WWW-Based Virtual Laboratories for Reinforced Concrete Education[1]

HUA JIANG
Graduate Assistant, Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, Indiana

YAHYA C. KURAMA
Assistant Professor, Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, Indiana

DAVID A. FANELLA
Manager, Buildings and Special Structures, Portland Cement Association, Skokie, Illinois

ABSTRACT: This paper introduces three interactive virtual laboratory modules for undergraduate and graduate level education on the behavior and design of reinforced concrete structures using the World Wide Web (WWW). Users can select and configure module parameters (such as reinforcement) to investigate the design and behavior of a reinforced concrete member or section.

Keywords: interactive, Java, reinforced concrete, virtual laboratory, World Wide Web

INTRODUCTION

This paper describes the development and use of three WWW-based interactive virtual laboratory modules for undergraduate and graduate level education on the analysis, behavior, and design of reinforced concrete (RC) structures. Recent studies show that engineering students can be educated most effectively through examples and experiments (i.e., experiential learning) [1]. Conventional methods of conducting examples are based on analytical methods and/or laboratory tests. However, limitations on time and other resources (e.g., space and financial resources) often restrict the number of examples and what-if studies that can be covered in class, in the laboratory, or as homework assignments. It may be possible to overcome some of these limitations by using the WWW as a means to develop interactive educational tools geared towards experiential learning.

The rapid growth of the WWW has provided educators with unprecedented flexibility in recent years [2-5]. As described by Wallace and Weiner [6], WWW-based instructional materials have a wide range of sophistication and intended use, varying from course administration, lecture, and assignment tools, to laboratory simulation and experiment platforms. While the use of these materials in engineering education is increasing at a fast rate, most of the instructional courseware that can be found on the WWW is completely "static" and "non-interactive", offering little advantage over conventional methods in experiential learning. Recent advances in technology demand a more significant evolution in education, which is the main motivation for the development of the virtual laboratories described herein.

One of the most exciting recent developments for engineering education is the availability of computer programs, referred to as Java™ applets, specifically designed for the WWW. This paper uses these advancements to achieve four specific objectives: (1) to develop effective and modern educational tools in order to overcome some of the limitations of conventional teaching methods in experiential learning; (2) to develop interactive tools that allow the students to investigate the subject matter at their own pace and in the order that they choose, rather than follow a limited number of examples selected and designed by the instructor; (3) to use these tools to demonstrate fundamental concepts on the analysis, behavior, and design of RC structures; and (4) to stimulate the students' interest, creativity, and thinking, and thus, encourage them to pursue higher degrees.

The virtual laboratory modules described in the paper address the following topics in structural engineering: (1) flexural design of RC beams; (2) axial-force-moment-curvature relationships for RC sections; and (3) uniaxial stress-strain relationships for confined and unconfined concrete. Users can configure the system parameters (e.g., geometry, reinforcement, concrete confinement, material properties, loading) in each module and observe the effects of these parameters on the behavior and design of a RC member or section. These capabilities allow the users to interactively design and conduct their own examples, what-if studies, and experiments on the Web.

An overview of the modules and their interactive capabilities are described below. A brief background on Java applets, which form the core computational algorithm for the modules, is also given. Structural engineering students, educators, and practicing engineers can utilize the modules freely by accessing the URL at http://www.nd.edu/~concrete/java. The paper includes three introductory sample laboratory sessions to facilitate the use of the modules by interested individuals.

BACKGROUND

This section provides a brief overview regarding the use of Java applets on the development of the virtual laboratory modules. The results of a literature survey on other Java-based educational resources are also discussed.

Java Applets

As stated above, Java applets are computer programs that have been specifically engineered for the WWW [7, 8]. Users download the applets through a Java-enabled browser such as Netscape™ or Microsoft Explorer™, and then run the applets on their computer. Java provides significant advantages for the development of educational software using the Internet, including [9]:

1) One of the most important features of Java applets is that they are completely browser and platform (i.e., computer hardware and operating system) independent. In other words, a Java applet can run as well on a PC or Macintosh™ as it does on a Sun™, IBM™, or Hewlett-Packard™ workstation.

2) Once downloaded, the running speed of a Java applet is governed by the speed of the user's computer. Thus, the performance of an applet on the user's computer does not depend on the network connections.

3) Java applets are full-featured, fully-interactive, and easily-maintainable computer programs, which make them extremely versatile for use in engineering education. The fact that they are full-featured computer programs means that complex engineering procedures can be coded using them.

4) Java is interactive. Once an applet is downloaded, the user has full control over the executable and can utilize its full capabilities on his/her own computer to conduct virtual experiments and what-if studies. Java applets can display graphics (still or animated), play audio or video files, and receive user input from a mouse and keyboard.

More information on Java is available over the Internet [10]. There are specially designed utility software packages that can be used in the development of Java applets. These software packages are readily available from many sources, including free software that can be downloaded from the Internet [10].

Other Java-Based Laboratory Modules

An extensive review of the WWW and the published media indicate that Java-based interactive courseware in the area of RC structures, other than the modules described in this paper, is not available over the Internet. Java-based virtual laboratories that focus on other areas of engineering do exist (e.g., Earthquake Engineering [11], Electrical Engineering [12], Industrial Engineering [13], Computational Science and Engineering [14]). However, an overview of these laboratories is not within the scope of this paper.

Today, Java applets are widely used on the WWW but, in spite of their potential, they are not utilized much for education purposes. Java has given the Web the power of continuous, interactive, real-time, visual, and aural instruction. The laboratory modules that are described below aim to utilize this power in engineering education on RC structures.

DESCRIPTION OF THE LABORATORY MODULES

This section describes three new WWW-based laboratory modules on the analysis, behavior, and design of RC structures. The verification of the modules is also discussed.

Flexural Design of RC Beams

This virtual laboratory module, referred to as Module A, allows the users to investigate the flexural design of rectangular RC beams with various support and span loading conditions. The beams are designed as singly-reinforced prismatic members (i.e., the compression reinforcement is ignored in the design) with straight reinforcing bars. The design is conducted in accordance with *ACI-318 Building Code Requirements for Structural Concrete and Commentary* published by the American Concrete Institute [15].

The module follows general design procedures that can be found in any undergraduate level textbook on RC (e.g., Nilson [16]). Thus, these procedures are not described herein. Up to five designs can be conducted during a laboratory session to allow for parametric exercises. As shown in Figure 1, the module-user interface consists of four windows and a control panel. The four windows display the results from the laboratory session as follows:

Window 1 displays the design details at selected sections along the length of the beam, including section dimensions, amount of reinforcement, and placement of reinforcement. As an example, Figure 1 shows the details at Section 1 (section adjacent to the left support) from a sample laboratory session referred to as Laboratory Session A. More information on this session is given later.

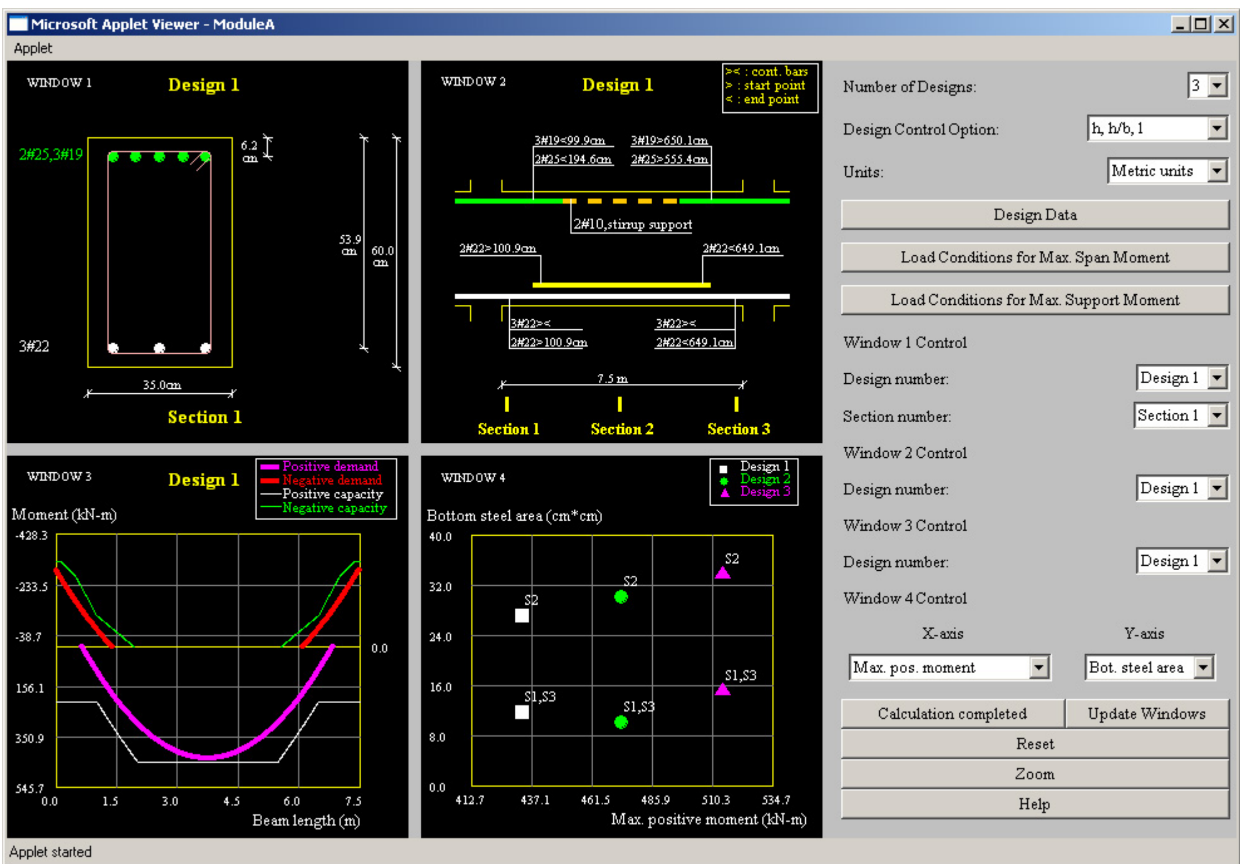


Figure 1 User interface for Module A.

Window 2 displays the design details along the length of the beam, including the amount, placement, and beginning and end points (i.e., cut-off locations) of the reinforcement. In Figure 1, the details for Design 1 from Laboratory Session A are shown.

Window 3 shows comparisons between the design flexural capacity (after the application of a capacity reduction factor, $\varphi=0.90$) and the factored design flexural demand along the length of the beam for positive and negative bending. In Figure 1, the capacity-demand comparisons for Design 1 are shown.

Finally, Window 4 plots user-selected design output parameters as functions of input parameters to allow for a comparative investigation and evaluation of the results. As an example, Figure 1 shows the variation in the area of the bottom steel reinforcement at Sections 1-3 as a function of the maximum positive factored moment demand along the length of the beam for three different designs conducted in Laboratory Session A. These three parametric design examples are described in more detail later.

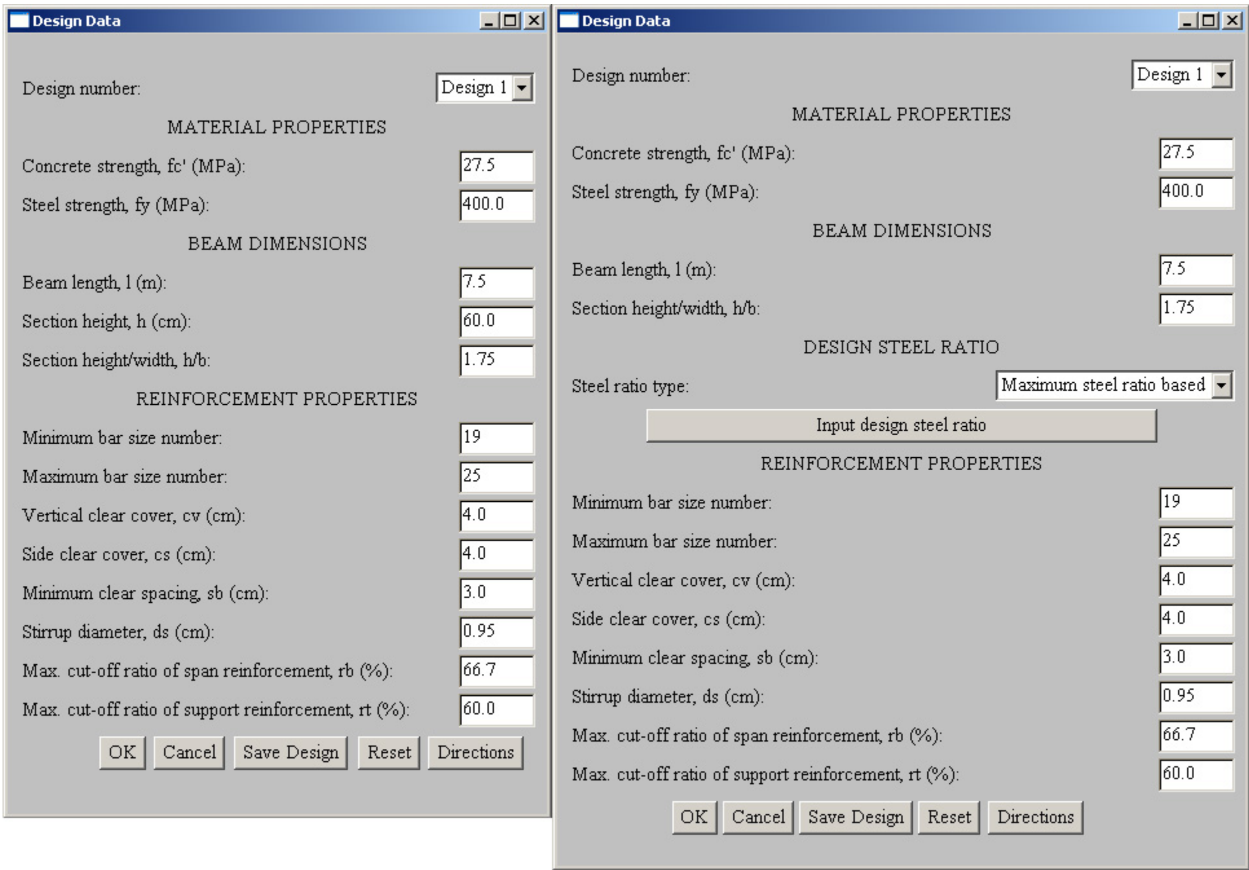
The control panel for Module A includes the following information:

● Number of Designs - Up to five designs may be conducted during a laboratory session.

● Design Control Option - One of two design control options may be selected for the session as follows. Option 1: Design using known cross-section height, h, and height-to-width ratio, h/b; or Option 2: Design using known reinforcement ratio, ρ, and cross-section height-to-width ratio, h/b.

● Units - English or metric units may be selected. The units may be changed at any time during the session.

● Design Data - Required design data is specified based on the design control option selected above. The required data for Control Option 1 (i.e., known cross-section dimensions) and Control Option 2 (i.e., known reinforcement ratio) are shown in Figure 2. The small rectangular boxes in Figure 2 indicate areas for user input. The module displays error messages for invalid user input (e.g., negative h) and warning messages for user input that does not conform to the ACI-318 [15] provisions.



(a) (b)

Figure 2 Design data for Module A: **(a)** control option 1; **(b)** control option 2.

● Load Conditions for Maximum Span Moment - These load conditions are used to specify the factored beam moment demand (along the beam length) corresponding to the maximum moment within the span. A combination of factored design beam end moments, span distributed loads, and span concentrated loads may be used, as shown in Figure 3. The sign convention for the loads is also shown in Figure 3. Beam span distributed and concentrated loads acting in the upward direction are not allowed.

● Load Conditions for Maximum Support Moment - In order to allow for the consideration of pattern loading in design, a different set of loads may be used to specify the factored beam moment demand corresponding to the maximum moments at the supports. A combination of factored design beam end moments, span distributed loads, and span concentrated loads may be used, similar to Figure 3. The sign convention for the loads is also shown in Figure 3. Span distributed and concentrated loads acting in the upward direction are not allowed.

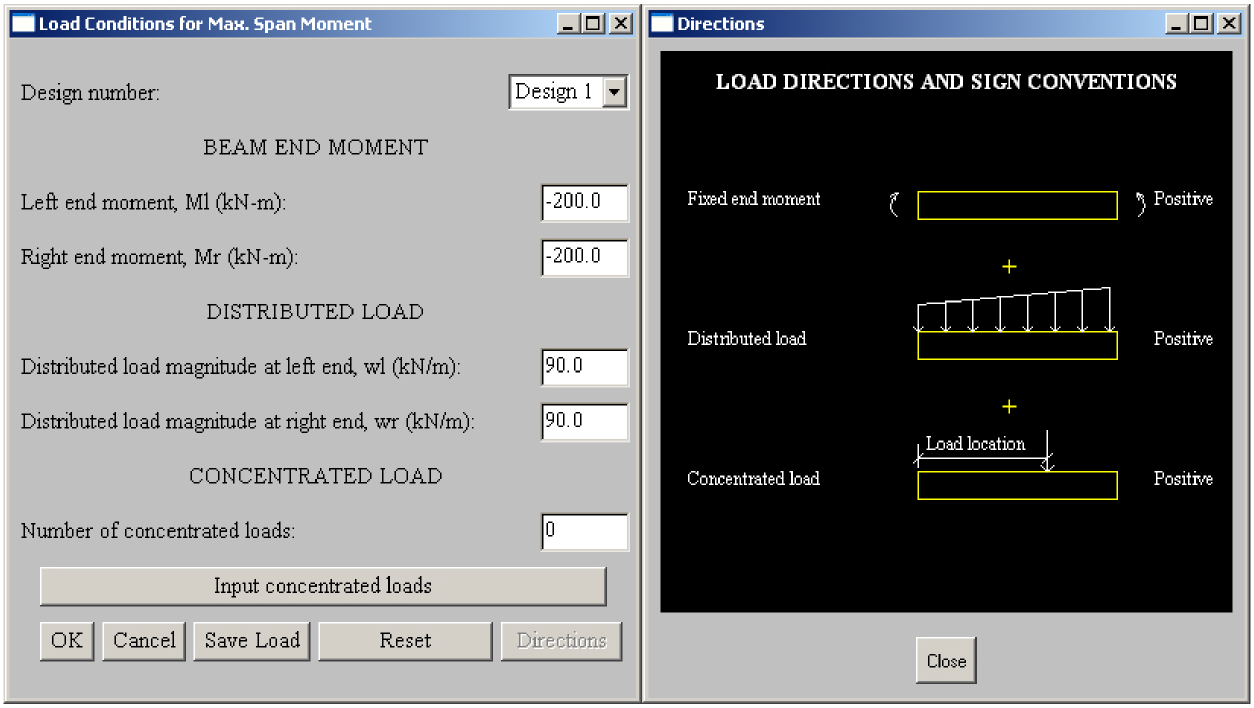


Figure 3 Load conditions for maximum span moment for Module A.

- Window 1 Control - The design number and section number to be displayed in Window 1 are selected. The design details at three sections along the length of the beam can be displayed as follows. Section 1: Section adjacent to the left support; Section 2: Section at beam midspan; and Section 3: Section adjacent to the right support.
- Window 2 Control - The design number to be displayed in Window 2 is selected.
- Window 3 Control - The design number to be displayed in Window 3 is selected.
- Window 4 Control - The input and output parameters to be displayed in Window 4 are selected.
- Solve - Solve laboratory session (displays "Calculation completed" after execution).
- Update Windows - Display current results in Windows 1-4.
- Reset - Reset all session input data, results, and display.

● Zoom - Zoom Windows 1-4.

● Help - Display module help and background information (currently under development).

Axial-Force-Moment-Curvature Relationships for RC Sections

This virtual laboratory module, referred to as Module B, allows the users to investigate the nonlinear axial-force-moment-curvature relationships for rectangular RC beam-column cross-sections. The module determines the expected behavior of a user-defined cross-section by first dividing the section into a number of parallel concrete and steel "fibers". Then, the section forces and deformations are determined from the fiber strains and stresses using fundamental principles of equilibrium, strain compatibility, and constitutive relationships assuming that plane sections remain plane. A total of fifty fibers are used to model the concrete in compression.

More detailed information on the procedure used to develop the axial-force-moment-curvature relationship of a cross-section can be found in most undergraduate/graduate level textbooks on RC structures (e.g., Nilson [16]). Up to five cross-sections can be analyzed during a laboratory session to allow for parametric exercises. Figure 4 shows the module-user interface, which consists of four windows and a control panel similar to Module A above. The four windows display the results from the laboratory session as follows:

Window 1 displays some of the user-defined properties of the cross-sections investigated in the session. The cross-section dimensions, material properties, amount of reinforcement, and placement of reinforcement are shown. As an example, Figure 4 shows the properties of Section 1 from a sample laboratory session, referred to as Laboratory Session B. More information on this session is given later.

Window 2 displays the estimated nonlinear bending-moment-curvature relationships for the cross-sections investigated in the session. The bending moment is assumed to act such that the top of the cross-section is in compression. In Figure 4, the moment-curvature relationships for Section 1 from Laboratory Session B are shown for three user-specified axial force values, P1-P3. The last point on each curve represents the ultimate curvature (curvature at crushing of the concrete in the extreme fiber).

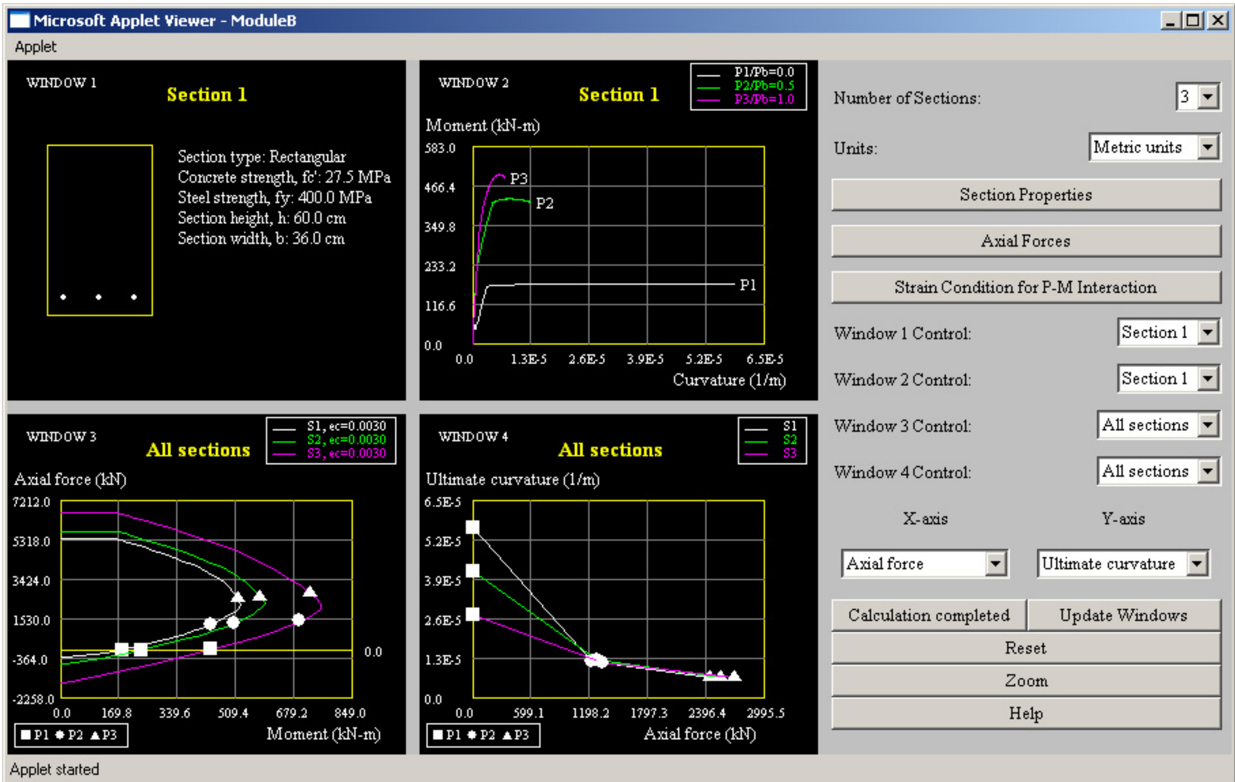


Figure 4 User interface for Module B.

Window 3 shows the estimated axial-force-bending-moment (P-M) interaction diagrams corresponding to user-specified strain conditions for the cross-sections investigated in the session. In Figure 4, the interaction diagrams corresponding to a maximum concrete compression strain of ε_c=0.003 are shown for three different cross-sections, S1-S3, from Laboratory Session B. These cross-sections are described in more detail later.

Finally, Window 4 plots user-selected analysis output parameters as functions of input parameters to allow for a comparative investigation and evaluation of the results. As an example, Figure 4 shows the estimated variation in the ultimate curvature (i.e., curvature at crushing of concrete) as a function of the applied axial forces for the three cross-sections analyzed in Laboratory Session B.

The control panel for Module B includes the following information:

- Number of Sections - Up to five cross-sections may be investigated during a laboratory session.

● Units - English or metric units may be selected. The units may be changed at any time during the session.

● Section Properties - The properties of the cross-sections to be investigated in the session are specified. As shown in Figure 5, the section properties that need to be defined by the user include the material properties for concrete and reinforcing steel, cross-section dimensions, and reinforcement amount and location. The concrete is assumed to be unconfined. The compressive stress-strain relationship of the unconfined concrete is determined using a model described in Mander et al. [17]. The tensile strength of concrete is assumed to be equal to $7.5\sqrt{f_c'}$ .The module displays error messages for invalid user input (e.g., negative h) and warning messages for user input that does not conform to the ACI-318 [15] provisions.

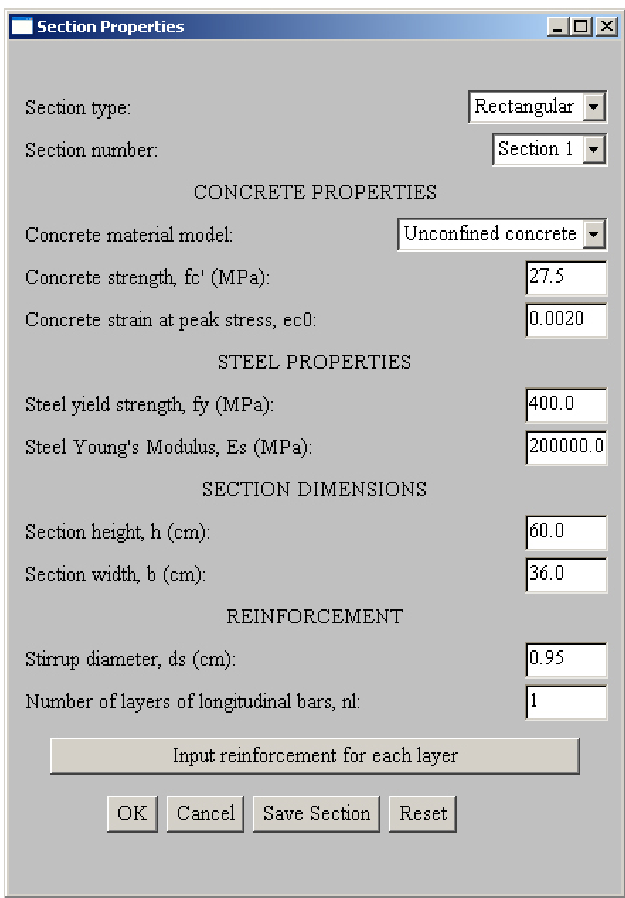


Figure 5 Section properties for Module B.

● Axial Forces - Up to five compressive axial forces may be specified to generate moment-curvature relationships for each cross-section. One of the following three formats may be selected to input the axial forces for each section: (1) percentage of the balanced axial force, P_b; (2) percentage of the axial force capacity under concentric loading, P_o; and (3) numeric values of the axial forces.

● Strain Condition for P-M Interaction - The P-M interaction diagrams in Window 3 correspond to a user-specified maximum concrete strain in each cross-section. A strain value less than or equal to the concrete crushing strain may be used.

● Window 1 Control - The cross-section number to be displayed in Window 1 is selected.

● Window 2 Control - The cross-section number to be displayed in Window 2 is selected.

● Window 3 Control - The cross-section number(s) to be displayed in Window 3 are selected.

● Window 4 Control - The cross-section number(s) as well as analysis input and output parameters to be displayed in Window 4 are selected.

● Solve - Solve laboratory session (displays "Calculation completed" after execution).

● Update Windows - Display current results in Windows 1-4.

● Reset - Reset all session input data, results, and display.

● Zoom - Zoom Windows 1-4.

● Help - Display module help and background information (currently under development).

Uniaxial Stress-Strain Relationships for Confined and Unconfined Concrete

This virtual laboratory module, referred to as Module C, allows the users to investigate the effect of lateral confinement on the uniaxial compressive stress-strain relationship of concrete, including the effect of confinement on concrete ductility and strength. Concrete confinement in the form of steel ties, hoops, or spirals is usually needed to increase the ductility of concrete in seismic regions. A number of confinement models are available in the literature to estimate the compressive stress-strain behavior of concrete (e.g., Mander et al. [17], Kent and Park [18], Sheikh and Uzumeri [19]). The model developed by Mander et al. [17] is used in Module C.

Detailed information on the compressive stress-strain behavior of confined concrete can be found in many graduate-level textbooks, particularly in textbooks that focus on the seismic behavior and design of RC structures (e.g., Paulay and Priestley [20]). Thus, this topic is not discussed further in this paper. Up to five concrete specimens can be investigated during a laboratory session to allow for parametric exercises. Figure 6 shows the module-user interface, which consists of four windows and a control panel similar to Modules A and B above. The four windows display the results from the laboratory session as follows:

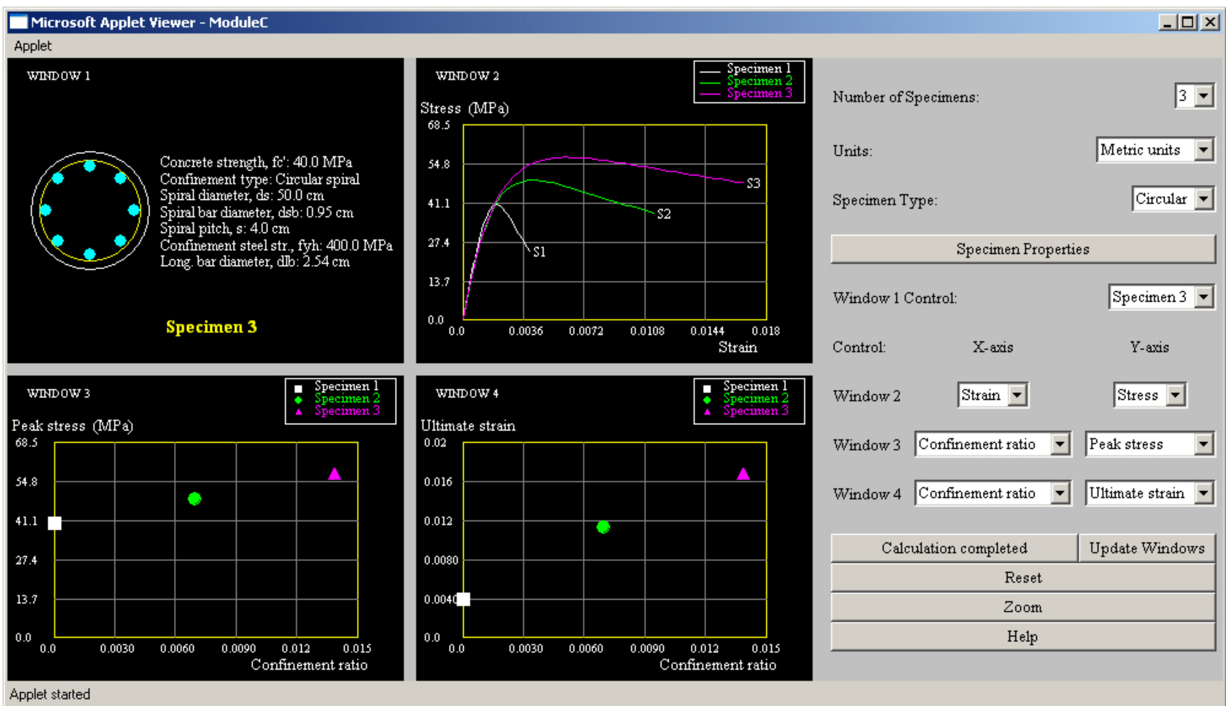


Figure 6 User interface for Module C.

Window 1 shows the user-defined properties of the concrete specimens investigated in the session. The material properties and amount of reinforcement are displayed. As an example, Figure 6 shows the properties of Specimen 3 from a sample laboratory session referred to as Laboratory Session C. More information on this session is given later.

Window 2 displays the estimated stress-strain relationships for the concrete specimens investigated in the session. In Figure 6, the stress-strain relationships for three specimens, S1-S3, from Laboratory Session C are shown. More information on these specimens is given later.

Windows 3 and 4 are used to plot user-selected analysis output parameters as functions of input parameters to allow for a comparative investigation and evaluation of the results. As an example, Windows 3 and 4 in Figure 6 show the estimated variation in the concrete strength and ultimate strain (i.e., strain at crushing of concrete), respectively, as a function of the confining steel ratio, ρ (defined as the ratio of the volume of lateral confining steel to the volume of confined concrete core [17]), for the three specimens analyzed in Laboratory Session C.

The control panel for Module C includes the following information:

● Number of Specimens - Up to five concrete specimens may be investigated during a laboratory session.

● Units - English or metric units may be selected. The units may be changed at any time during the session.

● Specimen Type - Currently, only circular specimens can be investigated by the module. Rectangular specimens will be included in the future.

● Specimen Properties - The properties of the specimens to be investigated in the session are specified. As shown in Figure 7, the specimen properties that need to be defined by the user include the material properties for concrete and steel, and the amount of reinforcement. The module displays error messages for invalid user input (e.g., negative s) and warning messages for user input that does not conform to the ACI-318 [15] provisions.

● Window 1 Control - The specimen number to be displayed in Window 1 is selected.

● Window 2 Control - The analysis output parameters, stress and strain, to be displayed in Window 2 are specified.

● Window 3 Control - The analysis input and output parameters to be displayed in Window 3 are selected.

● Window 4 Control - The analysis input and output parameters to be displayed in Window 4 are selected.

● Solve - Solve laboratory session (displays “Calculation completed” after execution).

● Update Windows - Display current results in Windows 1-4.

● Reset - Reset all session input data, results, and display.

● Zoom - Zoom Windows 1-4.

● Help - Display module help and background information (currently under development).

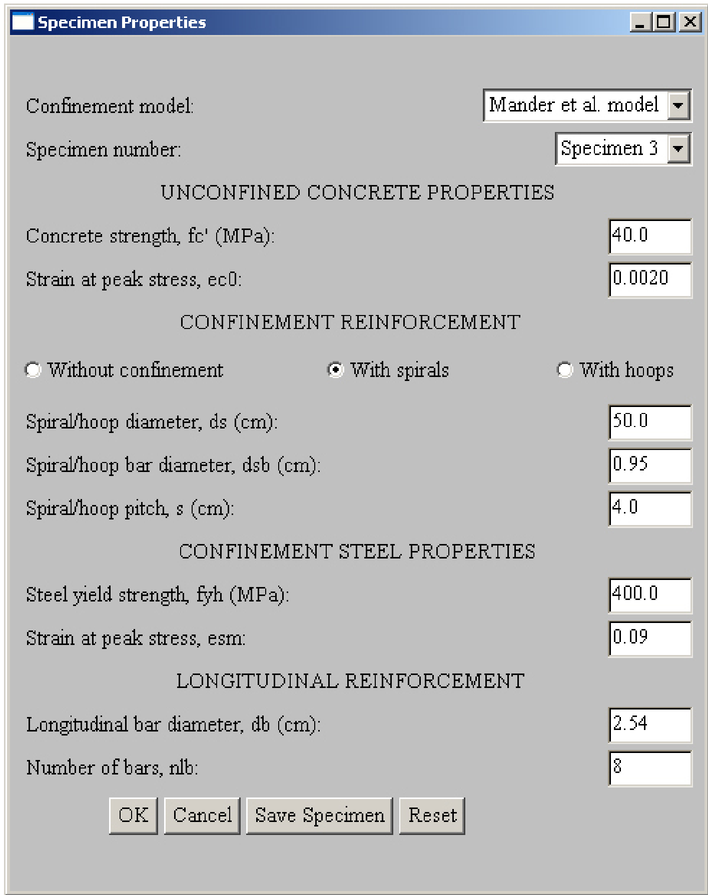


Figure 7 Specimen properties for Module C.

Verification of the Modules

This section describes the verification of the laboratory modules. Module A was verified by comparing the results with designs from manual calculations as well as from a widely-available RC beam design software package, PCABEAM [21], developed by the Portland Cement Association (PCA). Similarly, Module B was verified based on manual calculations and comparisons with a structural analysis software, DRAIN-2DX [22]. The fiber beam-column element in DRAIN-2DX [22] was used for this purpose. Finally, Module C was verified by comparing the results with manual calculations based on the procedure described by Mander et al. [17].

In order to minimize the number of errors in the modules, the computational algorithms were first coded and verified using the Matlab™ Program [23]. Then, the Matlab codes were converted into Java codes. A large number of verification analyses and designs were conducted to identify and correct any errors in the modules. However, it is recognized that like any software, unidentified errors may still exist.

USE OF THE LABORATORY MODULES

The WWW laboratories described in this paper may be utilized for a variety of purposes in structural engineering. Firstly, the modules can be used as tools to supplement classroom, home, and laboratory exercises and assignments in undergraduate and graduate level RC design and analysis courses. Three courses offered at the University of Notre Dame use the modules: (1) CE486-Reinforced Concrete Design (senior level); (2) CE598E-Advanced Behavior and Design of Concrete Structures (graduate level); and (3) CE598G-Earthquake Engineering (graduate level).

Flexural design of RC beams is one of the fundamental topics covered in undergraduate curricula, and thus, Module A would be suitable for use in undergraduate level courses on RC design. Moment-axial-force interaction diagrams are usually covered in undergraduate curricula, while nonlinear moment-curvature relationships may be more suitable for graduate level students. Thus, Module B can be used in both undergraduate and graduate level courses. Finally, Module C may be more suitable in graduate courses on the seismic behavior and design of RC structures.

Secondly, the modules may be used by practicing engineers to carry out routine design calculations and checks. Clearly, the complete design and analysis of a RC structure cannot be conducted using these modules. However, some engineers may find it convenient and attractive to complete or verify isolated components of the design or analysis over the Internet. Furthermore, it may be possible to develop more sophisticated and comprehensive design and analysis modules in the future.

Finally, the modules may provide new opportunities for distance education, outreach activities, and education of local communities. Because of their free and instant availability and accessibility over the Internet, the modules can be used to give demonstrations as part of a distance education/outreach program. Java applets provide an excellent means for these applications, since they are platform independent and their performance is not affected by network connections.

In order to facilitate the use of the modules by interested individuals, three introductory sample laboratory sessions, Sessions A, B, and C, are described below. In general, any valid user-specified data can be selected to conduct a parametric investigation using the modules. However, because of limited space, only a limited number of design and analysis parameters are demonstrated in the sample sessions below. As part of a design/analysis course, it is recommended that the students are asked to first conduct similar sample sessions and verify the results based on manual calculations. Then, the students can select and conduct their own parametric investigations, possibly within a set of guidelines provided by the instructor.

Sample Laboratory Session A

This sample laboratory session demonstrates the use of Module A on the flexural design of rectangular RC beams. A parametric investigation is carried out with three different designs using Design Option 1 (i.e., known cross-section dimensions). The three designs are conducted for increasing amounts of loading as shown in Figure 8. Table 1 summarizes the data input for the session. The values in italics show the data that are varied between the different designs.

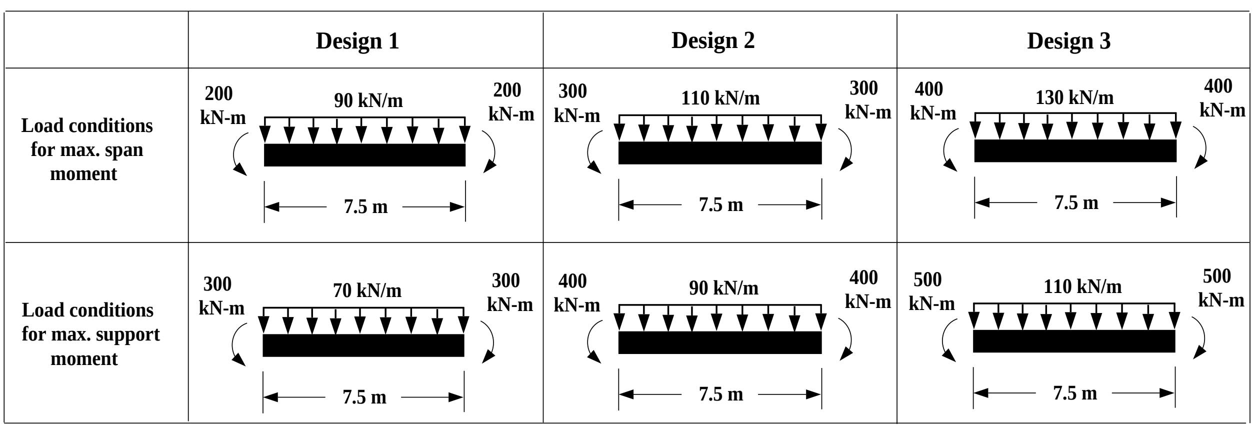


Figure 8 Load conditions for Sample Laboratory Session A.

Table 1 Sample Laboratory Session A

Session Input	Design 1	Design 2	Design 3
Design control option	Known h, h/b		
Concrete compressive strength, f_c' (MPa)	27.5	27.5	27.5
Steel yield strength, f_y (MPa)	400	400	400
Beam length, l (m)	7.5	7.5	7.5
Section height, h (cm)	60	60	60
Section height/width, h/b	1.75	1.75	1.75
Minimum bar size number	19	19	19
Maximum bar size number	25	25	25
Vertical clear cover, c_v (cm)	4	4	4
Side clear cover, c_s (cm)	4	4	4
Minimum clear bar spacing, s_b (cm)	3	3	3
Stirrup diameter, d_s (cm)	0.95 (No. 10)	0.95 (No. 10)	0.95 (No. 10)
Max. cut-off ratio of span reinforcement, r_b (%)	66.7	66.7	66.7
Max. cut-off ratio of support reinforcement, r_t (%)	60	60	60
Load Condition	**Maximum Span Moment**		
Left end moment, M_l (kN-m)	*-200*	*-300*	*-400*
Right end moment, M_r (kN-m)	*-200*	*-300*	*-400*
Distributed load magnitude at left end, w_l (kN/m)	*90*	*110*	*130*
Distributed load magnitude at right end, w_r (kN/m)	*90*	*110*	*130*
Number of concentrated loads	0	0	0
Load Condition	**Maximum Support Moment**		
Left end moment, M_l (kN-m)	*-300*	*-400*	*-500*
Right end moment, M_r (kN-m)	*-300*	*-400*	*-500*
Distributed load magnitude at left end, w_l (kN/m)	*70*	*90*	*110*
Distributed load magnitude at right end, w_r (kN/m)	*70*	*90*	*110*
Number of concentrated loads	0	0	0

Selected results from the session are displayed in Figure 1. Window 1 shows the beam dimensions, amount of reinforcement, and placement of reinforcement at Section 1 (section adjacent to the left support) from Design 1 and Window 2 shows the reinforcement along the length of the beam in Design 1. Window 3 shows comparisons between the design flexural capacity (after the application of a capacity reduction factor, φ=0.90) and the factored design flexural demand along the length of the beam for positive and negative bending. Finally, Window 4 is used to plot the area of the bottom steel reinforcement at Sections 1-3 as a function of the maximum positive factored moment demand along the length of the beam for the three designs. As expected, the reinforcement area in Section 2 increases with the applied moment.

Sample Laboratory Session B

This sample laboratory session demonstrates the use of Module B on the axial-force-moment-curvature relationships of rectangular RC beam-column cross-sections. A parametric investigation is carried out using three cross-sections (S1-S3) with different amounts of steel reinforcement as shown in Figure 9. Table 2 summarizes the data input for the session. The values in italics show the data that are varied between the different sections. As described earlier, the required module data input includes the material properties for concrete and reinforcing steel, cross-section dimensions, reinforcement amount and placement, magnitudes of axial forces, and strain condition for P-M interaction.

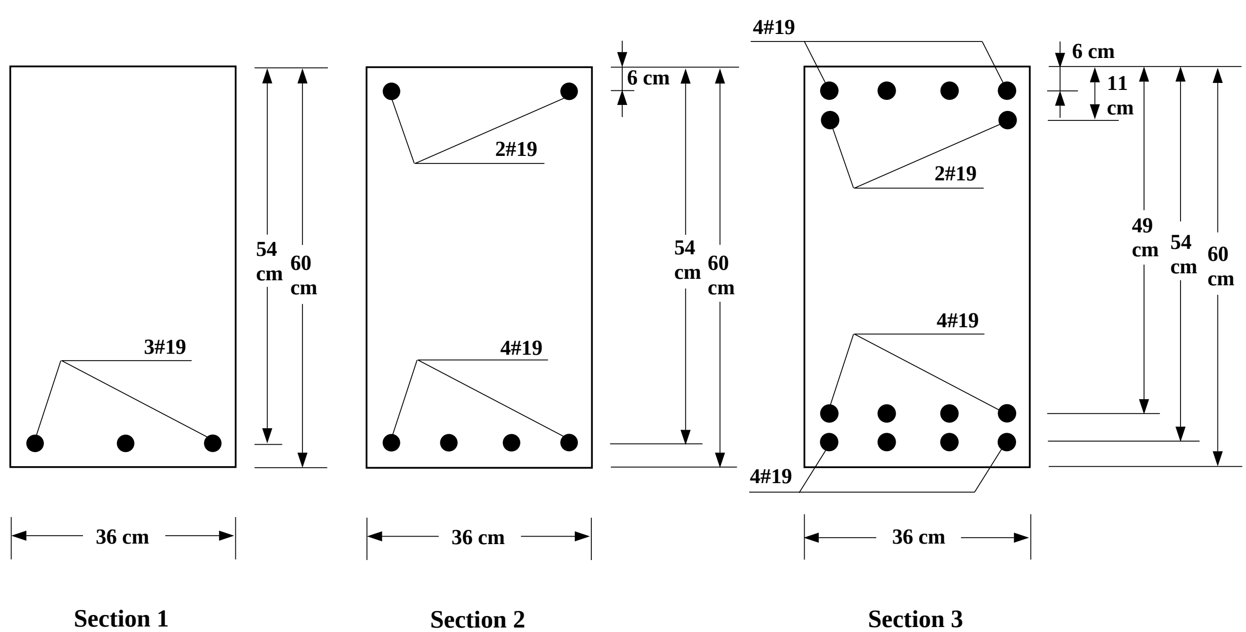


Figure 9 Section reinforcement for Sample Laboratory Session B.

Table 2 Sample Laboratory Session B

<table>
<tr><th>Session
Input</th><th>Section 1
(S1)</th><th>Section 2
(S2)</th><th>Section 3
(S3)</th></tr>
<tr><td>Concrete compressive strength, f_c' (MPa)</td><td>27.5</td><td>27.5</td><td>27.5</td></tr>
<tr><td>Concrete strain at peak stress, ε_{c0}</td><td>0.002</td><td>0.002</td><td>0.002</td></tr>
<tr><td>Steel yield strength, f_y (MPa)</td><td>400</td><td>400</td><td>400</td></tr>
<tr><td>Steel Young's Modulus, E_s (MPa)</td><td>200000</td><td>200000</td><td>200000</td></tr>
<tr><td>Section height, h (cm)</td><td>60</td><td>60</td><td>60</td></tr>
<tr><td>Section width, b (cm)</td><td>36</td><td>36</td><td>36</td></tr>
<tr><td>Stirrup diameter, d_s (cm)</td><td>0.95 (No. 10)</td><td>0.95 (No. 10)</td><td>0.95 (No. 10)</td></tr>
<tr><td>Number of layers of longitudinal bars, n_l</td><td>1</td><td>2</td><td>4</td></tr>
<tr><td rowspan="4">Number of longitudinal bars in each layer</td><td rowspan="4">3</td><td rowspan="2">4</td><td>4</td></tr>
<tr><td>4</td></tr>
<tr><td rowspan="2">2</td><td>2</td></tr>
<tr><td>4</td></tr>
<tr><td rowspan="4">Diameter of longitudinal bars, d_b (cm) in each layer</td><td rowspan="4">1.91 (No. 19)</td><td rowspan="2">1.91 (No. 19)</td><td>1.91 (No. 19)</td></tr>
<tr><td>1.91 (No. 19)</td></tr>
<tr><td rowspan="2">1.91 (No. 19)</td><td>1.91 (No. 19)</td></tr>
<tr><td>1.91 (No. 19)</td></tr>
<tr><td rowspan="4">Distance of each layer of longitudinal bars to compression face, d (cm)</td><td rowspan="4">54</td><td rowspan="2">54</td><td>54</td></tr>
<tr><td>49</td></tr>
<tr><td rowspan="2">6</td><td>11</td></tr>
<tr><td>6</td></tr>
<tr><td>Number of axial forces</td><td>3</td><td>3</td><td>3</td></tr>
<tr><td rowspan="3">Axial force, P (as percentage of P_b)
(P1, P2, and P3)</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>50</td><td>50</td><td>50</td></tr>
<tr><td>100</td><td>100</td><td>100</td></tr>
<tr><td>Strain condition for P-M interaction</td><td>0.003</td><td>0.003</td><td>0.003</td></tr>
</table>

Selected results from the session are displayed in Figure 4. Window 1 shows the user-defined properties of Section 1 and Window 2 shows the estimated bending-moment-curvature relationships for Section 1 under the three axial forces given in Table 2. Window 3 shows the estimated axial-force-bending-moment (P-M) interaction diagrams for Sections 1-3 corresponding to a maximum concrete compression strain of ε_c=0.003. Finally, Window 4 is used to plot the ultimate curvature (corresponding to concrete crushing) as a function of the applied axial force. As expected, the ultimate curvature decreases as the axial force is increased. Note that crushing of the concrete is assumed to occur at a strain of $2\varepsilon_{c0}$ (where ε_{c0} is the strain at the peak stress), according to the model [17] used to generate the concrete stress-strain relationship. Thus, the concrete crushing strain for Sections 1-3 is assumed to be equal to (2)(0.002)=0.004 (ε_{c0}=0.002 is assumed, see Table 2).

Sample Laboratory Session C

This sample laboratory session demonstrates the use of Module C on the compressive stress-strain relationships of confined and unconfined concrete. A parametric investigation is carried out using three specimens (S1-S3) with different amounts of spiral confining reinforcement as shown in Figure 10. Table 3 summarizes the data input for the session. The values in italics show the data that are varied between the different specimens. As described earlier, the required module data input includes the steel and concrete properties, and the amount of reinforcement [17].

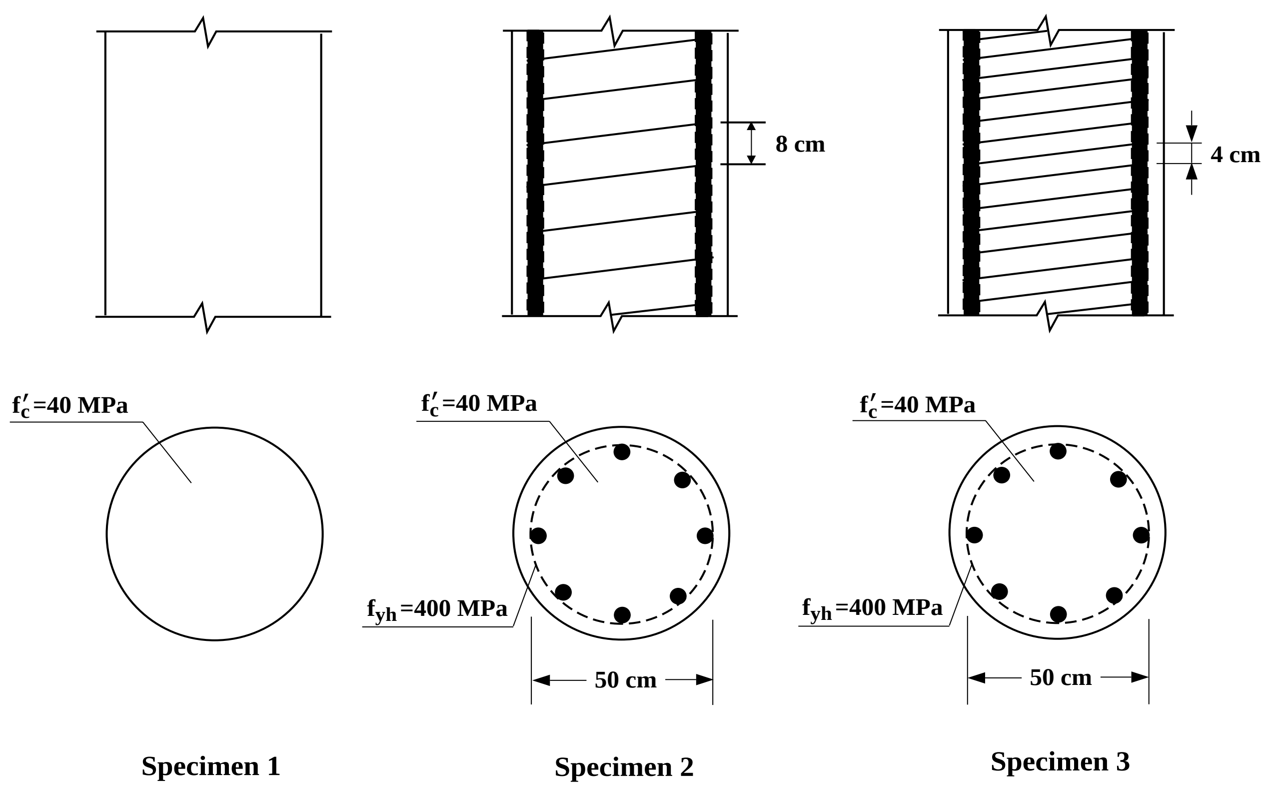


Figure 10 Specimen details for Sample Laboratory Session C.

The spiral pitch, s, is chosen as the main parameter to vary the amount of confinement. Specimen 1 has no confinement and Specimen 3 has the largest amount of confinement (Table 3). Selected results from the session are shown in Figure 6. Window 1 displays the user-defined properties of Specimen 3 and Window 2 displays the estimated stress-strain relationships of the three specimens. Windows 3 and 4 are used to plot the concrete strength and ultimate strain, respectively, as functions of the spiral confinement ratio [17], $\rho=(\pi d_{sb}^2)/(d_s s)$. As expected, the concrete strength and ultimate strain increase as the confinement ratio is increased.

Table 3 Sample Laboratory Session C

Session Input	**Specimen 1 (S1)**	**Specimen 2 (S2)**	**Specimen 3 (S3)**
Unconfined concrete comp. strength, f_c' (MPa)	40	40	40
Unconfined concrete strain at peak stress, ε_{c0}	0.002	0.002	0.002
Confinement type	None	Spiral	Spiral
Spiral/hoop diameter, d_s (cm)	-	50	50
Spiral/hoop bar diameter, d_{sb} (cm)	-	0.95 (No. 10)	0.95 (No. 10)
Spiral/hoop pitch, s (cm)	-	*8*	*4*
Steel yield strength, f_{yh} (MPa)	-	400	400
Steel strain at peak stress, ε_{sm}	-	0.09	0.09
Longitudinal bar diameter, d_b (cm)	-	2.54 (No. 25)	2.54 (No. 25)
Number of longitudinal bars, n_{lb}	-	8	8

ONGOING AND FUTURE WORK

The WWW is an extremely dynamic environment that continually undergoes significant changes over short periods of time. One of the primary tasks for future work is the maintenance and upgrade of the existing laboratory modules to keep up with these changes and new developments, as well as changes in ACI-318 provisions [15]. In addition, comments are sought from the users for the identification of possible errors and areas of improvement for the modules.

Some of the efforts that are underway for the existing modules include: (1) printing capabilities; and (2) incorporation of video files from actual laboratory experiments. Print capability is a feature that is necessary for the reporting and saving of the module results in hard format. Currently, the module results can be printed using the "print screen" option on the user's computer. The use of videos and results from actual experiments is envisioned to supplement the virtual environment of the WWW. For this purpose, experiments of confined and unconfined concrete cylinder specimens to be used in Module C are being conducted at the University of Notre Dame.

Plans for the development of new modules are also ongoing. Possible topics for these future modules are: (1) load-deflection behavior of RC beams; (2) design of RC structures under earthquake loads; and (3) analysis of RC structures under earthquake loads. The last module may require the use of nonlinear static and/or nonlinear dynamic time-history analyses using a built-in analysis subroutine. The results from this module may be presented using hysteretic load-deformation plots, time-history plots, and animation of dynamic response.

SUMMARY AND CONCLUSIONS

This paper introduces three interactive Java-based educational laboratory modules using the WWW to demonstrate and investigate fundamental concepts on the analysis, behavior, and design of reinforced concrete structures. Structural engineering students, educators, and practicing engineers can utilize the modules freely by accessing the URL at http://www.nd.edu/~concrete/java. The following conclusions are made regarding the development and use of the modules.

1. The modules allow the users to configure the system parameters (e.g., geometry, reinforcement, concrete confinement, material properties, loading) and observe the effects of these parameters on the behavior and design of a reinforced concrete member or section. The users can interactively configure and conduct their own examples, what-if studies, and experiments on the Web to investigate the subject matter at their own pace and in the order that they choose, rather than follow a limited number of examples selected and designed by the instructor.

2. The modules can be utilized for a variety of purposes in structural engineering, such as undergraduate and graduate level courseware, design and analysis tools for practicing engineers, and tools for distance education and outreach activities.

3. The Java programming language is well-suited to code complex engineering procedures. Furthermore, Java-based modules have two important characteristics: (1) the modules are platform independent and can be executed on any type of computer and operating system connected to the Internet and running a Java-enabled Web browser; and (2) the performance of the modules on the user's computer does not depend on the network connections. The future of engineering education utilizing Java-based courseware appears to be very promising.

4. The WWW has given educators the power of continuous, interactive, real-time, visual, and aural instruction. The laboratory modules described in this paper are effective in utilizing this power to supplement conventional teaching methods in experiential learning.

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DISCLAIMER

No responsibility is assumed by the authors, the University of Notre Dame, or the Portland Cement Association for any errors or misrepresentations in the laboratory modules, or that occur from the use of these modules.

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