

The Art and Science of Structural Concrete Design



A Symposium Honoring Richard W. Furlong

Editor:
S. Ali Mirza



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Richard W. Furlong*

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PREFACE

Integrity, honesty, and a strong desire to help others are guiding principles of Richard W. Furlong. These personal qualities, combined with his professional philosophy that innovative research ought to lead to solving real problems faced by practicing engineers, make him rather unique among educators and researchers of structural engineering. This led a group of his colleagues, friends, and former students to hold an all-day symposium at the American Concrete Institute Convention in Detroit, Michigan. Lawrence G. Griffis, Franz N. Rad, and I served as moderators for the symposium. The objective of the symposium was to honor Professor Richard Furlong; to celebrate his outstanding contributions to research, education, professional practice, and ACI; and to disseminate results of recent experimental and analytical research and code development studies in structural concrete. The symposium was very well attended and very well received. The papers included herein are mostly a result of presentations made at the symposium.

This special publication offers technical papers on topics that include high-strength high-performance concrete columns and biaxial bending, role of FRP reinforcement and strut-and-tie models, use of precast prestressed concrete in building and highway pavements, composite steel-concrete construction, and teaching of structural concrete design. In addition, a biographical sketch of Dr. Richard Furlong highlights the volume. All papers were reviewed using the ACI peer review process. In order to protect the anonymity of reviewers, Timo K. Tikka handled reviews of the paper coauthored by myself, while I managed reviews of the remaining 12 papers.

The work for the Richard W. Furlong Symposium: The Art and Science of Structural Concrete Design and this volume started in October 2000. During different phases of the symposium and special publication, I have received advice and assistance from Todd R. Watson as well as several other ACI staff members and I thank them for that. An expression of thanks also goes to Timo K. Tikka. And, of course, it goes without saying that this volume would not have been possible without the authors and the reviewers of the papers. As a result of their hard work, the quality of this volume is extremely high for which I acknowledge them gratefully. I am also thankful to Edward G. Nawy and Richard N. White for sustained encouragement they provided during the preparation of this publication. Finally, I wish to take this opportunity to thank Richard Furlong for his extensive and varied contributions to the structural engineering profession in general and the art and science of structural concrete design in particular. I do so not just on my behalf but also on behalf of all of his colleagues, friends, and former students.

S. Ali Mirza
Editor



IN TRIBUTE TO RICHARD WILSON FURLONG: AMALGAMATING RESEARCH WITH ENGINEERING PRACTICE AND EDUCATION IN STRUCTURAL CONCRETE

On Monday, April 22, 2002, colleagues, friends, and former students of Dr. Richard W. Furlong gathered for an all-day symposium at the American Concrete Institute Convention in Detroit, Michigan. The symposium's aim was to honor Professor Richard Furlong for his outstanding contributions to research, to engineering education and practice, and to ACI.

The symposium included 14 presentations recognizing and honoring the enormous contributions made by Richard Furlong in advancing the state of the art and the state of the practice for structural concrete design. The papers included in this special publication are mostly a result of the presentations made at the symposium.

Richard received his early education in Norwalk, Ohio. He completed his BSCE at Southern Methodist University in Dallas, Texas, while working as a co-op student involved in construction and steel fabrication. In 1952, he enrolled at Washington University in St. Louis, Missouri, to earn a Master's degree in 1957 while working full time. Integrating the design experience he gained during his professional practice with his undergraduate as well as graduate education helped him shape his philosophy of research, i.e. effective, useful research ought to lead to solving real problems faced by practicing structural engineers.

His desire to learn and contribute more to knowledge in structural engineering led Richard to begin in 1958 to pursue a Ph.D. degree at the University of Texas at Austin under the tutelage of Professor Phil M. Ferguson, and to start his teaching career as an assistant professor. That career spanned 40 years before he retired from the research chair of E.C.H. Bantel Professor for Engineering Practice, and has included a rich mixture of teaching, supervising research, serving the profession, and consulting. Richard Furlong's research has involved reinforced concrete columns, beams, and frames; composite columns and beams; inelastic response analysis; and design aids. His research on framed columns developed into building code provisions, and his pioneer works on composite columns and bridge bent cap inverted T-girders continue to be used by the profession. He is author of over 100 refereed articles, books, book chapters, and reports, and he has supervised 10 Ph.D. dissertations and scores of M.S. theses. He has successfully completed numerous consulting assignments on special industrial structures and rehabilitation of structures, and he is a forensic specialist on structural failure investigations.

Richard Furlong has an outstanding record of serving the professional community. His awards and accolades are too numerous to list, but the following serve as a sample: Honorary Member, American Society of Civil Engineers (2001); W. C. Schoeller Award (2000); History and Heritage Award, Texas Section, ASCE (2000); President, Texas Section, ASCE (1997); Distinguished Engineer of Texas Engineering Foundation (1996); Engineer-of-the-Year, Travis Chapter, Texas Society of Professional Engineers (1996); Award of Honor, Texas Section, ASCE (1993); Raymond C. Reese Structural Research Award, American Concrete

Institute (1990); Engineer-of-the-Year, Bexar Chapter, Texas Society of Professional Engineers (1986); Engineer-of-the-Year, Texas Society of Professional Engineers (1986); Fellow, Canadian Society for Civil Engineering (1986); Executive Secretary, Texas Section ASCE (1979-85); Board of Direction, ACI (1979-82); Fellow, American Concrete Institute (1976); John Erskine Fellowship, Canterbury University, Christchurch, New Zealand (1973); Fellow, American Society of Civil Engineers (1973).

At the symposium in Detroit the authors of this tribute made a presentation entitled “Case Studies on ‘Solid-as-Concrete’ Relationships Between Students and Mentor: Richard W. Furlong.” We examined our relationships with our mentor over the span of more than 35 years. We acknowledged and cherished the technical and non-technical knowledge we gained from Professor Furlong on structural analysis, reinforced concrete and structural steel behavior, limit design, and even more importantly, knowledge on fostering relations with colleagues, and undergraduate and graduate students who later became colleagues and friends.

We recalled the challenges of learning structural analysis; the real meaning of a “knife-edge,” a “roller,” and a “fixed-end;” the approximations made in frame analysis, the Hardy Cross moment distribution, and the “Two-Cycle” methods. Later, we learned from our mentor how to design frames made of reinforced concrete; the real story behind “factors of safety;” applicability of “elastic frame analysis” to inelastic nonlinear materials that crack, creep, and shrink; and frames that distort, drift, settle, and behave in ways not well-understood.

Through the early works of A. L. L. Baker, L. Beedle, M. Z. Cohn, K. W. Johansen, and others, we learned the basics of limit design, and were enticed as graduate students to pursue a path of research in areas that are even more “gray” than the color of concrete itself! After we completed an array of courses, the mentor chaperoned us into the practice of designing with concrete by providing and supervising real-world projects.

In summary, in knowing Richard W. Furlong, what we have experienced over the past 35 years or so has been a non-fictional tale of exemplary teaching, mentorship, collegiality, and friendship that fostered lasting relations between a master and his two former students, Franz N. Rad, Portland State University, Portland, Oregon; and S. Ali Mirza, Lakehead University, Thunder Bay, Ontario, Canada.

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Precast Prestressed Concrete Pavement

by N. H. Burns, D. K. Merritt, and B. F. McCullough

Synopsis: With traffic volumes continuing to increase on a rapidly deteriorating infrastructure, new methods are needed for expediting construction of durable, high performance concrete pavements with minimal disruption to traffic. One method, which has received significant attention in recent years, involves the use of precast concrete panels. Precast concrete panels can be cast and cured in a controlled environment, stockpiled, and set in place in a short amount of time, allowing for construction to take place during overnight or weekend operations. In March 2000, the Center for Transportation Research at The University of Texas at Austin completed a feasibility study which investigated the use of precast prestressed concrete panels for pavement construction. Following the feasibility study, a pilot project was initiated by the Texas Department of Transportation to test and refine these concepts on an actual project. Recently, construction of this pilot project was completed on a section of frontage road along northbound Interstate 35 near Georgetown, Texas. Although it was constructed without the time constraints and complexities that will eventually need to be considered for precast pavement construction, the viability of the concept for precast prestressed concrete pavement was clearly demonstrated and will ultimately lead to development of future precast prestressed concrete pavements.

Keywords: expedited construction; post-tensioned pavement; precast concrete pavement; precast pavement panels; prestressed pavement; user costs

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David K. Merritt, ACI member, is a Research Associate with the Center for Transportation Research at the University of Texas at Austin. He received his BS in civil engineering from Northern Arizona University in 1998, and MS in civil engineering from The University of Texas at Austin in 2000. He has been a researcher at CTR for four years specializing in precast and prestressed concrete pavement.

Dr. B. Frank McCullough is the Adnan Abou-Ayyash Centennial Professor Emeritus of Civil Engineering at The University of Texas at Austin and former Director of the Center for Transportation Research. Dr. McCullough has a particularly strong interest and background in pavement design. During his career, Dr. McCullough has supervised over 50 research projects involving development of quality assurance and quality control specifications, planning, design, construction, rehabilitation, and maintenance of pavements.

RESEARCH SIGNIFICANCE

New methods are continually being developed for expediting construction of durable concrete pavements. This paper describes one such method using precast prestressed concrete panels. Although other methods for expediting construction, such as fast-setting concretes already exist, precast concrete is presented as an alternative to these methods. With the degree of quality control afforded at a precast plant and the incorporation of post-tensioning, durability should be greatly enhanced, making precast concrete an appealing alternative for transportation agencies.

BACKGROUND

In response to an ever-increasing demand for methods to expedite pavement construction, the Center for Transportation Research (CTR) at The University of Texas at Austin completed a feasibility study, sponsored by the Federal Highway Administration (FHWA), which examined the use of precast concrete panels to expedite the construction of portland cement concrete pavements. From this feasibility study, a concept for precast pavement was developed which incorporated the use of prestressed precast panels.

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A final recommendation from the feasibility study was a staged implementation strategy for testing and refining the proposed concept, in order to develop design details and construction specifications that will be acceptable to contractors and transportation agencies and easily adapted to current practices. Staged implementation begins with small pilot projects without stringent time constraints, aimed at streamlining the construction procedures for use on future projects.

The first precast pavement pilot project was constructed by the Texas Department of Transportation (TxDOT) during the fall and winter of 2001 on a section of frontage road along northbound Interstate 35 near Georgetown, Texas. This project incorporated precast concrete pavement panels into the reconstruction of 0.7 km (2,300 ft) of frontage road on either side of a new bridge, based upon the proposed concept described below. Ultimately, this pilot project not only demonstrated the viability of using precast panels to expedite construction of concrete pavements, but also the benefits and viability of incorporating post-tensioning.

PROPOSED CONCEPT

The proposed concept for a precast pavement, constructed on a section of frontage road near Georgetown, Texas, uses full-depth prestressed precast panels. Based upon the feasibility study mentioned previously, it was believed that full-depth precast panels would be the most efficient way to expedite construction, and that a sufficiently smooth riding surface could be attained using full-depth panels with occasional diamond grinding.

Previous experience with prestressed pavements has shown that prestress in both the longitudinal and transverse directions is essential (1). Therefore, prestress is incorporated in a precast pavement by pretensioning the precast panels during fabrication (for transverse prestress), and post-tensioning all of the panels together after placement (for longitudinal prestress). Pretensioning not only accounts for in situ stresses but also counteracts lifting stresses. Post-tensioning not only provides the necessary prestress in the longitudinal direction, but also serves to tie all of the panels together so they act as a continuous slab.

Two key factors which must be considered when using full-depth panels are: 1) base preparation so that the panels are resting on a flat surface and are fully supported, and 2) method for ensuring vertical alignment of adjacent panels to achieve satisfactory ride quality over the joints. With regard to base preparation, profile measurements obtained from a newly placed asphalt pavement in Austin, Texas revealed that it is possible to place a thin (25 – 50 mm) asphalt leveling course smooth enough and flat enough that the panels can be placed directly over the leveling course (2). This is not only an economical solution, but an efficient

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solution in that the asphalt leveling course can be placed well in advance of the precast panels, allowing traffic onto the leveling course prior to panel placement.

To ensure vertical alignment between adjacent panels, the proposed concept features continuous shear keys cast into the edges of the panels which will interlock the panels as they are set in place. Although shear keys along the panel edges require strict casting tolerances, the panels can be set in place rapidly without the need for additional measures to level-up adjacent panels. This was demonstrated prior to construction by trial assemblies, described below.

A typical panel assembly for the proposed concept is shown in Figure 1. The panels are oriented with the longitudinal axis perpendicular to the flow of traffic, incorporating both traffic lanes and shoulders. There are essentially three types of panels: base panels, joint panels, and central stressing panels, shown individually in Figure 2. As mentioned above, all of the panels are pretensioned lengthwise (transverse pavement direction), and post-tensioning ducts are cast into each panel widthwise (longitudinal pavement direction) to allow the panels to be post-tensioned together after they are set in place. The base panels (Figure 2a) are the “filler” panels between the joint panels and central stressing panels. The number of base panels between the joint panels and central stressing panels will depend on the post-tensioned slab length (between expansion joints). The joint panels (Figure 2b) contain an armored expansion joint, similar to that used for bridge decks, which will absorb the significant expansion and contraction movements of the post-tensioned slabs. The joint panels also contain self-locking post-tensioning anchors to receive the post-tensioning strands. Small access pockets (150 mm x 300 mm) cast into the joint panel provide access to the strand prior to insertion into the self-locking anchors. Finally, the central stressing panels (Figure 2c) are similar to the base panels, with the addition of larger pockets (1.2 m x 0.2 m) cast into the panels at every post-tensioning duct. The purpose of the pockets is to allow for post-tensioning to be completed from the center of the slab rather than at the post-tensioning anchorage in the joint panel. This allows for a more continuous pavement placement operation, as access to the anchorage is not needed in order to tension the strands. The post-tensioning strands coming into the stressing pockets from either side of the slab are coupled in the pocket, and then tensioned, as shown in Figure 3.

In order to protect the post-tensioning strands crossing the joints between each of the panels, epoxy is applied to the edges of the panels as they are assembled, similarly to segmental bridge construction. This not only protects the strands from water intrusion, but also prevents grout from leaking at the panel joints during tendon grouting. The epoxy also serves to bond the panels together so that they act more like a continuous slab, while also serving as a lubricant during assembly of the panels.

In certain cases it may not be possible to replace the entire pavement width, but rather one lane at a time. In this situation, it will be necessary to place two or more “partial-width” precast pavement slabs adjacent to each other and tie them

together transversely. To accomplish this, an additional post-tensioning duct is cast into each of the panels in the transverse pavement direction, as shown in Figure 4. A flat, oversized duct will permit slight misalignment of adjacent slabs and will accommodate any differential movement of the slabs.

Following assembly (Figure 1) and post-tensioning of the precast panels, the pockets in both the joint panels and central stressing panels are filled with a fast-setting concrete. If time constraints do not permit filling the pockets, the pockets can simply be covered and filled during a subsequent operation. After filling the pockets, the post-tensioning strands are grouted in the ducts. Grouting not only bonds the strands to the pavement so that there will not be a significant loss of prestress if a strand is cut, but more importantly, provides an extra layer of corrosion protection for the strands, which is particularly important at the joints between panels where the post-tensioning ducts are not continuous. Grouting, also, can be completed during a subsequent operation if time constraints do not permit immediate grouting.

Another aspect of the precast pavement concept is a friction-reducing medium between the precast panels and the asphalt leveling course. A friction-reducing medium is essential for minimizing prestress losses in the pavement due to frictional restraint developed between the bottom of the panels and the leveling course during post-tensioning and over the life of the pavement. Previous research has shown a single layer of polyethylene sheeting to be a very effective and economical material for use as a friction-reducing medium (3). This material was used successfully for construction of a cast-in-place post-tensioned pavement near West, Texas (4). In addition to the friction-reducing medium, the middle of each post-tensioned slab must be anchored to the base. A mid-slab anchor forces the slabs to expand and contract outward from the center, ensuring uniform expansion joint widths. Dowel bars drilled and grouted into the base material at the stressing pockets provide a simple and effective solution for the mid-slab anchor.

DESIGN OF THE GEORGETOWN PRECAST PAVEMENT

Project Site

The precast pavement constructed near Georgetown, Texas was placed on a section of frontage road along northbound Interstate 35. The project consisted of 700 m (2,300 ft) of precast pavement on either side of a new bridge, as shown in Figure 5. The site for this project was ideal for several reasons. First, the frontage road was closed to traffic during construction. This allowed initial problems to be worked out without restrictive time constraints. Although the ultimate application for precast pavement will be in urban areas, under extreme time constraints (overnight or during weekends), the purpose of this initial pilot project was to test

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and refine the panel details and construction procedures. Secondly, there are no horizontal curves and very gradual vertical curves. Although horizontal curves and superelevations must eventually be addressed, a roadway with a simple geometric layout allowed for the basic details of the precast pavement concept to be worked out first. Finally, the site for the Georgetown precast pavement was ideal because it will eventually experience heavy traffic, particularly truck traffic, as it will become part of an interchange for Interstate 35 and (proposed) State Highway 130. Heavy traffic will provide a good test of the durability of the finished precast pavement.

The precast panels were oriented transverse to the flow of traffic, as shown in the panel assembly (Figure 1). This required panels which would span the full 11 m (36 ft) roadway width (two 3.7 m lanes, 2.4 m outside shoulder, and 1.2 m inside shoulder). To accomplish this, both full-width (11 m) and partial-width (5 m + 6 m) panels were used, although partial-width panels were not required. The full-width panels were placed on the north side of the bridge, and the partial-width panels on the south side of the bridge, with the joint between the 5 m and 6 m panels located at the center stripe of the road. A standard slab length (between expansion joints) of 76 m (250 ft) was selected based upon prior experience with the post-tensioned pavement near West, Texas (4). To meet the project limits, a longer slab length of 100 m (325 ft) for the partial-width panels, and a slightly shorter slab length of 68 m (225 ft) for the full-width panels were also incorporated. A standard panel width of 3 m (10 ft) was selected for all of the panels based upon fabrication (casting bed width) and transportation (weight limit) considerations.

Prestress Requirements

The Georgetown pilot project was designed for an equivalent fatigue life, in terms of expected 80 kN (18-kip) equivalent single axle load (ESAL) applications to that of a 355 mm (14 in) continuously reinforced concrete pavement (CRCP). Although a 355 mm pavement is a much thicker pavement than needed for this frontage road, the purpose of this pilot project was to simulate what might be used on the main lanes of an interstate pavement.

The pavement was placed as a new pavement directly on the asphalt leveling course over compacted subbase material. A 200 mm (8 in) pavement thickness was selected primarily on the basis of handling considerations. Using layered theory analysis, elastic design for fatigue loading was used to determine the prestress requirements for a 200 mm precast pavement with an equivalent design life to a 355 mm CRCP for the given subbase support conditions. Elastic design for environmental and wheel loading was then used to determine the final prestress requirements. Elastic design for environmental and wheel loading takes into account stresses generated from slab curling due to top-bottom temperature differentials in the slab, prestress losses due to both frictional resistance at the

bottom of the slab and strand relaxation, and stresses generated from wheel loading (simultaneous to environmental loading).

Based on this design, the maximum required prestress (at the ends of the slab), for a 200 mm (8 in) precast pavement, was found to be approximately 1.45 MPa (210 psi). This translates into 15 mm (0.6 in) diameter 1,860 MPa (270 ksi) post-tensioning strands spaced at approximately 71 cm (28 in) across the width of the pavement (strands to be stressed to 80 percent of ultimate strength). However, for the purpose of standardization of strand spacing for future projects, a strand spacing of 61 cm (24 in) was selected, which further increased the effective thickness of the pavement.

Elastic design for environmental loading was also used to determine the expected minimum and maximum expansion joint widths for the given slab lengths (76 m, 100 m, 68 m). Anticipated joint widths were checked to ensure that the expansion joints would never be open more than 100 mm (4 in) and would never be completely closed under extreme summer and winter temperatures relative to weather typically experienced in Georgetown, Texas. Based upon these joint widths limitations, a table was developed for the recommended initial joint width, at panel placement, based on approximate ambient temperatures during panel placement. The initial joint width was then set, prior to casting the joint panels, by tack welding the armored joint together at the specified width.

In addition to longitudinal prestress requirements, transverse prestress requirements were also determined based on environmental and wheel loading. However, it was determined that the governing factor in transverse prestress design is the stress generated from lifting the precast panels. Therefore, a minimum prestress (from pretensioning the panels during fabrication) of 1.4 MPa (200 psi) was specified in order to prevent cracking in the 11 m (36 ft) long panels when lifted approximately at the quarter points.

Panel Details

The post-tensioning ducts were located at mid-depth of the precast panels. This was to ensure that a camber was not introduced into the pavement during post-tensioning. The pretensioning strands, likewise, were centered at mid-depth by alternating them just above and just below the post-tensioning ducts. Flat, four-strand post-tensioning ducts were cast into the partial-width panels (for transverse post-tensioning) with two standard dead-end post-tensioning anchors at the ends of the ducts.

Mild steel reinforcement in the precast panels was minimal. Although the transverse pretensioning strands provided a significant amount of bonded reinforcement, additional mild steel (13 mm, 414 MPa) reinforcement was provided around the perimeter at the top and bottom of each of the panels. Mild

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steel was also provided in the central stressing panels and joint panels, with two reinforcing bars crossing through the stressing pockets and access pockets to tie concrete in the pockets to the rest of the panel. Additional “bursting steel” was added to the joint panels directly in front of the post-tensioning anchors and in front of the transverse post-tensioning anchors in the partial-width panels.

To aid with assembly of the panels, sleeves were cast into the edges of each of the precast panels, as shown in Figure 2. The edge sleeves provided a means for pulling the panels together as they were lowered into place to get the joints between panels as tight as possible before post-tensioning. Chain winches or “come-alongs” linked between the edge sleeves were used to pull the panels together.

The armored expansion joints cast into the joint panels were similar to those used for the cast-in-place prestressed pavement near West, Texas, mentioned previously (4). Figure 6 shows the expansion joint detail used for the Georgetown precast pavement project. The seal receiver extrusion at the top of the expansion joint is a standard receiver for bridge decks commonly used in Texas. A 6 mm (0.25 in) thick steel angle was welded to the bottom of the steel extrusion to provide encapsulation of the concrete and a bearing structure for the joint. Deformed bar anchors, 0.6 m (2 ft) in length, were welded to the top and bottom of the expansion joint to tie it to the precast panel and prevent rocking of the joint under repeated wheel loading. The top and bottom anchor bars were alternated over the length of the joint, spaced every 200 mm (8 in). Stainless steel plated dowel bars were spaced at 305 mm (12 in) along the length of the expansion joint with an expansion sleeve cast into one side of the joint to receive the dowel. The self-locking post-tensioning anchors, discussed previously, were fastened to the expansion joint with 13 mm (0.5 in) threaded studs spaced at 61 cm (24 in) over the length of the expansion joint.

PANEL FABRICATION

The panels for the Georgetown precast pavement project were cast on a “long line” casting bed 122 m (400 ft) in length. Long line casting allowed for ten full-width (11 m) panels, and up to twenty partial-width panels to be cast at one time end to end. The pretensioning strands extended continuously the full length of the casting bed passing through all of the panels. After release of prestress, the pretensioning strands between each of the panels were cut and the panels were removed from the forms. Long line casting did require special attention for the side forms to make sure there were no imperfections or misalignment that might prevent the keyed panel edges from matching up.

The mix design for the precast panels was similar to that used for precast prestressed bridge beams. The mix contained seven sacks of Type III portland cement per cubic yard, with a water/cement ratio of 0.42, and superplasticizer for

increased workability. A mix of this nature, which is not typically used for pavements, was necessary to develop sufficient strength for release of prestress and removal from the forms the following day. The specifications for the precast panels required that the concrete reach a minimum compressive strength of 24.1 MPa (3,500 psi) at release of prestress, and a 28-day compressive strength of 34.5 MPa (5,000 psi). The mix was also required to be sufficiently fluid during casting that a carpet drag finish could be applied at sheen loss.

Handheld concrete vibrators and a vibratory screed were used to ensure a flat surface and proper consolidation of the concrete around the keyways, post-tensioning ducts, and pockets during casting. An intermediate curing compound similar to monomolecular film was applied to the panels after screeding to minimize water loss. After any necessary hand finishing, a carpet drag texture was applied to the panels, transverse to the flow of traffic. Immediately following the carpet drag, two coats of curing compound were applied to the panels to minimize further water loss from the surface of the panels. Adequate curing was particularly important as many of the panels were cast during the hot months of July and August. The panels were generally cured in the forms overnight before releasing prestress, then removed from the forms and stacked. Once the panels were stacked, wet mats were applied to the stack of panels and a tarp was used to cover the stack. The panels were allowed to cure in this condition until 48 hours from the time of casting. In total, 123 full-width (11 m) panels and 216 partial-width (5 m and 6 m) panels were cast.

PANEL ASSEMBLY

Trial Assemblies

Prior to actual construction on the frontage road, two trial panel assemblies were conducted. The first trial assembly was conducted at Ferguson Structural Engineering Laboratory at The University of Texas at Austin. For this trial assembly, three panels were cast representing one half of a joint panel, and two base panels. The panels were all 200 mm (8 in) thick and 3 m (10 ft) wide (half joint panel was 1.5 m wide). However, due to the scale of the trial assembly, the panels were only 1.5 m (60 in) long, as opposed to the full length of 11 m. The panels were all cast with the same details, including edge keyway dimensions, specified for the actual panels with the exception of pretensioning. The laboratory trial assembly proved the viability of several aspects of the precast pavement concept, including keyed panel edges, assembly the panels over the plastic sheeting, edge sleeves used to pull the panels together, and self-locking post-tensioning anchors.

The second trial assembly was carried out at the precast plant in Victoria, Texas. The primary purpose of this trial assembly was to evaluate how well full-width

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(11 m) panels could be assembled using the same methods demonstrated in the laboratory. For the second trial assembly, three full size panels were cast and assembled using equipment available at the precast plant. The three panels fit together tightly, as they did in the laboratory test, assuring the viability of assembly on the frontage road.

Both trial assemblies proved to be very useful for evaluating the viability of some of the aspects of the proposed precast pavement concept with only minimal expense. After completion of these trial assemblies, approval was given for full-scale panel production.

Frontage Road Assembly

As the pavement panels were being cast, the asphalt leveling course was placed on the frontage road. To achieve the full 11 m roadway width, three sections of asphalt were placed, being careful that ridges were not created at the joints between the three sections. To ensure that the leveling course was placed as flat and uniform as possible, a string line was staked to the subbase material as a depth gauge approximately every 7.5 m (25 ft). After final compaction of the leveling course, any obvious defects were marked and removed, and a laser profilometer was used to check the smoothness.

After all of the full-width (11 m) precast panels had been cast, panel assembly began on the frontage road. The panels were delivered to the site and placed one section (between expansion joints) at a time. The panels were delivered to the site one panel per truck due to weight restrictions. As each truck was waiting to unload, epoxy was applied to the panel edges. The polyethylene sheeting was rolled out prior to the placement of each panel. A 578 kN (65 ton) capacity crane was then used to lift each panel off of the truck and set it directly in place. In general, two 11 m panels could be set in place before the crane had to be moved. This prevented excessive extension of the boom, reducing the amount of sway as the panels were being set in place. To ensure that the lifting lines were nearly vertical (to minimize bending stresses in the panels), lifting lines approximately 9 m (30 ft) in length were used. During placement of the first few sections, approximately 25 full-width (11 m) panels could be placed over an 8-hour period. This placement rate varied depending on the number of workers available. At the end of the project 25 panels could be placed in approximately 6 hours.

As the panels were being set in place, the post-tensioning strands were cut to length. Once all of the panels had been set in place, the post-tensioning strands were fed into the ducts at the central stressing pockets and through the panels on either side of the central stressing panels. The strands were each fed to the access pockets in the joint panels where the end of each strand was inspected prior to being pushed into the self-locking anchors. After all of the strands were anchored, a coupler similar to that shown in Figure 3 was used to couple the strands coming

from each end of the slab in the stressing pockets. Each tendon was then stressed with a monostrand post-tensioning jack to 80% of the ultimate strength of the strand, as specified in the design plans. After all tendons were stressed, the stressing pockets and access pockets were filled in preparation for grouting.

Placement of the partial-width panels could be completed slightly faster than the full-width panels due to the fact that more panels could be set in place before it was necessary to move the crane. Initially, one section of 6 m (20 ft) panels were set in place and post-tensioned, followed by the adjacent section of 5 m (16 ft) panels. The purpose of this was to simulate the staging for a one-lane operation that may be required on future projects. After it was determined that this would work, each 6 m panel and matching 5 m panel were set in place simultaneously in order to expedite assembly.

After each set of partial-width panels were in place, two 13 mm (1,860 MPa) strands were fed through each transverse post-tensioning duct. A diverter in the duct directed each of the strands to separate anchors. The longitudinal post-tensioning tendons were threaded through the ducts using the same procedure as that described for the full-width panels. After all transverse and longitudinal strands had been anchored, two longitudinal tendons on each of the 6 m and 5 m slabs were stressed in order to pull the panels together as tightly as possible. Each of the transverse tendons were then stressed, followed by the remaining longitudinal tendons. All post-tensioning was completed within 24 – 48 hours after placement of the panels while the epoxy was still pliable.

After all strands were stressed and the pockets were filled, the tendons were grouted. Longitudinal tendon grout vents were located at the post-tensioning anchors, at the central stressing pockets, and at approximately every 12 m (40 ft), or every fourth panel, in between. A standard cable grout mix with an efflux time (ASTM C 939) between 15 and 20 seconds was used for grouting the longitudinal tendons. Initially, grout was pumped into the grout vents at the anchorage assuming it would flow out of the intermediate vents and the vent at the stressing pockets. However, it was soon discovered that significant leakage was occurring at the panel joints and grout was flowing between ducts as well as beneath the slab. Therefore, it became necessary to pump grout into every grout vent, including the intermediate vents, to fill the ducts as much as possible. Ultimately, it became very difficult to determine how well each tendon was grouted. Unfortunately, an economical solution could not be developed in time for ensuring complete grouting of the longitudinal tendons. This is an issue which must be addressed in future projects, but should not have a significant effect on the performance of this particular precast pavement as it is significantly over-designed for a frontage road pavement.

The grout vents for the transverse tendons were located below the post-tensioning anchors on the outside edge of the pavement. Grout was pumped from low side of the pavement (as determined by the cross-slope of the pavement) to the high side. Grout was pumped until it flowed out of the grout vent as well as around the

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wedges in the anchors. No problems were experienced with grouting the transverse tendons.

After tendon grouting was complete, any areas that needed to be patched, due to minor spalling that occurred during panel placement, were sawcut and chipped out to a depth of 50 mm (2 in). Epoxy was spread over the interior faces of the patch, and normal strength concrete was used to fill the patch. The recesses in the top of the panels from the lifting devices were, likewise, coated with epoxy, then filled with a non-shrink grout.

No additional measures were required to improve the ride quality of the finished pavement. A smooth enough riding surface was provided and diamond grinding was not necessary.

COST COMPARISON

As stated at the beginning of this paper, the biggest benefit of precast pavement is expedited construction. Using precast pavement panels, additional time is not required for the concrete to reach sufficient strength before traffic is allowed onto the pavement. Precast panels can be set in place quickly and the pavement can be opened to traffic almost immediately. This will allow for construction to take place during overnight and weekend operations when traffic volumes are low. Construction during off-peak hours will result in a significant reduction in user delays caused by pavement construction using conventional paving methods. This reduction in user delays translates into a significant savings in user costs, which are costs incurred by the users of the roadway due to the presence of construction activities, such as increased fuel consumption and lost work time.

During the feasibility study, completed prior to the Georgetown pilot project, a sample user cost analysis was conducted to compare the user costs of conventional concrete pavement construction versus precast pavement construction. For a typical 8 km (5 mi) urban interstate pavement reconstruction, a 24-hour traffic diversion was assumed for conventional pavement placement, while an 8 PM – 6 AM traffic diversion was assumed for precast pavement placement. With this traffic diversion scenario, user delay costs of approximately \$383,000 per day can be expected for conventional pavement construction, as opposed to only \$1,800 per day for precast pavement construction (2). Although it may not be possible to place as much precast pavement as conventional pavement in a daily operation, this savings in user costs will generally always outweigh any additional construction time. For a more detailed explanation of this example analysis and for more information on the user cost model, the reader is referred to reports by Wilde et al (5) and Merritt et al (2).

With the implications of user costs in mind, construction costs should be evaluated accordingly. The total cost of the Georgetown precast pavement,

including panel fabrication, placement of the leveling course, and panel placement was estimated to be approximately \$203/m² (\$170/yd²). Although this cost is significantly higher than what might be expected for an equivalent 355 mm CRCP (\$36 – \$48/m²), there are several factors which greatly contribute to this higher cost. First, the Georgetown precast pavement was a relatively small (0.7 km) project, and as with any construction project, there are economies of scale. A much larger project would, most likely, have resulted in a significantly lower unit cost. Secondly, the Georgetown precast pavement project was experimental in nature. Neither the contractor nor the precast supplier were familiar with precast paving techniques and therefore likely submitted higher bids to cover any unexpected problems. It is important to remember that, as with any new construction method (such as the first continuously reinforced concrete pavement), the initial costs will be higher until contractors and transportation agencies become familiar with the techniques. Despite these factors, as shown above, the significant savings in user costs with precast pavement will far outweigh higher construction costs. Although user costs are not yet tangible costs to transportation agencies, these are costs that the general public understands.

CONCLUSIONS

The precast pavement pilot project near Georgetown, Texas is just the beginning for precast pavement construction. While this project did not include all of the intricacies of anticipated future precast pavements, such as stringent time constraints and geometric complexity, it demonstrated the viability of the basic concepts proposed by CTR for precast prestressed pavements.

This pilot project also demonstrated the numerous benefits of precast pavement over conventional concrete pavement. Expedited construction is perhaps the most obvious benefit. Using precast panels, pavement construction can take place during overnight or weekend operations, minimizing the impact on the motoring public, thereby significantly reducing user delay costs. Although this was not a factor for the Georgetown pilot project, the project did demonstrate the how quickly precast panels can be set in place and post-tensioned. As a result, future pilot projects with stricter time constraints will employ more streamlined construction procedures.

In addition to savings in user costs, increased durability and long-term performance will be realized with precast pavement. Controlled fabrication conditions at a precast plant will ensure a consistent concrete mix and proper curing of the panels, and will allow for the use of high performance and lightweight concretes. Post-tensioning will not only reduce required slab thickness, but also improve durability by reducing or even preventing cracking, that eventually leads to pavement failure, from occurring.

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The Georgetown pilot project presented many challenges for precast pavement implementation. Perhaps the most difficult aspect was meshing precast concrete and concrete pavement specifications. This required flexibility on the part of both the precast supplier and TxDOT. This project also represented unknown territory for the contractor, precast supplier, and TxDOT. Flexibility and a willingness to develop new techniques on the part of all parties were essential for the success of this project.

This project led to the development of streamlined fabrication and construction procedures, which will be very useful for future projects with stricter time constraints. Ultimately, it is hoped that precast pavement will be used where it is needed most, on urban freeways, intersections, and even airport runways where construction must have virtually no impact on traffic; this is where the true benefits of precast concrete pavement construction will be realized.

ACKNOWLEDGMENTS

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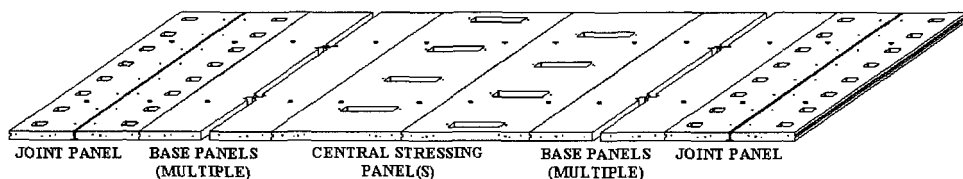


FIGURE 1. Typical Panel Assembly.

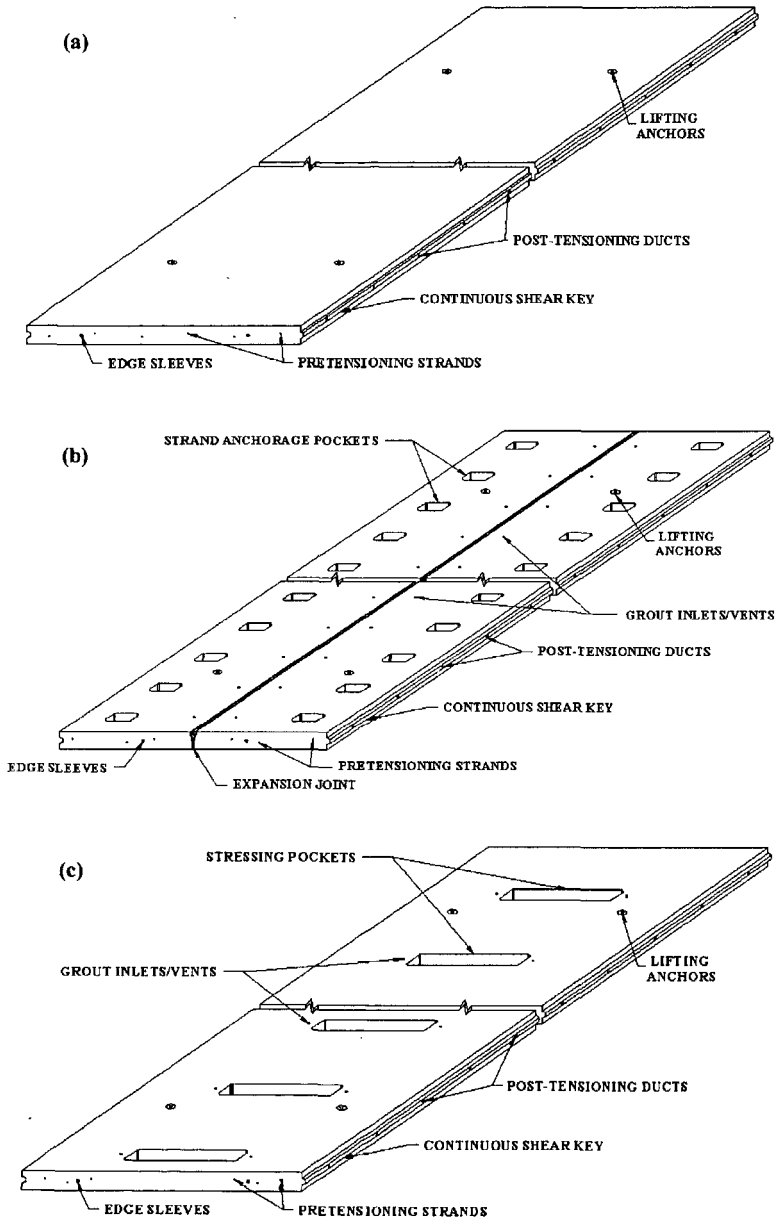


FIGURE 2. Three types of panels used for precast pavement: (a) typical Base Panel, (b) typical Joint Panel, (c) typical Central Stressing Panel. (Typical dimensions: 11 m x 3 m x 200 mm)

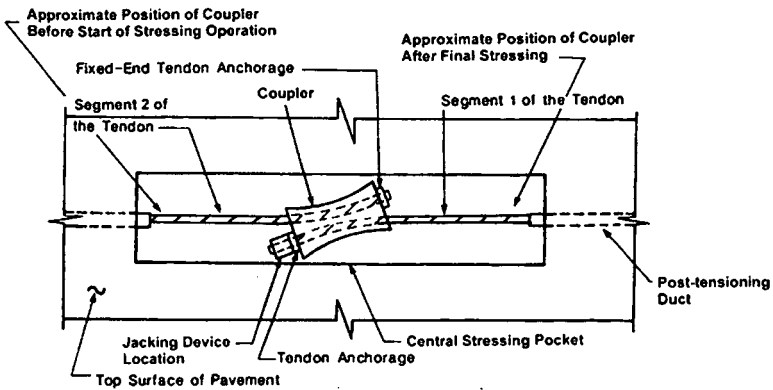


FIGURE 3. Coupler used for the post-tensioning strands in the stressing pockets (2).

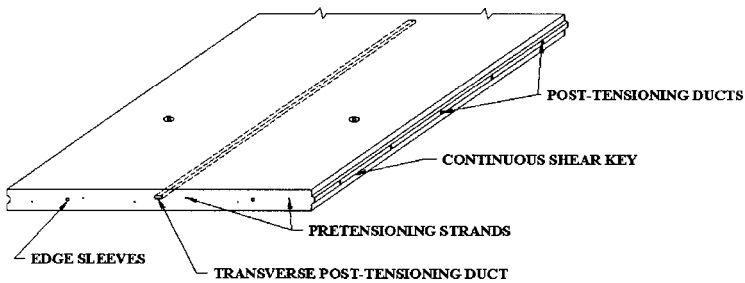


FIGURE 4. Typical "partial-width" base panel with additional transverse post-tensioning duct. (Typical dimensions: 5 m or 6 m x 3 m x 200 mm)

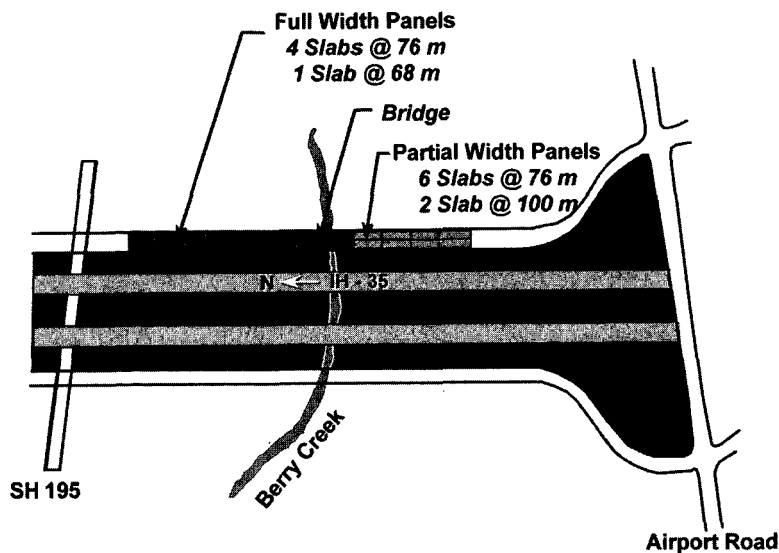


FIGURE 5. Location and layout of the Georgetown precast pavement pilot project.

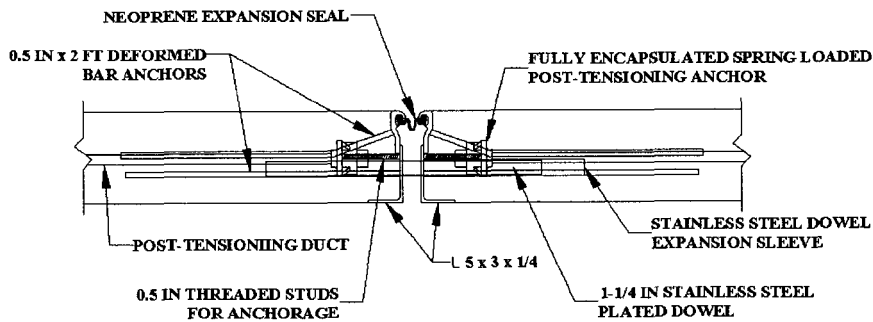


FIGURE 6. Armored expansion joint cast into Joint Panels.

Improved Teaching of Structural Concrete Design

by R. N. White

Synopsis: This paper provides discussion and suggestions on the very difficult question of how to best teach the design and construction of concrete structures at the undergraduate level and beyond. The end goal remains unchanged—to provide the best possible constructed facilities for the public and private sectors. After presenting the background and scope of coverage, important issues in structural design are discussed, including a definition of the three types of knowledge bases needed in performing any design. Expectations of new graduates as they enter the work force are covered, and implications for professional registration are discussed. The paper continues with extended discussion on a host of important issues that need coverage to varying degrees in the curriculum. The critical importance of proper integration of materials selection into the overall design process is explored. Given that learning must be a life-long process, professional post-B.S. education approaches (both “conventional” and internet-based) are presented, along with comments on the ASCE position that the professional Master’s degrees should become the degree of entry into the profession. The paper concludes with suggestions and recommendations.

Keywords: analysis; civil engineering curricula; construction; design; professional education; professional registration; structural concrete

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INTRODUCTION AND SCOPE OF COVERAGE

This paper explores how education can be shaped to achieve improvements in designing and building structures. "Improvements" should be measured from the multiple perspectives of overall quality, safety, serviceability, economy of materials usage, durability, constructability, impact on the environment, aesthetics, and initial and lifetime costs. Discussion is aimed at new facilities as well as the rehabilitation of existing facilities.

This paper is based on the premise that improved and expanded education is more critical than ever before as we cope with construction needs in our crowded urban areas, utilizing a mix of new construction and rehabilitated existing infrastructure, with both types of construction utilizing improved "conventional" materials and a host of new materials. Owners face increasingly complex alternative scenarios with optimal solutions dependent upon a complex set of technical, technological, financial, social, environmental, and aesthetic issues. Some of these parameters complement each other and some are in direct contradiction. Hence the challenges to the project team -- engineer, architect, materials supplier, contractor, sub-contractor, quality control and quality assurance personnel, maintenance organization, and owner -- are daunting.

Meeting these challenges during the coming decades will provide almost unlimited opportunities for our young people, and we bear the responsibility of informing them about the excitement and challenges in the planning, engineering, and construction of tomorrow's infrastructure. Unfortunately, our ability to attract the best and brightest young people into the civil engineering business seems to have suffered from the perception that we are an old-fashioned, overly mature industry. I believe this is a false impression, but it is up to us to change how people think of concrete structures and the fields of concrete engineering and construction.

We need to capitalize on the following facts: (1) concrete and masonry will continue to be the most widely used construction materials into the indefinite future (2) research and development efforts in the past two decades have produced tremendous advances in cement-based materials, and (3) the future

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holds great promise for many technological developments, such as more environmentally acceptable cement production and usage, new families of high performance concretes with greatly enhanced durability and with high efficiency in transmitting loads, and exciting combinations of concrete with structural steel and with new non-metallic, composite reinforcements.

Coverage in this paper builds on my February 1998 ACI Presidential Memo on Concrete Education in the 21st Century published in *Concrete International* (1), and on a paper presented in Hawaii at the First International Structural Engineering and Construction Conference (2). My comments are directed primarily at four year B.S. degree programs in civil engineering in North America, but some also may be applicable to our many excellent technology programs leading to Associate degrees or to the Bachelor of Technology. Space limitations do not permit coverage of overseas educational trends and practices, other than to comment on the fact that many foreign civil engineering and construction programs are very strong. It should be noted that the separate discipline of construction engineering, available at a number of schools and universities, is not treated here, even though it is a critical part of the overall picture.

This paper begins with discussion of several general design-related issues, followed by a critical review of topics that need coverage in our civil engineering curricula. Post-B.S. education and training are discussed. The paper concludes with suggestions and recommendations.

STRUCTURAL DESIGN ISSUES

General Issues

Concrete has been called the ideal architectural material because of its plastic nature and its ability to be cast into almost any shape or form. Do we, as faculty members in civil engineering, really capture the inherent excitement of being part of the design team that produces new concrete structures? My feeling is that in general, we do not. The primary reason for this shortcoming is well-intentioned but quite unfortunate -- we become almost overwhelmed in trying to cover all the intricacies of analysis, strength of sections, beam-column and stability effects, time-dependent behavior, prediction of cracking and deflections, connection difficulties, etc. This fact of life has some quite undesirable effects, however, particularly in the minds and attitudes of our students, who often do not develop much real enthusiasm about the intellectual rewards of being key participants in creating and building exciting new structures. How can these approaches and attitudes be changed?

Holgate (3) produced a book that should be required reading for all faculty and students of structural engineering. His theme, "the art of structural design", is

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developed from the perspective of a structural engineer with strong ties to architecture. He delves deeply into the philosophies of architecture and structural engineering. He points out that in the early years of civil engineering studies the standard approach is for students to learn analysis and calculation procedures and then apply them to obtain “the right answer” to a “clear-cut” problem. This implies that there is a world of standard, clear-cut problems waiting to be solved by practicing structural engineers. Holgate says “Once the mind becomes set in this view of the world it becomes very difficult to break out of the mould at a later date”, and that “traditional engineering courses reduce the creativity of students”. He also points out, quite correctly, that students begin to believe that design is the repetitive application of formulas and rules, and hence boredom soon sets in once the joy of mastering and applying new knowledge begins to dissipate.

Holgate says “Structural design can be seen as the process of disposing material in three-dimensional space so as to satisfy some defined purpose in the most efficient manner possible”. While this definition seems rather direct, two words require very careful definition -- “purpose” and “efficient”. Purpose is defined primarily by the owner, while efficiency is more the province of the engineering and construction team. Structural efficiency often must be compromised to accommodate HVAC needs and other issues. The other critical point is that many important issues may be classified as non-numerical and fall quite outside the coverage typically found in civil engineering curricula.

The challenge is to introduce into our structural engineering courses the many less predictable aspects of design without sacrificing student’s understanding of the rational aspects -- those based on equilibrium and compatibility of deformations.

Structural Design and Its Three Bases of Knowledge

Successful design results from the skillful amalgamation of three quite different types of knowledge: (a) purely analytical approaches, (b) experimentally-based behavior models, and (c) non-computational factors.

Analytical approaches based on structural mechanics principles -- most of these approaches for calculating forces and displacements are based on equilibrium and compatibility of deformations for linear elastic structures; hence they are applicable to structures made of any material with an appreciable range of linear elastic response. Another distinctly different yet rational approach is “limit design” which assumes linear elastic-fully plastic material behavior; full implementation of this method requires input from the second category of knowledge discussed immediately below. Nonlinear analytical methods are increasingly available to account for geometric and/or material nonlinearities.

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Experimental observations generalized into behavioral models formulated to provide predictions by the structural engineer -- this part of the design spectrum is critically important to designers of concrete structures, given the highly nonlinear nature of concrete as it shrinks, cracks from applied forces and environmental actions, and then experiences significant time-dependent deformations for many years after construction is completed. These behavior models utilize simplified models of how materials (e.g., concrete and steel) respond to load. They form the basis for equations used to predict flexural, shear, and torsional strengths of reinforced and prestressed concrete members, as well as for calculating splice lengths, slab strength, frame connection strength, moment redistribution effects, beam-column behavior and long column effects, strut-and-tie models, displacements, and most other topics covered in books on reinforced and prestressed concrete.

Factors critical to any project -- functional planning, economics, aesthetics, environmental effects and serviceability, architect-engineer-builder-owner interactions, the construction process, social and political issues, operations and maintenance plans, etc. Holgate calls these the “non-computational factors”. From the perspective of the owner, these factors are often far more important than calculation of forces or predictions of strengths and displacements. Addressing these issues is normally the responsibility of a team of individuals coordinated by an architect (for building projects) and by a civil or structural engineer for other projects such as bridges, dams, heavy industrial facilities, etc.

Civil engineering students should be familiar with the fundamental differences between these three types of knowledge and how each complements the other in structural engineering practice.

Do Young Structural Engineers Have the “Right Background”

The breadth and depth of course coverage in civil engineering programs have been debated “ad nauseum” for many decades. The issues are simple to state but very difficult to resolve. There is always more to teach than time permits, particularly when an ever-expanding list of important topics need coverage. These topics include computer science, materials science, probability and statistics, systems engineering, environmental issues, construction, costs and economics, and the like. We also want our students to be more cognizant of relevant social issues and of the aesthetic impact of constructed facilities, as well as having strong communication skills and a reasonably broad background in humanities and the arts.

A crucial issue is to decide how much to accomplish in the undergraduate curriculum and how much to achieve in subsequent graduate study, continuing education, or on-the-job training. Opinions vary widely on this issue, of course, and only a few of them can be presented here.

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Warren (4) comments in some detail on preparation of civil engineering undergraduates who are heading to careers in structural engineering. This study was done under the auspices of the National Council of Structural Engineer Associations to provide a basis for recommendations for possible separate professional certification (registration) requirements for structural engineers. He says: "Undergraduate preparation should include all the basic structural materials, analysis procedures and foundations. Education requirements for certain specialty certifications should include all base certification requirements and graduate level courses in advanced design of steel, concrete (including prestressed concrete), computational structural analysis, soil dynamics, structural dynamics and structural stability analysis. Perhaps this could be achieved with a Master of Science Degree from a recognized engineering program that included the completion of specific recommended coursework".

A quite different perspective on expectations for entry level engineers was presented at the CEO Forum at the 2001 ASCE Conference in Houston. Consensus among these distinguished individuals was that civil engineering curricula have too much emphasis on the technical side, and too little on such topics as communications (both written and oral), practice in team efforts, thinking critically, instilling a willingness to work hard and have the right attitudes, development of confidence to undertake new assignments, and creativity. Given that these individuals were operating at the upper levels of their companies, their comments were not at all surprising.

Weingandt in *Modern Steel Construction* (5) has written a rather provocative article on whether or not structural engineers have the appropriate education and training to serve as leaders of design or design/build teams. He reports that some individuals feel that the high degree of specialization needed in leading-edge structural design leaves too little time for broadening one's knowledge base or for refining the management and people skills needed in positions of leadership. Although structural engineers often are the team leaders on jobs primarily structural in nature, they seem to be quite scarce in many top level positions such as in leading the largest construction projects or heading up large public or private agencies.

Weigandt says "If current trends continue, narrowly focused structural engineers will be pushed into the background more and more. They'll be treated as highly specialized technicians. And fewer of them will head design/build teams."

He concludes with this challenge to the structural engineering profession -- "To lead rather than be led demands that young structural engineers, especially those who want to expand their horizons, be more broadly trained and aware of all the other engineering and architectural systems that make up the total building package -- and encouraged to hone their leadership, communications, and people

skills to the highest level possible”.

Thus we have, as always in other discussions of what should be taught in civil engineering curricula, a full spectrum of views ranging from narrow specialization to broad engineering and beyond to management skills. It becomes obvious that the education of a structural engineer (or any engineer) must be a life-long process, with some portions formal, some informal, some on-the-job, and some by self-study, reading and simply satisfying one's curiosity about the world we live and work in.

Professional Registration Issues

The National Council of Structural Engineer Associations (NCSEA) passed a resolution in September 2000 to establish a standing committee on Structural Engineering Certification, with the charge to develop a model for the establishment of a “Professional Certification Program for Structural Engineers” to be implemented by NCSEA. The committee is in the process of formulating a vision for structural engineering. A summary of this effort was reported by Williston Warren IV in *Structure* (4). He points out that in the U.S. there are some 55 separate jurisdictions that regulate the practice of structural engineering. Individual states establish minimum licensing requirements based on widely varying criteria. Quoting Warren, “This has resulted in states having general civil engineering practice licenses, general professional engineering practice licenses, specific structural engineering practice licenses, and multi-tier civil and structural engineering licenses. In addition to the licensing models that differ on a state-by-state basis, there are differences in examinations, professional conduct administration, and standards of practice.” NCSEA proposes to eventually reach national certification for the practice of structural engineering with the goal of producing “a uniform criteria by which structural engineers are evaluated and licensed”.

The proposed conceptual model for certification would consist of general structural engineering certification supplemented by specialty certification “to address areas of practice requiring additional levels of education, experience and examination. . . . examples that might fall in this specialty certification category are specialties in the design of bridges, cold regions, long span structures, soil-structure interaction, special vibrations, and essential structures”. The specialty certifications could be obtained by some combination of additional education, training, and experience and appropriate examinations.

NCSEA also suggests the possibility of coordinating and offering a formal training program for recent college graduates. Seminar programs would be available on the complete spectrum of structural engineering material, with content including those topics typically not covered in university curricula along with review of material considered crucial to the practice of structural



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engineering. ACI should consider its possible role in such a training program. The Institute would come to such discussions from a position of considerable strength, given our rich base of knowledge and solid reputation for high quality publications and seminar programs.

CURRICULAR CONTENT

The challenges are formidable ! Over the past several decades, the structural engineering and materials coverage in typical undergraduate civil engineering curricula have been “pared down” to permit coverage of more science, more humanities, and new engineering topics. And these additions been done within the context of fewer courses required for the degree. In the typical CE curriculum, we’ve experienced increasingly sophisticated elastic analysis and a decreasing amount of coverage of concrete as a material, while maintaining a reasonable level of effort on studying the behavior and design of members. Coverage of connection behavior and design has decreased in many programs. Over the same time period, structures have become substantially more complex, high strength concrete has emerged as the material of choice for many applications, design procedures have increasingly been based on inelastic behavior of concrete members and connections, time allotted for construction continues to shrink, and a new discipline of engineered rehabilitation and repair has developed. The challenge is to devise strategies to do better in our engineering curricula.

It is obvious that all these topics cannot fit within the typical undergraduate civil engineering program.

ASCE now advocates the Master’s degree as the first professional degree for civil engineers; should we be doing our curricular planning based on the assumption that this will become reality in the near future, and that we can “count on” having 5 years to educate tomorrow’s young structural engineers ? How much of an engineer’s formal education should be delayed beyond college, with a much higher utilization of continuing education (including use of the rapidly evolving distance learning via the Internet)?

We should strive to make improvements in a number of key areas, including (a) conceptual design, (b) simple methods for estimating loads in members, (c) preliminary design, (d) design of the entire structure, (e) connections, (f) variability in loads and in material properties, (g) the proper role of analysis in design and the effects of modeling assumptions on analysis results, (h) materials aspects, (i) integration of materials selection and behavior into structural design and analysis processes, (j) achieving economies in teaching analysis and design fundamentals, (k) constructibility and feasibility, (l) identification and control of errors encountered in design and construction, (m) aesthetic impact of our

structures, (n) sustainability and environmental effects of concrete construction, and (o) life cycle costs and maintenance plans and operations.

Conceptual Design

Most of the readings assigned to undergraduate students in structures course deal with pre-defined structures with little or no discussion as to how each particular structure was selected to meet the design requirements. While the selection of structural types and forms often requires the expertise of an architect (particularly for buildings), the structural engineer should be well-versed in the fascinating subject of conceptual structural design, where multiple schemes are conceived for a given design situation and then evaluated for consideration for preliminary design calculations.

Several fundamental structural engineering topics can be covered in lectures and problem assignments on conceptual design, including:

- a. force transmission and flow of forces for both gravity and lateral loadings.
- b. basic methods of resisting forces with axial members acting in tension or compression, bending members acting in flexure, combined-action members, and surface structural elements such as slabs and shells.
- c. typical feasible span lengths and general proportions for the many typical forms used in reinforced concrete structures, such as frames, arches, cable-supported concrete decks, walls, slabs, folded plates and shells, etc.
- d. example structures, both simple and “monumental” that illustrate these principles.

These topics should be presented initially in perhaps 2 lectures, and then expanded on later in every structures course offered, particularly topics (c) and (d), with visuals livening up the lectures. Problem assignments can be a mixture of individual and group assignments, with brief oral reports by students to present and defend their choices of structural forms and concepts.

The decision-making leading up to the final geometrical form for a given structure represents the highest level of structural engineering practice. Although much of this topic must be learned on the job, I believe that it is important to provide more coverage at the undergraduate level. The inherent motivational value alone makes this worthwhile; at the same time, it provides an excellent counterpoint to the considerable calculation-based material taught in structural engineering courses.

Simple Methods for Estimating Loads in Members and Preliminary Design Approaches

I believe that we must teach more preliminary design approaches, which includes

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simple methods for estimating loads in members (slabs, beams, columns, etc.) and then establishing sizes and approximate reinforcing for these primary components of any concrete structure. Even a modest coverage of approximate preliminary design can have a profound effect on the way students think about structures. With this knowledge they can establish initial proportions and dimensions of any structure without having to resort to complex and time-consuming structural analysis. This gives them a start on developing “structural intuition” and adds a new sense of confidence to deal with real structural design.

I will draw an example from an undergraduate reinforced concrete structures course I taught two years ago at Cornell in a classroom in Hollister Hall, a late 1950s reinforced concrete building with rather sizeable span one-way slabs supported on beam-and-column framing. I gave an assignment during the very first lecture -- to determine the approximate quantity of reinforcing steel needed at the center of the multi-span reinforced concrete beam spanning over the classroom. I provided the design live load intensity, load factors for dead and live load, slab thickness, and reinforcement yield strength, while spans and column dimensions were measured by the students.

Many students struggled with this assignment, of course, as they decided on load transfer paths, made meaningful estimates of bending moments, and modeled the beam behavior by the internal couple approach with an estimated location of the compressive force resultant in the mid-span section of the T-beam. I believe that this exercise, which produced results with an accuracy that surprised the students, was an extremely valuable part of the course and made later lectures much more meaningful, particularly for topics such as flexural strength and the calculation of moments and shears in reinforced concrete frames.

Instruction in preliminary design and approximate analysis should begin as early as possible, using appropriate examples and homeworks. Subsequent courses should keep coming back to this topic. The sketching of approximate deflected shapes and location of inflection points, along with simultaneous sketching of approximate bending moment diagrams provides a real learning experience for students.

I advocate allocating at least 25% of the total time spent in teaching analysis to determining approximate forces. The ability to quickly calculate approximate forces in any structure is also an absolutely necessary skill in checking the results of computer-based analysis and design.

Design of the Entire Structure

We must provide more emphasis on design of the entire structure, including the critical process of selecting the basic structural type to be used, and how the

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structural elements are connected. Perhaps the best way to accomplish this is to have a substantial portion of the total problem set assignments in the form of open-ended problems -- rather simple structural situations at the undergraduate level and much more comprehensive and realistic projects at the graduate level. An example from the author's own undergrad concrete structures class follows:

"Working in teams of 3 engineers, we will be designing selected portions of a three-story general-purpose academic building with a footprint of 5000 square feet and a total gross floor area of 15,000 square feet, to be located in the current parking lot behind Thurston Hall. The building is to have a full basement, a freight elevator, and two sets of stairs. In this first assignment, you are to propose a typical floor framing plan (location of columns, definition of slab spans and supporting beams and girders). Clear height between top of floor and lowest part of underside of floor framing above is to be 10 feet. Live load is to be 125 psf (conservatively selected to permit changing use of the building space by different groups). Material strengths are to be selected by each team." In subsequent assignments the building design was refined, with final design being completed for all typical elements of the building, including foundations.

Further discussion on designing the complete structure is given below after materials instruction is discussed.

Connections in Concrete Structures

Member design has become increasingly "computerized" and this tendency will undoubtedly continue to grow as software becomes more sophisticated and readily available to engineers in firms of all size. But the joining of members remains a more elusive design function because determination of relevant forces and their effects is so much more difficult. Also, the adoption of higher strength concretes accentuates this situation because members get smaller and congestion of reinforcement and construction issues can be a real problem.

Frame joint efficiency, particularly for joints subjected to moments that open the joint, is not at all obvious to students. The dramatic effects of reinforcement location and bend patterns can be treated well in a single lecture.

The introduction of the strut-and-tie modeling approach into the ACI 318 Code (6) provides a more rational basis for many connection designs. It is important that this topic receive at least some coverage at the undergrad level and considerably more in graduate level concrete structures design courses.

Treating Variability in Loads and in Material Properties

We (the faculty) have traditionally placed strong emphasis on calculating member forces (axial, shear, bending, and torsion) to what appears to the student to be a

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high level of accuracy. The elegance of the calculation processes tends to overpower what really happens in an actual structure. In the vast majority of structures, we simply do not know load magnitudes very well. Students deserve to get better explanations of the approximate nature of design, including the high variability of live load values and the real-world variability of material properties. We also need to do a much better job of explaining how poorly-defined effects such as shrinkage, support movements, unexpected restraining forces, and the like can introduce very substantial changes in the stress resultants experienced by the actual structure.

How can we do this without having students think that “sloppy” calculations are adequate? An obvious starting point is to never use more than two significant digits in expressing any final design calculation result. Our textbooks, journals, and other publications routinely have moment values expressed in as many as 8 digits, and deflections to as little as 1/100 of an inch. We should provide more insight for students into the accuracy of the parameters going into bending moments -- the loading intensities, the “real” span lengths, and the coefficient K in the denominator of $M = wL^2/K$. Quoting “precise” values are misleading, particularly for short-term deflections of concrete structures where we do not know E values and the state of actual cracking makes the calculation of moment of inertia values very difficult at best. Add to this the problem of shrinkage and creep deflections and the situation gets even worse. Any coverage of deflection calculations for concrete structures should include presentation of predicted and measured deflections for both beams and slabs. Only these direct comparisons of theory and reality can drive home to the student the fragility of our ability to predict deflection behavior.

Role of Analysis and Defining the Effects of Modeling Assumptions on Analysis Results

The proper role of analysis in the design process needs better definition. We need to continually stress that the prime role of analysis is to improve design and hence improve the overall quality of the completed project. Student attitudes on any subject correlate well with faculty attitudes. There is far too much separation of analysis and design in academia; often we see one group of faculty teaching analysis and another group teaching design. A solution is pretty obvious! However, if tradition or some other reason still dictates that separate courses be given, then it is essential to have some modest coverage of the behavior of steel and concrete structures prior to teaching analysis, in order to have realistic and meaningful discussions on effective stiffness of members and behavior at loads beyond the proportional limits.

Effects of assumptions on types of supports, boundary conditions, foundation stiffness, and the like need to be integrated into the lecture material and in the problem assignments. Students too often begin to think that supports are either

hinged or fixed, and that building frames stop at ground level. Fundamental concepts on foundations should be integrated into the structures classes, with continual linkages between courses in structures and in soil mechanics and foundations. Another issue needing more attention is the influence of degree of concrete cracking on displacement calculations.

At the upper-class level, and in graduate education in structural engineering, we need to convey the sensitivity of results (forces and displacements) to the modeling assumptions involved in the analysis, particularly the more complex problems that utilize finite element approaches. Behavior beyond the elastic limit is particularly sensitive to material properties, mesh fineness, and load increment size. An effective approach is to have students (or teams of students) model and analyze the same structure, using the finite element approach, and then compare results and critically discuss the effects of different modeling assumptions.

The Materials Aspects

As evidenced by the generally deteriorated state of a sizable portion of our infrastructure, we have an urgent need for the development and employment of better materials for constructing new facilities, as well as improved materials for use in repair and retrofitting. Just as we need more coverage of materials, the typical U.S. civil engineering department has reduced the time given to traditional construction materials, particularly to understanding the complexities of concrete, soils, and rock. Several issues are involved -- the pressure to reduce required hours for graduation to ensure that most students finish in four years, the desire to cover new materials such as plastics, and the gradual reduction in laboratory sessions to reduce costs.

The difficult problem we face in providing the proper coverage on construction materials is well illustrated by considering the Civil Engineering Research Foundation (7) statements on high-performance construction materials and systems, expressed in terms of the long list of desirable characteristics of infrastructure performance. These characteristics include (a) superior strength, toughness, and ductility, (b) enhanced durability/service life, (c) increased resistance to abrasion, corrosion, chemicals, and fatigue, (d) initial and life-cycle cost efficiencies, (e) improved response in natural disasters and fires, (f) ease of manufacture and application or installation, (g) aesthetics and environmental compatibility, and (h) ability for self-diagnosis, self-healing, and structural control.

How do we possibly do justice to this complex set of concrete material characteristics which goes so far beyond the typical mechanical properties we've always covered in undergraduate courses? How do we get young practicing engineers educated to the point where they can make informed decisions on choices of materials for each new project they work on? All of this cannot be

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done in the typical B.S. degree program, but at the same time we must educate our students to be sensitive to these issues (particularly durability) and to be motivated to continue learning about materials as an integral part of improving their design skills.

We also must have some coverage of advanced composite materials consisting of strong fibers (glass, Kevlar, carbon) embedded in a resin matrix. These materials have already found substantial use in construction and in retrofitting projects, and they have excellent potential for becoming an important construction material. But their properties are much different from those of traditional civil engineering materials; similarly, design approaches may well be quite different than for, say, steel and concrete. We must provide young engineers with the opportunity to become proficient in designing and building with advanced composites, including both reinforced and prestressed concrete and the entire array of repair and strengthening applications.

A number of formidable educational tasks must be addressed that go far beyond undergraduate course work. Programs are needed for several quite different user groups -- undergraduate and graduate engineering students, engineers in practice, materials suppliers, construction workers, quality control personnel, etc.

Integration of Materials Selection and Behavior into Structural Design and Analysis Processes; the "Capstone" Design Experience

The specification of proper materials, and the integration of pertinent material properties into all phases of the analysis and design process, may well be the most critical steps in arriving at a durable, top-quality constructed facility. While the emphasis at this symposium is on concrete structures, it is a fact of life that the majority of constructed facilities utilize several materials, including concrete, masonry, steel, timber, and perhaps plastics. Academia has been less than stellar in helping students think broadly about materials selection, given that we tend to have quite separate courses on concrete and steel structures, with much less coverage of masonry and timber structures in most civil engineering programs.

As an example of how most designs incorporate two or more primary construction materials, many modern high-rise buildings now utilize some type of composite (hybrid) framing to carry gravity loads and lateral forces (wind and seismic). Composite construction utilizes concrete and steel, each to its best advantage, providing a fire-resistant, economical structural system that is fast to construct and provides substantial stiffness to resist lateral drift. The extensive activity in composite construction (8) is expected to continue, with an ever-increasing usage of high strength concrete and high-performance structural steel, and with extensions to buildings of medium and moderate height. One of the

greatest challenges in designing and building a high-rise composite framed building is developing a strategy that will guarantee reasonably flat floors after time-dependent deformations in the columns have essentially stabilized. This requires a level of knowledge about the concrete in the columns that far exceeds what we typically know about concrete in the usual structure.

I suggest that the first course in structural engineering include an abbreviated coverage of the primary issues met in designing and building with a variety of materials (concrete and steel as a minimum), with subsequent courses having more detailed coverage on individual materials, and perhaps the final course going back to “general design” where students must make decisions on which material(s) to use. This type of course is also called “capstone design” and is used widely in civil engineering programs across the country. A good example is the course at Purdue University, started in 1960 and continually refined and improved over the years. A summary of the course was presented by Drnevich at the Third National Congress on Civil Engineering Education (9). He summarizes the course objectives: “By the end of the course, the student will be able to:

1. Integrate the technical subdisciplines of civil engineering, develop criteria for design, and perform trade-off and alternatives analyses to produce cost-effective solutions,
2. Gather relevant data, have discussions with the clients, identify and use applicable regulations, codes and other information.
3. Communicate site analyses, work programs and engineering design detail to both technical and non-technical customers.
4. Do integrated project planning, scheduling, and cost analysis for a moderately-sized civil engineering project.
5. Perform a reasonably detailed design to meet customer requirements, using, where appropriate, software and computer techniques to satisfy design objectives and to prepare requested construction documentation, and
6. Work more effectively on a multi-disciplinary team.”

Achieving Economies in Teaching the Fundamentals of Analysis and Design

Economies in coverage can begin early, say during the teaching of mechanics of materials, where problems should be designed to illustrate practical situations, with later courses building directly on the mechanics coverage. I believe we spend more time on flexure than is really needed; it is a “comfortable” topic with experimental results agreeing very well with basic assumptions and simple calculation methods. Teaching flexure from the standpoint of two internal forces (C and T) separated by an internal moment arm provides a fundamental basis that can be then readily adapted to any material and to both elastic and inelastic behavior. This approach also helps in teaching shear, with horizontal shear stress resulting from differential values of either C or T along the beam axis. Emphasizing the internal couple facilitates better understanding of prestressed

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concrete flexural members, where the values of internal force resultants remain nearly constant under changing loads, while the effective internal moment arm increases.

Hard decisions must be made on what displacement-calculation methods to teach; we simply cannot be encyclopedic in coverage. Virtual work is the most general; if a student understands virtual work concepts and how to apply them, then he or she can solve any displacement problem. I also like students to know the moment-area method for quick and relatively error-free calculation of displacements of simple structures.

Structural analysis procedures can be some combination of stiffness-based computer methods and a thorough coverage of approximate analysis utilizing assumed points of inflection. The teaching of moment distribution has “fallen by the wayside” in many curricula. I still like to have students know how to do beams and frames (without sway) by moment distribution, not only because it is a very good method to get answers but also because it illustrates so convincingly the dependence of bending moments on flexural stiffness.

Construction and Constructibility

Construction engineering and construction management are disciplines by themselves and certainly extend far beyond the conventional undergrad civil engineering curriculum. But their importance in arriving at a successful, high quality constructed facility cannot be overstated. Courses in construction engineering and management, with substantial systems engineering content, should be available to the civil engineering student. This might include a simplified, motivational version at the freshman level, followed by an upperclass course or two containing strong coverage of construction methodologies, costs, and bidding strategies. Construction projects, particularly the larger ones, are wonderful examples of applied systems engineering, with high potential for creating a sense of excitement for students. Case studies of outstanding projects should be used in regular structures courses.

Constructibility needs to be integrated into all structural design and project courses. As we blend these ideas into our courses, we also need to find ways to transmit the philosophy and thought modes involved in the successful execution of any construction project. The bottom line of most of our efforts is the realization of constructed facilities, a fact that we sometimes tend to forget as we get so involved in the niceties of analysis and advanced design methodologies.

Identification and Control of Errors Encountered in Design and Construction

Students at both the undergrad and grad levels should have a reasonable level of understanding of errors in design and construction. They need to appreciate the

most common types of errors and mistakes as well as their potential impacts on safety and serviceability. Civil engineering students should receive some formal training about error control in the office and in the field, particularly on strategies for checking calculations, drawings, and specifications. A small volume published by ASCE (10) contains a wealth of useful information, including some highly practical material contributed by practicing structural engineers. The paper by Dr. Franz Knoll provides a systematic, rational approach to definition of errors and mistakes and how to best develop methods to control them. He categorizes errors and mistakes in both design and construction, and describes the assignment of probability of occurrence and then the likelihood of serious consequences when each type of error does occur. He suggests establishing priorities for combatting error effects by considering the weighted product of probability of occurrence and likelihood of serious consequences.

This topic can be introduced part-way through a design course in a single lecture. Supplementary selected readings and a homework exercise done with teams of 3 students, followed by group discussion of the homework results, further reinforce this important topic, which should be revisited systematically in subsequent courses.

Cultivation of a Sensitivity about the Aesthetic Impact of Everything We Design and Build

Although space limitations prevent any significant discussion of this topic, it is appropriate to comment on the fact that there are far too many poorly proportioned, poorly detailed, and downright ugly structures in every corner of the world; at times they tend to outweigh our many elegant and graceful structures. We must be more sensitive about aesthetics and the fact that most civil engineering “products” are out in the open, to be seen by hundreds of millions of people each and every day. It is also an unfortunate fact that many buildings classified as “ugly” by the average observer were designed by architects, not engineers.

Even if an engineering instructor has no formal training in architecture, it seems worthwhile to encourage students to discuss how they feel about the appearance of those case study structures used in lectures and readings. Relationships between form and function and simplicity of structural systems should be included in those lectures given on conceptual design. Ref. (3), the ACI volume on concrete bridge esthetics (11) and the books by Billington (12,13) are excellent sources for lecture background and for student reading assignments. Bringing in outside speakers and having students attend “outside” lectures on campus are also good techniques to cultivate sensitivity to aesthetics. And students should be advised carefully on their selection of humanities electives, with encouragement to take some courses in the visual arts and art history, architecture, and the like.

Sustainability and an Understanding of the Environmental Effects of Concrete Construction

Sustainability in construction receives considerable press these days. Michael Dickson describes the issues very well in his essay "Touching the Earth Lightly" (14). He says; "Construction without depletion is not just a convenient style for altruistic developers. Rather it is a movement that is gathering pace, driven by compelling reasons: the current, relatively low cost of primary energy and the unrestricted use of irreplaceable materials can no longer be sustained indefinitely. Because the issues are complex, and different for each building type, the language of 'green' architecture with high comfort and low environmental impact needs to be expanded immediately -- otherwise through our activities as a species we may overload the planet."

Dickson concludes with: "Sustainability in the built environment requires multi-disciplinary and inter-disciplinary work; it needs to be applied in all cultures, climates, and geographical locations; it calls for an ethical stance and, very often, the confidence to depart from the norm. This is perhaps our greatest challenge as responsible engineers -- to test our limits, to question our solutions, to risk our reputations in order to save our planet. At the same time a better process will also create a better asset for the client, for the user and for subsequent generations."

For too many decades we've regarded concrete structures as "permanent", while at the same time spending excessively on repairs, rehabilitation, and premature demolition. This is not a proper use of our natural and financial resources. We now know enough about materials and construction practices to eliminate most of these problems, but it will take new levels of technical effort along with a continuous commitment to achieving a defined service life. Our current students will be the generation most directly charged with these responsibilities, so it is essential that they be exposed to the ideas and concepts and that they are in the proper position to build up their expertise in the many issues of sustainability and service life definition and extension.

A suggested format for one or two lectures is provided by Mehta (15) in a paper on concrete technology for sustainable development. He defines and discusses three crucial elements needed for an environment-friendly concrete construction technology: (a) conservation of concrete-making materials, (b) enhancement of durability of concrete structures, and (c) a paradigm shift from reductionistic to holistic approach in concrete technology research and education.

Mehta has more specific recommendations in a second paper (16) on reducing the environmental impact of concrete. He points out that the annual world production of 1.6 billion tons of cement produces about 7% of the carbon dioxide

going into the atmosphere (one ton of carbon dioxide for each ton of Portland cement clinker produced). Environmental effects from the mining and transportation of limestone and clay needed to make cement can be quite severe, and the mining, processing, and transportation of aggregates for concrete construction involves some 10 to 11 billion tons of sand, gravel and crushed rock each year. And, we need roughly 1 trillion liters of fresh mixing water to produce the world's concrete each year.

Mehta offers several suggestions for reducing environmental impact of concrete construction: (a) conserve Portland cement by using blended cements containing large amounts of pozzolanic and cementitious by-products such as fly ash and granulated blast-furnace slag, (b) conserve aggregate by judicious use of demolition waste (old concrete rubble and masonry which is now generated at the rate of roughly 1 billion tonnes per year) for the coarse aggregate in concrete, and dredged sands and mining wastes for the fine aggregate, (c) reduce the volume of fresh potable water by better aggregate grading, by using more admixtures and superplasticizers, and by using recycled industrial waters and even brackish waters for some applications, and (d) by making new concrete structures more durable by stepping back from the modern practice of making concrete gain strength very quickly by using too much Portland cement with high-early strength properties.

Defining True Life Cycle Costs and the Need to Plan for Maintenance and its Costs

Getting students involved in sustainability issues creates a natural path into treatment of true life cycle costs, life extension methodologies, and the need for a carefully planned and implemented maintenance program for all structures. As a minimum, these issues need basic definition and then illustration with a few case study examples distributed over several courses. The available literature on these topics is growing by leaps and bounds, particularly in the form of conference proceedings.

PROFESSIONAL DEGREES BEYOND THE B.S.

We need to supplement our many fine B.S. programs with more professional education programs to produce engineers with the type of technical background that just cannot be achieved in a four year B.S. program. The Master of Engineering (M.Eng.) model has been used for more than three decades at Cornell University, in nearly all branches of engineering. The M.Eng. degree is inherently different from Master of Science programs, with heavy emphasis on design, no research components, and strong involvement of practicing engineers in helping teach design. Programs with similar goals are offered at many other

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schools. In the Structural/Geotechnical Engineering M.Eng. option at Cornell, about 80% of student effort during the intensive 9 month program is spent in taking graduate level courses in civil engineering topics (including advanced materials courses) and in supporting disciplines such as management, labor relations, architecture, and the like.

The other 20% of the total effort is a comprehensive design project -- the cohesive element that most sharply defines the program. The design project provides students with a rich experience in open-ended preliminary design and in formulating and modeling real structural systems. It provides them an opportunity to work in guided team situations with students from several different concentrations (typically structures, geotech, and management), with constant stress on constructability, practicality, and economics, and in close contact with eminent practicing professional engineers who bring the design projects to campus. Conceptual and preliminary design is done in the fall semester, followed by a full-time three-week final design period in January, and a formal, public presentation in February covering financial feasibility, design results, and construction planning and costs.

Practicing engineers have been exceptionally generous in donating their time and talents in bringing projects to the Cornell campus and then returning repeatedly to work with students and faculty. They also like to hire the M.Eng. graduates. And added benefits include informal talks to undergraduates by the visiting engineers, along with undergraduate attendance at presentations given by the M.Eng. students.

ASCE's decision that the Master's degree should be the first designated civil engineering degree, and thus serve as the entry point into the civil engineering profession, has received considerable discussion, both pro and con. The basic concept is fine, I think, because it is very difficult to argue against the considerable additional knowledge gained during this intensive advanced study. But I have trouble with requiring everyone to follow this path. Some students may be better off pursuing additional graduate studies on a part-time basis while working, either at a local campus or by internet-provided programs. Some need the maturity and direction provided by getting into the full-time job market after getting their B.S. degree; those who follow this path and then come back for the M.Eng. degree always do exceptionally well in their graduate studies. Others may choose to supplement the B.S. in civil engineering with a degree in business or management. So my personal position is to enthusiastically recommend the 5th year, but not require it.

CONTINUING EDUCATION; THE INTERNET

The audience for continuing education spans a broad spectrum, ranging from

construction personnel to highly experienced designers. The offering of short courses and seminars to civil engineers has been a “big business” for some time. Most typically, teams of professors and practicing engineers prepare and present these materials to an assembled audience at locations around the country. But the available delivery mechanisms are expanding! The rapidly evolving distance learning opportunities afforded by the Internet will have a major impact on education at all levels. For example, the popular masonry design seminar put on by ACI in various cities has been converted into a high-quality format for distribution on the internet and is now available from the ACI Website, as is the course on fiber-reinforced concrete. These offerings will be followed by a host of other “concrete education” offerings on the web by ACI and other technical groups. They could have a strong central position in the wider group of structural engineering educational modules envisioned by the NCSEA as discussed in an earlier section of this paper.

More publications directed specifically at materials technicians and construction workers are needed. These must be highly specific, brief, and in the right language. A specific example might be a half-hour explanation, along with a single sheet of text, on handling and placement of high-strength concrete containing silica fume and other admixtures. ACI has developed such a “tool-box series” of publications on a number of construction techniques, involving both regular and high-performance materials.

Designers, material specifiers, and contractors must have ready access to material properties and related data on the performance of each new material. As stated so well in the CERF publication (7), “To transmit the benefits of high-performance construction materials and systems to all potential users, we must make reliable data about composition, properties, and performance available to owners, designers, contractors, and the construction community.”

As an example of what might be done, one of the information transfer mechanisms envisioned by the CONMAT concrete group (15) is the establishment of a computer bulletin board with detailed data on properties and behavior of HPC, directed to designers, architects, ready-mix suppliers, contractors, facility owners, and researchers. This would provide, on a 24/7 basis, a powerful new tool for enhancing the use of high-performance materials. However, it is crucial that common formats for data be agreed on, and that the on-line electronic data base system be well-designed, user friendly, and properly integrated. International agreements on formats, methods of updating, etc. are needed.

SUMMARY AND RECOMMENDATIONS

This paper has delved into a host of topics related to educating civil engineers for

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a career in structural design, with strong emphases on concrete structures. The end goal of these educational efforts is to produce engineers who are equipped to ensure that society has the very best structures and facilities, as measured from the multiple standpoints of functionality, safety, aesthetics, durability, serviceability, minimal impact on the environment, and total life cycle cost.

The paper began with a review of structural design issues, the three basic types of information needed in design, the right background for new graduates, and implications for professional registration. Numerous suggestions for curricular content were then made, along with extended discussion on the many non-calculational aspects of successful design and project implementation. Some specific recommendations include the points given in the next three paragraphs.

The technical aspects of college curricula must remain rigorous while at the same time we find ways to streamline coverage of these essential topics. Additional emphasis needs to be given to approximate analysis and preliminary design, and to the materials aspects of concrete. Strong ties to the real world of construction are essential to help the student develop a sense of what's right and what's wrong, a feeling of confidence in his or her efforts, and skills in constructibility. Teamwork and communications need to be included at every level of student effort. More of the teaching of design should be done with the direct assistance of practicing professional engineers who can provide actual project situations, with real constraints and conditions.

Visiting engineers should have informal meetings with students to discuss recent projects and to comment on life in the design profession. Likewise, materials suppliers, construction companies and precast suppliers can take an active role in enriching education, including hosting field trips to illustrate the many aspects of the real world that cannot be taught effectively in the classroom/lab.

Education beyond the B.S. should be made available to all who want it, using a variety of formats including (a) the Master of Engineering degree or practice-oriented M.S. programs, (b) conventional continuing education via attendance at conferences, short courses and seminars, and (c) Internet-based learning with modules, seminars, and courses on topics spanning from basics of concrete mix design on through design, repair and retrofit, and structural design.

What can we, as members of ACI, do to help improve the teaching and learning processes? In addition to some of the activities suggested above, we all need to take a much more proactive role in "preaching the gospel" about the unlimited opportunities in expanded usage of improved cements and concretes. Everyone can get involved, and working together, we will have a major positive impact on improving education.

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