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TRADITION AND INNOVATION IN TEACHING STRUCTURAL DESIGN IN CIVIL ENGINEERING

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TRADITION AND INNOVATION IN TEACHING STRUCTURAL DESIGN IN CIVIL ENGINEERING

Abstract

This paper briefly reviews the history of structural engineering education: the dawn, development and consolidation of traditional education systems as well as their fall into decline in the contemporary technological world. Recent graduates in civil engineering do not have all of the skills and knowledge that the labor market is demanding and civil engineering is losing the social prestige and professional recognition that our profession deserves. It is necessary to improve traditional education systems to produce the best civil engineers. The authors present a detailed discussion of their experiences teaching structural design at the School of Civil Engineering of Ciudad Real, Spain, using project-based and cooperative learning methods, as well as implementing knowledge management and transference to the learning process. Results and costs of these methods, as well as the problems related to faculty selection, are set out. The paper concludes with a reflection on the major educational possibilities and historical opportunities presented through the introduction of these new methods and suggest that this is the best way to combine Engineering Education and Practice.

Keywords: Teaching Methods, Engineering Education, Structural Engineering, Education-practice interchange, Structural Design, Bridge Design, Building Design.

INTRODUCTION

Following the many technological advancements of the past few decades, companies in the labor market have begun to demand civil engineering graduates with even more skills and knowledge than ever before. In addition, some of the skills that were required of engineers in the past are no longer necessary, since the tasks requiring these skills are now routinely performed by computers rather than engineers. The instruction of civil engineering students must improve with the aim of ensuring that future graduates in civil engineering have the skills and knowledge required to satisfy the demands of industry. The discussion about how to improve the civil engineering education should not only be focused on the length of study, but also in its content, and the methods employed in the instruction of the material.

The authors think that it is necessary to have a historical view of civil and structural engineering education and to be aware of the new and innovative teaching methodologies that are now available, before making any decision about the future of civil engineering education. It is for this reason that we have decided to write this paper. To begin, we briefly review the dawn, development, consolidation and fall into decline of traditional education systems. Then, after analyzing the current situation, we describe an innovative course on structural engineering design that is presently implemented and that has lead students to possess the new skills and knowledge that labor market is now demanding.

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TEACHING METHODS AT CIVIL ENGINEERING SCHOOLS IN THE EIGHTEENTH AND NINETEENTH CENTURIES

In the early eighteenth century, King Louis XIV of France wanted to transform his country into a modern state with good transport connections. He analyzed the existing situation and found that bridges were the road network's weak point. Thus, the King set out to create safe bridges. In 1716, he ordered Gabriel (Grattesat 1981) to found the *Corps des Ingénieurs des Ponts et Chaussées* (Association of Civil Engineers). Initially, this organization consisted mainly of military engineers and a few architects dedicated to the art of bridge building. In 1747, a school was created specifically to train future professionals. Under Jean-Rodolphe Perronet, its first director, the *École de Ponts et Chaussées* in Paris became the world's first civil engineering school.

During the French Revolution, which started in 1789, education at schools and universities was abolished and former lecturers and students were viewed with suspicion by the revolutionary government. At that time, France was also at war with the other European powers. Therefore, it needed engineers, not only military engineers to develop artillery and fortifications, but also civil engineers to build roads and bridges. A group of scientists and engineers led by the great mathematician Gaspar Monge approached the government and proposed a new type of school to replace the one created by the previous regime (Timoshenko 1983). Their proposal was approved in 1794 and the school opened at the end of the same year. In 1795, it adopted its current name: *École Polytechnique* (Polytechnic School).

The organization of this new school differed in many ways from that of the school it replaced. Privileges of all sorts were abolished and young people from all social classes were allowed to enter the school (Gradwell 1996). Entrance examinations were introduced to recruit the best students and the teaching system was radically altered.

The old system lacked a uniform set of entrance requirements for all candidates and did not teach common subjects to large groups of students. Instead it was based on an atmosphere conducive to teacher-student relationships, in which the engineers of the Association explained to each individual student or to small groups how to design or build a certain type of structure. If the students were unfamiliar with mathematical or mechanical theory, the explanation would be provided by the engineering professor himself or by an advanced student with more mathematical training. The old school did not offer classes in mathematics, mechanics or physics.

The concept of the new polytechnic school was based on completely different ideas. It was decided that students of the different branches of engineering needed the same preparation in subjects like mathematics, mechanics, physics and chemistry. It was believed that if students received good training in these basic sciences, they would be able to acquire the special knowledge required of any specific branch of engineering without any trouble. Thus, in keeping with this new conceptual framework, the first two years of the studies covered the basic disciplines and specific courses in engineering were not taught until the third year. As a result of this approach, less time was spent on teaching specific engineering subjects. The *École Polytechnique* became a school of the basic sciences that provided the necessary preparation for students who would later go on to study at engineering schools focusing on disciplines such as mining, or civil, engineering, for example.

The French model was emulated in several continental European countries. The continental system of education and training of engineers put special emphasis on sound theoretical understanding as the basis of engineering practice, rather than practical experience (Chrimes 1991). In southern Europe (France, Spain and Portugal), this teaching style has essentially remained in place to the present day.

However, this new system did not spread through all the European countries. In Great Britain, until almost the end of the nineteenth century, an engineering education consisted of a simple course of apprenticeship, usually with a premium paid to a practicing engineer, and the pupil was educated by taking part in the ordinary business routine in order to gradually become familiar with the practical duties of the profession (Happold 1983). This training stage could last about five years. Practical experience had to be picked up on the job, while theoretical knowledge gleaned from textbooks and papers in journals (Birse 1983). However, the new skills required as a result of the technological advancements of the nineteenth century were not able to be provided through ‘rule-of-thumb’ methods; it was becoming increasingly necessary for workers to understand the scientific principles upon which their work was based. Engineering degrees were established in some British universities in the last two decades of the nineteenth century (Brown 1985), but the strong emphasis on training based on practical application remains a feature of the present British engineering education (Happold 1983).

Engineering arrived to the U.S. in the late eighteenth century via two European traditions, the British and the French (Lyons 2000). In 1802, the United States Military Academy (USMA) at West Point was founded to produce leaders in engineering, exploration and war. This academy followed the French tradition under Thayer’s leadership. In 1824, the Rensselaer School was founded in New York by Amos Eaton. The first civil engineering degree in this innovative school, in which the teaching philosophy was based on ‘learning by doing' rather 'learning by telling', was in 1835 (Griggs 1997). However, despite the existence of these new schools, most practicing civil engineers received their training in the tradition of on-the-job apprenticeship, without academic training as engineers (Calhoun 1960). After the American Civil War, an industrial development boomed, and technically trained people were needed. After the Land Grant College Act, in 1862, the number of engineering schools began to increase significantly (Griggs 2001). Eventually, the British model prevailed, since the economic development dynamics of the United States at that time would not allow the luxury of an engineering education system in the French tradition (Lyons 2000).

STRUCTURAL ENGINEERING KNOWLEDGE AND TEACHING IN THE EARLY TWENTIETH CENTURY

Gradually, more formal theoretical education was developed and all qualified engineers had to be educated to the equivalent of university degree standard. The British and the French tradition had to take in all the theoretical knowledge developed in those years. In both cases theoretical knowledge gained ground to technological knowledge, but both approaches kept their identities: the British and American models with a strong emphasis on practical application, and the French and European model with a strong emphasis on theory.

In the specific field of structural engineering, although most of the theoretical basis for Strength of Materials and Elasticity Theory had been developed by the second half of the nineteenth century and a bridge with a span of over 500 meters had been built in 1895 at the Firth of Forth, there are two anecdotes —told in class by the outstanding Professor Carlos Fernández Casado (1905-1988)— that shed light on the state of structural knowledge and teaching methods at the turn of the twentieth century.

The first of these anecdotes involves the construction of an industrial building for a Catalan textile factory sometime in the first two decades of the twentieth century. The steel three-bay basilica-type portal frame was the structural type systematically used for these factories. At the time, structures were always calculated assuming a wrong non-sway condition. Although the order of magnitude of the bending moments does not vary much between the sway and non-sway schemes, their signs are opposite. However, since the steel sections were symmetrical, the sign of the bending moment had little practical consequence, and this type of structure had consequently performed well. The trouble began when they started using reinforced concrete. As the story goes, the resident engineer sent the following series of telegrams to the head office:

First telegram: “Structure cracks when falsework removed” – STOP. “Rushing to check numbers” – STOP. Second telegram: “Numbers correct” – STOP. “Structure on ground” – STOP.

The second anecdote concerns the teaching of structural engineering. At the School of Civil Engineering of Madrid, a classic summer project in the second to last year of the degree involved solving several load hypotheses for a continuous twelve-span beam. One year, while this sort of summer project was in it’s infancy, one student with a lot of free time —perhaps after having been disappointed in love— probably spent the whole summer working on these problems and managed to solve them all correctly. Copies of these solutions were passed to the following class year after year, and neither the lectures nor the students discussed the matter. Everybody preferred that the problems just kept on being the same, since nobody wanted to have to dust off the Gauss-Seidel method in order to manually, and iteratively, solve the set of equations. What a summer!

The conclusion is clear: despite the fact that the theoretical knowledge was available, the absence of tools with which to apply that knowledge, in addition to a limited understanding of how to adequately characterize reinforced concrete, led to a reliance upon the design of statically determinate structures, such as Gerber and cantilever beams. They were even the only types admitted in early codes for reinforced concrete structures. During that period then, structural engineering was reduced to designing structures that could be calculated using the principles of Statics; indeed, the ability to carry out calculations determined the outcome of a project. In practice, statically indeterminate structures were practically unattainable as the problem of whether or not one could actually determine the internal loads and movements in a structure ultimately prevailed over any other aspect of design.

THE CONSOLIDATION OF TRADITIONAL TEACHING IN ENGINEERING AND ARCHITECTURE

Between the 1930s and the 1950s, two developments in the theory of structures made a profound impact on its immediate future. Firstly, in 1930, the great U.S. engineer Hardy Cross published the Moment Distribution Method, which made it possible to calculate internal forces in frame structures (Cross 1930). Unlike other classical methods, such as the slope-deflection method, this new method did not require the solution of any equation system (Timoshenko 1983; Eaton 2001). Secondly, Ray Clough developed the finite-element method (Turner et al. 1956), which, at first, was used to solve the structural problem of determining internal loads acting on triangular airplane wings. Cross's method did not introduce new structural concepts, but substantial training and a certain degree of specialization were required to carry out the calculations. This was also the case for the finite-element method, although at a different level: this latter method required, in addition to a more solid background in mathematics, knowledge of computer manipulation and programming. In those days, computers were still viewed as sacred monsters that were housed in immense air-conditioned rooms, and people believed that communicating with them involved some sort of special ritual. Thus, relative specialization became "hyper-specialization". The term "structural analyst" was coined and became established, which, at least in Spain, then relegated the terms "structural designer" or "structural engineer" to the background. The acquisition of all the required skills for analysis ended up determining the contents of subjects. In short, a higher degree of scientific knowledge was required by structural engineers and, as a consequence, theoretical aspects began to dominate the curriculum of structural engineering students.

In contrast to the path taken by structural engineers, architects, interested in space, light and formal details, eventually abandoned their concern for strength, function and construction altogether and generally devoted less time to the teaching of science. Their discipline was —and continues being— Art, with a capital A. Their teaching and learning methods have not changed much since the time of fine-arts schools. Their methods focus on design: first in the classroom and later in professional studios, in which there is always a "workshop" atmosphere and a craft-oriented relationship between master and apprentice.

Until the Renaissance, all construction professionals had professed to belong to a single trade. After engineering schools were created, their paths began to diverge. Faced with the need to specialize, the engineers and architects permanently split up. Modern-day builders could not be "Renaissance men" even if they wanted to, simply because the amount of knowledge, and its degree of sophistication, has increased so much that a single person cannot be an expert in every aspect of construction.

Are we condemned, then, to make a radical choice between these two types of teaching and learning: the scientific approach, typical of engineering schools, and the design-based approach, typical of architects? As engineers, we must learn that practical experience is also a source of knowledge and we must also be aware of the architectural significance of our works in the landscape. Architects, on the other hand, must learn that, in a world governed by the laws of physics, only scientific knowledge can provide successful structural solutions to major new problems.

What can be done in the field of teaching structural engineering? Pier Luigi Nervi, one of the greatest structural engineers of the twentieth century, and also an architect, provided an important clue: “We must increase the static and aesthetic sensitivity of our students” (Nervi 1956). This powerful idea may well help us to devise a set of guidelines for innovation in teaching structural engineering.

FALL INTO DECLINE OF TRADITIONAL SYSTEMS. CURRENT SITUATION.

However, in spite of Nervi’s stated opinion, current education systems do not promote an increase in either the static, or aesthetic, sensitivity of our students. In 1989, the Institution of Structural Engineers (IStructE) published a report (IStructE 1989) in order to encourage the improvement of teaching of structural engineering with respect to qualitative analysis. The main problems that exist within structural engineering education are the same problems that exist in all of the technological subjects within the broader civil engineering curriculum. Although there are specific education problems in each country, there are some common features that prevail all around the world, even within different education models.

Nowadays, companies are demanding a type of civil engineer that is not the one created by our current education systems and there are several surveys which confirm this fact (Robertson 2002; Russell and Stouffer 2005; Bernold 2005). Students are required to have certain skills, such as communication, teamwork, innovative thinking, critical thinking, creativity, design capability, which are not developed with the traditional education systems. Many recent graduates are incapable of formulating creative solutions to problems they have never seen before; therefore, they do not have the ability to solve "real world messy problems" and open-ended problems. This situation has been described by several authors (Bordogna 1998; Russell et al. 2000; Koehn 2001; Nehdi 2002; Schneck 2002; Teng et al. 2004; Bernold 2005). The pragmatic 'know-how' approach, typical of a British, or U.S. education, and the scientific 'know-why' approach, typical of a continental European education, are, independently, not enough.

There are several key problems in the present curriculum of civil engineering: (1) all the basic and scientific subjects are concentrated in the first courses, and the absence of technological and design based subjects in the first courses is the cause of many dropouts who could have become good engineers; (2) many subjects are completely unconnected with the rest, and the relationship between all of them are not appreciated until the end of the studies when the students have to complete their first design project; (3) practical, technological and design based subjects have lost weight in the studies; (4) the curriculum has not been designed taking into consideration what a recent graduate needs to know to be successful in the workplace, rather than on what the teachers want to teach; (5) curricula are full of subjects and there is no more space for anything else (Griggs 1997; Bordogna 1998;

Jennings 1998; Russell et al. 2000; Roesset and Yao 2002; Bernold 2005; Russell and Stouffer 2005).

In addition, the type of academic that succeeds within the present university system is not necessarily the type of teacher that is most suited to molding the best civil engineers. Presently, the successful academic is focused on research rather than on teaching; they seldom have little practical experience and are not necessarily interested in the real/practical issues facing today's civil engineers. They develop research projects in profitable areas defined by agencies or governments and produce papers that are often not of interest to practicing engineers. In addition, many such academics instruct their students as though they were to become academics, or scientists, rather than engineers. This situation, which has been denounced by many authors (Porter 1997; Liggett and Ettema 2001; Norton 2001), has been magnificently portrayed by Professor Roesset (Roesset and Yao 2000; Roesset and Yao 2002). In the background, there is a widespread problem: the lack of funding; and it is being solved by increasing research incomes and reducing teaching costs (Roesset and Yao 2000; Russell et al. 2000). However, universities and specific studies must prove their worth by means of accreditations given by agencies such as ABET in U.S., ANECA in Spain, and the future accreditation agencies for the European Higher Education Area (EHEA) that will be created soon.

Over recent decades, the civil engineering profession has lost part of the social prestige that it once had. Salaries have been reduced in comparison to other professions (Liggett and Ettema 2001), and in the U.S. civil engineering is not even considered a profession by the federal government (Lyons 2000).

Civil engineering curricula are being analyzed and are likely to be changed in both Europe and the U.S.; in the former as a result of the implementation of the EHEA (European Union 2003), and in the latter as result of attempting to correct the aforementioned situation (ASCE 2004). The length of the studies (4, 5 or 6 years), the nature of the degree (a unique civil engineer degree or several specialty degrees), teaching methodologies, course content, and the level to achieve the professional degree are being discussed. Many papers have been published about this matter. It is not the aim of this paper to analyze the whole situation and the various different options, but rather to demonstrate how civil engineering education in general, and structural engineering education in particular, can be greatly improved by means of new and innovative teaching methodologies.

EARLY INNOVATION

Thanks to the computing power of today's personal computers, the quality of pre-processing and post-processing programs and, especially, the graphic interfaces that have been developed, we can use computers as educational tools to help students visualize the behavior of structures. With today's structural-analysis programs, we can quickly change any parameter and see the new result. When it is used correctly, this function allows us to develop the static sensitivity of our students, as long as excessively complex models are not used. Some educational programs that have been developed (ED-TRIDIM 1997; Chou et al. 1997; Oreta 1999; El-Rimawi and El-Hamalawi 2003; Yuan and Teng 2003) can be very valuable tools for teaching basic courses on the theory of structures.

Major business schools are very proud of the "case-based" teaching method, which they believe they invented. In fact, architecture schools —and to a lesser extent, engineering schools— have been using the case-based teaching method for centuries. In our field, this method simply consists of engineering design problems and exercises. A specific problem is put forward; students seek primary data, study several solutions, choose the best option and develop it almost to the very last detail. Additionally, if students are required to defend their work before a committee or make corrections in public —as architects do— this creates opportunities for transferring knowledge and for improving communication skills. The degree to which the learning system is organized around design problems may vary greatly.

Traditionally, all civil engineering programs have a compulsory subject in the last year which is a design project. In each country, it has its own name, “Capstone Project”, “Group Design Project”, “End-of-studies Project (ESP)”, etcetera, but the aim is always the same: synthesize, integrate and apply the knowledge and concepts learned throughout the entire course of the studies by means of completing a real civil engineering project. Recently, the “Research Dissertation” has appeared in some civil engineering programs in different ways: in some cases, it is elective; in others, compulsory; and even in other cases, it has replaced the ESP, which is really worrying.

In the Civil Engineering School of Barcelona (UPC), besides of the compulsory ESP, students can choose between a research dissertation and a specialization project. The research dissertation acts as an introduction to research. In both cases, students are supervised by a tutor. Students who like design are thus given two opportunities to acquire knowledge in this discipline: the ESP and the specialization project. In practice, however, most lecturers propose theoretical topics for the research dissertations and only 5% of students choose to do a specialization project (Aparicio 2002).

During the 1997-1998 academic year, linked to the Consortium Linking Universities of

Science and Technology for Education and Research (CLUSTER), the first author of this paper was involved in an innovative experience of combined ESPs between civil engineers and architects at UPC. The ESPs were carried out by two-student groups: one from architecture and one from civil engineering, and were supervised by three professors: two from architecture schools (Lausanne and Barcelona), and one —the first author— from a civil engineering school (Barcelona). The first author of this paper and the students found the experience very enriching. The architecture students felt confident in proposing ideas, because the engineering students took these ideas up and discussed or gave shape to them. The engineering students were enriched by their partners' point of view —focus on aesthetic and architectural aspects— and reflected on aspects of the design process that had never though about before. Because of the engineering students' concern for contractual and construction-related aspects, the architecture students discovered a world they thought did not influence them. The experience was not repeated subsequently because the architecture lecturer from Barcelona felt that the work completed in six months was insufficient and that his students' ESPs should involve a heavier workload. However, the main outcome of this project was the positive experience that both the architectural and engineering students gained through their mutual interaction.

Other innovations in teaching structural design have been developed by other authors by means of designing and testing models in the laboratory (Glynn and Fergusson 1994; Romero and Museros 2002; Unterweger 2005) and even building a footbridge (Elazouni and Raslan 2003).

However, a great innovative step in teaching can be, and in fact, has been, accomplished if knowledge management, cooperative learning (team work) and new teaching technologies are implemented in the learning process.

Knowledge management is one of today's hot topics among business-management professionals. Dutta and De Meyer (Salazar 2003) define knowledge management as “people's ability to understand and manage information by using technology and sharing knowledge”. Other experts define it according to its different stages: identifying accessible knowledge, selecting useful knowledge, storing information in a structured way, transferring and using the knowledge created and, finally, storing the knowledge created. All of these aspects of knowledge management should be of interest to university lecturers as they offer many perspectives for us to reflect upon. We currently do many of these things intuitively and systematically, but not all of them. When our students work in groups, why not treat each group of students as if it were a department within a company? In such a scheme, each team, or group of students, would obtain (at their level) new knowledge that could be transferred to their co-workers, use the knowledge created by the whole group and store the information in a structured way. The organization of the groups, the type of work done, the way the knowledge is transferred to the rest of the group and how it is stored could —once devised, tested and implemented— lead to new teaching methods in the future, thereby creating a more participatory teaching method and increasing the returns on the same level of effort.

Another hot topic is the application of new technologies to teaching. Many lecturers have adopted new technologies without much reflection, doing little more that changing from using transparencies and slides to using video projectors and PowerPoint. Many academic authorities —especially managers— dream of replacing teaching staff with DVDs that teach perfect classes. Universities’ financial deficits would disappear and the surplus could be allocated to budget items for service staff! Jokes aside, new technologies are simply new tools. They are no different from current teaching techniques unless they are used to increase interactivity with students. What is the difference between a collection of transparencies handed out to students on paper, with text and diagrams, or even a book, and a CD that has the same text and diagrams in a PowerPoint presentation? The answer is almost none, except for the fact that today's students are more attracted to the computer format. Nevertheless, interactive DVD lessons with exercises and an online marking system do help students learn. One advantage of such materials is that all of the technological innovations in a discipline can be incorporated quickly and cheaply. Furthermore, the intelligent use of new technologies in teaching will help students learn and will make distance learning more feasible.

THE GREAT INNOVATION: THE IMPLEMENTATION OF PROJECT-BASED AND COOPERATIVE LEARNING METHODS IN TEACHING STRUCTURAL ENGINEERING

In this section we will explain what we have done in the Civil Engineering School of Ciudad Real, Spain. Following a thorough bibliographic review of the main international journals of engineering education, the authors have no record of the existence of any comparable experience teaching structural design.

The School of Civil Engineering of Ciudad Real has an ambitious and innovative educational program. The School’s key aims are the following:

- It attempts to prevent ‘dropouts’.
- It emphasizes learning rather than teaching with a learning process that focuses on

students.

- It has a small number of students per course (50 new students per year).
- This new School (first graduation in June 2003) aims to provide the labor market with engineers whose training is more oriented towards professional practice. Its goal is to produce engineers trained to design infrastructures, solve real-life problems and show greater sensitivity toward regional and environmental issues.
- The School aims to train highly skilled professionals who are fully competent when they enter the labor market. Project-based learning (PBL) and cooperative learning (CL) are used in several subjects to encourage students to acquire professional competence by solving problems similar to those they will face in their professional careers. In Spain, students acquire professional competencies when they graduate (universities themselves grant the professional degree, and there is not a PE exam for graduates as in U.S. or in U.K).

The degree courses consist of five academic years, each of which is divided into two terms lasting four months each. The teaching load for a degree is 3800 contact hours. More than 20% of the contact hours (800 h) are spent on projects, of which there are a total of seven: two projects in the second, third and fourth years and one ESP in the fifth year. In all of the projects PBL and CL are used, so a course explaining how to work with them is given to students when they join the school. The first two projects (for sophomores) are less ambitious and more limited and guided, whereas the last two ones (for seniors, fourth course), before the ESP, are closer to real projects. The projects grow up parallel to students' multidisciplinary knowledge. In addition to these projects, in order to enhance the freshmen's engineering introduction, four strategies have been developed: the introduction, in the first course, of subjects that are not traditionally included (such as material technology, geology, topography, and cartography); whenever possible, all of the proposed problems in base subjects (mathematics and physics) are focused on civil engineering applications (and this fact has meant an extra effort for non-engineering lecturers teaching these courses as well as a close collaboration between non-engineering and engineering lectures); the inclusion of many laboratory tests and the undertaking of extensive fieldwork (topography, geology, physics, and materials); and two several-day trips (one per term) to visit construction sites are completed (these types of trips are scheduled into all of the courses).

The first project in the fourth year is part of a subject called “Structural Project: Outstanding Building or Bridge”, which was designed and planned by the first author of this paper. To the subject, he brought his extensive experience as a full professor (training future engineers at UPC) and as a professional (designing structures and bridges). The second author has taught the subject since its inauguration and has previous experience in bridge design in practice. The experience so far —five academic years— has been very interesting. We shall now describe the conceptual and organizational aspects of the subject at length.

The subject is taught during the first semester of the fourth year in three-hour classes, three times a week. This makes a total of 120 contact hours. In the same semester, the students also take the ‘Structural Technology II’ course, which is a basic course in steel structures and structural concrete (95 contact hours). Together, these two classes make up 65% of the contact time for the semester. The idea of immersion in a subject area has previously been exalted (Griggs 1997). At the beginning of the year, the students' structural knowledge is limited to that acquired from the subjects: ‘Theory of Structures’ (a second year course with 90 contact hours that covers the strength of materials) and ‘Structural Technology I’ (a third year course with 75 contact hours that covers matrix analysis of structures). They also have a reasonable degree of familiarity with both a commercial structural analysis program and a computer drafting program.

The main educational goal of the ‘Structural Project: Outstanding Building or Bridge’ subject is clear: to help students acquire the knowledge and skills they need to design and construct bridges and buildings. At the end of the course, they are expected to be able to imagine a structure, select the material, draw it geometrically, carry out a structural analysis, verify it, make the appropriate adjustments and submit a project that consists of four documents: 1) a report of the project, with calculations attached as an appendix, 2) structural drawings, 3) the main technical specifications of the structure, and 4) a list of costs of principal items and an estimated budget. The structure of the documents that the students submit is similar to that of real Spanish engineering projects, which consist of the same four documents. During the course, students are expected to put a lot of effort into the first two documents, while less is expected for the last two. This is because the students take a subject the following term that focuses on the skills and knowledge required to develop the last two documents. Students carry out the project in groups of up to three people. In the presence of their classmates, they publicly present and defend their project before a committee that includes the lecturers who teach the ‘Structural Technology I’ and ‘Structural Technology II’ subjects and a full Professor from another civil engineering school in Spain.

The unofficial goals of the course are more ambitious. To paraphrase Nervi, we aim to educate the static sensitivity of our students, awaken their aesthetic sensitivity, train them to work in groups, improve their communication skills through working in groups and having to present their ideas and defend their decisions, and use group presentations as a means of transferring knowledge between the students. In addition, the requirement to present their ideas and to disseminate their results enhances their learning as teaching others is the best way to learn (Elshorbagy and Schonwetter 2002). We have also worked on the format of the presentation and the documents the students submit to the lecturers and their classmates, which act as a record of the knowledge they have obtained.

The subject is divided into four basic educational areas:

1. Classes on concepts, technology and structural analysis of prestressed concrete.
2. Classes on buildings and bridges: types of structures, structural behavior, design criteria, and specific construction means (there is also a whole subject in the fourth year, with 90 contact hours, devoted to construction means and sites).
3. Students' presentations of the *course exercises* (on prestressed concrete, buildings and bridges) after being carried out.
4. After the design topics have been defined, students and lecturers attend *design workshops*. Students also attend tutorials and take a final examination that involves giving a presentation, which is considered as an additional educational tool.

Thus, the classes are taught in two different spaces: the fourth-year classroom, where the lectures are given and the students give their presentations, and the fourth-year design room, where the course exercises are carried out and the project workshop sessions are held. The fourth-year classroom has a blackboard, an overhead projector, and a computer with a projection system. The design room has a computer and some tables for each group, networked printers, a plotter and a technical library (with codes, guidelines and over two hundred catalogues of technical products).

How can students in the first semester of their fourth year be expected to complete the design of realistic structural project when they only have a limited theoretical knowledge of structural analysis? The secret lies in several key aspects: 1) total coordination with the 'Structural Technology II' subject; 2) the work of the students on finding solutions to the course exercises, which enables them to draw conclusions and define criteria that can be applied directly to the design; and 3) transference within and between groups of the knowledge that is attained, which "multiplies" the knowledge acquired. We shall now explain these three aspects in detail.

As mentioned above, 'Structural Technology II' is a basic course in steel structures and structural concrete. Teaching the two subjects together makes them more concise, because limit state theory and structural safety theory have to be explained just once. Furthermore, prestressed concrete and reinforced concrete are covered together, as is the treatment in modern codes. This issue has been the subject of much academic debate. However, we feel that this teaching method is inappropriate for undergraduate courses, because a historical approach is the best possible way of introducing students to new concepts, such as prestressing. It is very interesting to point out the attitudes inherent to prestressed concrete (active) and reinforced concrete (passive) and then to compare them to the intellectual attitudes of the structural engineer (active and inventive) and that of the structural analyst (passive and routine). When Stephenson assembled the spans of the Britannia Bridge (Beckett 1969), he managed, once they were joined, to lower the supports and to change the bending moment diagram from that of a simply supported beam to that of a continuous beam; in doing so, he was interacting with the structure in a very proactive way. To calculate the deflection in the load test, he hired a mathematician. If the history of the great engineers and their major achievements were well known, we would be better placed to approach our current problems. This approach gets students' attention and makes them reflect. Furthermore, prestressed concrete has its own technology, which students must be familiar with before they can use it. Therefore, whilst the ‘Structural Technology II’ lecturers are making progress in their subject, we present the concept, technology and structural analysis of prestressed concrete, which does not require the students to know much about concrete, just the bare essentials. If the students grasp the principles of prestressed concrete and reinforced concrete sufficiently well, this provides them with all the conceptual criteria they need to understand the responses of these materials in ‘Structural Technology II’.

The *course exercises* are another key aspect of the course. These exercises are carried out in the first few weeks of the term and have two goals: developing students’ static sensitivity and training them to carry out computer-aided structural analysis. Students are asked to consider four topics (two on prestressed concrete, one on buildings and one on bridges) and there are as many different exercises for each topic as there are groups. The aim of the sequence of questions in each exercise is to take the students through the different topics, and the last question is always the same: “Draw some conclusions that you feel would be useful in designing this type of structure.” This is a guided means of acquiring new knowledge from the exercises, which always deal with real-life cases. Such knowledge is essential for the project students will work on later.

The following are the topics and exercises proposed:

- Topic 1 is Structural Analysis of Prestressed Concrete I. The goal is to teach students to calculate the internal forces due to prestressing in statically determinate and indeterminate structures (bridges with internal prestressing, with external prestressing; water tanks; prestressed flat slabs; etc.)
- Topic 2 is Structural Analysis of Prestressed Concrete II. The goal is to teach students to quantify the real value of prestressing, taking into account instantaneous and time-dependent losses, and its effect on the structure.
- Topic 3 is Building Structures. The goals is to allow students to reflect on the way different structural systems used in building construction respond to vertical and horizontal loads.
- Topic 4 is Bridges and Footbridges. The goal is to make students reflect on the way different types of bridges respond to vertical and horizontal loads.

In all of these exercises, students use a commercial structural-analysis computer program. Bit by bit, they learn to model structures; they become acquainted with the order of magnitude of the loads, the actions to be introduced and the codes to be considered; they learn to interpret results in physical terms and to adjust these results to prevent what have been referred to as “Computer-Aided Disasters”. In short, they learn mechanisms and develop techniques for checking the suitability of the results offered by the computer. They are encouraged to use simple models rather than complex ones and are given guidelines on how to present results.

Each group presents the exercises they have completed in class. By setting a surprise exam —with very good results— we have verified that the students learn just as much from the exercises carried out and presented by their classmates as from their own work.

About halfway through the course, the students feel confident with structural analysis and begin to understand structural behavior. By then, they have seen the most common structural types and morphologies of building structures and bridges and are a good way into the ‘Structural Technology II’ subject, so it is time to present the design topics.

As mentioned above, there are as many projects of building structures, bridges and footbridges as there are groups in the class. The buildings are defined by drawings of architectural plans and sections and a geotechnical report. Existing buildings are always used, but if they are very complex we simplify certain aspects or set limits for the project. The bridges and footbridges are defined by the plan, elevation, survey and geotechnical report, and situations that could lead to complex construction processes are avoided (for example, a cantilever construction of a cable-stayed bridge would be analyzed without taking into consideration time-dependent effects during construction, but warning students about the simplification). In at least two projects for each topic, different materials or types of structures are imposed. The lecturers present the topics in class and the groups then choose which topics they prefer. Priority is given to those who received the highest marks in the course exercises. In this way, the students know from the start that the better their marks, the more likely they are to be assigned a project that interests them, and this, in turn, increases their motivation.

After the design topics are assigned, most of the second half of the course is held in the design room, where students work under the supervision of the lecturers who teach this subject and the lecturers who teach ‘Structural Technology I’ and ‘Structural Technology II’. Experience tells us that one lecturer is needed for every five groups of three students and that groups of more than three students are hard to control (groups and lecturers have problems making sure that all group members contribute equally to the project). The students obviously need to work outside of class time to complete the project, which they generally do at the School and in the design room (24 hour access is provided by means of security guards).

At the end of the term, students hand in their projects to the lecturer one week before their presentation, which acts as the final examination. Presentations take place over two full days (morning and afternoon sessions). Students must attend all presentations. The examination is thus designed to be yet another educational activity —a very important one— in which the students see their classmates' designs and compare them to their own. They learn many new things and have the chance to see applications of all the knowledge acquired in ‘Structural Technology I’ and ‘Structural Technology II’.

After the course has ended, the competition for the “Government of Castilla La Mancha” Prize is announced and only the three projects receiving the best marks are invited to participate. The prize is sponsored by ACCIONA (a major construction company). The selected groups present their designs once again; this time to a committee that includes the lecturer of the subject, a representative of the regional government and a representative of the sponsoring company. The prize is awarded at a formal ceremony in the presence of the rector of the university and representatives of both local and regional authorities. Again, this esteemed opportunity is another element of the course design that is included to motivate.

The results obtained over the past five years have been very good for all the parties involved: students, lecturers and companies. When the subject ends, the students respond anonymously to a questionnaire (in addition to the one that the University carries out) with questions addressing a wide range of aspects relating to the course (methodology, structure, level of interest in the coursework, level of interest in the proposed projects, attitudes and skills of the lecturers, skills and knowledge acquired, etc.). The results of this questionnaire are unanimously positive. The students feel that they have learned a lot in a short time in a very interesting and motivating way. They also unanimously recognize the extent of their own efforts and the responsibility they have taken on as part of the learning process. The lecturers also have a high opinion of the course. We enjoy teaching design: design is part of our professional activity, in addition to the teaching and research we carry out at the university. However, we are aware that lecturers must make much more effort that which is required if one adopts more traditional teaching methods (search and preparation of new appropriate projects; coordination; search and preparation of "ad hoc" materials necessary for the students while they work in their specific project; tutorial times and office hours are completely used by students; reading and grading different projects and different course works; two-day exams; and so on). This fact has been remarked upon by other authors with PBL experiences (Johnson 1999; Padmanabhan and Katti 2002; Chinowsky et al. 2006). Companies, which, after all, will be hiring these future engineers, have shown a lot of interest in our school's educational framework. They offer the students summer internships and then recruit them when they graduate. At the companies, the students verify the good design skills and real-life problem-solving abilities that they acquired through exposure to this teaching method.

In terms of learning, the results of this teaching method are superb, but extra costs, when compared to more traditional approaches, must be considered: more materials (design rooms, computers, software, and 24-hour access) and human resources (a high lecturer/student ratio, a small number of students in each year and lecturers who have professional experience in design). Syllabuses must be organized around the method (subjects with many contact hours, long class sessions, and effective coordination between different subjects). We must also be aware of the greater efforts required of both students and lecturers. The very high-level learning attained through the use of this method is incomparably greater than that attained through the use of more traditional teaching methods. Even if we take into consideration the additional effort required, when we compare the two approaches in terms of “learning efficiency” (i.e. the ratio of the amount of students’ achieved learning to the effort required to obtain it), this method is considerably better —i.e. with a higher learning efficiency—, and constitutes a substantial improvement in the efficiency over traditional teaching methods. When time is a limited resource, and this is the case, it is necessary to make time highly profitable using the most efficient learning methods.

THE FUTURE

We are presently within a period of change. The creation of the EHEA requires that the European university education systems converge on a unique system. The immediate future of engineering education throughout Europe will be determined by how well the current education systems in each country adapt to the recent European directives. Besides this, there is another significant reason to think about the need to improve the education systems: In both U.S. and Europe, Civil Engineering should achieve a high level of education in our universities in order to form the best civil engineers with the necessary knowledge and skills to carry out their work with the quality levels that society and companies are already demanding.

Under the new European system, engineering education will be organized in three cycles: undergraduate, master and doctoral degrees. It is just the system used in U.S., and in all the countries which followed the British and U.S. tradition. In Europe, the four-year undergraduate degree programs will be very market-oriented. It is not yet clear what level will be required to obtain the professional degree. In Spain, ten years ago, it was a six-year degree; nowadays, it is a five-year degree; and it is currently being discussed as to whether or not a four-year degree can be the level required to achieve the professional degree. In U.S., the four-year degree has been the level to achieve the professional degree, but ASCE has claimed that it should be the master degree (ASCE 2004). It is time to discuss, and reconsider, the current education system for civil engineering in its entirety: the length, the contents, the degree, the level to achieve the professional level, the type of civil engineer demanded by the society, the methodologies, and so on.

What teaching system will adapt better to the times: the traditional European system (focus on why), the traditional British and American system (focus on how) or an innovative system (merging both traditional conceptions with the most innovative education models), such as that described in this paper? Can generalist engineers be trained in just four years? What is a generalist engineer? One who knows everything or one who is ready to learn everything? Four years, and even six years, doesn't seem long enough to “learn everything”. Life long learning seems to be the only way, and the project-based learning system can be a great tool for producing excellent engineers for the labor market.

In the medium and long term, the future of engineering education will involve training lecturers to be true *teachers* of engineering, which is not necessarily as self-evident as it seems. In recent years, Spain has implemented policies aimed exclusively at encouraging research by teaching staff at universities, which in some cases has led them to neglect their educational responsibilities. Unfortunately, this is a worldwide problem (Roesset and Yao 2000). Everyone agrees that one mission of modern universities is to create new knowledge, which requires research. However, we must not forget that the primary mission of universities is to transmit knowledge, not only that which we develop ourselves, but also that which is handed down by our predecessors, which is always superior to our own. The recruitment of teaching staff must not be based exclusively on research experience, as it is also extremely important to make sure lecturers are trained to be good teachers. Quality teaching is only possible when the lecturers are dedicated enough, when they are able to prepare good classes and when they pay attention to students. Above all, lecturers must be engineering teachers, not specialists in research topics financed by governments or agencies at any given point in time. The staff recruitment process for a lecturer post should require the assessment and consideration of the applicant’s engineering experience and training, not just in the field of research, but also in practical design and in teaching; therefore those who judge these applicants should also have similar, or comparable, experience. It is impossible to overcome the actual problem of civil engineering education if the type of lecturer appreciated by the university system is the one who is only focused on research and remains distant from the real aspects of civil engineering. Lectures with professional experience are essential for a teaching model such as the one we actively offer and presented here in this paper.

CONCLUSIONS

There are many opportunities for innovation to be introduced into the teaching of civil engineering and it is time to put them into practice in order to solve the current problems in civil engineering education. It is not a question of eliminating traditional education methodologies, but complementing them with the new innovative methodologies, making the most of both of them in order to form the best possible civil engineers for the future. Teaching structural design, organizing learning process around and by means of projects (PBL), promoting team working (CL) and implementing knowledge management, has a lot of advantages (development of static and aesthetic sensitivity; development of design capability working with "real world messy problems" and open-ended problems; development of connections among the different subjects involved in the structural project; acquisition of technological knowledge; increase in student motivation; improvement of communication and teamwork skills; development of innovative thinking, critical thinking and creativity; and use of the multiplier effect of knowledge management and transference). We have confirmed all of these potential benefits during out practical experience at the Civil Engineering School in Ciudad Real, Spain. Organizing the learning process, and indeed, the entire structure of the civil engineering degree, around projects creates an educational environment far more conducive to producing quality 'real-world' engineers that cannot be compared to simply appending a capstone project to the end of a traditional degree. These new methods can really help improve our future engineers' training efficiency, thereby making it possible to train high-quality marketable engineers at our universities. The new methods will also be a magnificent teaching tool for use in graduate courses as well in professionally-oriented-masters courses. It would be a serious mistake to miss this opportunity to systematically implement these new teaching methods in technical disciplines, such as structural design, in all our civil engineering schools. But let us not forget that quality civil engineering education is only possible when lecturers are well trained in real civil engineering and dedicated to their work as teachers.

In addition, the way of teaching structural design that we have shown in this paper fits perfectly with the new directives established in Europe (European Union 2003), and especially in USA (ASCE 2004), for the education of tomorrow's civil engineers. The ideas that have been provided in this paper and the way they have been tested will help to shape and put into practice the required answers to the ASCE's questions "What Should be taught and learned? How should it be taught and learned? And who should teach and learn it?", especially in the field of structural design.

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