A Capstone Course for Reinforced Concrete Buildings

Bridging the gap between academia and practice

by David A. Fanella and Michael C. Mota

Students in structural engineering programs at universities and colleges are taught the fundamentals of analysis and design. While it is safe to assume that most graduates are proficient in designing individual structural members for a given set of loading conditions, many probably do not have a solid understanding of how those members are integrated within a complete structural system. Some graduates may have had the opportunity to take a capstone course during their final year of study, however, and this allowed them to apply the knowledge they acquired in their previous classes to a multifaceted assignment. Their capstone course thus served as a culminating academic and intellectual experience.

Upon graduation, students have many options, including attending graduate school, working for a contractor or developer, or taking a position at a structural engineering consulting (design) firm. The latter option has been and continues to be popular. However, students who choose to pursue a career in a structural engineering firm but who have not had any experience working at one (those, for example, who did not participate in an internship program) probably do not know exactly what they will be doing once they start their new position. The consulting world is a mystery to them, and the basic question they typically ask is: "Now what?"

As a response, the Concrete Reinforcing Steel Institute (CRSI) has created a capstone course that introduces students to life in a consulting firm. Real-world problems are solved in a group setting, engineering skills are enhanced, and practical topics, such as the creation of construction documents, are taught. In essence, the course helps bridge the gap between academia and practice.

A student who takes this capstone course will have an advantage over those who have not: Employers spend significant resources training new employees, so firms will value a recent graduate with the experience obtained from this course.

Course Overview

The CRSI capstone course is an opportunity for students to:

- Integrate and apply knowledge attained in engineering coursework on a broader scale;
- Practice decision-making and team collaboration skills; and
- Create and deliver the documents that are required for a structure to be built.

The students work with a set of architectural drawings for a real six-story hotel, so they will experience some of the same constraints they are likely to encounter in a structural engineering consulting office. At the completion of the course, the students will have acquired an understanding of:

- The overall stages in the design of a reinforced concrete building, thereby eliminating some of the mystery surrounding what they will be doing once they are working in a consulting office;
- How to economically design and detail a reinforced concrete building from start to finish;
- How to acquire resources that are available in every stage of the design process;
- How to produce construction documents for a reinforced concrete building (drawings and specifications); and
- How reinforcement is manufactured and how reinforced concrete buildings are constructed.

Course Level

The capstone course is geared to students enrolled in civil, structural, or architectural engineering programs and who have successfully completed undergraduate- or graduate-level courses in reinforced concrete design. Students are expected to possess basic skills in analysis and design of cast-in-place concrete beams, slabs, columns, walls, and foundations containing nonprestressed (mild) reinforcement. The students should also be familiar with national building codes and standards related to the design of these reinforced concrete members.[1,2]

ABET Objectives

The scope of this course addresses ABET objectives for student outcomes.[3] In particular, the course encourages students to:

- Apply knowledge of mathematics, science, and engineering;
- Design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability factors;
- Function on multidisciplinary teams;
- Identify, formulate, and solve engineering problems;
- Understand professional and ethical responsibility;
- Communicate effectively;
- Understand the impact of engineering solutions in a global, economic, environmental, and societal context;
- Recognize the need for (and an ability to engage in) lifelong learning;
- Recognize and participate in contemporary issues; and
- Use the techniques, skills, and modern engineering tools necessary for engineering practice.

Course Structure

The course is organized based on a 16-week semester, with two 75-minute sessions per week. It can easily be restructured for schools on quarter systems or that have other class durations.

The main goal is successful completion of a class project. Working in groups, the students are required to create a set of structural drawings, developed for a set of architectural drawings for a real building. To help accomplish this goal, numerous CRSI and ACI resources are made available throughout the semester. The design and detailing methods that are presented are applicable to buildings located in areas of low seismic risk (Seismic Design Categories A and B). Design and detailing methods required for buildings in areas of moderate or high seismic risk (Seismic Design Categories C and higher) are not covered.

During the first week, the major phases in a building project are covered with emphasis on the role of the structural engineer during:

- Predesign;
- Design;
- Preconstruction;
- Construction; and
- Postconstruction.

Also presented is the traditional organization of a project team and the interrelationships of the team members (Fig. 1). Other types of team organizations are given as well.

The major design and construction phases for typical building projects are also covered: schematic design, design development, construction documents, and construction administration. The course is basically structured around these phases. An overview of each phase and the corresponding weeks in the semester are given in Table 1.

During the schematic design phase (weeks 2 and 3), the students are given the architectural drawings of the building used for the class project along with the project data and assumptions. A partial plan of a typical floor in the building is shown in Fig. 2. Information on how to determine the applicable loads is also provided, and methods and resources are presented on how to achieve economical reinforced concrete buildings based on the three main components in any reinforced concrete building (formwork, concrete, and reinforcing steel). The students are provided with descriptions of the various reinforced concrete floor systems, and they are introduced to a tool that can be used to determine an economical reinforced concrete floor system for a given set of criteria.[4] This tool—the Reinforced Concrete Concept (Concept)—allows designers to conduct parametric studies to quickly obtain an economical reinforced concrete floor system for given span and load criteria. Sample output from Concept is shown in Fig. 3 for a flat plate system.

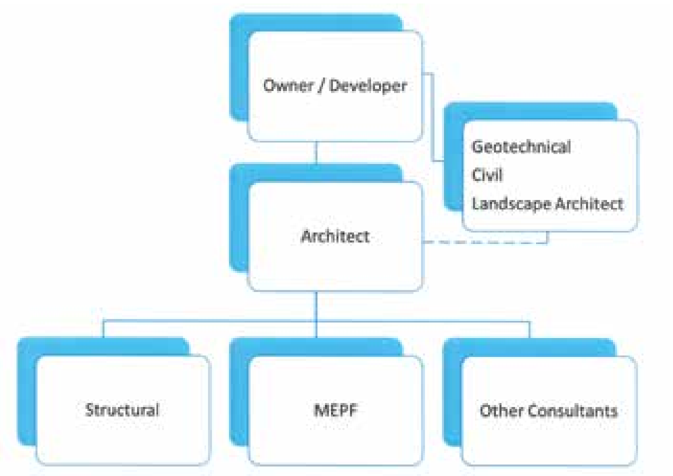

Fig. 1: Traditional project team organization

The design development phase is covered in weeks 4 through 7. A wealth of information is presented on how to determine preliminary sizes for the structural members in a building, along with an explanation of the importance of this preliminary information. Approximate methods of lateral analysis are covered for low-rise buildings, including an overview of diaphragms and how to determine the center of rigidity. The importance of establishing load paths in a reinforced concrete building is discussed, including load paths for wind (Fig. 4). Procedures used for the creation and organization of design drawings are also given. It is unlikely that students (other than those who have consulting office experience) are familiar with this topic. Finally, a sample

Table 1:
Capstone course structure

Weeks	Phase	Overview
2 and 3	Schematic design	• Architectural drawings are distributed and reviewed; • Project data and assumptions are provided; • A general overview of load determination is given; and • Methods and resources are presented on the economics of reinforced concrete structures and selection of an economical reinforced concrete floor system.
4 to 7	Design development	• Information is provided on how to perform preliminary designs of foundations, columns, beams, one-way slabs, two-way slabs, and walls; • Approximate methods of lateral analysis of low-rise buildings are covered, including how to determine center of rigidity; • Procedures on how to create and organize design drawings are given; and • A sample specification for reinforced concrete buildings is presented.
8 to 12	Construction documents	• Information is provided on how to economically design and detail foundation systems, slabs-on-grade, columns, walls, flat plates (including diaphragms), and beams; and • Methods are presented on how to transfer design and detailing information for each type of structural member to the structural drawings (that is, how to create plans, sections, details, and schedules).
13 and 14	Construction administration	• Information is given on design and construction processes, production and fabrication of reinforcing steel, and placing and field considerations of reinforcing steel; • The construction sequence of reinforced concrete buildings is presented, which includes a discussion on forming systems; and • Duties and responsibilities of the structural engineer during the construction administration phase are covered, including review of placing drawings, responses to requests for information, and periodic site visits.

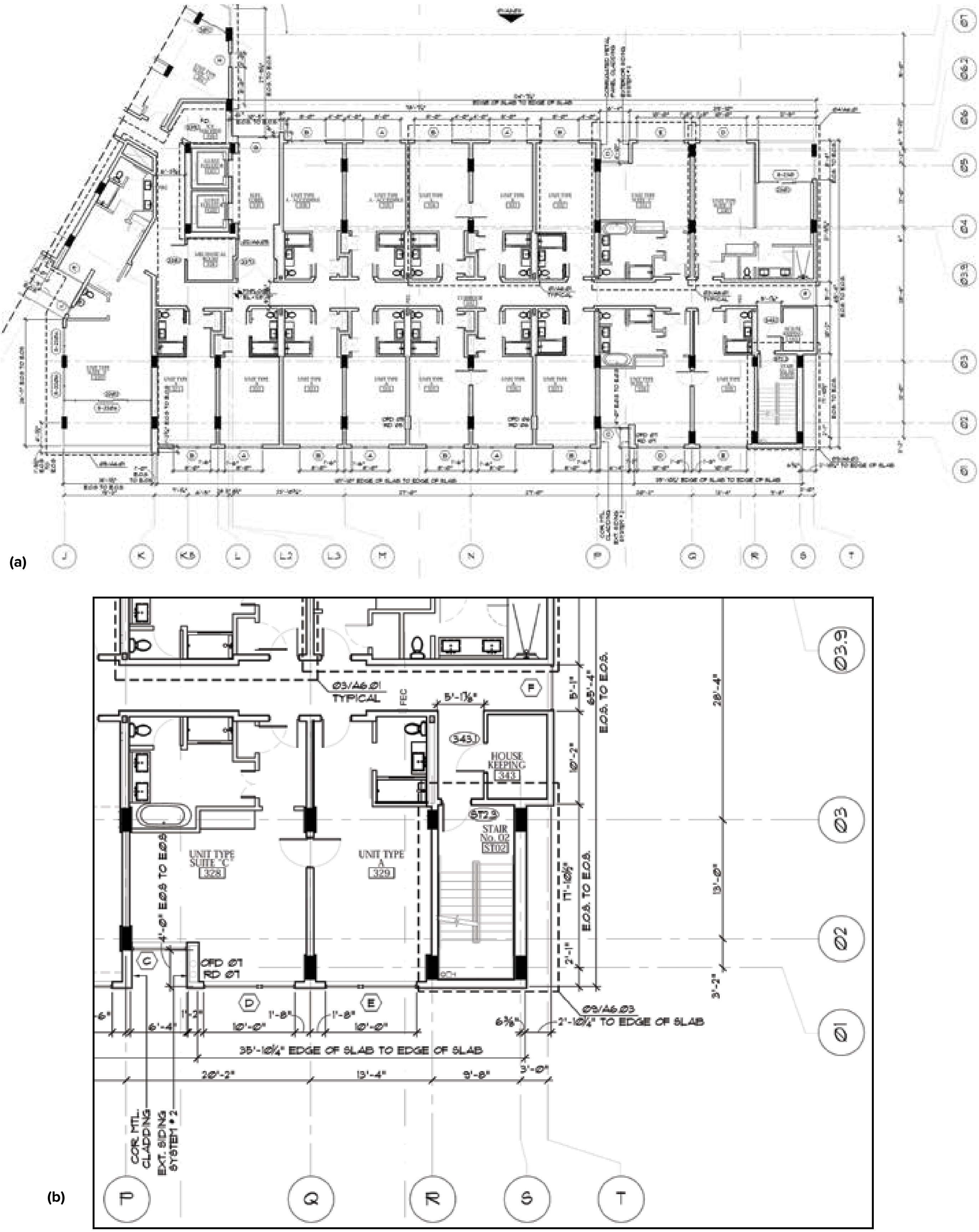

Fig. 2: Partial floor plan of the building for the class project: (a) overall view; and (b) closeup of lower right corner

Fig. 3: Tools provided to the students include Reinforced Concrete Concept (visit www.crsi.org/index.cfm/rcconcept for more information)

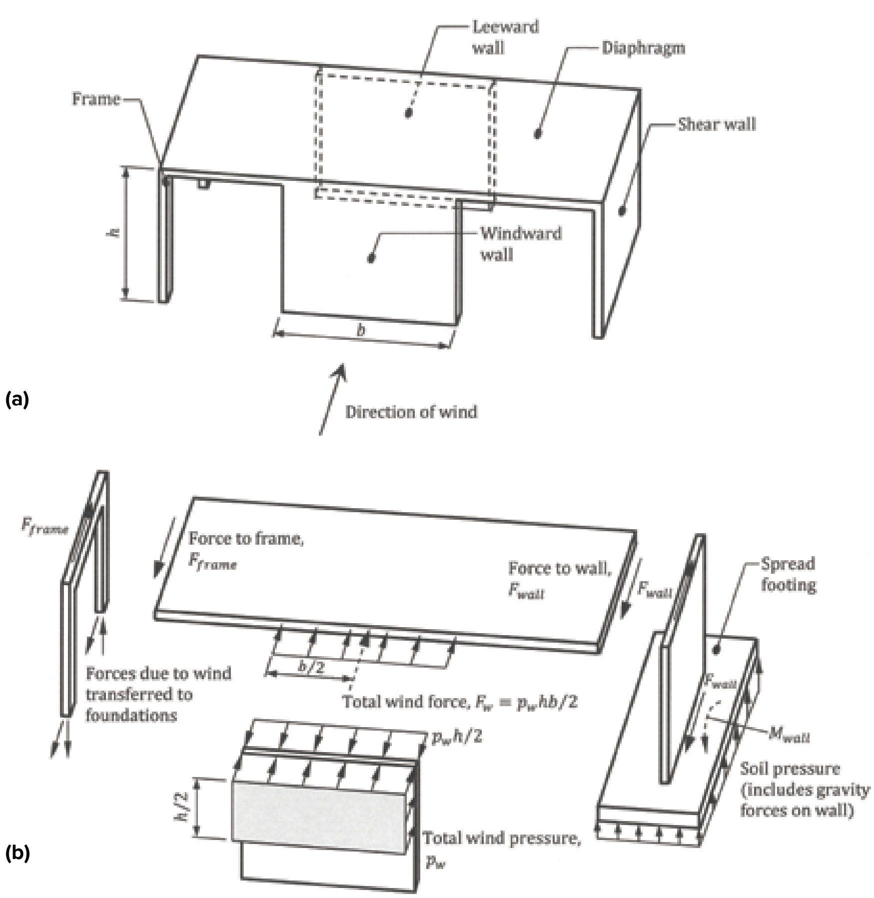

Fig. 4: Lessons include discussions of load paths: (a) schematic of a reinforced concrete building; and (b) exploded view showing load path for wind load

specification for reinforced concrete buildings is presented.

In the construction documents phase (weeks 8 through 12), practical methods for design and detailing an economical reinforced concrete building are provided via design aids, flowcharts, and worked-out examples. Many resources are available to the students during this phase, including the CRSI Student Detailing Card (Fig. 5).

One of the most important topics covered during this phase is how to transfer design and detailing information to the structural drawings. The course material emphasizes that structural drawings are a culmination of all analyses, design, and detailing performed by the structural engineer. As such, they are essentially the only means to communicate the required structural systems and members to the other members of the design and construction teams. In other words, the most comprehensive set of calculations are basically worthless unless all the required structural information obtained from analysis and design can be conveyed in a comprehensive and straightforward manner on the structural drawings. Procedures on how to create plans, sections, details, and sections are provided that can be used to achieve this important task.

The following topics are covered during the construction administration phase (weeks 13 and 14):

- Design and construction processes;
- Production and fabrication of reinforcing steel;
- Placement of reinforcing steel;
- Construction sequence of reinforced concrete buildings;
- Formwork systems; and
- Duties and responsibilities of the structural engineer related to placing drawings, responses to requests for information (RFIs), and periodic site visits.

This portion of the course is designed to stress the importance of the administration phase—students must clearly understand that the duties and responsibilities of the structural engineer do not end once the construction documents are submitted.

STUDENT DETAILING CARD

ASTM STANDARD INCH-POUND REINFORCING BARS

BAR SIZE	NOMINAL DIMENSIONS		
	AREA (in.²)	WEIGHT (lb/ft)	DIAMETER (in.)
#3	0.11	0.376	0.375
#4	0.20	0.668	0.500
#5	0.31	1.043	0.625
#6	0.44	1.502	0.750
#7	0.60	2.044	0.875
#8	0.79	2.670	1.000
#9	1.00	3.400	1.128
#10	1.27	4.303	1.270
#11	1.56	5.313	1.410
#14	2.25	7.650	1.693
#18	4.00	13.600	2.257
#20	4.91	16.690	2.500

The current A615 specification covers bar sizes #3 through #18 in Grades 60, 75, 80 and 100, and bar sizes #3 through #6 in Grade 40.
The current A706 specification covers bar sizes #3 through #18 in Grade 60 and 80.

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90° AND 180° STANDARD HOOKS

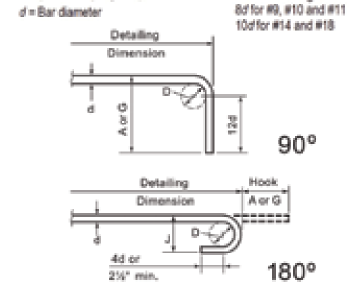
All specific dimensions recommended by CRSI below meet minimum requirements of ACI 318.

RECOMMENDED END HOOK DIMENSIONS
(All Grades of steel.)

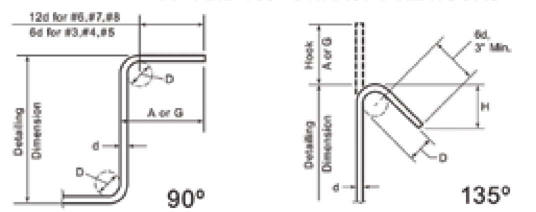
BAR SIZE	D	180° HOOKS		90° HOOKS
		A or G	J	A or G
#3	2¼	0-5	0-3	0-6
#4	3	0-6	0-4	0-8
#5	3¾	0-7	0-5	0-10
#6	4½	0-8	0-6	1-0
#7	5¼	0-10	0-7	1-2
#8	6	0-11	0-8	1-4
#9	9½	1-3	0-11¾	1-7
#10	10¾	1-5	1-1¾	1-10
#11	12	1-7	1-2¾	2-0
#14	18¼	2-3	1-9¾	2-7
#18	24	3-0	2-4½	3-5

D = Finished inside bend diameter (includes springback)
d = Bar diameter

ACI 318 min. bend diameter:
6d for #3 through #8
8d for #9, #10 and #11
10d for #14 and #18



90° AND 135° STIRRUP / TIE HOOKS



D = Finished inside bend diameter (includes springback)
d = Bar diameter

ACI 318 min. bend diameter:
4d for #3 through #5
6d for #6 through #8

RECOMMENDED STIRRUP / TIE HOOK DIMENSIONS*
(All Grades of steel.)

BAR SIZE	D, (in.)	90° HOOK, (ft.-in.)	135° HOOK, (in.)	
		A or G	A or G	H**
# 3	1½	0-4	4½	3
# 4	2	0-4½	4½	3
# 5	2½	0-6	5½	3¾
# 6	4½	1-0	8	4½
# 7	5¼	1-2	9	5¼
# 8	6	1-4	10½	6

* 180° stirrup/tie hooks were added in ACI 318-14. CRSI does not recommend their usage.
** H dimension is approximate

Fig. 5: Design aids provided to the students include a reinforcing bar detailing card

The final weeks of class include submission of the final structural drawings and calculations for the class project and the group presentations to the class. There is no class during week 15 so the groups can finalize their projects. During week 16, the final drawings are submitted, and each group is required to make a concise presentation to the instructor and the other groups.

Throughout the course, assignments and quizzes are given weekly. Progress sets of structural drawings are to be submitted at key dates within the semester to check that the groups are on track.

In addition to the actual building used for the class project, another actual low-rise reinforced concrete building is used throughout the course to illustrate the design and detailing methods that are presented for each type of structural member. Structural drawings for that building are distributed to the students and are used as a reference when creating the project structural drawings.

Information on location, owner, design team, and other identifying items have been removed from the architectural drawings for the class project building, and permission has been obtained to use these drawings in this course. Permission has also been obtained to distribute the structural drawings for the other low-rise building used as an example in the course.

Course Materials and Resources

The following items are provided to the instructor of this capstone course:

- A detailed course outline;
- Complete set of PowerPoint presentations for each session (these can be edited);
- Quizzes and answer keys;
- Reference publications and documents;
- Architectural drawings of the low-rise building that is used as the class project;
- Structural drawings of the low-rise building that are used to illustrate design and detailing methods throughout the course; and
- Sample specifications for a reinforced concrete building.

The required text for the course is *Design and Detailing of Low-Rise Reinforced Concrete Buildings*.[5] It contains a wealth of information on the design and detailing of reinforced concrete members and includes many practical design aids, flowcharts, and fully worked-out design examples. Other resource documents from CRSI and ACI are also made available to help students through all aspects of the course.

Many jurisdictions throughout the United States have adopted the 2015 International Building Code[1] as the basis of their local code. The code adopts by reference industry standards and other technical documents that supplement its provisions, including ACI 318-14[2] and ASCE/SEI 7-10.[6] These documents are also used throughout the course.

Project Information

The six-story hotel used as a class project is located in an area of low seismic risk in the United States. A low-rise building was chosen because such buildings account for well over 90% of the floor area constructed in any given year in the United States. In other words, a graduate will be much more likely to design a low-rise building than a mid- or high-rise building. Also, the students can focus on key issues without getting bogged down in more sophisticated lateral load analyses typically required for taller structures.

The design of a low-rise building also offers the opportunity to understand more fully what constitutes an economical design. Specifically, cost-effective design topics include:

- Designs that allow simplified concrete formwork usually result in a more cost-effective structure because formwork typically accounts for about 50 to 60% of the cost of the structure;
- Repeating the same member sizes throughout an entire low-rise building may not appear to be the most effective solution with respect to material use, but the increased cost in materials is more than offset by the substantial cost savings obtained by minimizing changes in the formwork; and
- Other cost savings can be realized by simplifying the reinforcement detailing.

Strength by Design

The CRSI capstone course on reinforced concrete buildings provides a unique learning experience for students in structural engineering programs. The course offers a wealth of useful and practical information on the economical design, detailing, and construction of reinforced concrete buildings, and it prepares students for life in the consulting world.

Faculty members can obtain the material for this course free of charge, either by contacting the authors directly or by downloading the resources at the CRSI RebarU website (**https://learning.crsi.org**). As noted previously, the course can be modified to suit any curriculum. Portions of the course can also be used to supplement content in existing courses on reinforced concrete design.

References

1. "2015 International Building Code," International Code Council, Washington, DC, 2015, 700 pp.
2. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)," American Concrete Institute, Farmington Hills, MI, 2014, 519 pp.
3. "Criteria for Accrediting Engineering Technology Programs," Accreditation Board for Engineering and Technology, Baltimore, MD, 2017, http://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-technology-programs-2018-2019/.
4. "Reinforced Concrete Concept," Concrete Reinforcing Steel Institute, Schaumburg, IL, 2014, http://www.crsi.org/index.cfm/rcconcept.
5. *Design and Detailing of Low-rise Reinforced Concrete Buildings*, first edition, Concrete Reinforcing Steel Institute, Schaumburg, IL, 2017, 544 pp.
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Selected for reader interest by the editors.

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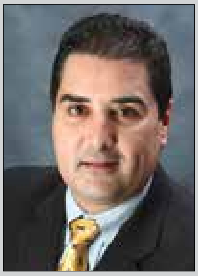

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