UNIVERSITY OF CAMBRIDGE
Department of Engineering

Instrumentation of the new Civil Engineering Building

1 Introduction

Funded as part of a £138M UK Government investment in infrastructure and cities research (part of the UKCRIC network, see www.ukcric.com) the new Civil Engineering Building is currently under construction at our site in West Cambridge. The building was designed by Grimshaw architects, and will house the majority of the civil engineering team, along with the National Research Facility for Infrastructure Sensing (NRFIS). The building is three storeys in height and occupies a plan area of 32.4 x 57.6 m.

The building is instrumented with six sensor packages, from the roof to the foundations. The sensors are an integral part of research being undertaken in Civil Engineering at Cambridge and link closely to the Centre for Smart Infrastructure and Construction (CSIC), also at the University of Cambridge. We are developing the technologies to display, store, interpret, and visualise these data streams. This information will be used to understand the performance of the new research facility and assess this performance against the predictions made during design. By examining any differences, we aim to understand performance, and help improve future design.

Figure 1: New civil engineering building

2 Context

The global construction industry is worth $10tr annually and creates and maintains the built environment that emits about half of the planet's carbon emissions. Construction creates the vast majority of the infrastructure that is essential for trade and commerce. It underpins the *productivity* of most industries, and the *healthiness* of building occupants.

Despite this, we still know surprisingly little about the real performance of buildings, and their interaction with occupants. In order to understand such interconnections, efforts must be made to measure effects in a continuous manner. This has only recently become possible at scale, as exemplified in NRFIS and through the work of CSIC. This progress has not yet been matched by the same level of understanding of what to do with the sensor data. How can it be turned into something useful, beyond specific criteria in one building?

3 What is being instrumented?

As part of the funding for NRFIS, the building has been instrumented in six major areas.

1) **Distributed temperature sensing in ground source heat pump (GSHP) boreholes**
    a. Led by Professor Giulia Viggiani
    b. Temperature-sensing DFOS loops in 2 GSHP boreholes and 1 sacrificial borehole. Total of 980m of DFOS sensing cables.

Summary:

A distributed fibre optic temperature sensing system was installed in GSHP boreholes as well as in the ground in a dedicated borehole.

The distributed temperature data in the GSHP boreholes and in the soil will be used to assess the long-term performance of the ground source heat pump system and feedback into its efficient operation. It will also allow the detection of possible long-term heat imbalance and associated system efficiency loss as well as potential environmental issues.

The distributed data will be used to calibrate heat transfer models and estimate the thermal properties of individual geological strata. The data associated with the numerical simulations will be used to investigate the ground and closed loops thermal response as well as boreholes interaction.

This will help optimise future system design by, for example, optimising the number of loops per boreholes, the boreholes depth, spacing and layout. The acquired knowledge will be valuable when designing new systems during the phased move of the Engineering Department to the West Cambridge Campus.

2) **Embedded sensors in the basement raft and perimeter walls**
    a. Led by Dr Mohammed Elshafie
    b. Strain- and temperature-sensing distributed fibre optic sensor (DFOS) system and a fibre Bragg grating (FBG) sensor system, to monitor long-term ground effects on the basement structure
    c. Two DFOS and two FBG loops installed in the raft (top and bottom of the raft), as well as four FBG loops in the retaining walls (one in each wall), to be monitored intermittently.
    d. Total of 120m DFOS sensing cables and 108 FBG sensors.

Summary:

A fibre optic sensor system was installed in the cast in-situ reinforced concrete raft at basement level and in the cast in-situ reinforced concrete walls around the perimeter of the basement. The sensor system comprises two sub-systems installed in parallel: a distributed fibre optic sensor (DFOS) system and a fibre Bragg grating (FBG) sensor system.

The objective of this instrumentation is to enable the measurement of changes in strain along selected lines in the raft and walls, in order to observe the performance of the basement structure as a whole:

i. under the effect of ground movement (from unloading and loading); and
ii. under operational conditions, such as when the strong floor and corner walls above are being heavily or dynamically loaded.

It will also be possible to measure any long-term changes in strain that could occur during the lifetime of the building. This will enable a better understanding of the interaction between the strong floor, the basement structures and the ground, potentially providing input for performance based design of similar basement structures during the phased move of the Engineering Department to the West Cambridge Campus.

The DFOS and FBG systems were installed in parallel but will be operated independently, such that measurements can be taken from each system separately of both systems together. The FBG system will provide point measurements of dynamic strain at regular intervals along the instrumentation lines. On the other hand, the DFOS system will provide a measure of distributed strain along the instrumentation lines over long distances. With current DFOS measurement technology, it is only possible to measure quasi-static (slow changing) strain. However, the capabilities of DFOS spectrum analysers are improving steadily as technology advances and this installation will provide a sensing system that will improve with time rather than degrade. It is expected that future distributed fibre optic sensing systems will be able to acquire dynamic measurements of strain at centimetre or millimetre spatial scales, from the same embedded instrumentation.

Both systems have been installed and terminated in such a way that they can be combined with the DFOS and FBG systems in the other instrumentation packages, so as to enable measurements to be taken simultaneously from the different parts of the building. This would enable a more holistic understanding of structural interactions between the instrumented parts of the building.

3) **Embedded sensors in the strong floor slab**
    a. Led by Dr John Orr
    b. Strain- and temperature-sensing DFOS system and FBG sensor system, to monitor the effects of experimental loading on the strong floor slab, as well as long-term relaxation of post-tensioning.
    c. 12 DFOS and 10 FBG loops (top and bottom of slab), to be monitored intermittently
    d. Total of 640m DFOS sensing cables and 319 FBG sensors.

Summary:

A fibre optic sensor system was installed in the cast in-situ reinforced concrete strong floor at ground floor level. The sensor system comprises two sub-systems installed in parallel: a distributed fibre optic sensor (DFOS) system and a fibre Bragg grating (FBG) sensor system.

The DFOS system will provide a measure of distributed strain along the instrumentation lines over long distances. With current DFOS measurement technology, it is only possible to measure quasi-static (slow changing) strain. However this is expected to change and, as DFOS technology advances, it is likely that future DFOS systems will also be able to acquire dynamic measurements of strain. On the other hand, the FBG system will provide point measurements of dynamic strain at regular intervals along the instrumentation lines.

The objective of this instrumentation is to enable strain measurement during construction and throughout the life of the strong floor. During construction, the objective of monitoring strain is to quantify prestressing effects, so the in-situ initial strain (and stress) state of the strong floor is known.

Throughout the life of the strong floor, the objective of measuring strain is to:

a) Verify the integrity of the strong floor in the long term, including:

- Quantifying any loss of prestressing over the life of the structure, which might reduce the capacity of the strong floor.
- Evaluate any potential local damage due to overloading.

b) Quantify strains within the strong floor during large scale experiments. This is important to:

- Verify that the strong floor is behaving as expected, and that very large applied loads are not causing unpredicted behaviour or damage.
- Quantify any compliance in the strong floor during very large experiments.
- Quantify dynamic strain during dynamic tests.

Item b) is particularly important when very high tensile loads are applied to single bolts, or during large scale reaction wall experiments, where very large lateral loads are applied at a significant height above the floor. The density of fibre optic sensing cables (spaced at approximately 1.25 m in both directions) is important to enable measurement of strong floor performance for a test rig (or reaction wall) located anywhere on the strong floor itself. This will provide the necessary flexibility to monitor any foreseeable test layouts.

The above practical objectives will have research benefits, both in terms of understanding of pre-stressing of concrete slabs, and assurance of the integrity of the research facility for years to come. For example, the loads that can be safely applied to the strong floor in the current civil engineering structures laboratory are severely limited (requiring the researchers to do many experiments in self-reacting frames) because there is no measure of the integrity or capacity of the existing strong floor. Having the proposed sensing capabilities in the strong floor at the new civil engineering building will enable the safe loading limit to be tailored for certain high-load tests, based on the measured strain within the concrete.

4) **Sensors on the frame structure**
    a. Led by Dr James Talbot
    b. Strain-sensing FBG sensors to monitor the long-term performance of the structural frame of the building under occupancy loading.
    c. A single frame comprising of 12 columns and 9 beams instrumented with one sensor pair each (one sensor on each flange), to be monitored continuously
    d. A total of 42 sensors comprised of 66 FBGs.

Summary

A fibre Bragg grating (FBG) fibre optic sensor system was installed on a portion of the steel structural frame of the building. The FBG system will provide dynamic strain measurement capability at point locations on all columns and beams along one entire cross-section of the structure. In total 21 members are to be instrumented (12 columns and 9 primary girders).

The objective of this instrumentation is to measure both static and dynamic longitudinal (i.e. axial and bending) strain in the primary members of one entire cross-section of the structure, in order to:

a) Monitor vibrations in the structure, including:

- Quantifying vibrations induced by experiments conducted on the strong floor in the main structures workshop or in the adjacent labs.
- Quantifying vibrations induced by adjacent construction activities throughout the Engineering Department move to West Cambridge over the next ~10 years.
- Quantifying vibrations induced by footfall.
- Conduct future research experiments on vibration propagation through buildings (including the nature of dynamic coupling between structural elements, vibration damping and power distribution) using shaker equipment that will feature as part of the Structural Dynamics Lab.

b) Quantify strain (and therefore stress) in primary elements to understand load distribution. This will allow:

- Quantification of in-situ stress of primary beam-column elements, in order to evaluate design predictions versus actual performance. The objective would be to provide evidence for leaner, more sustainable design.
- Evaluation of assumptions regarding how load is transferred through buildings.
- Provide evidence of structural behaviour that could enable more efficient future reconfiguration or additions to the building (in the long-term). This aligns with the original objective of building a “kit-of-parts” building that is easily adapted throughout its lifespan.

Both a) and b) include practical objectives related to building performance and future construction in West Cambridge. They also contain research objectives that will contribute to knowledge in the fields of vibration propagation in buildings and structural design. Finally, they will allow the building to act as a live demonstration for teaching activities within the Engineering Department.

5) **Blue roof instrumentation**
   a. Led by Dr Dongfang Liang
   b. Weather condition, soil moisture content, water level and temperature sensors
   c. To assess the effectiveness of the blue roof, as well as provide environmental parameters for the other sensing packages.

Summary:

Blue roofs are designed to reduce the rate of surface water run off so as to prevent the overloading of the external drainage infrastructure. Hence, it acts to reduce overland flows and surface water flooding risk, as well as conserve water resources by storing rainwater for later use. In addition, these roofs enhance thermal insulation and reduce indoor noise.

A blue roof is commonly constructed to allow the storage of water above the roof waterproofing membrane up to a designed hydraulic head, so that the discharge of rainwater from the roof does not exceed a specified flow rate within a pre-defined period of time. The peak discharge and hydraulic head are usually specified based on the budget, location, corresponding storm return period and storm duration as well as a climate change factor.

Blue roofs are often associated with a layer of green roof. Green roofs provide ecosystem supports, notably complementary water retention capacity, and important water detention ability through water infiltration in the vegetated growing medium.

Although the design of the allowable discharge at the outlets is relatively straightforward and can be achieved by specifying the head and orifice geometry at the outlet, the prediction of the individual contributions to water detention and flood mitigation of all components is more challenging. Current design methods of the green roof do not take into account the complexity of unsaturated flow through porous media (dependent on the hydraulic properties of the growing medium), the potential interception from vegetation (dependent on vegetation type), the precise role of evapotranspiration (dependent on plant type and climate), the effect of irrigation schedule, and the boundary conditions such as the lower growing medium boundary.

The overall aim of this instrumentation package is to evaluate the effectiveness of the building's blue and green roof on regulating drainage run off from the roof while supporting healthy vegetation growth. By monitoring closely and continually the annual evolution of the water resources, it will be possible to gain a better understanding of the environmental and ecological functions of the roof to optimise its performance.

One of the major objectives is to characterise the contributions from the various components of the blue and green roof, such as the water storage board layer and the growing medium layer. To do so, it is necessary to measure or estimate the various components used for calculating the water balance. These are water inputs (rainfall and irrigation water), water outputs (evapotranspiration and drainage) and water storage (growing medium moisture content and storage basin volume). Ultimately, these can be used to estimate the drainage outflow rates into the sewer and evaluate the overall performance of the system in mitigating flood risk and conserving water resources.

The data can be fed into an unsaturated groundwater flow model to characterise the hydrological function of the growing medium. This would be used to refine the standard blue roof analyses for the prediction of outflow discharges. This would also provide an opportunity to assess the condition of the growing medium and to recommend to the maintenance team an efficient irrigation schedule.

This package would help optimise future system design (drainage outflow, hydraulic head, growing medium hydraulic property and thickness) and may prove valuable when designing new blue and green roofs during the phased move of the Engineering Department to the West Cambridge Campus.

The instrumentation proposed will allow valuable engineering judgment to be made on the performance of the system. It will also provide the foundation for a living green / blue roof laboratory to which further instrumentation, such as automated lysimeters and atmospheric sensors, can be added for more advanced studies in the future.

6) **Building environment sensors**
   a. Led by Dr Mauro Overend
   b. Suite of measurements including: Volatile organic compounds, humidity, air velocity and temperature, radiative temperature, lux levels, noise levels, energy use, CO_2 levels, lights, windows, heating controls, façades: inner and outer surface temperature; inner, outer and cavity air temperatures; external, internal and cavity humidity level (when an air cavity is present); solar radiation and lux levels close to the façade; and outdoor noise levels.
   c. To assess the effect of external and internal environmental factors on the working environment and on workers' wellbeing.

Summary:

A network of environmental sensors were installed in the new Civil Engineering building.

The purpose of the environmental, occupant interaction and energy sensors is to allow the measurement of the internal/external environment, occupant interaction and energy use within the building. The level of detail and extent of these measurements shall be sufficient that it could be used for state of the art research related to occupant comfort and satisfaction as well as day to day building operation.

Power meters and dashboards used to monitor energy consumption of the building could also be used to incentivise energy efficient behaviours, lowering the environmental impact of the building. Further, the extensive environmental and occupant interaction sensors shall allow the building to be fine-tuned to maximise the wellbeing of occupants and subsequently their productivity and health.

The following parameters will be measured:

- Volatile organic compounds (VOCs) through air quality sensors. These are often associated with unpleasant odours in new buildings. Research into the effects of VOCs is difficult due to their low concentration and slow to develop effects but it is of interest to track the levels of VOCs throughout the life of the new building and assess if and how it affects occupant well- being.
- At selected workstations: humidity, air velocity and temperature, radiative temperature, lux levels, noise levels, energy use and CO2 levels.
- At a room level: monitor lights, windows and heating controls for occupant interaction.
- On selected façades: inner and outer surface temperature; inner, outer and cavity air temperatures; external, internal and cavity humidity level (when an air cavity is present); solar radiation and lux levels close to the façade; and outdoor noise levels.

When used in combination with the existing sensing system, the additional sensors shall provide a state of the art sensing tool for research.

4 Contact

For more information on any of the above the sensor packages, please contact:

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5 Outputs

As the project progresses, links to data and publications will be added to this page. There are various data collection and logging methods across the above six packages. All of the sensor data will be merged with a digital twin of the building, and the digital twin of West Cambridge being developed by CSIC. During design and construction a Revit BIM model has been used, Figure 2.

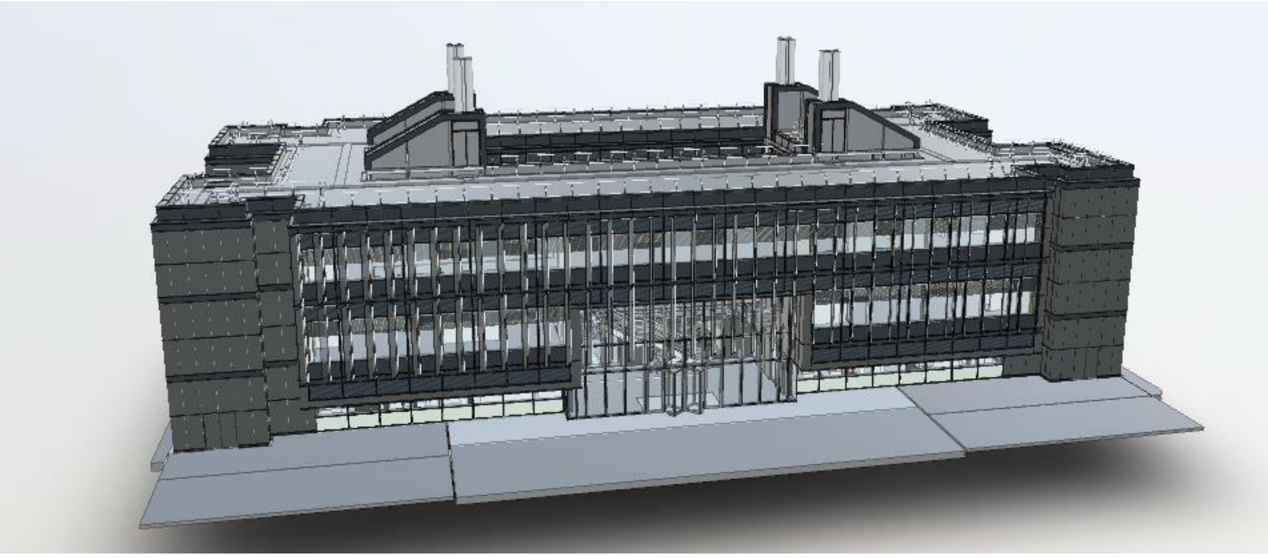

Figure 2: BIM model screen shot