structural analysis systems with no one provider dominating. Many institutions introduce students to at least two different packages, typically one for frame analysis and one for continuum analysis.

- Software usage tends to be confined to relatively routine sample analyses and as an adjunct to design projects.

- Students are not generally introduced to formal validation and verification schemes schemes for computer analysis.

Industrial experience of graduates' ability to use analysis software appropriately

Problems encountered by graduates and mistakes made

The main problems cited centred on a lack of appreciation of structural behaviour; an inability to model appropriately (especially support conditions); and insufficient experience to "predict" results intuitively or by approximate calculations. These concerns were also echoed by one of the student respondents who considered that the difficulty was *"correct modelling ….(such as the boundary conditions…)"*The principal sources of mistakes were suggested to be problems with axes and sign conventions and a lack of appreciation of the limitations of elastic analysis that could lead to *"an obsession with high elastic stresses"* or a failure to appreciate the non-linear, time-dependent behaviour of a material such as concrete. Overconfidence in computer results was further widely considered to lead to an uncritical acceptance of computer generated analyses.

The general consensus on how to improve matters was to give additional emphasis on hand calculations, especially based on approximate models; to study cases from practice; and a greater concentration on basic material properties and the assumptions underlying different types of analysis, especially plastic in relation to elastic analysis.

Validation and verification procedures

Larger companies tended to have quality assurance schemes that required a formal validation and verification of results and often specified repeated analysis with different software. Smaller concerns usually operated a checking system based on validation and verification undertaken by a senior engineer.

Summary and suggestions

- Graduates are uncritical of computer results and lack the experience to effectively validate analyses.

- Academics will probably be relieved to learn that industrialists do not expect them to provide detailed training in software usage, which is accepted to be a practice responsibility, but do hope that a deeper understanding of structural behaviour and theory can be engendered at colleges.

- Validation and verification schemes for computer analyses used in practice vary from extremely formal to informal peer review.

RECOMMENDATIONS

A variety of suggestions have been made in relation to the findings of the surveys of academic, practitioner and student opinion. These have subsequently been discussed with teachers in selected university departments and the principal recommendations made as a result of all of these enquiries as follows:

1. Given the consensus on the importance of a firm understanding of determinate structures, buckling and plastic analysis, the time devoted to buckling and plastic analysis would currently appear to be low and might be usefully increased

2. Substantial time is devoted to the hand analysis of indeterminate structures, in the expectation that this will lead to an understanding of the mode of behaviour of such structures. It can, however, be contended that a more direct approach would be to utilised qualitative analysis, computer/case studies and laboratory investigations and that these approaches would increase student motivation and allow a wider range of structural forms to be explored than the traditional continuous beams and rigid frames.

3. Conceptual design, approximate analysis and the recognition of patterns of structural behaviour are all highly valued attributes and need to be incorporated throughout analysis courses. Discussion of these topics on a regular basis can also offer a design link in programmes that separate analysis and design.

4. Laboratory and model investigations, although resource intensive, are highly regarded by many students and should be retained or enhanced. The national model building competition run some years ago by the University of Leeds might be usefully re-established. It is accepted that it is unlikely that laboratory work will increase in the future; however, it can be supplemented by videod laboratory work when such a resource is available.

5. CAL is rarely (never?) integrated into analysis teaching and learning. As an add-on for occasional student use, it would not appear a cost-effective learning resource.

6. Textbooks are an underutilised and undervalued resource. There is a need for better quality, lower priced and more accessible texts. The use of textbooks can be promoted if a "course text" is adopted and this can lead to efficiencies.

7. A wide range of analysis software is employed in academic departments. A more detailed survey might be useful to establish the most appropriate system/s for educational purposes. The use of a simplified frame package in the initial stages of a course can speed familiarity with computer analysis.

8. Current usage of computer analysis tends to be routine comparisons with hand solutions. More imaginative applications to case/parametric studies and a wider range of structural forms should be considered. This might replace detailed study of the matrix analysis, since it is likely to lead to a deeper understanding of structural behaviour and of the capabilities of structural software than is a detailed knowledge of the workings of the stiffness method.

9. Discussion of the reasons why design calculations do not reflect real behaviour is necessary as is the limitations of analysis procedures. This should include an introduction to the effects of ductility, buckling, and brittle materials.

10. An introduction to more formal validation and verification processes of computer analyses (Macleod, 2007) should be provided within academic courses.

11. Some use is made by academics of case studies in their teaching. These might include new, unusual structures, existing structures and failures. It would be useful to have details, for example drawings, photographs etc. available as a resource, on a cd, for example. Lecturers could then "pick and choose" from this resource in order to supplement their teaching.

12. The lecturers in some subjects meet on a regular basis to discuss the teaching – and research – in that area, for example the annual meeting of lecturers in concrete. It would be useful if this idea was extended to structural analysis. There was a study group of The Institution of Structural Engineers on "The qualitative behaviour of structures" which might benefit from a name change and reforming.

IMPLICATIONS FOR SYLLABUS DESIGN

The authors believe that the current syllabus would benefit from significant changes based on the recommendations given above and have benefited from a suggestion made by Professor Iain MacLeod that the curriculum should comprise two interlinked parts, Mechanics and Modelling Processes, the overall aim being to move the focus of learning from *doing* calculations, for example, in relation to statically indeterminate structures, to *controlling* calculations.

In such a scenario, hand calculations based on mechanics, specifically related to statically determinate structures, would still occupy a major role, but there would be a significantly enhanced emphasis on the underlying assumptions relating to small/large deflections, buckling and material behaviour, for example. Laboratory work and physical models can be helpful to many students in this context.

Modelling processes would be seen as no less important than mechanics and would seek to educate students in setting up, validating, and optimising models and in verifying the results of analyses. Emphasis should be placed on the interpretation of results so as to gain understanding of behaviour and a link with design should be offered by encouragement for the creative development of alternative designs, based on the knowledge gained. Conceptual design, approximate analysis and the use of case studies would all have important roles to play in these activities.

CONCLUSIONS

There is a consensus between academics and practitioners as to what should be taught within Structural Analysis courses and the priority that should be given to different topics. All the topics cited as being particularly valued are included as core material in current MEng courses. The increasing dominance of computer analysis over the past thirty years has led to a reduction, but not elimination, of the number of techniques taught for the analysis of indeterminate structures, but this has been perhaps more than compensated by the introduction of matrix and finite element methodologies, together with an increasing amount of dynamic analysis.

Conceptual design, approximate analysis and structural behaviour pattern recognition are abilities that are especially valued by both academics and practitioners but competence of graduates in these respects is considered to be no better than thirty years ago. Possible reasons include pressure on relevant course time both during and previous to undergraduate study.

CAL, textbooks and computer studies are used sparingly within courses and are not generally valued highly by either academic staff or students. Students tend to value "hands-on" approaches more than staff. Innovation in the teaching of structural analysis is limited and there is no consensus as the degree of integration with design that is desirable.

Despite the routine application of computer analysis in practice, undergraduate students are rarely exposed to more than routine checking of hand solutions by computer and unlikely to be exposed to the structured validation and verification of computer analyses.

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Appendix 1

Academic Survey

What structural analysis capabilities should a graduate engineer have?

	Tick if covered in **core** course	Tick if covered in **optional** course	Assessment of importance for "structural understanding" (0-5 (high))	Assessment of importance for practice (0-5(high))
Knowledge/capabilities				
Hand analysis of statically determinate structures				
Hand analysis of indeterminate structures				
Matrix structural analysis				
Plastic analysis				
Torsion				
Theory of elasticity (plane stress/plane strain)				
Plates & Shells				
Finite element analysis				
Buckling				
Dynamics				
Other (please specify)				
Skills/competencies				
Conceptual design and approximate analysis				
Patterns of behaviour of standard structural systems				
Computer analysis skills				
Study of failures and historical structures				
Use of models				
Case studies and project studies				
Laboratory skills & investigations				
Other (please specify)				

* The **core** course is the total compulsory structural analysis taught throughout the under-graduate degree programme.

Is this response in relation to a MEng; BEng or BSc course – please provide individual replies if you offer more than one course.

In which years is Structural Analysis taught?

What proportion of your course is devoted to compulsory structural analysis?

What computer analysis software do you use and how satisfactory is it for teaching purposes? Describe briefly how you use it and how students validate results.

What, if any, computer-aided learning packages do you use and how helpful do you assess them to be?

Which textbook/s would you recommend for a) the analysis of determinate structures b) analysis of indeterminate structures c) matrix/finite element analysis d) approximate analysis?

What would you consider to be the distinctive or innovative features of your Structural Analysis course?

How much integration of analysis and design exists in your course and how much would you consider desirable?

What do you consider to be the main problems for students in learning analysis and what do you find most helpful in overcoming these problems?

Appendix 2

Industry Survey

What structural analysis capabilities should a graduate engineer have?

	Assessment of importance for "structural understanding" (0-5(high))	Assessment of importance for practice (0-5(high))
Knowledge/capabilities		
Hand analysis of statically determinate structures		
Hand analysis of indeterminate structures		
Matrix structural analysis		
Plastic analysis		
Torsion		
Finite element analysis		
Theory of elasticity		
Plates & Shells		
Buckling		
Dynamics		
Other (please specify)		
Skills/competencies		
Conceptual design and approximate analysis		
Patterns of behaviour of standard structural systems		
Computer analysis skills		
Study of failures and historical structures		
Use of models		
Case studies and project studies		
Laboratory skills & investigations		
Other (please specify)		

How important do you consider a graduate's ability in structural analysis to be in relation to other desirable attributes?

What are the main problems encountered by graduates in analysing structures?

What do you consider would be likely to be most helpful in improving graduates' analytical abilities?

What are the main mistakes made by graduates in using computerised analysis packages? Do you have a company scheme for validation (apart from independent checking) of results?

What would be most helpful in minimising mistakes made using computerised analysis packages?

What, if any, specialist skills in structural analysis does your practice require that is not covered on an under-graduate course?

Appendix 3

Student Survey

Perceived difficulty/importance of structural analysis topics
(leave blank if topic not covered in your course)

	Assessment of degree of difficulty in understanding (0-5 (high))	Assessment of likely importance for practice (0-5(high))
Topic		
Hand analysis of statically determinate structures		
Hand analysis of indeterminate structures		
Matrix structural analysis		
Plastic analysis		
Torsion		
Theory of elasticity (plane stress/plane strain)		
Plates & Shells		
Finite element analysis		
Buckling		
Dynamics		

Perceived usefulness/interest of learning approaches
(leave blank if approach not used in your course)

	Usefulness in promoting "structural understanding" (0-5 (high))	Usefulness for success in assignments and exams. (0-5 (high))	Usefulness in promoting an interest in Structures (0-5(high))
Learning approach			
Lectures			
Problem solving classes			
Liaison with fellow students			
Liaison with others (non-students)			
Computer analyses			
Study of failures			
Use of internet			
Study of historical structures			
Use of models (e.g. design, make, break tests)			
Case studies from practice			
Laboratory tests & investigations			
Computer Aided Learning Packages			
Use of textbooks			
Qualitative work (e.g. BM diagram sketching)			

Relationship of structural analysis to other topics

	Rate structural analysis in relation to other topics studied on scale (0-5 (high))
Degree of difficulty	
Degree of interest	
Degree of relevance to practice	

What computer analysis software do you employ and how easy have you found it use. What problems have you experienced?

Which structural analysis textbook/s have you found most useful?

What would you consider to be the best features of your Structural Analysis course?

How much integration of analysis and design exists in your course and would you consider more or less integration to be desirable?

What do you consider to be the main problems in learning analysis and what do you find most helpful in overcoming these problems?

Appendix 4

Textbooks cited

Statically determinate texts

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This new report into the teaching of structural analysis by Prof Ian May and Dr David Johnson follows an approach to the Foundation by the authors. It addresses areas of interest and relevance to academics, engineering students and their prospective employers. It is being published in a format which will make it widely available.

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