A STUCTURES CURRICULUM FOR THE 21st CENTURY

By

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ABSTRACT

The complexity of the analysis of structural systems to assess their ability to carry the environmental loads led to (1) the development of a variety of computational procedures, and (2) an undue emphasis on analysis in engineering education. Yet the determination of forces, stresses or displacements in a mathematical model of a specified structure under a given set of loads, is the least creative part of the design process. The advances in computational capabilities inherent in digital computers have made many of the analysis procedures obsolete. However, they have also led to their replacement by more modern procedures lacking any physical insight. As a result many civil engineering graduates specializing in structures today have great proficiency in the use of computer software but little knowledge of structural behavior and lack the ability to estimate the order of magnitude of the expected forces or displacements. What is ironic is that the developments in computer technology should have allowed us to put more emphasis on the creative, conceptual, parts of structural design. In this paper we look at the material that should be covered in a structures curriculum to teach structural design and behavior while taking full advantage of today's available technologies. We want to emphasize the need for course continuity and integration, the importance of early exposure to real structures, the increased use of case studies and visualization programs, and the development of creativity in engineering education. At the same time it is necessary to expose the students to the new demands of society (the need to maintain, retrofit and rehabilitate a vast existing infrastructure in addition to designing new structures, which is not being taught in most American universities), and new technologies that will change the way we design structures, with the ability to monitor their performance and control automatically their behavior.

INTRODUCTION

The many education conferences, workshops, and sessions on engineering education that have taken place over the last two or three decades seem to indicate some degree of dissatisfaction with the way we are educating civil engineers. The advances in computation and information technologies have affected significantly the role that civil engineers will play in the future. As a result, the material they should be learning must also change. Yet in most universities the curriculum has changed little over this period of time, with only piecewise modifications to some specific courses, and without a

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comprehensive redesign of the overall process. It has been said by some that universities do a good job at teaching basic science and engineering fundamentals (particularly theory) but not at forming true engineers, a statement that is not without merit. It seems in fact that the so-called 'research' universities are primarily interested in creating researchers and teachers rather than professional engineers, with the attention of the faculty devoted primarily to doctoral students and to cloning themselves. As a result many major companies have now their own one or two years in-house training programs to teach their new hires what they should know to be successful professional engineers in practice. The fact that universities could not teach all the details needed in practice (some of them peculiar to each individual company) and that the education of an engineer must be continued on the job and for life has long been recognized. It has also been commonly accepted that universities should concentrate primarily on the rigorous coverage of material that engineers will not acquire from everyday exposure to practice (Hsu, 2003). The present situation goes however well beyond this recognition with students learning material that is often obsolete and that has become increasingly abstract and removed from reality.

As pointed out by Eduardo Torroja (1957) the design of a structure requires the consideration of: its ability to perform satisfactorily and aesthetically its intended mission or function; its capacity to withstand safely the environmental actions to which it may be subjected during its lifetime; and the possibility of building it at an optimum life cycle cost consistent with the available resources. The design process has to satisfy therefore functional, aesthetic, strength/performance, construction and economic requirements. In this process it is necessary to select first a geometric layout compatible with the functional requirements, a structural type that fits the geometry and that is aesthetically pleasing, and one or more materials appropriate for the structural type and the geometry. It is also necessary to assess what are the types and magnitudes of the actions to which the structure may be subjected and how it will respond to these actions. One must finally select the dimensions of the different components and the most appropriate construction plan. This is an iterative process in which more than one structural solution may be explored, modifications are introduced and the effect of different arrangements on the construction sequence and cost are investigated. Unfortunately the complexity of the calculations involved in the determination of the forces acting on the different members, and the resulting deformations and displacements, limited sometimes the possibility of checking alternatives, and placed an undue emphasis on the verification of the strength requirements, the least creative part of the design process. To make things worse, with increasing specialization there has been a continuous disintegration of the structural design process: the determination of the forces acting on the members and the computation of the stresses due to these forces (the last step of the analysis), comparing them to allowable values given by the appropriate codes or standards, and selecting the required member dimensions, became two separate, independent activities, the first one being labeled analysis and the second one design. The design of the structure and its foundation became two separate, independent activities performed by different persons, often with little communication between them. Finally the design process was separated from the construction planning, leading structural engineers to design structures without any consideration of how they were to be built (or whether they could be built at a reasonable cost) and to the creation of a new word: 'constructability'. This situation has been reflected of course in our engineering curricula, tending therefore to perpetuate itself. The design of foundations is now specialized and separated from structural engineering. So is the construction planning and management.

In this paper we look first at how the structural component of civil engineering curricula have evolved over the past 50 years or so. We discuss next what should be in our opinion a logical structures curriculum for the 21st century, taking advantage of the new tools available for teaching and in engineering practice. We look finally at some of the new emerging technologies that are likely to impact the way we design or maintain structures. These are topics to which, in our opinion, students should be exposed.

HISTORICAL EVOLUTION OF STRUCTURAL CURRICULUM

Spain 1950s.

When the first author was in college as a student, in the mid 50's, there were no electives and all civil engineering students were required to take the same courses. These had all nine months duration. The teachers were all professional engineers selected because of their reputation and accomplishments in their specific fields. They gave the lectures and left the university immediately after. There were neither faculty office hours nor opportunities for consultation. Students were responsible for learning and understanding the material on their own, which required more work on their part but ensured probably better grasp of it in the long run. In addition to the basic courses on classical mechanics (statics, kinematics and dynamics), the structural part of the curriculum included: a course on Structural Analysis and Theory of Elasticity; courses on Reinforced Concrete and Steel Structures (one of each); separate courses on Building Design, Design of Bridges, Harbor Design and Design of Dams; a course on Conceptual Design with 2 preliminary design projects; and a Design Project course where each student was required to define the functional needs, select an actual site, do a preliminary design, verify that the functional requirements were satisfied, perform the analysis and dimensioning, check code requirements, plan the construction and submit cost estimates. Students were also required as part of the general curriculum to take a course on Soil Mechanics and Foundations. Courses on Prestressed Concrete and Plates and Shells were added in the late 50's.

United States 1950s and 60s.

In the 50's and 60's in the United States most faculty members were full time employees of the universities spending the complete day at the office when not teaching classes, doing research or in meetings with students. Most of them, however, had several years of professional experience, either before they decided to go into teaching, or later through consulting work. Some universities started to have around this time professional engineers teaching some design courses as Adjunct Professors, complementing the regular faculty. It was still common for full time faculty members to have an open door policy so that students could go and ask questions essentially at any time. At the University of Illinois, where the second author was a student, and many other institutions there were several options and therefore a core of required courses and many electives. However, most students took the structures option. The structures requirements in the curriculum varied widely from one institution to another, something that is still true today. The duration of the courses was a semester (actually 4.5 months) in some institutions and only 3 months (a term) in others. At one extreme all civil engineering students may have been required to take, in addition to the basic coverage of statics and dynamics in the first Physics course, only a course on Strength of Materials (or Solid Mechanics), a course on Structural Analysis, a course combining reinforced concrete and steel design, and a capstone design course that involved a complete design. All students would also have been required to take a course on Materials and a course on Soil Mechanics. Students specializing in structures could then take a variety of electives, including courses on Advanced Structural Analysis, Theory of Elasticity, Plates and Shells, Steel Design, Concrete Design, Experimental Design, Numerical Methods, Structural Stability and Structural Dynamics. Some of these courses were often graduate offerings but they were open to undergraduates. At the other end of the spectrum the requirements of all students may have been: a course on Engineering Statics; a course on Engineering Dynamics; a course on Strength of Materials; a course on Structural Analysis; a course on Reinforced Concrete Design; and a course on Steel Design; as well as a capstone design project. All students may have been also required to take a course on Materials, a first course on Soil Mechanics and even in some cases a course on Foundations. The electives for structures majors may have involved a second analysis course (titled Advanced Structural Analysis or Indeterminate Structures), second courses on Concrete and Steel Design, a course on Prestressed Concrete, and courses on Masonry and Wood design. All of these could have been undergraduate offerings, although in some cases they were graduate or very similar to other graduate offerings.

Strength of Materials courses covered typically simple statically determinate structures (trusses and beams), equilibrium of forces, shear and bending moment diagrams, stress distributions under axial and shear forces, and bending and torsional moments (for simple sections), Mohr's circle and Euler buckling. The first structural analysis course covered the determination of forces and displacements in statically determinate and indeterminate trusses, beams and simple frames. A large number of different procedures had to be covered: to find forces in trusses the method of joints, the method of sections and graphical procedures (Cremona); to find displacements in trusses the solution of the displacement equations in terms of elongations, virtual work, and graphical procedures (Williot-Mohr); to find displacements in beams the analytical solution of the differential equation (integrating over each segment between loads and imposing compatibility at the ends of the segments, or writing a unique expression in terms of singularity functions), conjugate beam, moment area, the column analogy and virtual work (or Castigliano); to solve statically indeterminate beams (including multi-span continuous beams) the direct application of the flexibility formulation (selecting redundants, writing compatibility equations and finding displacements), the slope deflection equations, and the three moments equation; to find influence lines the direct analytical solution and Muller-Breslau's method; to solve simple frames without and with sidesway the slope deflection equations, moment distribution (Cross) and Kani's method. Students were supposed to master all these methods. So-called reinforced concrete and steel design courses were devoted primarily to learning the various code requirements in order to select member dimensions. They were from that viewpoint dimensioning courses, dealing exclusively with the last step of the analysis. They did not cover any conceptual design and the implication seemed to be that the only significant factor in the design of any facility (buildings, bridges, dams, harbors, or power plants) was the material selected. At the first undergraduate level (when there were two courses on concrete and two on steel, and in some cases even when there was only one on each) the emphasis was in teaching how to use and follow the codes, making sure that students could perform efficiently routine computations and be of immediate use to industry upon graduation (some faculty members believed in fact that that was the mission of a university). When there was a second undergraduate course, or at the graduate level, the emphasis was on the reasons for the various code requirements. In this case the courses were more concerned with material and structural behavior than just with rules for dimensioning and their emphasis was more on educating than on training.

United States. 1970s to 90s

The launching of Sputnik in the fifties had a profound influence on engineering education and research in the United States. The first effect was to increase the science base of the curriculum providing a more rigorous and extensive education in Mathematics and Physics. This was a welcome change. However it was carried out unfortunately at the expense of the more practical knowledge that had characterized American engineers. At the same time engineering research, which had previously an important applied nature, trying to solve actual problems, started to become more abstract and general in an effort to produce papers with archival value. The value of the considerable amount of research that ensued cannot be denied, but again it was regrettable that this was accomplished at the expense of the more practical subjects. The fact that a primary source of funding for American universities and research is the National Science Foundation, that the mission of this government agency is to promote science, with only a relatively small engineering component, and the lack of a National Engineering Foundation that might have provided a balance, aggravated the situation. Over the last half of the 20th century universities switched from being primarily educational institutions, where research was conducted as part of the educational process, to become 'research' universities, where research was the primary goal. The emphasis was on graduate education, and particularly that of Ph.D. students who would contribute to the research effort, and faculty had little time for undergraduate students. The open door policy disappeared from many universities and was replaced by a few office hours. If students had a conflict (like other classes) at those times, they had no possibility of consultation with the faculty member. One faculty member pointed out that this was the price students had to pay to attend a 'research' university! The importance of the amount of research funding generated in some of the rating systems of universities, and the very large bureaucracy that had to be created to handle the research grants (particularly when federal funds were involved), made universities increasingly dependent on research funds for their survival. A point was reached where research was no longer carried out as part of the educational process or to improve the state of knowledge, but it had to be conducted to support the daily operation of the institution. Moreover where before faculty members could decide what was the needed and worthwhile research based on their own feeling and experience, the research topics started to become a mandate of government agencies (such as the NSF) through the recommendations of panels whose members might be looking primarily at the continuation of their own projects and areas of work. The result of this new emphasis on research, and particularly marketable research, is that faculty members are hired in most cases fresh out of school, upon completion of their Ph.D., and in some cases even before, without any practical experience. Their success at a university will depend primarily on the amount of research funding they can generate and the amount of papers they can publish in refereed journals over the next five years (in order to get tenure), and on a continuing basis for future promotions and salary raises. This leaves them little opportunity to learn about professional practice. As a consequence many universities in the States are having difficulty now finding faculty members who can teach design or construction courses and must have recourse to professional engineers as Adjunct Professors.

A second important factor affecting civil engineering education has been the ever-expanding breadth of activities of the profession and the creation of new fields whose members are anxious to become independent. With the increase in knowledge and the broadening in each of the traditional sub-disciplines (Construction, Hydraulics, Materials, Soils, Structures, Transportation) it became impossible to teach all the required subjects needed to be proficient in each one of them within a 4 year program. Even within each sub-discipline distinctions started to be made: in Structures, analysis and so-called design (codes) were considered two separate areas, both for students and faculty (the faculty in the former being engaged in theoretical research, that in the latter in testing and curve fitting); in Fluids a clear split occurred between the traditional hydraulics and hydrodynamics areas and the water resources field; in Transportation the distinction was between highway design and pavements on one hand and transportation planning on the other, and in some cases within the latter between supply and demand modeling. With the creation of Environmental engineering as a new specialty and one with substantial changes in basic requirements (more Biology and Chemistry than Physics) the situation got even more complicated. Many faculty members in Environmental engineering are not educated in fact as civil engineers. Specialization became a necessity, reducing the number of required courses and increasing correspondingly the number of electives. By the mid seventies the civil engineering department at MIT had only five required courses, and only one of them had any relation to Structures (a combination of Strength of Materials and Structural Analysis). Although most of the more traditional and conservative universities criticized this drastic change they all followed the same general trend over the next 15 years. The design courses were eliminated from the general requirements and in several cases students were not even required to take a soil mechanics course. Many programs made a clear distinction between the curricula for civil and environmental engineering as if the latter was not really a part of the former. This had already been suggested by the perceived need of many departments to change their name to Civil and Environmental Engineering. One had to wonder why not Civil and Construction, Geotechnical (the new name for Soil Mechanics), Hydraulic, Structures or Transportation Engineering. The fragmentation of the civil engineering curriculum was mirrored in practice with the creation of separate professional organizations for environmental, geotechnical, structural, transportation or water resources engineers. Even the American Society of Civil Engineers, that had provided a unifying umbrella, had to convert its divisions into semi-independent Institutes. Environmental engineers found that their interests were closer in many cases to those of chemical engineers and scientists in Chemistry than to those of civil engineers; geotechnical engineers decided that they would rather deal with geologists and geophysicists than with structural or transportation engineers; structural engineers working on mechanics (or engineering mechanics) have a closer interaction with some mechanical or aeronautical (aerospace today) engineers than with other civil engineers or even structural designers. And thus what was once a proud profession has been slowly but inexorably disintegrating. Or perhaps this is just a reflection of the fact that the engineering disciplines as established 100 or 200 years ago no longer respond to the needs of society and to the present realities, and that other groupings might make more sense today, an observation already made in the 60's by Gordon Brown, then Dean of Engineering at MIT.

United States. The 90s.

By the 90's many universities required at most one structures course (a course on Structural Analysis) from all civil engineering students, although some of them might still require the basic courses on Mechanics (Engineering Statics, Engineering Dynamics, and Strength of Materials, common to various engineering disciplines). Structures majors had still the same number of electives. The content of the courses had changed, however, substantially. At some institutions as part of a move to make the first two years common to all engineering departments, under a grant from the National Science Foundation, the basic mechanics courses were taught from the point of view of energy principles, without ever considering explicitly equilibrium conditions, or drawing free body diagrams (material that is apparently of no interest to mechanical, aeronautical or electrical engineers, but that is vital to civil and in particular structural engineers). Requiring all engineering students to take the same engineering science courses is all right. However, the approaches used in teaching these courses were wrong. This serious void in their background was clearly noticeable when they took the Structural Analysis course, and once the financial support from the National Science Foundation expired the courses reverted to their original form. Matrix structural analysis, the basis for all computer programs for structural analysis, was introduced in graduate courses in the 60's. It was followed soon after by Finite Elements as applied to Theory of Elasticity, Plates and Shells. Through the ensuing years the concepts of matrix structural analysis were introduced first in the second analysis course at the undergraduate level, then at the end of the first analysis course. Teaching matrix methods (sometimes referred to as finite element methods to appear more impressive) at the undergraduate level, and as early as possible, became a matter of pride, a clear sign of progressive thinking in the curriculum. By the late 90's even some textbooks intended for the first analysis course boasted of the fact that matrix methods were covered not at the end but from the beginning. Eliminating the teaching of all the approximate methods that were no longer used in practice and had become obsolete was clearly a welcome improvement, particularly when some of these methods were rather artificial and did not provide any physical insight. Replacing them entirely by mathematical formulations without any physical meaning where a structure becomes only an assembly of matrices to be manipulated in the computer was not a wise decision. Structural engineers must be able to understand and visualize how the applied forces are transmitted through the members of the structure to the foundation, and how the structure and the foundation deform under these forces. Even if the analyses are to be carried out in a computer, using software that is widely accepted and that has been calibrated, structural engineers have to be able to verify the adequacy (order of magnitude) of the results and to detect possible errors due to mistakes in the input data or in the modeling assumptions.

In response to the new concerns about engineering education and following the recommendations of various panels and committees there has been in the late 90's and the beginning of this century a welcome trend towards reemphasizing the importance of teaching at universities (even 'research' universities), and of design within engineering curricula. At MIT for instance there are now two distinct curricula, one in civil engineering, the other in environmental engineering science. Within the first one there are three different tracks: civil engineering mechanics, civil engineering systems, and environmental engineering. All students, irrespective of their track, are required to take 13 courses that include courses on: Project Evaluation, Solid Mechanics, Materials, Fluid Mechanics, Introduction to Civil Engineering Design, two laboratories (Solid Mechanics and Materials) and 2 design courses (to be selected from Engineering Systems, Geotechnical and Structural Design). Students in the civil engineering mechanics track must take in addition courses on Structural Analysis and Control, Geomaterials and Geomechanics, Mechanics of Materials, Mechanics of Structures, Mechanical Vibrations, either the Geotechnical or the Structural Design course if one of them was not selected as part of the general requirements, Project Management, and Mechanics and Design of Concrete Structures. We do not know what is the actual content of these courses but the fact that students in some tracks can take the Structural Design course without taking Structural Analysis or the Geotechnical Design course without any course on Geomechanics as a pre-requisite would seem to imply that the design courses involve some basic analysis. Even so what seems significant is that all civil engineering students are required to take three courses with at least the word Design in their title, and mechanics majors are supposed to take one or two more.

SUGGESTIONS FOR A STRUCTURES CURRICULUM

In the following we look at what we perceive as the main deficiencies of our present structures curricula, and we suggest some potential remedial actions.

1.) The first problem, in our opinion, is that most structural students today lack an understanding of the special characteristics of different types of structures: buildings, bridges, power and industrial plants, harbors, dams, offshore platforms, space stations. They do not know what are the functional requirements, the types of loads, or the particular problems that one must look for in the analysis and design of each one of them.

Furthermore they have little exposure to what are the different types of structural arrangements and foundations possible, or commonly used, what are their individual advantages and disadvantages, or what are typical dimensions (spans, member sizes, etc.). This is the result of the lack of conceptual design and specific design courses, and of the emphasis on member dimensioning to satisfy code requirements in present design offerings. Because engineering design firms have specialized and are concentrating on particular applications (buildings, bridges, plants, harbors, offshore structures) the idea seems to be that students should learn this material, and become specialized, in practice. Yet even in this case students should have a basic understanding of the ranges of application of various structural typologies, what types of solutions are being used now, or have been used in the past, the reasons for their selection or for discontinuing their use, etc. This is essential to develop and enhance their creativity as designers. As pointed out by Santamarina (2003) although some types of creativity (in artistic endeavors for instance) require innate talents, there is always a need to develop it through hard work and learning. Architects do a much better job at this than civil engineers and we should learn from them. Students should be exposed to real structures of all types in all their analysis and design courses, learning about them, what were the requirements, and why the given solution was selected.

2.) A second deficiency is the lack of training on how to convert a physical system, like a structure, into the most adequate mathematical model, in order to perform the analyses. When engineers had to perform the computations by hand they spent some time deciding the significant aspects of structural behavior that had to be considered and investigated, and the simplest possible model capable of doing it with acceptable accuracy. As Einstein stated the mathematical model should be as simple as possible but not simpler. The ability to do this was a characteristic of a good engineer. With the availability of computers and of large analysis software packages there is a trend to make the model as sophisticated as possible and to eliminate the effort required to decide what are the main effects that must be reproduced. This may lead in some cases to sophisticated but erroneous models. As an example a team of students in a capstone design course had designed a roof consisting of a space truss with inclined plane trusses in four different planes. The horizontal square at the top, between the top chords of the trusses, had a plate covering it. This plate was included in the analysis modeling it with finite elements (shell elements) simulating a very stiff diaphragm. As a result the top chords of the trusses had essentially no force under the action of vertical loads. In analysis courses students are presented directly with the mathematical model, normally a series of lines (representing the centroidal axes of the members) intersecting at points (joints without dimensions). Little or no time is spent explaining how the model was obtained or what the real structure would look like, what elements are not considered and why, or what would be the key issues in the actual structure. Analysis courses should start by showing real structures (trusses, frames, roofs, buildings, arenas), then describe how the mathematical idealization is arrived at, what loads must be considered and what effects are important.

3.) Another problem, closely related to the previous one, is the students' lack of feeling for the order of magnitude of forces and deflections. The availability of computer software for the analysis of regular structures consisting of linear members or two and three-dimensional continua (plates and shells) should have liberated the structural engineer and the engineering student from the need to carry out by hand the tedious computations of structural analysis, allowing them to explore more alternatives and to learn about their behavior. Yet in many cases we continue to teach methods for hand computation that have little practical value nowadays, and in others we have replaced them entirely by matrix methods that lack any physical meaning. As a result students are proficient in the use of well-established software packages but are unable to check in a fast, simple, way whether the computer results make sense or someone committed an error in the input. More importantly they lack any feeling about how the structure behaves. This is one of the main complaints of the engineering companies hiring new graduates. At the same time the elimination of geometry from high school and college curricula and the emphasis on algebraic manipulations has deprived engineering students of the ability to visualize three-dimensional structures and how they behave. To remedy this situation we must teach the fundamental principles of structural analysis and simple approximate methods to estimate forces and deflections, eliminating the more complicated and tedious procedures for hand computation that are no longer used. At the same time, to accelerate the learning process, we must take advantage of present computational capabilities to develop in the student the feeling for structural behavior that engineers used to acquire through years of practice. For this purpose we would need powerful, easy to use, computer packages that simulate structural response to expected actions and that provide dynamic visual images of how forces are transmitted and how the structure deforms. The objective is to obtain better representations of the structural behavior through advanced simulation and better understanding of this behavior through advanced visualization.

4.) A fourth point of concern is the lack of integration between analysis and dimensioning (referred to as design), with the corresponding courses being taught by different faculty members with very little or no interaction among them. The analyses to determine the member forces and the structural deflections, and the dimensioning process to satisfy various code requirements cannot continue to be two independent, separate, activities. They are both parts of the overall design process and they must be integrated. The design of the structure and its foundation should also be integrated. Structural designers must know something about the most appropriate types of foundations for different structures and soil conditions and should be able to estimate the size of the foundation elements, the potential differential displacements, or other problems that could logically arise. The software packages to be used by the students to learn about structural behavior should not be limited to analysis but should be able to accommodate the complete design process. Students should be able to generate alternative designs and to evaluate them. They should also be encouraged to try different conceptual solutions in order to exercise their creativity. Ideally the students should be looking in design courses at some of the same structures they have studied in the analysis subjects in order to introduce some continuity in the learning process.

5.) In most cases our students lack also any understanding of how the structure will be built, or whether it can be built at all, at a reasonable cost. The above mentioned simulation/visualization software should be able to integrate on one hand the structure and its foundation (as well as perhaps the mechanical and HVAC subsystems for buildings), and on the other the design and the construction processes, providing a four-dimensional representation of the structure as it evolves through time (during the construction). These capabilities must be incorporated into classroom work and must be interactive. As recommended by Reinschmidt (2003) we should have a virtual design/construction laboratory, where the students can explore the effects of changes in the design on the behavior as well as on the necessary construction process and the cost. The focus of engineering education needs to shift from a passive emphasis on calculations, to a dynamic, interactive, approach to design and decision-making. The questions of how forces are transmitted through a structure and what will be the structure's behavior should be complemented by that of how to design the structure to get the forces distributed in a specified way and to have a desired performance.

6.) The emphasis, even dependence, on computational methods in engineering education as well as practice, carries with it the danger of losing touch with reality. As pointed out above there is a problem with students lacking a feeling for how real structures look like and how they behave. This problem has been aggravated by the reduction, or even elimination, of experimental courses and laboratory work. Coupled with the teaching of analysis and computational methods, we must expose students to the observation of laboratory models and actual structures and teach them how to instrument them and measure how these systems behave. Formerly, this was done exclusively using small-scale models, but now technology allows full-scale, in-situ metrology on actual, existing, systems. Field work has become today an essential complement to computational and laboratory work. There are those who believe that our new computation and simulation capabilities have made physical experimentation and observation unnecessary (and obsolete). We do not agree. While computer simulations can enhance significantly the way to teach, making easy for the student to look at many different cases, there is still an important place for physical observation of the real world and much can be learnt from it. In addition instrumentation and continuous observation (monitoring) of structures is an essential part of the new maintenance and damage assessment procedures and of the design of intelligent structures in the future.

7.) A final deficiency is the apparent lack of continuity and consistency in some structural engineering curricula. Most civil engineering departments in the United States require now a course on Probabilities or Statistics to be taken in the freshman or sophomore year. In some cases the course is taught within the department and has primarily civil engineering applications. In others it is a regular course in the Mathematics department and the applications or examples are of a general nature. This course is required because we believe that it is important for engineering students to realize that there are uncertainties and that they should be taken into account in design and in planning the construction process. Unfortunately most structural students never see again any application of this material to actual engineering problems (this is not the case in transportation, water resources or even in construction/project management, where following courses have problems requiring the use of probabilities for their solution). In the structural field a clear application of probabilistic concepts is the LRFD (Load Resistance Factor Design) codes, based on the recognition of the uncertainties inherent in material properties and loads. Yet these codes do not make explicit mention of their probabilistic basis and are used applying factors calibrated so as to obtain similar dimensions to those provided by the earlier working stress design codes. This is also the way the requirements are often presented in design courses, even when the instructors are covering the LRFD codes. There are no undergraduate courses covering principles of structural reliability or risk and decision analysis, and yet these are essential topics in assessing the condition of structures and in the planning of any major project (particularly when dealing with public works). Similar comments could be made about principles of economics and financial analysis or about structural dynamics. Students are required to take a basic course early in the curriculum but do not see any further application of the material unless they go to graduate school and take more advanced courses.

We believe as a result that an appropriate structural curriculum should consist of a sequence of well coordinated and integrated courses in which the students:

a) Get exposed from the first analysis course to actual structures instead of only their mathematical models, and learn why the structural type was selected, how the analysis model was constructed, how the loads were determined, how to estimate initial dimensions, etc.
b) Learn in a rigorous way the basic principles of structural analysis, then in detail simple approximate methods to estimate forces and deflections, conducting finally more accurate analyses with existing computer software to assess the validity of their estimates.
c) Use powerful computer software to carry out a large number of analyses of actual or realistic structures to gain familiarity with the expected order of magnitude of dimensions, loads, forces and deflections and the structural behavior. This should provide experience equivalent to various years of practice in an engineering office. It requires a careful selection of the appropriate structures.
d) Learn about conceptual design, as well as the applicability and the behavior of different structural types by looking at selected, well documented, case studies. The case study system, so popular in business courses, has not received sufficient attention in engineering education. These should include both successful solutions and failures because much can be learnt from both. Recently Delatte (1998, 2002) has compiled under a grant from the National Science Foundation a collection of case studies of famous failures, published by the American Society of Civil Engineers (ASCE). A workshop on their use for educational purposes was held during June 2003.
e) Learn about the different requirements for various types of facilities (bridges, buildings, dams, harbors, offshore structures, industrial and power plants), the factors that must be taken into account in the design, and the types of analyses that must be conducted.
f) Learn about the characteristics and behavior of different construction materials (mass concrete, reinforced and prestressed concrete, structural steel, masonry, wood, composites), and the code requirements for each, as in present design courses but looking also at complete structures and not just elements and carrying out the analyses with computers.

g) Get an integrated picture of the complete design/construction process, looking at the effects of changes in the design on the construction and at the economics of the complete project, investigating alternatives and seeing visually the behavior and condition of the structure at different stages of the construction.
h) Are given the opportunity to exert their own creativity by looking at original structural arrangements for actual designs and comparing them with the most common or traditional solutions, developing their own, and evaluating the relative merits of the various alternatives.
i) Are taught how uncertainties in as-built dimensions, material properties and magnitude of loads can change the results (forces and deflections, required dimensions and cost) through probabilistic analyses or simple Monte Carlo simulations, getting an exposure to the basic principles and concepts of structural reliability.
j) Develop an understanding of when dynamic considerations may be important, for what types of loads or actions, for what kind of structures, and under what conditions. This implies learning also how to estimate the importance and magnitude of dynamic effects and being able to recognize when more accurate dynamic analyses will be required.

There are a number of issues that must be considered when planning a curriculum to achieve the above goals. The first one is the degree of overlapping or duplication necessary between consecutive courses to ensure that the students have a solid knowledge and understanding of the topic. Looking at the course requirements at MIT in the 70's and 80's, with only one course on Strength of Materials/Structural Analysis after the basic Physics subjects, it is clear that this is an approach intended for very bright students who can grasp the material seeing it only once. On the other hand the curricula where the Physics course was followed by courses on Engineering Statics, Engineering Dynamics, Strength of Materials and Structural Analysis (four and in some cases five courses replacing the single one) have inherent a substantial amount of duplication. Most students will need to see the material more than once to really know it well. Yet there is a point where further duplication and repetition achieves very little. Most of us went through some amount of overlap in courses in elementary school, high school and even college, although the amount may have varied greatly. The selection of the optimum amount of overlapping is not easy and depends on the caliber of the students. We must notice in this respect that Civil Engineering is no longer attracting the brightest students as it once did, because the opportunities and social recognition in other fields of endeavor seem larger, and this must be taken into account. We must hope, however, that with the application of the new emerging technologies and the new need to maintain, repair and protect our civil infrastructure, this situation will change.

A second important point is how to arrange the sequence of coordinated courses to teach all this material. One could for instance cover for each type of structure the complete sequence of conceptual design, exposure to real cases, construction of the mathematical model, selection of initial dimensions, estimation of loads, analysis, code checks, re-dimensioning and construction planning, in a way similar to what used to be done when we had full courses on Building Design, Bridge design, etc. Alternatively one could have, as done at present, a sequence of different courses covering conceptual design, analysis, dimensioning and construction but have them integrated so that the same examples and case studies are used in all of them to provide continuity.

It should be finally noted that the engineering education imparted at a university is not limited to the classroom and the courses taken. This more formal aspect is, and must be, complemented by seminars (involving graduate students talking about their research, faculty members talking about diverse technical or non-technical topics, and professional engineers describing actual projects and talking about their practical experience), participation in student activities (such as the typical competitions-concrete canoe, steel bridge- organized by student chapters of professional societies), undergraduate research opportunities (programs held at the students' home university or at other institutions during the summers), cooperative programs, and internships or summer jobs in engineering firms. What is needed is to coordinate these activities making them part of a complete process. All too often, unfortunately, these are independent, unrelated activities.

EMERGING TECHNOLOGIES

The authors wrote a paper on structural engineering celebrating 150 years of the establishment of ASCE (Roesset and Yao, 2002) in which they presented their vision for important new developments and future trends in structural engineering. Civil engineers have always been concerned with the basic infrastructure needed for societal development: housing, water supply (disposal and treatment), sanitation and public health, transportation, and energy. This is a vital role in the development of a country's economy. Once the infrastructure is in place, however, society tends to forget about it until it starts to deteriorate. In many developed countries, like the United States, repair and retrofit of the existing infrastructure has become a major consideration, overshadowing the need for new construction. At the same time that we must be concerned with repair and rehabilitation of the decaying infrastructure, we must also consider new ways to design and build components and complete systems so that their performance can be monitored in a continuous way that can also lead to early diagnosis of potential distress

Recent advances in the field of instrumentation including fiber optics and more recently Micro Electro-Mechanical Systems or MEMS have revolutionized the way information can be obtained on performance or condition of a natural or engineered system. MEMS in particular allow one to place large numbers of instruments (due to their relatively low cost), to process data locally through intelligent sensors, and to transmit data without cables directly to a computer, from where it can be downloaded through the Web to any other computer at a remote location. Wireless technology can also be used to determine the coordinates of many points along a structure or a region through full scale in situ metrology, using 3D lasers, GIS systems, etc. Three-dimensional laser coordinate measuring devices require no physical access to the object and touch it only with light, eliminating any influence of sensors on the object measured.

At the same time a number of developments in the field of control (active or semi-active control), and new materials, suggest the possibility of designing systems and facilities that could adapt themselves to different scenarios. In some cases they would be able to react to data collected by sensors to improve their behavior on an instantaneous basis (applications in earthquake engineering), in others they may be able to correct small deficiencies, and finally in others they may provide some relief on a temporary basis until adequate repair or rehabilitation measures are taken. Passive control systems, such as base isolation, have been available for a number of years and their use is increasing in seismic design. Tuned mass dampers were introduced nearly forty years ago to limit the vibrations of very tall, flexible, buildings under wind. Active systems have already been installed in several buildings, notably in Japan. Although there is an understandable reluctance to rely on these systems for the safety of a structure under a severe earthquake, there is always the possibility of using them to improve the performance of the structure without exposing it to catastrophic collapse were they to fail. Much remains obviously to be done in this exciting field.

Engineering students should be made aware of these emerging technologies and get an understanding of their possibilities. This may imply their having to take a few additional courses to learn some basic, complementary, material, on topics such as control theory, instrumentation, non-destructive testing or reliability.

CONCLUDING REMARKS

As we look at the needs of our society we must conclude that civil engineering is a very promising career full of new challenges and opportunities. Successful civil engineers will not be doing, however, the same work they used to do 100 or 50 years ago. Changes in the needs of society and developments in computer science and information technology have changed the role of engineers and opened a series of exciting opportunities. If we want our students to be successful practicing professionals in this new environment we must change what we teach them and how we teach it. Many changes are already taking place. We are seeing a new emphasis on design by opposition to only analysis, a small integration of design and construction at least in a few courses, the development of some sets of case studies, the re-design of curricula, and the adoption by a number of universities of project based learning in different proportions. We are also seeing increased use of computer software and development of some modest visualization capabilities, more extensive use of the Web, at least to facilitate the communication between faculty and students, and the use of multimedia in the classroom. These are all good steps in the right direction. They have to be continued and expanded following a well thought out plan.

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REFERENCES

Delatte, N. J. (1998), "Failure Case Studies and Engineering Ethics in Engineering Mechanics Courses," *ASCE Journal of Professional Issues in Engineering Education and Practice* Vol. 123 No. 3, July 1997, and closure of discussion to above paper, *ASCE Journal of Professional Issues in Engineering Education and Practice* Vol. 124 No. 4, October 1998.

Delatte, N. J. and Kevin L. Rens (2002), "Forensics and Case Studies in Civil Engineering Education: State-of-the-Art," *ASCE Journal of Performance of Constructed Facilities,* Vol. 16, No. 3, August, 2002.

Hsu, D. S. (2003), "The characteristics of University Education for Cultivating Engineering Talents." Proceedings of the International Conference/Workshop on Engineering Education Honoring Professor James T. P. Yao, College Station, Texas, February 2003.

Reinschmidt, K. F. (2003) "Reintegration of Engineering Design and Construction in the Classroom." Proceedings of the International Conference/Workshop on Engineering Education Honoring Professor James T. P. Yao, College Station, Texas, February 2003.

Roesset, J. M., and Yao, J. T. P., (2002), "State of the Art in Structural Engineering," *ASCE Journal of Structural Engineering, …*

Santamarina, J. C. (2003), "Creativity and Engineering - Education Strategies." Proceedings of the International Conference/Workshop on Engineering Education Honoring Professor James T. P. Yao, College Station, Texas, February 2003.

Torroja, E. (1957) Razon y Ser de los Tipos Estructurales.