Integrating Problem Solving and Communication In the Structural Engineering Laboratory

Sara Wadia-Fascetti and Michael Tarnowski

Department of Civil & Environmental Engineering
Northeastern University, Boston, MA 02115

ABSTRACT
The Structural Analysis and Design Laboratory course (CIV 1226) first developed in 1986 had the objective to tie the concepts covered in the analysis course to laboratory models and experimentation. In 1996 the course outline, syllabus, assignments, labs, quizzes, and computer software were outdated and did not adequately meet the needs of students engaging in civil engineering professional careers. A new laboratory curricula (presented in this paper) designed to combine modeling and experimental activities with computer analyses and theory enables students to achieve an improved understanding about structural behavior. The resulting curriculum (description of each laboratory) and strategies to increase student learning are presented in this paper.

INTRODUCTION
At Northeastern University all civil engineering students are required take a theory-based structural analysis course and a structural laboratory course simultaneously. Building off elementary statics and mechanics courses, the theory-based course teaches students how to calculate deflections and forces in statically determinate and indeterminate frames. Specifically, students learn concepts such as virtual work, moment area, the flexibility method, slope deflection, and moment distribution. Over the past 10 years the curricula for the two courses diverged. The activities in the laboratory course remained static consisting of traditional activities such as working with strain gages, material properties, and concrete strength.

This paper focuses on a new laboratory curriculum that has been successfully integrated with the theory-based course. The design of the new laboratory curricula must have the following characteristics:

- The new laboratory curricula must complement the topics taught in the theory-based course and be modular to adapt to changes in the course content or instructor.
- The laboratory activities and project are to be designed such that students work in groups and participate in active, experiential, and cooperative learning.
- Each laboratory exercise will be linked with computer exercises to reinforce computer applications used in engineering practice.
- All laboratory activities and projects will be designed to reinforce written communication, teamwork, leadership, and problem solving skills.

The revised and updated curriculum consists of several independent laboratory modules, each requiring approximately 2-3 hours of student work. Within each module students are required to, in addition to observing physical behavior, verify the results with both theory and computer applications. Each laboratory activity is to be summarized in a concise technical memo. Students are graded on the quality of the technical work and the written communication. To reinforce writing skills students are encouraged to rewrite the technical memo to improve their grade.

COURSE DESCRIPTION

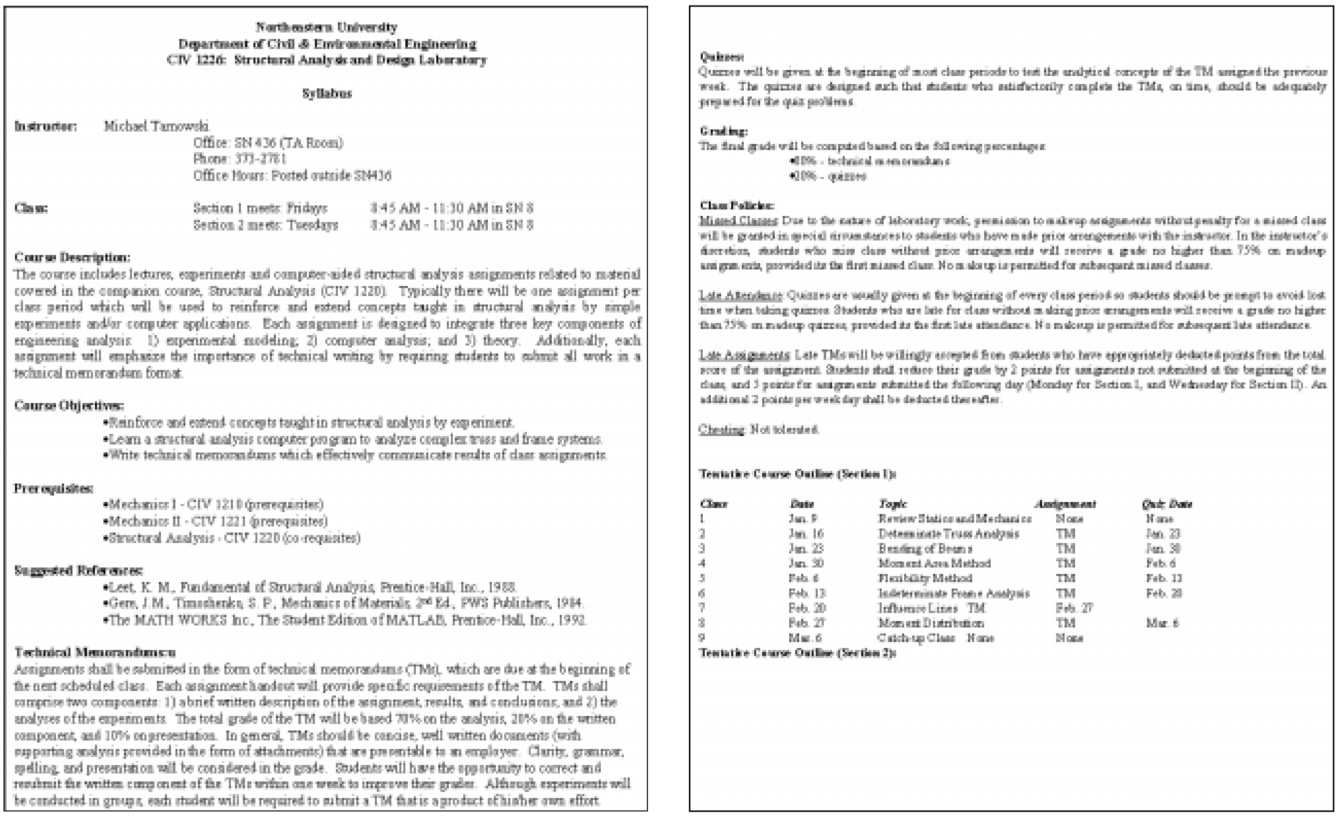
The syllabus for the revised laboratory course is shown in Figure 1. The re-designed laboratory curricula combine modeling and experimental activities with computer analysis and supporting theory into a global perspective for solving structural analysis problems. Through these efforts student benefit is maximized providing the student with a creative and integrated perspective towards problem solving.

Following is a presentation of each new laboratory module. In this presentation, each module consists of a simple laboratory set-up and a summary of the integrated (computer, theory, and experimental modeling) educational objectives required of the students.

LABORATORY EXPERIMENTS:

Experiment 1: Determinate Truss Analysis. The assignment is intended as a review of elementary statics and serves as an introduction to computer solutions. The teaching points of the assignment are: 1) determinate truss analysis is simply the application of elementary statics; 2) bar forces and reactions may be computed directly, as opposed to incrementally as in the method of joints, by solving a simultaneous system of equilibrium constraints for the entire truss; and 3) trusses without the ideal pin assumption include stresses from bending which may be negligible if bar elongations are relatively small. Students are required to solve a determinate truss using the methods of section and joints, which are then compared with computer results obtained for the same truss and loading. Both MATLAB and Visual Analysis software are required in the assignment. Students write MATLAB routines to analyze the truss for several load cases using simple loops to solve the simultaneous system of equilibrium equations for various load vectors (right hand sides of the equilibrium equations). Visual Analysis is introduced to assist in investigating differences in bar forces when the truss is analyzed with connections as pinned and rigid.

Experiment 2: Elementary Mechanics of Beams In the assignment students apply and confirm Hook's Law, Euler's equation for beam bending, and the bending stress equation using simple balsa wood experiments. The first task requires experimental deflections measured in a simply-supported beam to be back figured in a theoretical deflection formula to estimate the modulus of elasticity of balsa wood. By integrating Euler's equation twice and solving for boundary conditions (double integration method), students derive a theoretical deflection formula for the experiment. The deflection caused by a point load on a balsa wood beam are measured experimentally with a dial gage and back substituted into the theorectical deflection formula from which the modulus of elasticity is back figured. Having determined an experimental modulus of elasticity, the second task is to verify the bending stress equation in a second experiment. A balsa wood beam is instrumented with strains gages at the tension and



Northeastern University
Department of Civil & Environmental Engineering
CIV 1226: Structural Analysis and Design Laboratory

Syllabus

Instructor: Michael Tarnowski
Office: SN 436 (TA Room)
Phone: 373-2781
Office Hours: Posted outside SN436

Class:
Section 1 meets: Fridays 8:45 AM - 11:30 AM in SN 8
Section 2 meets: Tuesdays 8:45 AM - 11:30 AM in SN 8

Course Description:
The course includes lectures, experiments and computer-aided structural analysis assignments related to material covered in the companion course, Structural Analysis (CIV 1220). Typically there will be one assignment per class period which will be used to reinforce and extend concepts taught in structural analysis by simple experiments and/or computer applications. Each assignment is designed to integrate three key components of engineering analysis: 1) experimental modeling; 2) computer analysis; and 3) theory. Additionally, each assignment will emphasize the importance of technical writing by requiring students to submit all work in a technical memorandum format.

Course Objectives:
•Reinforce and extend concepts taught in structural analysis by experiment.
•Learn a structural analysis computer program to analyze complex truss and frame systems.
•Write technical memorandums which effectively communicate results of class assignments.

Prerequisites:
•Mechanics I - CIV 1210 (prerequisites)
•Mechanics II - CIV 1221 (prerequisites)
•Structural Analysis - CIV 1220 (co-requisites)

Suggested References:
•Leet, K. M., Fundamental of Structural Analysis, Prentice-Hall, Inc., 1988.
•Gere, J.M., Timoshenko, S. P., Mechanics of Materials, 2nd Ed., PWS Publishers, 1984.
•The MATH WORKS Inc., The Student Edition of MATLAB, Prentice-Hall, Inc., 1992.

Technical Memorandums:
Assignments shall be submitted in the form of technical memorandums (TMs), which are due at the beginning of the next scheduled class. Each assignment handout will provide specific requirements of the TM. TMs shall comprise two components: 1) a brief written description of the assignment, results, and conclusions; and 2) the analyses of the experiments. The total grade of the TM will be based 70% on the analysis, 20% on the written component, and 10% on presentation. In general, TMs should be concise, well written documents (with supporting analysis provided in the form of attachments) that are presentable to an employer. Clarity, grammar, spelling, and presentation will be considered in the grade. Students will have the opportunity to correct and resubmit the written component of the TMs within one week to improve their grades. Although experiments will be conducted in groups, each student will be required to submit a TM that is a product of his/her own effort.

Quizzes:
Quizzes will be given at the beginning of most class periods to test the analytical concepts of the TM assigned the previous week. The quizzes are designed such that students who satisfactorily complete the TMs, on time, should be adequately prepared for the quiz problems.

Grading:
The final grade will be computed based on the following percentages:
•80% - technical memorandums
•20% - quizzes

Class Policies:
Missed Classes: Due to the nature of laboratory work, permission to makeup assignments without penalty for a missed class will be granted in special circumstances to students who have made prior arrangements with the instructor. In the instructor's discretion, students who miss class without prior arrangements will receive a grade no higher than 75% on madeup assignments, provided its the first missed class. No makeup is permitted for subsequent missed classes.

Late Attendance: Quizzes are usually given at the beginning of every class period so students should be prompt to avoid lost time when taking quizzes. Students who are late for class without making prior arrangements will receive a grade no higher than 75% on madeup quizzes, provided its the first late attendance. No makeup is permitted for subsequent late attendance.

Late Assignments: Late TMs will be willingly accepted from students who have appropriately deducted points from the total score of the assignment. Students shall reduce their grade by 2 points for assignments not submitted at the beginning of the class, and 3 points for assignments submitted the following day (Monday for Section I, and Wednesday for Section II). An additional 2 points per week day shall be deducted thereafter.

Cheating: Not tolerated.

Tentative Course Outline (Section 1):

Class	*Date*	*Topic*	*Assignment*	*Quiz Date*
1	Jan. 9	Review Statics and Mechanics	None	None
2	Jan. 16	Determinate Truss Analysis	TM	Jan. 23
3	Jan. 23	Bending of Beams	TM	Jan. 30
4	Jan. 30	Moment Area Method	TM	Feb. 6
5	Feb. 6	Flexibility Method	TM	Feb. 13
6	Feb. 13	Indeterminate Frame Analysis	TM	Feb. 20
7	Feb. 20	Influence Lines TM	Feb. 27	
8	Feb. 27	Moment Distribution	TM	Mar. 6
9	Mar. 6	Catch-up Class None	None	

Tentative Course Outline (Section 2):

Figure 1. Structural Analysis and Design Laboratory (CIV 1226) Course Syllabus.

compression extreme fibers, and subject to an arbitrary load condition. Stains recorded by the gages are used with Hooke's Law to compute the maximum normal stresses that develop in the cross-section. The moment at the strain gage can now be back figured using the bending stress equation and compared with the theoretical moment that the students compute from statics. A non-symmetrical cross-section is used in the experiment for student practice in computing moment of inertia of an irregular cross-section and to emphasize the correct location of the neutral axis in their calculations.

Experiment 3: Moment Area Theorems & Discretization. The first and second moment-area theorems are applied to verify the end rotation and deflection of the non-prismatic wood cantilever beam. The implications caused by the non-prismatic section in applying the moment-area theorems become apparent as students attempt to evaluate the M/EI area in their computations. Consequently, students have to postulate a discretized physical model that is suitable to approximate the deformations that occur in the real beam when subject to a point load at its end. Initially, choosing a rather coarse representation (three prismatic elements), the moment area theorems are applied graphically and hand calculated results associated with the coarse model approximate the end rotation and deflection measured experimentally in the lab. By writing MATLAB routines to discretize the application of the moment-area theorems, students can use a computer to calculate and plot how the approximations improve as the number of elements is increased.

Experiment 4: Influence Lines The assignment reinforces the concept of influence lines (IL) by requiring students to experimentally construct influence lines diagrams in the laboratory and to confirm their results using the Muller-Breslau Principle. Reaction and moment IL diagrams are constructed for a simply supported two span beam which is made determinate by the introduction of a hinge at the middle of one of the spans. The reaction IL is found using a weight scale to measure the effect a unit load has on a support as the load is repeatedly applied at different points along the beam. In a similar manner, a strain gage is positioned at an intermediate point along the span to measure the effect the load has on strain at the extreme fibers. Students obtain the experimental reaction IL diagram directly by plotting the scale reading versus load position. The moment IL diagram is obtained by plotting the internal moment (computed using Hooke's law and the bending stress equation) versus load position. A simple demonstration is used to show similarities in the experimental IL diagrams and the deflected shape of the beam produced by the removing the capacity of the beam to carry a particular quantity (i.e. Muller-Breslau Principle). For further study of how IL diagrams are useful to solve problems involving arbitrary loadings (or worst case loadings), the exercise requires students to calculate the theoretical reaction and moment under a various loadings produced by distributed sand bags and concentrated point loads. Later these values are compared with the actual values determined from the scale and strain gage in an experiment with the same loading.

Experiment 5: Flexibility Method. The assignment requires students to apply the flexibility method to solve a second degree indeterminate beam problem (simply supported two span beam) analytically, by computer analysis, and experimentally. In the laboratory, students remove sufficient supports to obtain a statically determinate version of the original beam. Dial gages are then positioned at the released supports where deflections due to the original loading and from unit loads applied at each redundant are measured. Students are able to visualize how the flexibility matrix is formulated from equations intuitively generated by maintaining consistent deformations at the released redundants. The assignment also serves to prove by experiment the

Maxwell-Betti reciprocal theorem for cross diagonal terms in the flexibility matrix. In the analytical study, the assignment requires deflections (four coefficients of the flexibility matrix and the two deflections at the redundants from the loads) to be computed using double integration, moment-area, conjugate beam, and virtual work methods. Students solve the indeterminate problem using the Visual Analysis software to illustrate the exactness of the first-order software program in matching traditional hand solution techniques.

Experiment 6: Frame Analysis by Computer and Approximate Methods. A three-story frame is analyzed using approximate techniques and compared with first-order analysis results from the Visual Analysis software. A main goal of the assignment is to encourage students to use deflected shapes to assist in understanding the internal behavior of frames and its components under the wind and gravity loads. Moment diagrams are sketched from the deflected shapes and inflection points are identified to establish smaller substructures that can be used to approximate deflections, shears, and moments in the original structure. Solutions determined by approximate techniques are compared with first-order solutions obtained by the Visual Analysis software. From the computer generated results, the assignment requires students to extract various joints, girders, and column as free-bodies to verify equilibrium. Forcing students to extract free bodies builds their confidence in understanding printed results, differences in local and global coordinate systems, and sign conventions. Although the assignment introduces approximate techniques, the primary objectives are for students to study frame behavior and gain practical experience using a first-order analysis program.

Experiment 7: Moment Distribution with Side Sway. A one-story rigid aluminum frame is analyzed by hand using moment distribution, by computer using the Visual Analysis software, and by experiment in the laboratory. The non-symmetrical shape of the frame causes it to develop sidesway under the loading thereby forcing students to solve two separate moment distribution problems. In the laboratory, the frame is instrumented with strain gages at critical locations which enables students to measure strain, compute stress from Hooke's Law, and eventually determine internal moments and the frame's moment diagram. The moment distribution results and computer results are ultimately verified by the experiment, which also helps students visual how sidesway develops in rigid frames. Comparison of moment distribution and computer results illustrates that tradition techniques before the advent of computers, although sometimes tedious to apply, produce consistent results with today's software programs.

Experiment 8: Ductility of Reinforced Concrete Beams. Students study ductility in reinforced concrete using miniature mortar beams they prepare and use during experiments in the laboratory. Four mortar test beams in total are made. Each one is composed of different amounts of steel wire to simulate varying steel ratios used to resist tension stresses that develop during bending. One beam is made without reinforcing wire, while each of the other three are: slightly reinforced (smaller steel ratio than minimum required by ACI code), under reinforced (steel ratio meets requirements of ACI code), and over reinforced (higher steel ratio than maximum allowed by ACI code). Students are required to predict the type of failure (ductile or brittle) and the maximum allowable concentrated load that can be applied by a MTS when each beam is simply supported and loaded at its mid-span. Their predications are estimates based on elementary mechanics and fundamentals of reinforced concrete design. The compressive strength of the mortar is determined from test cylinders that are prepared as the mortar beams are constructed. After the 28-day strength is achieved, load-deformation data for each beams loaded to failure is obtained by a MTS and recorded using Lab View data acquisition software. After testing, students compare their predicted results with the load-deformation data recorded by the data acquisition system.

IMPLEMENTATION OF LABORATORY CURRICULA

Most of the data gathering and analysis is performed during the one hundred minute regularly scheduled meeting time each week. Students use the results from class meetings to prepare technical memorandums summarizing their analyses. Students work in the same groups throughout the quarter and submit individual memos.

Coordination with Lecture: Since different instructors teach both the theory-based course and the laboratory, the relationship between the two courses changes each quarter. At the beginning of each quarter the graduate student assigned to teach the laboratory course and the faculty member teaching the theory-based course determine the order that the laboratory modules will be taught. The curricula must complement this course for the students to fully benefit from the laboratory. The modular format of the laboratory curricula makes it possible to rearrange the order subjects are introduced in the labs and adapt to the different instructors who teach the theory-based course. At the beginning of each quarter modules are arranged such that the related theory is introduced first in the lecture course. The activities in the laboratory reinforce concepts taught in the course without simple repetition. Students have the opportunity in the laboratory setting to repeat and extend the knowledge obtained in the theory-based course through discoveries in the laboratory course.

Sample Assignments: A description of "influence lines," one module taught in the laboratory course, and the assignment's relationship to student assignments and lessons learned in the theory-based course is presented here. The influence line laboratory assignment given to the students is shown in Figure 2. Students do not explicitly learn about influence lines in the theory-based course, rather they learn the fundamental tools required to calculate influence lines. In the laboratory course, students are introduced to the definition of influence lines and use knowledge from the theory-based course to evaluate influence lines and verify their calculations with experiments. The laboratory course is used as a mechanism to help students discover the theory and fundamental theorems supporting influence lines.

Grading Policy: The grading policy (shown in Figure 1) motivates students to practice and improve their writing skills. Students have the opportunity to complete much of the analytical work required for the report during the regularly scheduled class period giving them the necessary time to prepare the written report outside of class and individually. After one submission of the laboratory reports students are allowed to improve their scores for communication up to 30% of the total TM score.

Northeastern University
Department of Civil and Environmental Engineering
CIV 1226: Structural Analysis and Design Laboratory

Assignment: Influence Lines

PURPOSE
The objective of this assignment is to study and understand the definition of influence lines and their purpose. An influence line is merely a graphical representation of the effect the movement of a unit load has on a particular internal force, reaction, or deflection, at a location of interest. As will be demonstrated in this assignment, an influence line may be constructed from its definition by deliberately applying its definition for multiple locations of a unit applied load. Alternatively, one may apply the Muller-Breslau Principle to construct influence lines in an efficient manner. In this assignments, students will experimentally construct a reaction influence line and a moment influence line for a determinate beam. Once constructed, the experimental influence lines will be used to compute the values for the reaction and moment under various load conditions, which will be compared with experimental values.

ANALYSES

1. Reaction Influence Line: For the determinate beam in Fig. 1, experimentally construct the reaction influence diagram for the support at location A by measuring the values of the support reaction due to a unit point load, P, that is moved along the beam. The influence diagram can be obtained by plotting the reactions on the y-axis and the corresponding location of the applied load on the x-axis. Experimentally obtain the reaction at A using a weigh-scale (P should be applied at one foot increments along the beam starting at point A). Use the Muller Breslau principle to construct the theoretical influence line diagram and use it solve for the support reaction at A due to the load condition shown in Fig. 2. Verify your solutions by experiment.

2. Moment Influence Line: For the determinate beam in Fig. 1, experimentally construct the moment influence diagram for location B by measuring strain and computing the moment due to a unit point load, P, that is moved along the beam. In a similar manner as above, the moment influence diagram can be obtained by plotting the moment on the y-axis and the corresponding location of the applied load on the x-axis. Determine the modulus of elasticity for the wood beam as done in prior assignments using Hooke's Law and the bending stress equation. Then experimentally obtain the moment at B using a strain gage (P should be applied at one foot increments along the beam starting at point A). Use the Muller Breslau principle to construct the theoretical influence line diagram and use it solve for the internal moment at B due to the load condition shown in Fig. 2. Verify your solutions by experiment.

WRITING ASSIGNMENT
Prepare a technical memo with attached supporting documentation to your boss that concisely presents the results of your assignment. The memo should begin by introducing the assignment (i.e., construct a

1

reaction influence diagram for point A and a moment influence diagram for point B of the beam shown on Attachment #). The body of the memo should 1) define the meaning of influence lines and their purpose, 2) compare the influence diagrams developed experimentally with similar diagrams developed from the Muller-Breslau Principle, and 3) comment on how an influence line was used to solve for the reaction and moment at points A and B, respectively. Conclude the memo by explaining how an influence diagram may be useful in design. Your memo should refer to the following attachments.

Attachment No. 1 (refers to part 1)

- Sketch of experiment (Fig. 1)
- Reaction measured at A by the weigh-scale for the load applied at each load point
- Scaled plot of the experimental reaction influence diagram

Attachment No. 2 (refers to part 1)

- Sketch & calculations for reaction at A computed using the MBP IL diagram
- Comparison of computed reaction at A to measured value using scale

Attachment No. 3 (refers to part 2)

- Sketch of experiment (Fig. 1)
- Moments measured at B (with the aid of a strain gage) for the load applied at each load point
- Scaled plot of the experimental moment influence diagram

Attachment No. 4 (refers to part 2)

- Sketch & calculations for moment at B computed using the MBP IL diagram
- Comparison of computed moment at B to measured value using strain gage

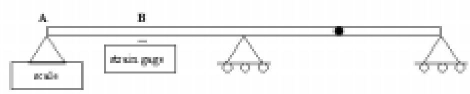


Fig. 1

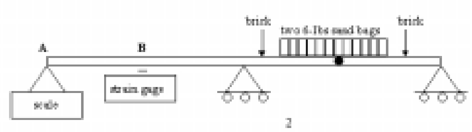


Fig. 2

2

Figure 2. "Influence Lines" Laboratory Assignment.

DISCUSSION

The new laboratory curriculum was designed during the 1996-1997 academic school year. Since its re-design, the course has been taught to 5 different sections. Antidotal evidence suggests that the structure's laboratory course is one of the best teaching laboratory courses with respect to student learning objectives and the theory-based course, its instructional partner.

Mid-course modifications have been made to help students improve their writing skills. These modifications have given students more opportunity to earn course points through the writing and the opportunity to improve and earn back points. Peer reviews have helped students learn from each other and significantly reduce the amount of time a teaching assistant spends grading the TM's. The attendance policy, not initially implemented, requires that students attend all classes and collect data themselves.

A number of future needs remain. Writing workshops for the students and the integration of an English teacher specializing in technical writing into the course instruction will help students improve their technical writing skills. From a technical point of view, the addition of data acquisition to the laboratory will bring the concepts taught in the laboratory into 21^{st} century technology.

Although the new curriculum is more rigorous than its predecessor, student feedback about the course is positive. Comments made by the students in informal conversations and the course evaluations before and after the change demonstrate that the new course design has met its curriculum and motivational objectives. Additionally, faculty who teach the same students in later years have noticed a marked improvement in student writing abilities. The laboratory course provides students with marketable skills in communication, teamwork, and with computer applications. Furthermore, the new laboratory curricula helps them in the theory-based course. Future plans for the laboratory include the integration of data acquisition methods.

SARA WADIA-FASCETTI is an Assistant Professor of Civil Engineering at Northeastern University where she is actively involved in a research program on structural condition assessment. She completed a B.S. in Civil Engineering at Carnegie Mellon and the M.S. and Ph.D. degrees in Civil Engineering at Stanford University. Sara teaches the structural analysis lecture course that accompanies the laboratory presented in this paper.

MICHAEL TARNOWSKI is a graduate student pursuing a Ph.D. in Civil Engineering at Northeastern University. He completed his B.S. and M.S. degrees at the University of New Hampshire and Northeastern University, respectively. Mike has taught the structural analysis and design laboratory course for the past three years and he was integrally involved with the recent laboratory design and development.