A LIVING LABORATORY

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"BUILDING-AS-LAB" CONCEPT

The College of Engineering and Applied Science has recently built a new laboratory facility designed to facilitate hands-on, team-oriented learning across all of its six departments. The three-story, 34,400 sq. ft. Integrated Teaching and Learning (ITL) Laboratory opened its doors in January 1997. Its curriculum-driven design accommodates a variety of learning styles and features two first-year design studios, an active-learning arena, a computer simulation laboratory, a computer network integrating all the experimental equipment throughout two large, open laboratory plazas, capstone design studios, group work areas and student shops.

Designing this facility from the ground up has given us a unique opportunity to use the building *itself* as an interactive teaching tool to give students, as well as the public at large,
an appreciation of the variety of engineering concepts and systems implicit in any modern building. Included in the "building-as-lab" (BAL) concept of the laboratory is the capability to expose, monitor and manipulate the facility's many complex engineering systems.

The various building-as-lab features can be grouped into four main levels of complexity; details are given in the body of the paper:

Exposure

Showing, through example, the various engineering systems required to make a building function. Virtually everything required to make the building function is exposed and incorporated as design elements.

Measurement

Sensors permeate the ITLL facility to allow real-time monitoring of the "pulse" of the building, including air flow and temperature, structural strain, electrical demand, soil moisture and temperature, etc. These data are available in real time on workstations located in gallery spaces, and long range plans call for the data from these sensors to be continuously monitored and posted on the ITL Internet page (http://itl.colorado.edu). As data are accumulated over months and years, clear trends should develop, giving a big-picture look at actual building behavior.

Manipulation

Students are permitted to control the climate of one of two identical side-by-side classrooms, and also to experiment with a high-speed, parallel computer network throughout the building.

Documentation

The construction process was documented with video, still images, AutoCAD drawings, structural calculations and a real-time image of the site posted every 15 minutes on the World Wide Web (http://itl.colorado.edu). A time-lapse video will show the complete construction sequence in a few minutes.

EXPOSURE

Building-as-Lab Interpretive Tour

We are developing a self-guided tour of the many BAL features of the ITL Laboratory using interpretive signs. Text and graphics will be located throughout the facility to explain the design of the building and its systems. The goal is to effectively communicate complex technical features in language understandable by children and non-engineers. Examples of visible BAL features on the interpretive tour are described below.

Exposed Building Systems

In the ITLL, portions of building systems that are normally hidden above ceilings or behind walls are exposed. These include:

Mechanical

Usually hidden out of sight, the air handling unit is prominently located on the upper level, accessible to the public. The supply air leaving the air handling unit passes through a single, five-foot diameter duct on its way through the maze of ducting that is an architectural design element throughout the building. View windows in the air handling unit reveal moving fans, and at a later date, a window placed into the side of an air duct will reveal streamers placed inside to help visualize air flow.

Mechanical equipment, such as pumps, compressors, heat exchangers, etc., is normally hidden from view, but in the ITL Laboratory it is visible through large windows, and students may walk through the two mechanical rooms unsupervised. Signs and system diagrams will explain the equipment, and various pipes are color-coded for easy identification (Fig. 1). Piping is also visible throughout much of the building. The Mechanical Room also houses one of the Andover computer workstations which graphically display the functional status of the building systems. Plexiglas on the underside of a variable air volume (VAV) box in one of the classrooms allows students to see damper actuation and the usually-hidden components of this standard piece of HVAC equipment.

Electrical

Although not accessible to students without supervision, the electrical distribution panels are prominently visible behind windows, and feature transparent panels to show their inner workings. Elsewhere in the building, dummy electrical and motor control panels adjacent to functional ones may be manipulated without affecting lab operation. Much of the electrical conduit is visible throughout the building, intentionally designed and carefully crafted to become an architectural design element.

Communications

Much of the network wiring runs in cable trays suspended from ceilings. While the primary function of the cable trays is to allow easy network access, they also help visitors visualize the extensive computer network. View windows into telecommunications closets and the building computer machine room expose the various wiring systems, boards and equipment necessary to support extensive computer networks

Structural

Variety of Structural Systems

For educational demonstration purposes, the building has been designed with four different structural types used in more than ten different applications; all are exposed. This includes:

- Wide flange steel columns;
- Long and short span beams;
- Tube steel bar joists and a 40-foot truss;
- Composite steel and concrete decking;
- Pre-cast concrete;
- Cast-in-place concrete;
- Load bearing masonry

Visible Re-Bar

Steel reinforcing bars are integral to the design and construction of concrete structures, but they are only visible during construction. In one location, representational “re-bar” has been applied to the outside of the column, to visualize what’s embedded *inside* (Fig. 2). A section of the steel deck attached with anchor studs has been welded onto a prominent steel beam to create a permanent display of the composite floor construction that is hidden from view elsewhere under the concrete and floor tile.

General

Cut-Away Walls

The building features cut-away walls enclosed in plexiglas to expose interior wall construction, plumbing, conduit, etc. Other transparent “slices” into the building include glass plumbing pipes in a roof drain, a plexiglas cover on a fire alarm panel, as well as a window into the elevator shaft to show the hydraulic piston and machinery required for door operation. However, the window into the wall between the men's and women's restrooms reveals plumbing and wiring, but little else!

Acoustical Panels

Sound absorbent acoustical panels are a design feature in the ITLL, as well as a very functional one. Ground-face concrete masonry not only protects the walls, it includes sound absorbing material behind open slits.

Light Shelves

Horizontal light shelves and vertical fins on the south and west faces of the building serve to shade the interior from harsh direct light, and also provide indirect daylighting. Students can track and study solar angles.

MEASUREMENT

A wide array of sensors located throughout the building connects to the Andover control system used to control building climate. Computer workstations located in several locations feature graphical building layouts and displays of current values of all sensor points, as well as allowing trending of the data. As mentioned earlier, this information will also be made available on the WWW.

Structural

Vibrating Wire Strain Gages

To introduce students to the workings of structural building systems, vibrating wire strain gages were installed in the foundation and column system within the ITL Laboratory. The vibrating wire instruments were attached to the reinforcing steel and the concrete was poured around them. Data was gathered showing strain in a caisson as load was built up during construction. Using this BAL project, students will be able to make measurements in a setting in which they can literally put their hands on the column in which the strains are being measured. They will have the opportunity to make a comparison of theoretical and actual loads. Gages have also been welded to the 40-foot steel truss in the upper Lab Plaza to allow students to see the distribution of tensile and compressive forces (Fig. 3). Finally, vibrating wire gages have also been attached to structural beams and columns supporting the upper Lab Plaza; students can track loads as they are carried horizontally across beams and vertically into columns. Systems are being designed to allow students to apply live loads to both the floor of the upper Lab Plaza and the flange of the truss.

Fiber Optics Cast in Concrete

This pioneering project is a good example of the BAL work that was done *during* construction. In order to instrument the ITLL building to measure structural strain (from occupant load, wind, snow, etc.), a scaled mock-up was built to test and research use of fiber optic technology. With 220 meters of fiber donated by Corning, 48 fibers were embedded in three levels of columns and two levels of beams of the building structure as the concrete was poured. Ultimately, the fiber optic leads will be connected to an optical time domain reflectometer currently under development for monitoring by undergraduate students in the ITL Laboratory.

Electrical

The ITL Laboratory is equipped with a state-of-the-art power monitoring system that allows engineering students to obtain data on building energy use and energy patterns. Power Logic software, by Square D Electrical, connects to the Andover system to track large scale (building) power consumption and small scale (designated circuits) usage, as well as power characteristics. Students can monitor the building's electrical distribution system, from main electrical feeders to branch circuits which feed computer classrooms. On screen, or on display panels in various locations throughout the building (Fig. 4), they can see the building's electrical system "come alive," and gain valuable insight into the way technology is currently being used in private industry.

Mechanical Systems

HVAC System

Like most modern buildings, the ITL Laboratory has a well-engineered central heating, ventilating and air conditioning (HVAC) system. However, several things distinguish our system. While most buildings are only monitored to provide effective system control, our building has more extensive monitoring of individual components and the complete system. At the component level, individual equipment is monitored to allow engineering analysis of its performance. This equipment includes heat exchangers, fans, pumps, and duct and piping systems. For example, two fin-tube heaters are equipped with temperature sensors to measure inlet and outlet water temperatures, and air temperatures above and below the heater, allowing measured performance comparisons with theoretical predictions of free and forced convection in heat exchangers. At the system level, the monitoring promotes an understanding of the interactions among the system components. For example, an increase in room temperature will cause a cascade of other system changes, all of which can be traced through the air distribution system, the air handler (Fig. 5), and the chilled water system.

The ITLL "Swamp Cooler"

Another interesting feature is that the bulk of the building is evaporatively cooled (with the exception of the conventional refrigeration system in the Simulation Lab to ensure the reliability of the high performance UNIX workstations). In the dry Colorado climate, most summer air conditioning requirements can be economically satisfied by evaporating water into the building air, cooling and humidifying the space. However, at times of high outdoor temperature and humidity, the indoor temperature and humidity are likely to be higher than usual. Using the monitoring in the cooling tower and air handler and fundamental psychrometric relationships, students can quantitatively link their indoor comfort to outdoor conditions and system operation.

Thermal Environment

Air Stratification

Temperature sensors are arrayed vertically approximately every eight feet throughout a three-story space to track air stratification.

In-situ Heat Conduction

Temperature sensors are embedded one inch apart through north, east, south and west facing, solid pre-cast concrete walls to study the effects of solar orientation and thermal characteristics of concrete. Sensors are also located at each change of material throughout a composite exterior wall. Knowing inside and outside temperatures, students can compare the actual thermal gradient with the predicted one.

Soil Temperature

Sensors along the exterior of the foundation wall enable students to monitor soil temperature, track freezelines, study thermal characteristics of soil and correlate this data to climatic data.

Thermal Performance of Windows

In accordance with current energy conservation principles, most of the glazing in the ITL Laboratory will be double-pane insulated windows. However, in one area of the lower lab plaza, students can compare the thermal performance of several different glazing systems using temperature sensors connected to the Andover system (Fig. 6). This includes conventional, 1/4 inch single-pane tinted glass (as used on the 30-year-old Engineering Center), as well as more “high tech” double-pane glass with Low-E coating (as used throughout the new ITL Laboratory), double-pane fritted (patterned) glass, and triple-pane Heat Mirror® glass.

General

ITL Weather

The equipment included in a meteorological data acquisition system mounted on the roof includes a data logger, temperature and humidity probes, barometer, rain gage, and anemometer. The meteorological instruments can be used to teach basic engineering science concepts relating to fluids, thermodynamics, pollutant transport and aerodynamics, and techniques for analyzing time series of data.

Ambient Air Quality

Students will investigate operating principles and practical aspects of ambient monitoring with EPA reference methods, and gain experience in using regression and time series analysis to better understand relationships between pollutant concentrations and meteorological conditions.

Hydrological Information

An automated hydrologic monitoring system surrounds the ITLL building. The system consists of soil moisture probes, and surface runoff and drain flow measuring equipment.

The continuously collected data, combined with data from the weather station, can be used to teach fluid flow, engineering hydrology, groundwater engineering, water resources engineering and transport processes. Handling the information will provide students with experience in data acquisition, data synthesis, data analysis and use of data in model simulations and engineering design.

MANIPULATION

Climate Control

The two identical first-year project classrooms have different climate control systems. One has conventional pneumatic controls, while the other has separately operable, direct digital controls (DDC) which students can manipulate (within reason!) and measure the effect of changing different variables, such as temperature and air flow. A mechanical VAV box with a plexiglas view panel is installed so that students can see the equipment in operation.

Experimental Computer Network

In the ITL Laboratory, all computers and data acquisition instrumentation are linked via high speed networks. The Production Network, using 100 MBit/sec-based technology, allows students to take data at any location and access it from any other location for analysis, simulation, printing, etc. To provide further BAL experiences, a second limited network, called the Experimental Network, using 500 MBit/sec-based, fiber optic technology, will allow students to experiment with the latest in network technology without jeopardizing the integrity of the Production Network.

DOCUMENTATION

ITLL On-Line

Information regarding the construction process was posted on the ITL web site (http://itl.colorado.edu) from groundbreaking in October 1995 until landscaping was complete in December 1996, including photos of the architectural model, construction schedule, information regarding touring the construction site, and the latest image of the site from a video camera mounted on the Engineering Center. This image was updated every 15 minutes and the stored images formed the basis for a time-lapse video showing the building rising (magically!) from the ground.

Educating Construction Engineers

The College’s Construction Management Program has taken advantage of the ITLL construction project to capture on-site construction lessons to enrich its curriculum for future students. The intent is to provide a real-world resource that features the principles and practice of construction for students for years to come. This includes:

- Creating a collection of real-time and time-lapse video tapes of the construction progress;
- Collecting all construction documentation (AutoCAD drawings, contracts, calculations, memos, meeting minutes, change orders, field clarification requests, etc.); and

- Creating a construction engineering video library (a user-searchable library on CD-ROM of short digital video clips of construction processes, materials and equipment).

CONCLUSION

The various “building-as-lab” features of the ITL Laboratory provide unique opportunities to learn about a variety of engineering principles as utilized in a modern structure. The concepts are being included in the curriculum in a variety of classes, ranging from construction management to a digital signal processing class utilizing the various pieces of sensor data. The capability to make this information available on the World Wide Web offers the potential for a truly world-wide learning opportunity.

BIOGRAPHICAL INFORMATION

LAWRENCE E. CARLSON is Professor of Mechanical Engineering and Co-Director of the Integrated Teaching and Learning Laboratory. He received his B.S. degree in mechanical engineering at the University of Wisconsin at Madison, and his M.S. and D.Eng. degrees from the University of California at Berkeley.

MICHAEL J. BRANDEMUEHL is Associate Professor of Civil, Environmental and Architectural Engineering and Director of the Joint Center for Energy Management. He received his Ph.D. in mechanical engineering from the University of Wisconsin at Madison in 1982.

Fig. 1 Mechanical equipment is color coded to identify different systems

Fig. 2 Exposed re-bar reveals innermost structure of concrete columns and beams

Fig. 3 40-foot truss has vibrating wire strain gauges at 10 locations

Fig. 4 Square D Power Logic monitors electrical system performance

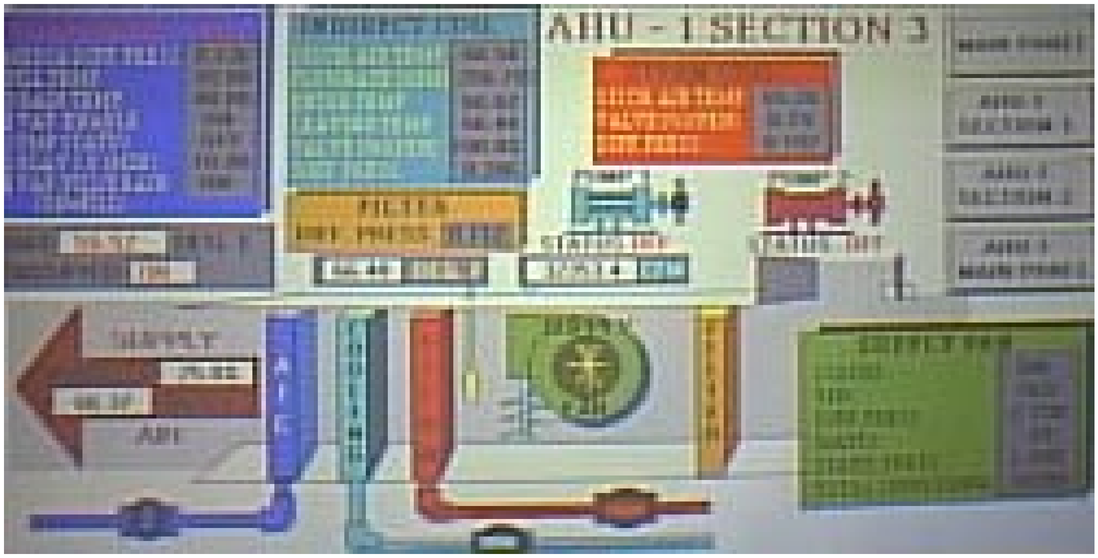

Fig. 5 Video screen image from the Andover system showing the real-time performance of the main air handling unit in the ITL Laboratory

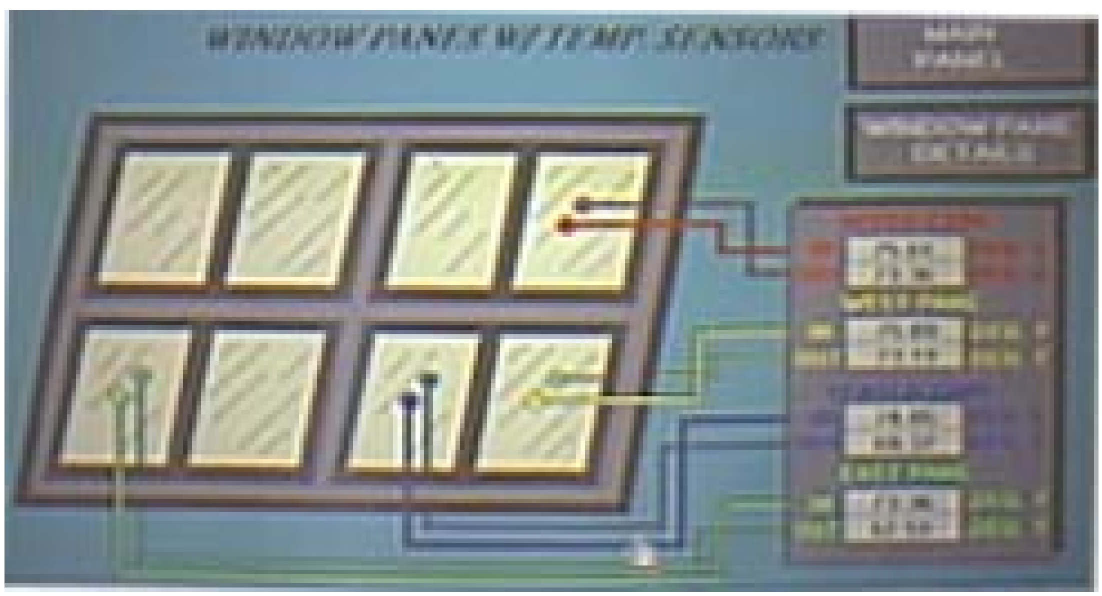

Fig. 6 Video image of the on-line data from the Andover system showing the thermal performance of different glazing at one location in the ITL Laboratory