Int. J. Engng Ed. Vol. 24, No. 3, pp. 529–539, 2008
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Floor Beam Testing Laboratory for Teaching Beam Bending Mechanics*

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A unique undergraduate laboratory, called the Learning Column, has been implemented at Queen's University. The laboratory consists of a steel column and hydraulic jack that are used to apply controlled and known loads to a floor beam that is part of a new engineering building at Queen's, the Integrated Learning Centre. Sensors mounted on the floor beam allow students to measure beam strains and deflections. Students can access the Learning Column facility at any time and can conduct the test on their own, following instructions provided by a touch screen. The Learning Column has been used to illustrate the basic concepts of axial member and beam bending behaviour for students in a second year undergraduate solid mechanics course. For example, data from the tests can be used to illustrate the linear variation in strain in the beam under bending, one of the fundamental assumptions for understanding beam behaviour. The Learning Column also provides an opportunity to discuss advanced structural design concepts and construction practices. For example, students can clearly see that the load and boundary conditions for a real beam are vastly different from the idealized beams normally analysed in a second year solid mechanics course.

Keywords: solid mechanics; undergraduate laboratory; steel; instrumentation; beam bending; column; connections; idealized boundary conditions; full scale structural testing

INTRODUCTION

BEAMS ARE IMPORTANT structural members in many engineering applications, including building frames, bridges and vehicles. Undergraduate solid mechanics courses in civil and mechanical engineering typically provide students with the theory required to calculate stresses and deflections in beams. Such idealized beams are assumed to be linear-elastic, and to undergo small deflections. Strain is also assumed to vary linearly with beam depth (also termed: 'plane sections remain plane') during bending. In addition, the beams usually have simplified loading (e.g. point loads or uniformly distributed loads) and boundary conditions (frictionless pins or rollers, or fixed supports). Students may take more advanced design courses in which composite beams or material non-linearity is considered. There may be one or two labs to reinforce these concepts that usually involve the testing of a simply-supported beam in a controlled lab setting. A typical approach is the use of bench-scale models, such as the cantilever model employed by [1]. In some cases, the internet is being used to improve the experience of students undertaking laboratory testing [2].

It is well acknowledged that an important learning component for engineering students is the opportunity for hands-on activities that allow them to physically observe behaviour described in lectures. In describing the elements necessary for improved learning outcomes for the teaching of fundamental engineering courses, Dollar and Steif [3] stated:

> Students learn in part through a process of constantly comparing their understanding and predictions with observations of the world. Making comparisons with observations is one way of obtaining feedback, which is necessary to refining one's understanding.

Lagoudas *et al.* [4] describe the development of an active learning laboratory for understanding beam behaviour. In this approach, finite element analysis software is used to model a cantilever beam, and students use the model to design an optimum beam for various load cases.

This paper describes the development of a unique undergraduate laboratory, called the Learning Column, at Queen's University, Ontario. This laboratory permits students to conduct tests on a structural floor beam that is part of a building on the Queen's campus. Students compare the behaviour of the real beam with theoretical predictions and test the assumptions that underlie such predictions. The Learning Column also provides them with an introduction to the most common types of structural engineering sensors and their application for monitoring structural response. The paper will outline the conceptual design of the Learning Column, describe its operation, present one of the labs students undertake using the Learning Column, and discuss the learning and teaching opportunities that arise out of the Learning Column.

* Accepted 18 November 2007.

INTEGRATED LEARNING AT QUEEN'S UNIVERSITY

Over the last six years, the engineering curriculum at Queen's University has undergone a renewal called Integrated Learning at Queen's. Integrated Learning seeks to:

- 'Provide students with the skills (communications, lifelong learning, teamwork) and attitudes (sensitivity to social, environmental and economic issues) that they need to elevate theory to practice.
- Increase the emphasis on active learning by the student, with the aim of increasing the depth of learning, the retention of understanding, and the development of learning skills.
- Provide students with an improved understanding of the role of other engineering disciplines and, indeed, of the role of professionals outside of engineering.' [5]

As part of this initiative, a new Integrated Learning Centre (ILC), shown in Fig. 1, was opened in 2004. A key feature of the ILC is an array of full-scale structural systems designed to illustrate solid mechanics concepts and advanced structural engineering systems. Some of these displays are static and consist of exposed systems so that students can observe actual construction practices. Three of these displays are shown in Fig. 2. In addition to the static displays, numerous sensors are integrated into the building to monitor building functions ranging from building envelope temperatures to power usage. The data from these sensors can be accessed by students and professors. .

Of particular interest to structural engineers and the teaching of solid mechanics concepts are sensors for measuring building component strains, deflections, and loads. During the design phase of the ILC, project engineers working with members of the Department of Civil Engineering identified sensible locations for mounting sensors to measure structural response. It was recognized that monitoring of the strains in typical structural members, such as the columns, the roof beams, the floor beams, and staircases, would provide valuable

Fig. 1. The Integrated Learning Centre.

information for teaching and learning. However, preliminary analysis showed that the strains in these members under typical service loads would be too low to measure. In addition, there was the problem of how to control the loading. As a result, a specialized Learning Column was incorporated into the design.

CONCEPTUAL DESIGN OF THE LEARNING COLUMN

Figure 3 shows the conceptual design of the Learning Column. This solution was proposed as a means of applying significant and controlled loads to a structural member so that the response could be monitored. The structural member being loaded and monitored is a typical floor beam located on the first floor of the ILC. The floor beam system is very common in building design in North America. It consists of a W460 $\times$ 61 steel beam with a total span of 7 m that supports corrugated steel decking with a depth of 38 mm. A concrete slab of depth 77 mm is supported by the decking. The concrete deck and slab are connected by shear studs to the steel beam to ensure composite action. The W460 $\times$ 61 beam is supported at its ends by a bolted connection, shown in Fig. 4 during the construction phase, that is anchored into a concrete wall.

(a) (b) (c)

Fig. 2. Exposed structural features in the ILC: (a) reinforcing bars in concrete column; (b) typical column footing; (c) details of wall insulation.

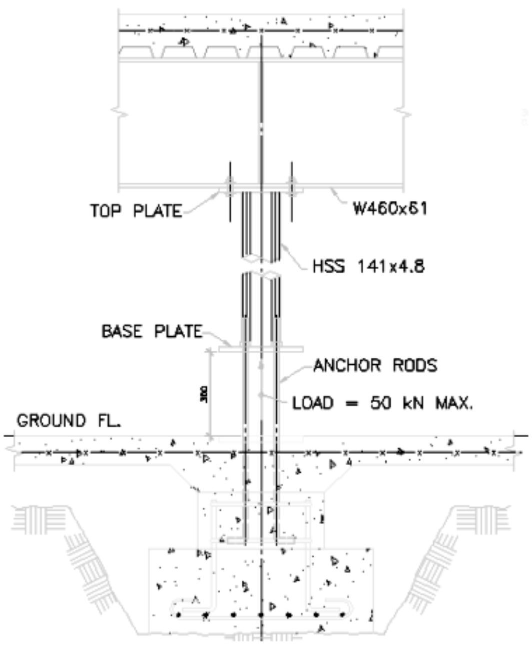


Fig. 3. Conceptual design for the Learning Column.

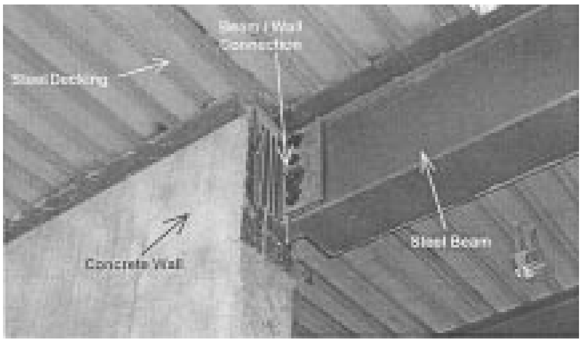
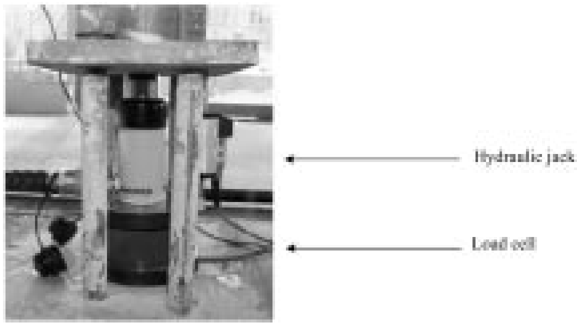
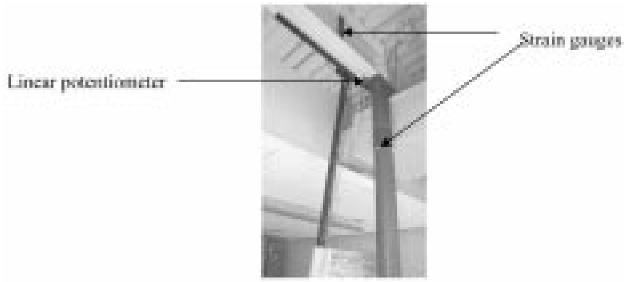


Fig. 4. Connection between floor beam and supporting concrete wall.

To apply known loads to the floor beam, a steel hollow structural section (HSS) was bolted to the bottom flange of the beam. A 300-mm gap was left between the bottom of the HSS column and the ground floor to accommodate a hydraulic jack for applying load to the floor beam and a load cell for measuring the applied load. Figure 5 shows the hydraulic jack and load cell located beneath the HSS column. Four threaded steel anchor bolts are anchored into the floor slab and footing to ensure the lateral stability of the HSS column as loads are applied. The anchor bolts slide freely through drilled holes in the base plate of the HSS column as load is applied.

The maximum force that can be safely applied to the Learning Column is 50 kN. This was determined by the project engineers to be the maximum load permissible before concrete cracking occurred in the slab supported by the beams.





(a)

(b)

(c)

Fig. 6. Location of instrumentation: (a) strain gauges and linear potentiometer; (b) strain gauges on beam web; (c) strain gauges on HSS column.

INSTRUMENTATION

In order to measure what the beam 'feels' as load is applied, sensors mounted on the HSS column and on the floor beam are required. In the case of the Learning Column, the instrumentation consists of: (1) a load cell; (2) strain gauges; (3) linear potentiometers. These are very common sensors

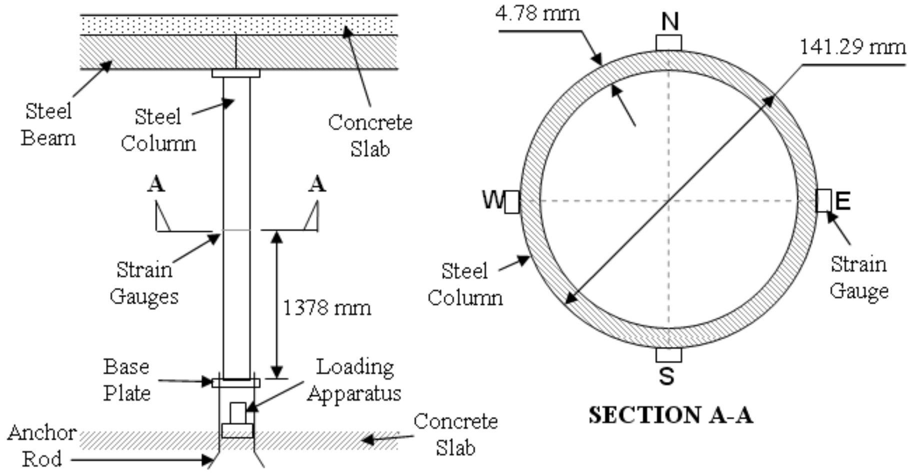


Fig. 7. Location of strain gauges on HSS column.

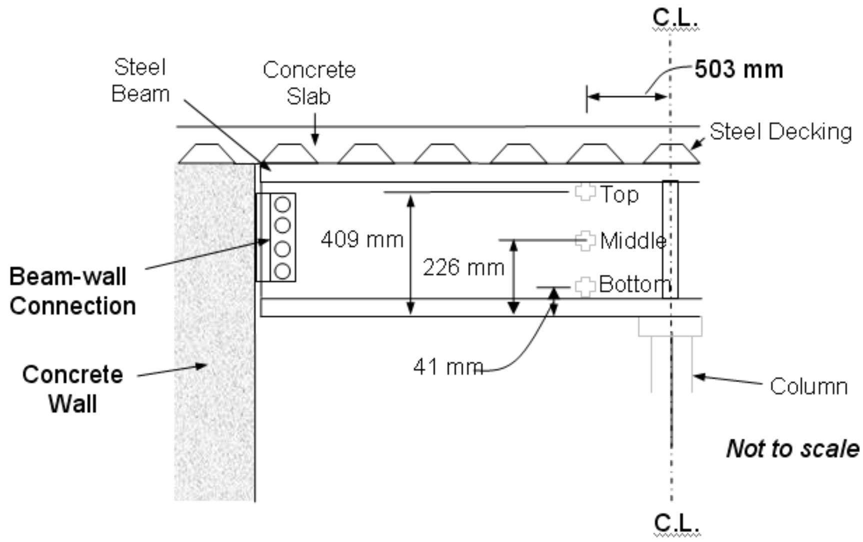


Fig. 8. Location of strain gauges on floor beam.

in structural engineering research, and are being used more frequently to monitor structures in the field. Because of time constraints, only the information from the load cell and strain gauges was used in the laboratory described in this paper.

Strain gauges were mounted on the HSS column, as shown in Fig. 6(c) and Fig. 7. The strain gauges were labelled North (N), South (S), East (E), and West (W) as indicated in Fig. 7. The location of the strain gauges on the floor beam is indicated in Fig. 6(b) and Fig. 8. Figure 6(a) shows a linear potentiometer (LP) that measures change in position (i.e. deflection) of the bottom flange of the beam. One LP is located at the bottom of the column, and the other at the top of the column.

All instrumentation was connected to a National Instruments data acquisition system (NI PCI-6034E) and the data were downloaded to the local network computer hub to facilitate Web-based access to the information.

PERFORMING TESTS USING THE LEARNING COLUMN

Figure 9 shows the display at the front of the Learning Column. To facilitate use by a wide range of students, the hydraulic jack and instrumentation are left in place. The display is surrounded by Plexiglas to prevent tampering with the hydraulics and instrumentation. The display case itself houses a hand operated pump that is used to extend the jack and apply loads to the column, a flat screen display that provides full instructions on the use of the Learning Column, and displays showing the current load and beam deflection. Students can access this set-up at their convenience, rather than during specific lab times. In fact, students can repeat the test as many times as they wish in order to obtain additional data.

All the data obtained during a test is collected and archived by the ILC Live Building Website;

Fig. 9. Learning Column display.

Fig. 10 shows the data query screen on the ILC web-site. Students can access the data at any time simply by logging on to the web-site and entering the date and time that the test was conducted.

INCORPORATING THE LEARNING COLUMN IN THE ENGINEERING CURRICULUM

The Learning Column has been used to reinforce concepts of beam bending for undergraduate Civil Engineering students at Queen's. Second year Civil Engineering students typically take an introductory solid mechanics course in the Fall term (CIVL 228), and an advanced solid mechanics course in the Winter term (CIVL 229). The advanced course covers topics such as indeterminate structures, composite beam bending, and non-linear material behaviour. A laboratory involving the Learning Column was introduced to the second year students during the Winter term 2006.

The objectives of the lab are:

- to investigate the response of a simple column and beam to applied loading;
- to become familiar with common structural engineering sensors, including load cells, strain gauges, and linear potentiometers.

The introduction to the lab describes some of the assumptions students investigated:

> 'This beam is different from the simple beams analysed in CIVL 229 because: (1) The connections are not simple pins, rollers, or fixed connections; (2) It consists of a steel beam and concrete slab connected together (a composite beam).
>
> We have made many assumptions about the behaviour of beams and other structural members throughout CIVL 228 and 229. We assumed linear elastic behaviour for the material, and we assumed 'plane sections remain plane' (i.e. the distribution of strain over the depth of the beam is linear) during beam bending. In this lab, we will look at these assumptions in the context of a real beam in a real structure and see if they have any validity. We will also learn about the most common sensors used to measure the response of structures to load.'

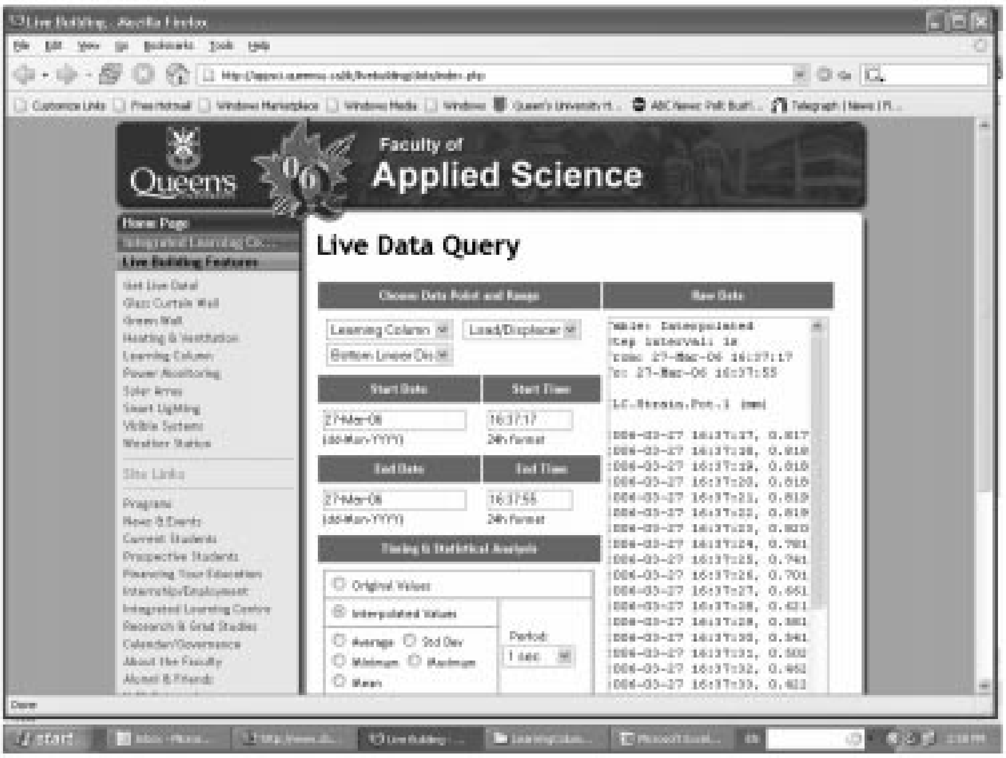


Fig. 10. Data query screen.

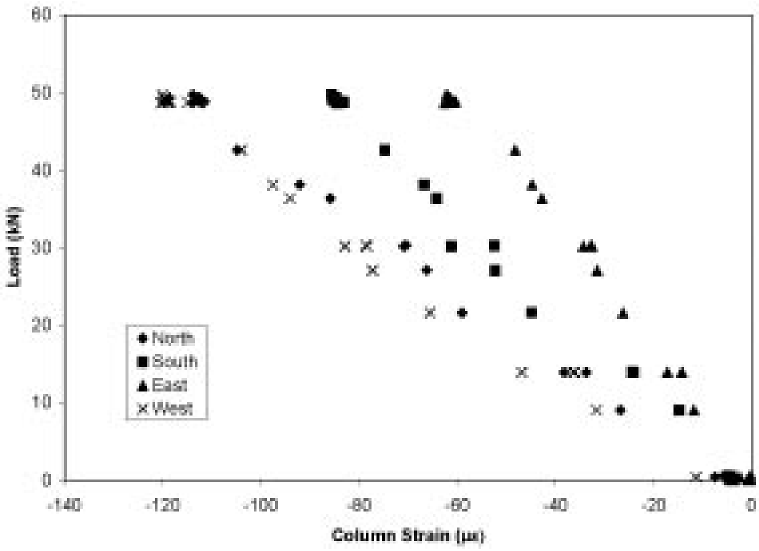


Fig. 11. Column strains.

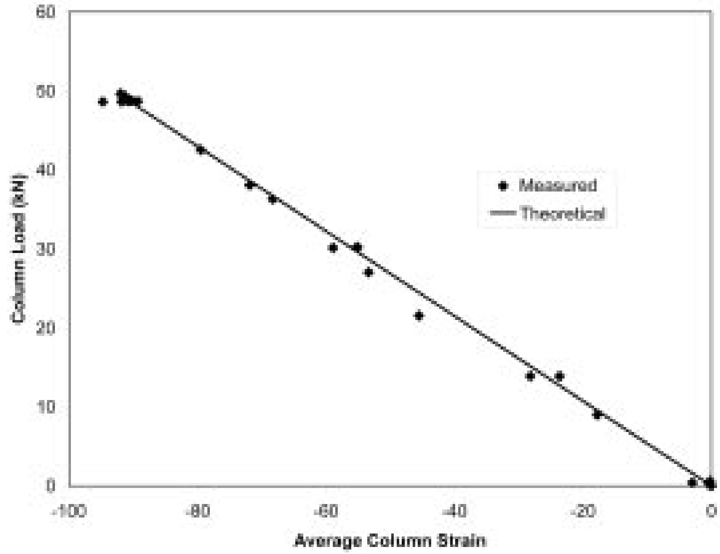


Fig. 12. Average column strains.

The instructor introduced the Learning Column exercise with a half-hour pre-lab lecture designed to discuss with the students the objectives of the lab, the mechanics of conducting the test, and learning expectations. It was also an opportunity to discuss how the beam they were about to test differed from the idealized beams usually considered in lectures and assignments and how this affected analysis at the design stage. In the pre-lab lecture, real construction practices were also discussed.

TYPICAL DATA AND ANALYSIS

In the following section, typical data and analysis from the laboratory will be described. Figure 11 shows typical strain readings obtained from the strain gauges on the HSS column as the load is increased. The negative sign on the strain gauge readings indicates that the strains are compressive. Students were asked to consider the following questions:

> 'Comment briefly on the strain gauges vs. load plots. Is each plot linear? This is a case of simple axial loading, and so we expect the strains over the column cross-section to be uniform at each loading level. Is this the case? Can you note any differences in the strain gauge readings? What do you think might be causing the differences, if any are noted?'

By observing this data, students could immediately see that, although the strain versus load response is generally linear for each strain gauge, it is not simply a straight line. In addition, although they were told that this was a case of simple axial loading on the column, it is clear that the strains

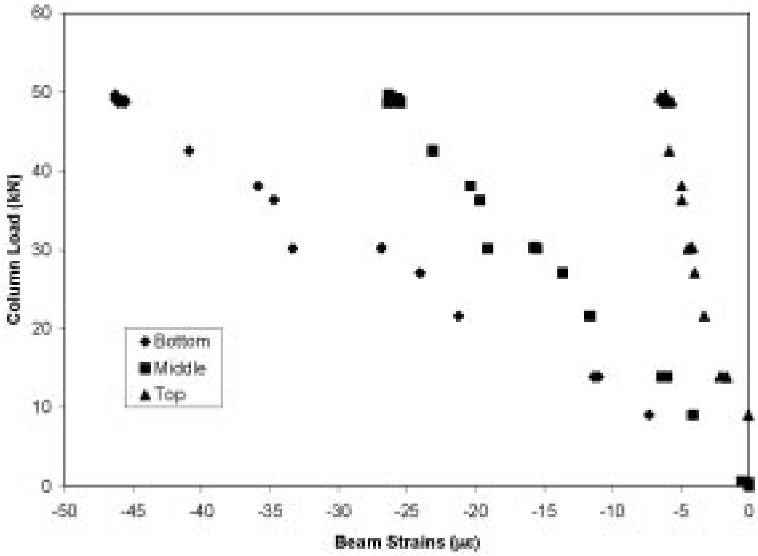


Fig. 13. Beam strains.

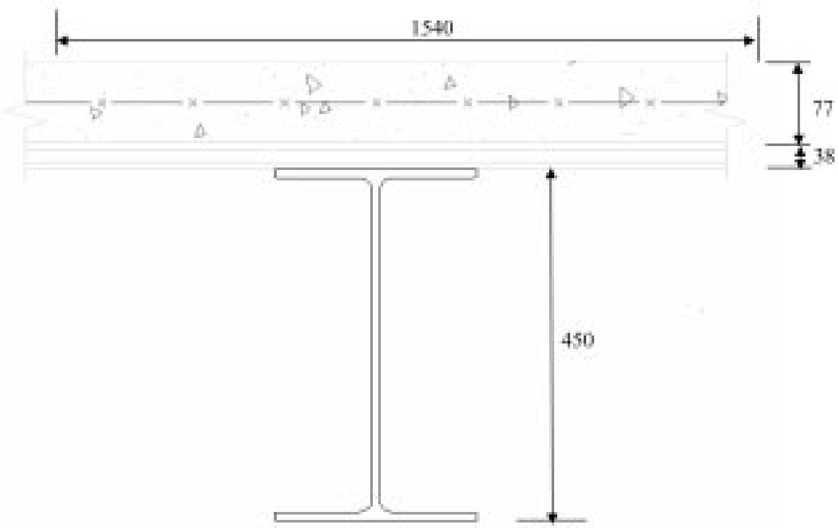


Fig. 14. Cross-section through floor beam.

at each gauge location are not equal at any given applied load. Students were encouraged through discussions with the teaching assistants and course instructor to consider why this may be so. Most students were able to identify the fact that the hydraulic jack is not perfectly concentric with the column as the source of the differences in the strain gauge readings.

Figure 12 shows the average column strain versus applied column load. The average of all four strain readings was calculated at each value of applied load. Students were asked to compare the measured strains with the theoretical strains given that the column cross-sectional area is 2690 mm^2 and assuming Young's modulus for steel is 200 GPa. The correlation between the measured and theoretical strains is excellent, showing students that, despite differences between the assumed and actual loading conditions, the simple theory for strains in an axial column works well.

Figure 13 shows the strains obtained in the floor beam as the load was applied. Because the load was applied to the bottom flange of the beam, it caused 'hogging' of the beam, leading to compressive strains below the neutral axis, and tensile strains above the neutral axis. Because each strain gauge is located at a different distance from the neutral axis, strains do not increase at the same rate with an increase in load. Based on their knowledge of beam bending, students would expect this behaviour.

Students were then asked to use the beam strain values to locate the neutral axis of the beam cross-section, to estimate the beam's moment of inertia, and to compare it with theoretical predictions. Figure 14 shows the cross-section through the floor beam. The theory taught in class on the bending of composite beams was used to analyse the beam. The concrete slab was transformed to an equivalent block of steel using the modular ratio, *n*:

$$n = \frac{E_c}{E_s} \quad (1)$$

where E_c is Young's modulus for concrete and E_s is Young's modulus for steel. The values of E_c = 25 GPa and E_s = 200 GPa were given to the students. The width of the concrete flange was based on the spacing of the floor beams, and made no consideration for continuity of the concrete slab. Based on these assumptions, the theoretical location of the neutral axis of the composite beam, and the moment of inertia of the beam about its neutral axis were calculated as indicated in Table 1.

Figure 15 shows the variation in strains over the depth of the beam at an applied load of 49.7 kN. The datum is located at the bottom of the bottom flange. The data indicate that the strains vary linearly over the depth of the beam (or as it is usually stated: 'plane sections remain plane'.), which is one of the assumptions of simple beam bending theory. Students were asked to use this data to estimate experimentally the location of the neutral axis of the composite beam. Simple beam theory states that the neutral axis is located where the beam undergoes neither tensile nor compressive strains when it is subjected to bending loads. By fitting a trendline to the experimental data, students are able to estimate the location of zero strain, and hence the neutral axis. The experimental measurement of the neutral axis location is given in Table 1. The difference between the theoretical and experimental values is only about 10%.

Students then used the data to estimate the moment of inertia of the beam about its neutral axis, *I*. The theoretical value of *I* is given in Table

Table 1. Comparison of theoretical and measured beam properties

	Neutral axis (measured above bottom flange) (mm)	Moment of inertia ($\times$ 109 mm^4)
Theoretical	424	0.72
Measured	466	3.44

1. The basic formula for stress in a beam under bending is:

$$\sigma = -\frac{My}{I} \quad (2)$$

where σ is the normal stress, *y* is the distance from the neutral axis, and *M* is the bending moment. Sagging moments are assumed positive in Equation (2). Re-writing Equation (2), we obtain:

$$y = -I\frac{\sigma}{|M} \quad (2a)$$

The slope of a plot of *y* versus the ratio σ/M should therefore be an estimate of the beam's moment of inertia.

The measured strains were converted to normal stress by multiplying by E_s. The stresses were then divided by the bending moment. This was calculated at the location of the strain gauges by assuming the floor beam was simply supported (frictionless pin and roller) and for the applied load of 49.7 kN was found to be 75.2 kN m.

Figure 16 shows the plot of y versus the ratio σ/M. A fitted line to the data is also shown. The estimated slope, and hence the estimated beam moment of inertia, is 3.44 $\times$ 109 mm^4. As indicated in Table 1, the measured moment of inertia is approximately five times larger than the theoretical value. Students were asked to discuss this differ-

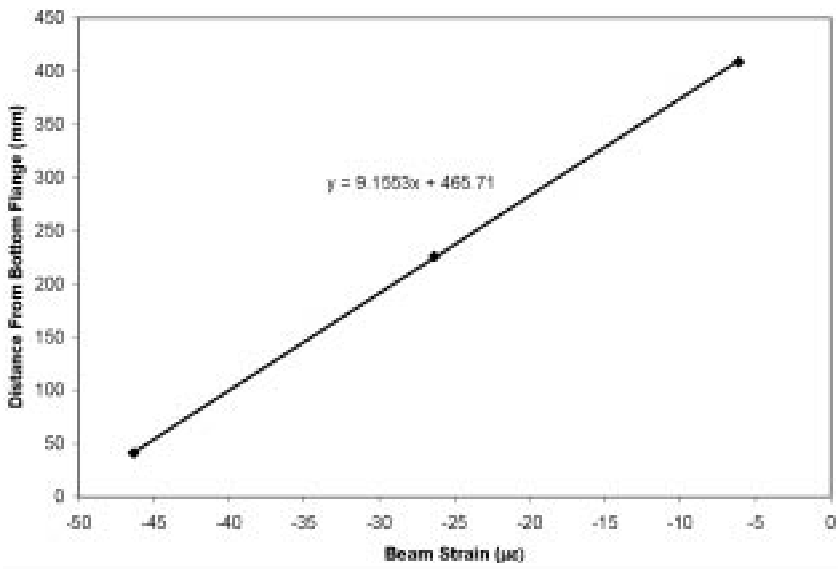


Fig. 15. Variation in strains over beam depth at an applied load of 49.7 kN.

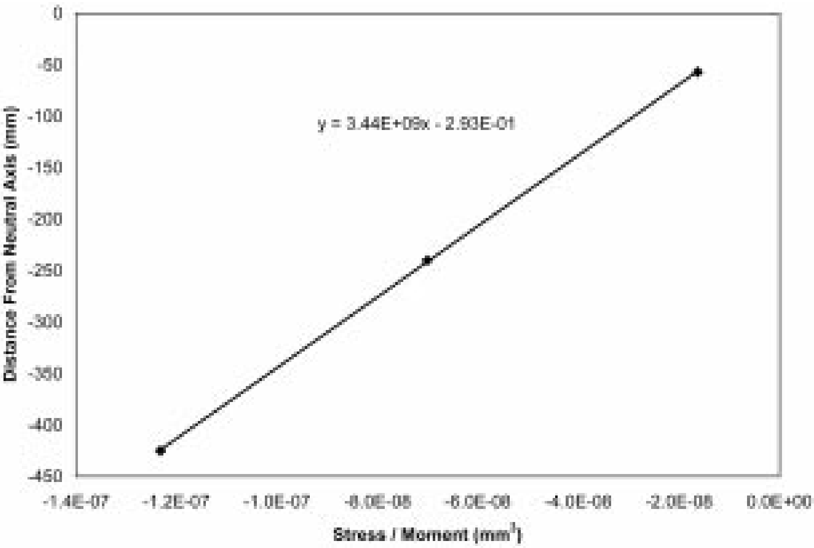


Fig. 16. Variation in stress to moment ratio over beam depth.

ence, and possible reasons for it. For example, one reason could be the assumption made for calculating the bending moment in Equation (2a). It was assumed the beam was a simply supported beam, when in fact the beam supports are likely to provide some fixity. This would reduce the bending moment and increase the estimated moment of inertia.

LEARNING OPPORTUNITIES

Noble [6] has identified a need to provide for students a 'discussion or exercise on how all of the topics . . .' in the undergraduate curriculum interrelate. The Learning Column provided many opportunities for the instructor to discuss 'big-picture' issues and to put the theory and analysis the students have learned into perspective. Through the Learning Column exercise, students are introduced to some advanced structural design concepts long before they are typically discussed in third or fourth year design courses. For example, the design of steel beams and columns is usually not taught until third year, and the design of bolted connections and composite beams is not taught until fourth year. The students have the opportunity to review the design drawings of the floor system and compare them with the actual structure. It is an opportunity to facilitate a discussion into many design issues that might not otherwise arise in a second year solid mechanics course. For example:

- How are various steel members specified? For example, what does W460 $\times$ 61 mean?
- Why is a concrete footing needed below the hydraulic jack?
- Why is a stiffener welded onto the web of the floor beam at the location of the HSS connection?

The Learning Column laboratory is an opportunity to discuss the design and analysis of a real structural member. The load and boundary conditions of a real beam are much different from the idealized beams analysed in a typical solid mechanics assignment or tested in a typical lab. However, simplifying assumptions are often made to ease the analysis of real beams or columns. For example, the floor beam that comprises the Learning Column lab was designed as if it were a simply supported beam, even though the supports are clearly not frictionless pins or rollers. Students were able to convince themselves in this laboratory that this is a conservative assumption.

The students begin to appreciate the high degree of over-design and redundancy that is typical of many civil engineering structures. For example, for the beam considered in this lab, a maximum load of 50 kN was specified. This was to ensure that cracking of the concrete slab did not occur. A load of 50 kN is equivalent to applying a mass of approximately 5100 kg to the mid-span of the beam. The students were invited to suggest what could apply such a load. In addition, the students were able to measure the true beam stiffness and see that it is about five times higher than the value used to design the beam.

Another important aspect of the Learning Column is that it is an introduction to typical structural sensors and how they are used. Students can see the type of information that can be obtained from the sensors and the precision that can be expected. This expertise is important because more sensors are being incorporated into civil engineering infrastructure to monitor long-term behaviour.

The feedback from students on the Learning Column laboratory has generally been positive. Some of the comments include:

> 'The Beam Bending Lab made understanding very easy and should be used more often.'

'Other labs in the course were not that useful. Only the Beam Bending Lab was worthwhile in my opinion.'

FUTURE IMPROVEMENTS AND DEVELOPMENTS

With the successful implementation of the Learning Column, its capabilities will be expanded, and it will be used for teaching in a variety of other courses. The Department of Civil Engineering currently teaches an introductory solid mechanics course to students from the Department of Mechanical Engineering, the Department of Mining Engineering, and the Department of Geological Engineering. This is a total of about 350 students. With a class of this size, it is difficult to provide hands-on learning opportunities for students. The Learning Column is an ideal way to bridge this gap and reinforce basic beam theory presented in class. The lab described above will be slightly modified, as students in this course are not taught about composite beams. One possible modification is to simply give the students the theoretical moment of inertia and have them check this value.

The use of the Learning Column will be expanded to other Civil Engineering courses. For example, students at Queen's Civil Engineering take a 4th year course in structural steel design. It is proposed that the students repeat the experiment in their 4th year, when they have greater knowledge of structural analysis and design of steel structural systems.

More instrumentation will be added to the Learning Column in the future. For example, strain rosettes can be added so that students can analyse shear stresses and use stress transformation concepts. More strain gauges will be mounted over the length of the beam, so that students can examine how strains, stresses and deflections vary with distance from the application of the load.

Teaching Assistants were not available as the students were performing the test. In the future, Teaching Assistants will be available at the Learning Column at specific times so the students can get feedback as they are conducting the tests.

In terms of implementing the Learning Column concept at other institutions, a number of challenges must be overcome. At Queen's, the Learning Column was implemented during the design and construction of a new building. The floor beam and HSS column were left exposed to facilitate the application of sensors. The floor beam was checked to ensure that it was safe to apply up to 50 kN load, and a footing was constructed beneath the floor slab for the loads from the jack. The cost and challenge of implementing this scheme in an existing building would be much greater. On the other hand, the Queen's experience suggests that institutions constructing new facilities should consider implementing sensors and loading systems to provide students with unique learning opportunities.

CONCLUSIONS

A unique laboratory for teaching engineering students the fundamentals of solid mechanics concepts of beam bending, called the Learning Column, has been developed at Queen's University. The Learning Column has been successfully implemented in a second year solid mechanics course for Civil Engineering undergraduates.

1. The facility allows controlled loads to be applied to a floor beam in an actual structure. The equipment necessary is conventional and readily available.
2. The Learning Column can be used to illustrate and test the assumptions of basic beam theory, including the location of the neutral axis, the 'plane sections remain plane' concept, and the stresses in beams under bending.
3. The Learning Column can be used as a means of discussing with students differences between design and theory, and how assumptions can be used to simplify the analysis of a complicated structure.
4. The Learning Column can be used to introduce undergraduate students to typical structural engineering sensors, their typical application, and their precision.

REFERENCES

1. T. Bele-Ndez, C. Neipp, and A. Bele-Ndez, Numerical and experimental analysis of a cantilever beam: a laboratory project to introduce geometric nonlinearity in mechanics of materials, *Int. J. Eng. Educ.*, **19**(6), 2003, pp. 885–892.
2. C. J. Lemckert, Incorporation of a demonstrator into internet-mediated laboratory experiments, *Int. J. Eng. Educ.*, **19**(3), 2003, pp. 433–440.
3. A. Dollar and P. Steif, Learning modules for statics, *Int. J. Eng. Educ.*, **22**(2), 2006, pp. 381–392.
4. D. C. Lagoudas, J. D. Whitcomb, D. A. Miller, M. Z. Lagoudas and K. J. Shryock, Continuum mechanics in a restructured engineering undergraduate curriculum, *Int. J. Eng. Educ.*, **16**(4), 2000, pp. 301–314.
5. Integrated Learning Centre (ILC), Integrated learning at Queen's, Faculty of Applied Science Website: http://appsci.queensu.ca/ilc/learning/accessed June 14, 2006.
6. J. S. Noble, An Approach for Engineering Curriculum Integration in Capstone Design Courses, *Int. J. Eng. Educ.*, **14**(3), 1998, pp. 197–203.

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