CDIO APPROACH FOR REAL−TIME EXPERIENTIAL LEARNING OF LARGE STRUCTURES

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ABSTRACT

The traditional approach of teaching structural analysis and design modules has several shortcomings. This paper describes and illustrates how real world structural engineering can be brought into campus. A large structure was conceived, designed, and implemented in the existing workshop space. Strain gauges are installed to show how the parts of the large structure behave under different loading conditions. In the context of Conceiving, Designing, Implementing, and Operating (CDIO) framework, a capstone project was designed for students to do active and real time experiential learning of large structures. In addition, other student-centred real-time prototype experimental activities have been developed and planned for implementation in the "Structural Learning Space." The space now allows not only for normal use by students to optimize the utilization of the workshop space but also for staff to conduct lectures, tutorials, and experiments of structural engineering modules in an integrated manner.

KEYWORDS

Conceiving, Designing, Implementing and Operating, real time prototype experiments

INTRODUCTION

Structural analysis and design are the core modules of Diploma in Civil and Structural Engineering (DCSE) from the School of Architecture and the Built Environment, Singapore Polytechnic. However, these modules are perceived by DCSE students as "abstract", "dry" and "hard to visualise". Students traditionally have difficulties in grasping the concepts of structural behaviour. They tend to adopt learning by concentrating on manipulation of equations and memorizing particular solutions which obscures the underlying important concepts and principles. The reasons are mainly because structural engineering modules require students' good understanding of abstract concepts in structural behaviour and an ability to use them qualitatively.

On the other hand, the approach at present to teach these modules by lecturers usually includes a series of lectures on physical laws, mathematical tools and methods for structural analysis and design by using a methodology which consecutively subdivides a real world structure into extremely small sub-components, focusing on a particular element, detaching it from all other connected structural members and then reducing it to a notation system of structural symbols, mathematical equations and annotations. Structural modules delivered in this way will only get students too much involved into calculation tedium and almost never attempts to connect detailed analysis back to broader building design and construction principles, which result in not seeing the wood from trees and thus lacking of fundamental conceptual understanding of structural system behaviour for the analysis, design and construction of building structures [1].

Although the traditional lectures on structural engineering modules are usually supplemented by laboratory experiments by using of scaled-down models to verify laws and to let students observe structural behaviours, however student feedback has shown that the traditional approach of lecturing and lab experiments have the following shortcomings:

1) Inaccuracy is always introduced when one transfers test results of scaled-down models to the large structures in the real world. The degree of inaccuracy is very much dependent on the similarities of geometries, materials and applied loads. When a scaled-down structural model is tested, dimensional analysis is always used to express the structural system with a few independent variables and as many dimensionless parameters as possible. However, due to its complexity, dimensional analysis can only be taught at the level of undergraduate or post-graduate studies. Hence there will always be a big question mark in our students' minds, "Can structural analysis methods verified by scaled-down model tests be truly applicable to large structures in the real world?"

2) Lectures and laboratory experiments are conducted in different sessions at different places. Students usually study concepts and methods for structural analysis and design modules during lecture sessions and then conduct laboratory experiments on other days. The time gaps between lecture and laboratory sessions will cause the following disadvantages in teaching and students' learning.

    - Lecturers are not able to verify the concepts and methods for structural analysis and design immediately during lecture sessions. The students' understanding is superficial and not rooted deeply into their minds.
    - When students come to the laboratories, they may have difficulties in relating the experiments with the concepts and methods that they learnt during their lecture sessions a few days ago. Some of them may even have forgotten what they have learnt during lecture sessions.

3) It is harder for lecturers to convince students that concepts and methods for structural analysis and design verified by scaled-down model tests can also be applicable to large structures in the real world without doing prototype real-time experiments in front of students.

As an ancient saying goes:

"Tell me, and I will forget. Show me, and I may remember. Involve me, and I will understand." – Confucius (551-489 B.C.E)

AN INNOVATIVE SOLUTION FOR REAL-TIME EXPERIENTIAL LEARNING OF LARGE STRUCTURES

To address the problems existing in the staff teaching and students' learning of structural engineering modules, the authors spoke to lecturers who are teaching structural modules, and carried out brain-storming sessions. A two-prong approach was adopted to overcome these problems and to give students integrated hands-on learning experience. The idea is to upgrade an existing laboratory space and design-build-operate a real size structural system [2].

The purposes of having such a real size structural system in the existing laboratory space are: a) motivating students in understanding of structural concepts and behaviours, b) integrating discrete and disconnected experiments across different structural engineering modules, c) providing a conducive learning environment within existing laboratory that was used for concreting and building technology work, and d) providing a platform for implementing principles and standards of CDIO in the context of civil engineering education.

Conceive-Design-Build the "Structural Learning Space"

During the stage of conceiving the "Structural Learning Space", the authors applied systems thinking to the problems at hand, and consulted significant staff members who involved in the overall course design, laboratory management, teaching of structural engineering modules and staff supervising concreting and building technology activities in the existing laboratory space. Then there was the consideration to prepare part of the laboratory space for design-build experiences required for the future implementation of CDIO as the context for civil engineering education.

The solution was to have a "Structural Learning Space" designed, built and operated at the rear of an existing laboratory that was used for concreting and building technology practice. The "Structural Learning Space" provides real-time experiential learning of the behaviours of a large structural system for civil engineering students across different structural engineering modules. It can also support the CDIO Education Framework which "provides civil engineering students with an education that stresses the engineering fundamentals in the context of real-world systems and products [3]."

During the stage of designing the "Structural Learning Space", the authors, by adopting the CDIO methodology, played various roles of 'owner' and 'design engineer'. Based on initial concept designs and requirements, engineering design specifications were written and the design of structural members and connections were carried out. Together with an external consultant, design drawings of the "Structural Learning Space" were issued to an external contractor for construction.

During the nine month construction stage of the "Structural Learning Space", working closely with the external consultant and contractor, the authors played the roles of 'site supervising engineer' and 'product system operator'. At the end of 2006, the "Structural Learning Space" was completed and ready for use. It is now located in a space within the workshop in W515. It is a single storey steel framed structure. Its columns are all UC 254×254×8, and the truss members are made out of hot rolled Rectangular Hollow Sections (RHS) with two different sizes of 160×80×8 RHS and 150×90×10 RHS respectively. Figures 1 and 2 show the external and internal appearances of the "Structural Learning Space".

Figure 1 External appearance of the “Structural Learning Space”

Figure 2 Internal appearance of the “Structural Learning Space”

The “Structural Learning Space” has the following unique features [4]:

1) All main structural members are not covered by ceiling boards so that students could see different parts of the steel members. This enables them to appreciate the actual size of various structural members. Students’ learning of structural engineering modules will become more vivid.

2) All typical connection details between truss members, trusses to columns and columns to foundations are painted with different colours to highlight the main structural members with different types of connections. In this way, students could see and understand how one member is connected to another in a truss system and how these trusses in turn are braced and supported by columns. This promotes students’ system thinking with regards to load transferring paths, structural system modelling and structural system design.

Install Structural Measurement System

In order to let students witness and experience the real-time response of large structures when loads are applied, state-of-the art structural measurement system was installed after the completion of the “Structural Learning Space”.

The structural measurement system comprises of testing equipment, sixty high resolution strain gauges, and two 30-channel digital data loggers which are connected to two desktop computers respectively.

The strain gauges are installed at critical locations of the steel structural members. They measure the strains of critical points of a structural member. Strain gauges are then connected to the two data loggers which convert the analogue signals from each strain gauge into digital strain data.

Software programmes are installed into two PCs which process the acquired data and display the results according to users’ requirements.

The installation of the equipment, strain gauges, wiring, data loggers and computers in the “Structural Learning Space” was completed at the end of March, 2007. Testing of the whole system was conducted at the end of April, 2007.

The schematic view of the monitoring system is shown in Figure 3.

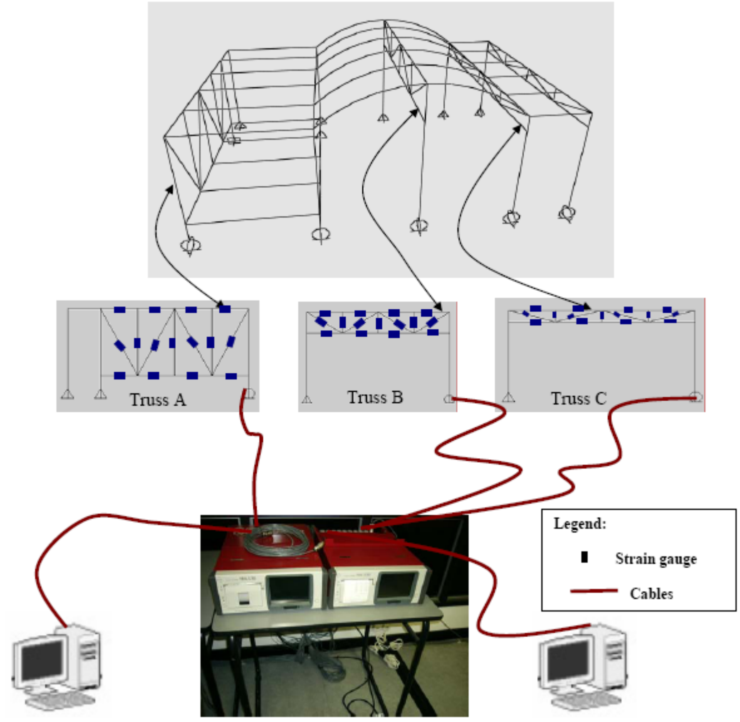

Figure 3 Schematic view of the structural monitoring system

CDIO APPROACH FOR REAL-TIME EXPERIENTIAL LEARNING OF LARGE STRUCTURES

The CDIO model is a model for engineering education that stresses the product lifecycle of Conceive-Design-Implement-Operate (CDIO). It should form the context for engineering education. The process of designing a CDIO programme is guided by CDIO standards.

The CDIO standards serve as guidelines for educational programme reform and evaluation, create benchmarks and goals, provide a framework for continuous improvement. The CDIO standards address programme philosophy, curriculum development, design-build experiences and workspaces, new method of teaching and learning, faculty development, plus assessment and evaluation [5].

With the help of the “Structural Learning Space” and its measurement system, staff can now apply the CDIO standards such as ‘CDIO Work Spaces’, ‘Integrated Learning Experiences’, ‘Active Learning’ and ‘CDIO Skills Assessment’ for staff teaching and students’ learning of structural engineering modules.

Based on the above-mentioned four CDIO standards, an integrated capstone project has been designed and implemented in module “Structural Steel Design & CADD” (A final year core module in DCSE course). A few student-centred experimental activities have also been developed for modules “Structural Analysis and Simulation” (A 2nd year core module in DCSE course) and “Structural Steel Design & CADD” to verify concepts and methods and to improve students’ understanding of structural behaviours. As the structure is full scale and the results obtained through experimental activities are “real-time”, students can be instantly convinced of structural theory and behaviour when subjected to different types of loads.

An Integrated Capstone Project on the "Structural Learning Space"

This integrated capstone project is designed by applying the above-mentioned four CDIO standards for module "Structural Steel Design & CADD" in final year of DCSE course. Students are to work in fours. They have to finish the whole project and submit a group report by the end of term 4 of each academic year.

Project objectives

The objectives of this integrated capstone project are to provide opportunities for students to: a) integrate all aspects of knowledge acquired and comprehended from other modules of the course in particular, in the areas of structural analysis, design and detailing using CADD, b) cultivate team spirit and team work through working with team members, c) practise technical skills, quality consciousness and time management, d) develop initiative, creative thinking and innovative ideas, and e) plan, organize and write a group project report.

Main tasks of the project

By applying the above-mentioned four CDIO standards (i.e. 'CDIO Work Spaces', 'Integrated Learning Experiences', 'Active Learning' and 'CDIO Skills Assessment'), the main tasks of this capstone project were set by the module team in such a way that by doing this project, students could learn how to design and construct real world buildings. The main tasks that our students need to complete within seven weeks in term 4 are as follows.

1) Scheming of structural floor plans based on architectural drawings

   Students are required to scheme and sketch structural floor plans which show the overall grid system, location of supports and floor support configuration from architectural drawings.

2) Load determination, calculation and transferring

   Students are required to determine loads based on the loading requirements for different types of buildings specified in Code of Practice for Design Loadings for Buildings and how the loads are transferred in the building.

3) Sizing, analyzing and designing of structural members

   Students are required to: a) try sizes for different structural members such as columns, beams and truss members, b) analyze the structural system using an integrated structural analysis and design software, either SAP2000 or Stadd.Pro 2007, to find internal forces of structural members, c) manually design structural members by following the design code: BS5950-Structural Steel Use of Steel Works in Buildings. This is a trial and error process which will continue until all the sizes of structural members meet the limit state design criteria (i.e. the Ultimate Limit State and the Service Ability Limit State) under the applied loads.

4) 3D modelling and virtual construction of the "Structural Learning Space"

   Students are required to: a) propose the construction sequence of the steel structural members, b) use a 3-Dimensional CAD software called Bentley Structural XM to draw 3D modelling of the "Structural Learning Space", c) animate the construction of the structural system according to their proposed erection sequence.

5) Report of the capstone project.

Each student group is required to submit a hardcopy of report which includes the details of tasks 1) to 4) and a softcopy of the 3D modelling and animation of the construction sequence of the “Structural Learning Space” which must be written into a CD and attached to the report.

Project schedule

The schedule of the capstone project is arranged as shown in the following table.

Table 1
Schedule of the Capstone Project

Week in Term 4	Tasks
Week 1	Project briefing and getting started on project
Week 2	Scheming of structural floor plans
Week 3	Load calculations & analysis using STAAD.Pro 2007/SAP2000
Week 4	Design calculations
Week 5	Design calculations and CAD 3D modelling using Bentley Structural XM
Week 6	CAD 3D Modelling and Animation of erection sequence using Bentley Structural XM
Week 7	Writing and Compilation of Report
Before 5:00pm, Friday of Week 7	Submission of the project report.

Project assessment

From CDIO point of view, assessment is regarded as learning-centred, that is, an integral part of the teaching process, promoting better learning in a culture where students and staff learn together [6].

Assessment is learning-centred in that it is aligned with learning outcomes [6]. With this statement and CDIO syllabus in minds, the module team came out the learning outcomes of the project, prudently chose suitable CDIO skills for assessment, and carefully allocated weightages to different learning outcomes as shown in table 2.

Table 2
Assessment Scheme of the Capstone Project

Item	Learning Outcomes	CDIO Syllabus [6]	Weightage
1	Reasonableness of assumptions of live loads, member sizes and modelling for structural analysis.	1.2 and 2.1.2	15%
2	Correctness of load calculation, load transferring, structural analysis and design calculations.	2.1.4, 2.4.3, 4.4.1 and 4.4.3	35%
3	Correctness of 3D CAD modelling and animation of construction sequence.	3.2.5	15%
4	Teamwork and communication	3.1 and 3.2.6	15%
5	Presentation of the report	3.2.3 and 3.3.1	20%

Student-centred experimental activities for real-time experiential learning on large structures

With the “Structural Learning Space” and its state-of-the-art monitoring system at place, many fun-filled experimental activities can be arranged to promote students’ active and real-time experiential learning on large structures under different types of load conditions.

Many fun-filled experimental activities such as “verification of the stress-strain formula”, “verification of superposition theorem”, and “behaviours of the structural system due to the dynamic load caused by a mass of students jumping up and down on the floor, etc. have been planned. And the “verification of stress-strain formula” is one of the most favoured activities that have been arranged in structural analysis and design modules in the past two year. The details of the activity are as follows.

The stress-strain relationship is a very important formula in structural analysis and structural design. Based on the stress-strain formula, the internal stress and deformations of structural members can be calculated. The stress-strain relationship is given by:

$$\varepsilon = \frac{\sigma}{E}$$

Where ε and σ denote internal strain and stress of a structural member respectively, and E denotes elastic modulus of the material.

To verify the above formula, students are required to do structural analysis based on above stress-strain formula using an integrated structural analysis software program. At present the Structural Analysis Software, either SAP-2000 or STAAD.Pro 2007, is recommend to be used. Students carry out the analysis of a steel truss as shown in Figure 4. Under a point load P which is generated by a hydraulic jack, the strains in the truss members are measured by the measurement system. If the strain calculated by the software approximately equals to what the measurement system has given out. The formula is verified immediately.

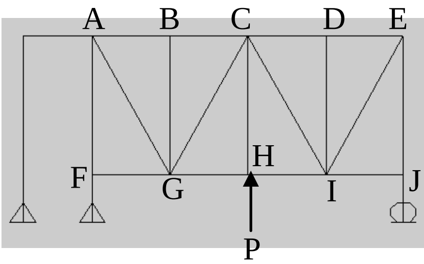

Figure 4 Experimental set-up for the verification of stress-strain formula

Table 3 shows a sample results obtained through the above activity by a group of students who took module “Structural Steel Design & CADD” in year 2008.

Table 3
Numerical Analysis and Experimental Results of Member BC

Applied Load (kN)	Numerical Results (ε_1)	Experimental Results (ε_2)	Difference ($\lvert\varepsilon_1 - \varepsilon_2\rvert / \varepsilon_1$)
14	4.3×10^{-6}	4.1×10^{-6}	4.6%
16	4.9×10^{-6}	4.7×10^{-6}	4.1%
18	5.5×10^{-6}	5.3×10^{-6}	3.6%

From the table 3 above one can see that the differences between theoretical analysis and experimental results are in a small range of about 5%, thus we can say that the stress-strain relationship is verified.

CONCLUSIONS

The “Structural Learning Space” is a two-prong approach to address problems faced by staff and students in the traditional mode of teaching and learning of structural engineering modules. After applying system thinking the authors came out with an innovative solution of designing and building a real size structure equipped with a state-of-the-art measurement system within the existing laboratory space for integrated learning. The entire system provides students opportunities to carry out integrated learning of structural engineering concepts, structural analysis, design and monitoring of structural behaviors under different load conditions.

By applying CDIO standards, an integrated capstone project was conceived, designed and has been implemented in module “Structural Steel Design & CADD” for the past two years. Many student-centered real-time experimental learning activities were developed and have also been implemented in Modules “Structural Analysis & Simulation” and “Structural Steel Design & CADD” for students to do active and experiential learning.

The “Structural Learning Space” is now intensively used by staff to conduct “on-site” lectures in a conducive learning environment and leverage students’ experiential learning by integrating discrete and disconnected experiments across different modules. Student feedback shows that by operating on the “Structural Learning Space”, learning of structural analysis and design modules is no longer boring but one that provides a pleasant experience.

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