



Provided by the author(s) and University of Galway in accordance with publisher policies. Please cite the published version when available.

Title	The creation of a living laboratory for structural engineering at the National University of Ireland, Galway
Author(s)	Goggins, Jamie; Byrne, D; Cannon, E
Publication Date	2012
Publication Information	Goggins, J; Byrne, D; Cannon, E (2012) 'The creation of a living laboratory for structural engineering at the National University of Ireland, Galway'. The Structural Engineer, 90 (4):12-19.
Link to publisher's version	<a href="http://www.istructe.org/journal/volumes/volume-90/issues/issue-4/articles/the-creation-of-a-%E2%80%98living-laboratory%E2%80%99-for-structur">http://www.istructe.org/journal/volumes/volume-90/issues/issue-4/articles/the-creation-of-a-%E2%80%98living-laboratory%E2%80%99-for-structur</a>
Item record	<a href="http://hdl.handle.net/10379/3827">http://hdl.handle.net/10379/3827</a>

Downloaded 2024-04-26T20:37:19Z

Some rights reserved. For more information, please see the item record link above.



**Please cite article as:** Goggins J., Byrne D., Cannon E., ‘The creation of a ‘living laboratory’ for structural engineering at the National University of Ireland, Galway’. *The Structural Engineer*. Vol 90, Issue 4, April 2012.

## **The creation of a ‘living laboratory’ for structural engineering at the National University of Ireland, Galway**

**J. Goggins**, B.A., B.A.I., Ph.D., CEng, MICE, MIEI

Lecturer, College of Engineering and Informatics, National University of Ireland, Galway

**D. Byrne**, B.E. (Hons), MIEI

Research Student, College of Engineering and Informatics, National University of Ireland, Galway

**E. Cannon** BE, MEng, DIC MSc CEng MIStructE, MICE

Senior Lecturer (retired), College of Engineering and Informatics, National University of Ireland, Galway

**Keywords:** concrete, electrical resistance strain gauges, instrumentation, structural engineering, teaching-tool, vibrating wire strain gauges, void-form flat slabs.

### **Synopsis**

The recently completed New Engineering Building (NEB) at the National University of Ireland, Galway (NUIG) is a new state of the art academic facility on the university’s north campus. The building unites all five engineering disciplines within the university and at 14,250m<sup>2</sup> is now the largest engineering school in Ireland. It represents a milestone in the construction of engineering educational facilities by incorporating the use of numerous types of sensors to create an interactive learning environment for engineering students. Not only will it be a centre of education, but the building itself will act as a ‘living laboratory’ and teaching tool. This paper outlines the instrumentation of the structural elements within the building and the part they will play in the teaching and understanding of structural engineering within the university.

### **Introduction**

The unremitting advances being made in technology, knowledge and understanding within the engineering industry mean that the practice is continuously evolving. It goes without saying that

to keep up with these developments there is an incessant need for teaching methods to evolve to ensure that future generations of engineers are educated to the highest level. Recent research and reports<sup>1-4</sup> have shown that there is a critical need to provide students with a deeper understanding of the general concepts and principles of engineering and to provide them with the means to meet the challenges of the 21<sup>st</sup> century. One such report by the Royal Academy of Engineers<sup>4</sup> highlighted the need for ‘university courses to provide more experience in applying theoretical understanding to real problems’. With these points in mind the New Engineering Building (NEB) at the National University of Ireland, Galway (NUIG) (Figure 1) was constructed to directly link the building into teaching methods, actively engaging with students to raise their awareness of the different aspects of building design and performance. The vision was for a building whereby future students will be able to analyse and understand its defining characteristics at first hand and on a personal level.

Central to this project is the instrumentation of the NEB at NUIG and its development as an interactive teaching tool for students. The NEB united all engineering activities on campus into an exclusive, state of the art academic facility by September 2011. The building not only provides a learning environment, but will itself act as a teaching and learning tool. It will be a ‘living laboratory’ for engineering, where live data sets from numerous types of sensors will be provided for use in illustrating structural engineering and building performance concepts in undergraduate teaching, and in the development of full-scale research in structural engineering and energy. Both energy and structural characteristics of the structure are to be monitored throughout the building’s entire life cycle. As such, it will be beneficial for a number of engineering disciplines.

Data measuring the strains, temperatures and movements due to loading of the building will be gathered along with energy demands and performance of the building. Monitoring of the power consumption of different electrical loads such as lighting, computing and HVAC equipment will be performed, so that their relative energy costs can be demonstrated. The information gained from this instrumentation is being used to create interactive tools for students, form the basis for future research projects and facilitate the advancement of engineering teaching methods. The instrumentation will be used for a number of studies such as structural health monitoring and energy performance monitoring. Sensors will complement each other and all will be integrated into the overall Building Management System (BMS). The BMS is the control system used to monitor and control the buildings mechanical and electrical equipment primarily through the use of ventilation, lighting and power systems. The BMS will monitor properties such as carbon dioxide levels, temperature and humidity ensuring energy costs are kept at a minimum, but all the while maintaining a suitable environment for the occupier. The NEB itself contains a variety of green-building

initiatives, such as the use of environmentally friendly heat generation using carbon-neutral biomass, rain-water recycling, ground source heat pump, low embodied energy construction materials and high-tech renewable energy systems. These have been designed to reduce the buildings impact on the environment and make it as sustainable as possible<sup>5</sup>. A number of structural elements have also been instrumented with over 260 gauges and sensors. These instrumented elements coupled with the green-building initiatives will provide working examples for engineering students to study. Several of the building's constructional elements have consciously been left exposed, as visual learning tools (Figure 2)<sup>6</sup>. The vision is for a building whereby future students will be able to analyse and understand a building's defining characteristics at first hand and on a personal level.

This paper concentrates on an aspect of the development of the NEB as a 'living laboratory' for structural engineering, dealing in particular with the embedded sensors – both those requiring to be installed prior to erection of structural elements and those fixed during construction on the NEB site. These are fundamental to the development of the building as an interactive teaching tool, reporting on the evolving dialogue of the structure with its environment<sup>7</sup>.



**Figure 1:** The recently completed New Engineering Building (NEB) at the National University of Ireland, Galway (NUI Galway).

## **The New Engineering Building**

The gross floor area of the NEB is 14,250m<sup>2</sup>, making it the largest engineering school in Ireland. It provides facilities for over 1,300 undergraduate and postgraduate students, including classrooms, laboratories, workshops, computer suites, lecture halls and research facilities. For example, in the civil engineering discipline, state of the art laboratories are provided for in specialised areas such as of materials, soil mechanics, fluids and hydraulics, timber, structures (heavy and light), concrete and environmental engineering. The building structure is composed predominantly of concrete, in-situ and precast, with some elements in structural steel. Superstructure

loads are transferred to rock through end-bearing piles, while the ground floor slab rests on engineered fill. Some structural aspects of the project which are of particular interest are:

1. the extensive use of ggbs in place of CEM I cement to reduce the embodied energy of the concrete in the building;
2. 40-tonne prestressed concrete transfer beams, precast by Banagher Concrete (Figure 3), positioned over the main lecture theatres;
3. prestressed double-tee units, precast by Banagher Concrete (Figure 4);
4. deep structural steel plate girders, fabricated by Duggan Steel;
5. a highly visible structural steel floor suspension system in one corner of the building (Figure 5).
6. the Cobiax flooring system, which is a two-way spanning, void-formed, flat slab system utilising slabs manufactured by Oran Precast and providing a high quality exposed soffit finish (Figure 6);

The general intention was to monitor as many aspects as possible of the response of the selected elements to their environment<sup>6</sup>. This would include response to discrete loading events, time-dependent variation in strain due to creep, shrinkage and temperature change, possible restraint effects in the large transfer beam and in the void formed slab system, and the load-sharing characteristics of the void formed slab system.



**Figure 2** – Visual teaching tools (a) Recesses in a concrete wall showing exposed arrangement of reinforcement and glass panel to show build up of ground floor slab and finishes, (b) Pile cap foundations, (c) Void form flat slab system.

## **Instrumentation**

There was a severe time constraint in relation to the purchasing of gauges and datalogging equipment and also a significant time requirement for installation. Due to these factors and to budgetary constraints, instrumentation with embedded sensors was confined to three large-span elements and a structural steel system. These were:

(i) a solid pre-tensioned concrete transfer beam located on the second floor above one of the main lecture theatres (Figure 3);

(ii) a pre-tensioned double-tee unit located on the second floor above one of the main lecture theatres (Figure 4);

(iii) a two-way spanning void-formed flat slab flooring system located on the third floor East wing of the building (Figure 6);

(iv) a highly visible structural steel floor suspension system (Figure 5).

Elements (i) and (ii) were instrumented with vibrating-wire (VW) gauges at Banagher Concrete's premises, while element (iii) was instrumented with both VW and electrical resistance (ER) strain gauges, partly at Oran Precast's premises and partly on the NEB site. Element (iv) was instrumented with ER strain gauges only. Embedment type VW gauges, manufactured by Gage Technique, were used for monitoring strain and temperature within the concrete elements of the NEB. Due to their robustness and reliability. They are of a type developed originally by the Transport and Road Research Laboratory (TRRL) in the UK <sup>8</sup> (Figure 6). VW gauges have been extensively used in bridge, dam and tunnelling projects <sup>9-15</sup>. Their long term stability makes them suitable for measuring time dependent phenomena such as creep and shrinkage. The embedment strain gauge is usually tied to the reinforcing cage, while in mass concrete applications the gauges can be installed either before or immediately after placement of the concrete. During instrumentation of the NEB the VW gauges were tied to 10mm U-bars to help keep them in place and protect them during the pouring of the concrete. The U-bars were then tied to main reinforcement mat (see, for example, Figure 6).

Electrical resistance strain gauges (Tokyo Sokki Kenkyujo model FLA-6-120-11-3LT) were used to determine the strains in reinforcing bars embedded in the void-formed slabs (Element (iii)), as well as strains in structural steel elements (Element (iv)). These gauges are installed on reinforcing bars in the old Civil Engineering laboratory at NUIG at room temperature conditions. The reinforcing bar surface was prepared by removing the ribs on the bars over a length of 25mm using a milling machine. The gauge was bonded to the bar using P2 TML strain gauge adhesive. A clamp

was applied to the gauge and the adhesive was left to dry overnight, after which a VM waterproof tape was applied to protect from moisture and chemicals within the concrete. Previous research<sup>16, 17</sup> demonstrated the benefits of monitoring strains through the use of electrical resistance gauges. The reported operational life of the strain gauges and adhesive is a minimum of 30 years. All the gauges were tested in the laboratory before installing the bars on site. The gauges had 3m of 3-wire 0.11mm lead wire pre-connected; up to 15m lengths of 3-wire 0.5mm lead wires were used to connect these to the data acquisition system. The lead wires were installed inside plastic ducting within the concrete.

The gauges are being monitored using dataloggers and additional equipment supplied by Campbell Scientific. A total of over 260 sensors and gauges were embedded within structural elements, in addition to temperature and carbon dioxide sensors in most rooms in the building and a weather station on the roof of the building. Novel technologies such as fibre-optic sensors and Tensiomag® - for use with prestressing tendons - were explored, but were not feasible in this instance for reasons of time and budget. It is envisaged that additional instrumentation (e.g. accelerometers, inclinometers) will be installed later in the programme to measure aspects of performance in use.

## **Structural Elements Instrumented**

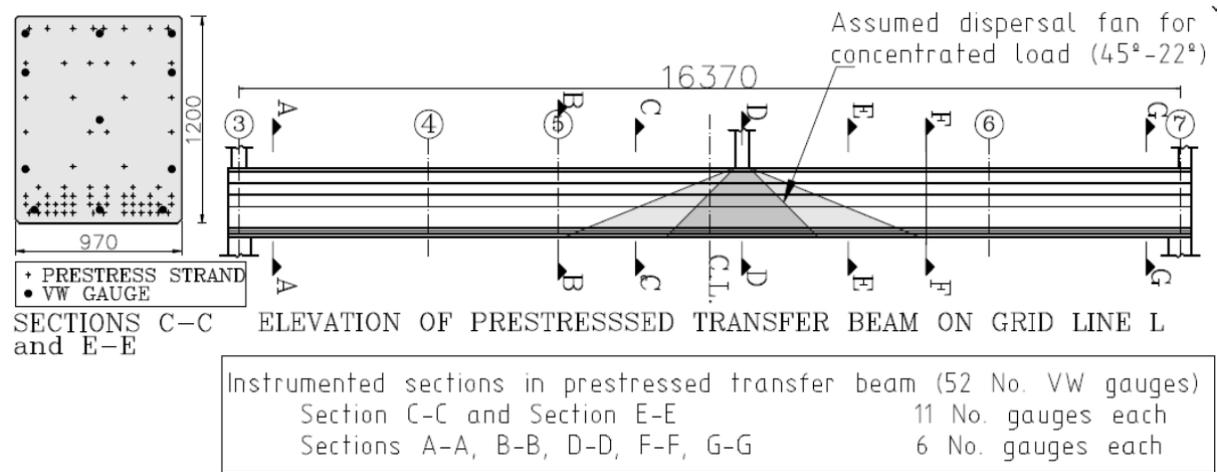
### **Prestressed Box and Double-Tee Beams**

Both the prestressed solid box beam and double tee units are located on the second floor of the south wing in the NEB, where they span over the two main lecture halls - a distance of nearly 16.5m. Both elements were instrumented with VW gauges, which were used to monitor both strain and temperature. The elements were cast in the fabrication yard of Banagher Concrete in January 2010 and both elements were installed on site in March 2010. Aspects to be analysed by instrumenting both the double tee and box beam include their instantaneous response to dead and live loading; effects of creep, shrinkage and temperature; to monitor the strains in concrete arising from restraint; and to determine the effectiveness of their thermal mass in minimising the energy usage of the building.

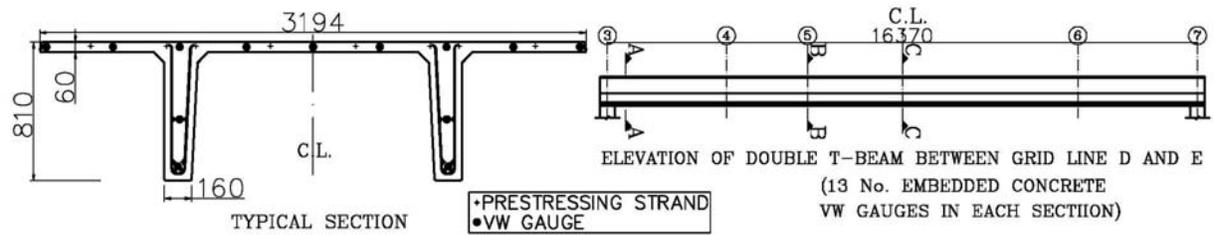
The transfer beam contains 52 VW gauges distributed over 7 sections, five of which are grouped around a concentrated load near midspan, while the other two are near the supports (Figure

3). Most sections contain six gauges - two at top, middle and bottom - but two of the sections contain eleven gauges with the intention of extracting fuller detail regarding strain and temperature variation within the beam. This 970mm by 1200mm deep beam is located over one of the main lecture theatres and, given its large mass, its role in the heating and cooling of the space will be of interest.

The double-tee contains 39 VW gauges in all - 13 at each of 3 sections (Figure 4). The narrowness of the rib and the arrangement of prestressing strand meant that only one gauge could be placed at any given height within the rib, but there is mirroring of provision between ribs. Nine gauges are arranged across the flange, with the aim of picking up possible variations in compressive strain across the flange, associated with shear lag<sup>18,19</sup>.



**Figure 3:** Sections showing instrumentation of prestressed box beam (top) and photographs showing installation of beam on site (bottom).



**Figure 4:** Sections showing instrumentation of prestressed double tee unit (top) and photographs showing installation of gauges in precasting yard (bottom).

### Structural Steel Truss

The structural steel truss instrumented is located on the third floor of the south wing, an important feature within the NEB (Figure 5). It impresses with a large glass front, but also in the complex nature in which its corner is supported. Both the second and third floors have a 7.5 m long cantilever span, which is supported using a complex structural system. Both slabs are supported by two 193.7mm diameter x 12.5mm circular hollow section, one at each corner of the slab bay. Encased within each circular hollow section is a M75 macalloy bar; the load from the slabs being transferred by means of a threaded nut bearing against steel washers onto a solid steel distribution plate. During construction the macalloy bars were prestressed to a predetermined load to support the system. Essentially the circular hollow section, acting as compression members, transfer the load from the third and second floors downward before transferring the load vertically via tension hangers in the form of the macalloy bar, where it is supported by a steel truss in one corner and a plate girder in the opposite corner, as seen in Figure 5.

The macalloy bar supported by the steel truss was instrumented with a total of six electrical resistance gauges; three located across the top section of the bar and another three located across the bottom section of the bar. As with all threaded-nut systems, load can be applied at different intervals and this was the case at the NEB. The prestress force was applied alternately between the macalloy

bar supported by the truss and the macalloy bar supported by the plate girder at intervals of 100kN. Strains were monitored throughout the loading process until the final prestress force was reached; 900kN for the macalloy bar supported by the steel truss and 850kN for the macalloy bar supported by the plate girder. Subsequent data from the gauges will be used to track the response of this unique structural system to monitor the load paths from floors during the construction stage and during the life of the building.



*Figure 5: Image showing location of structural steel truss in south wing of the NEB.*

### **Void Form Flat Slab System**

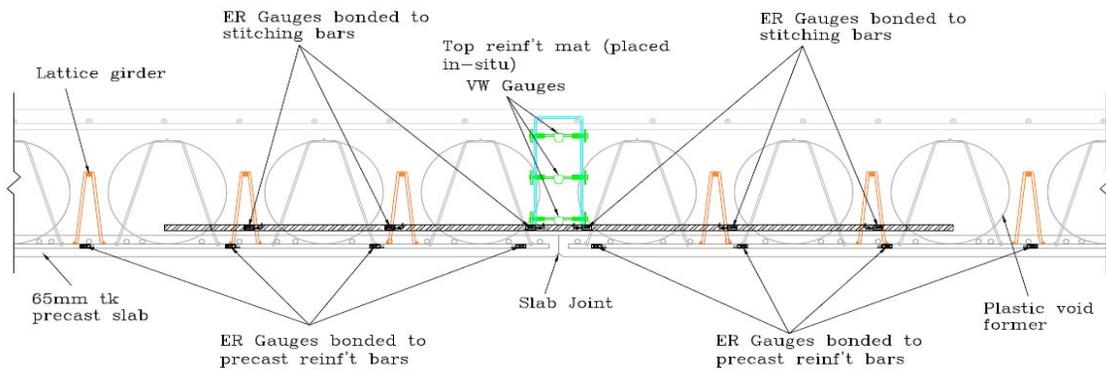
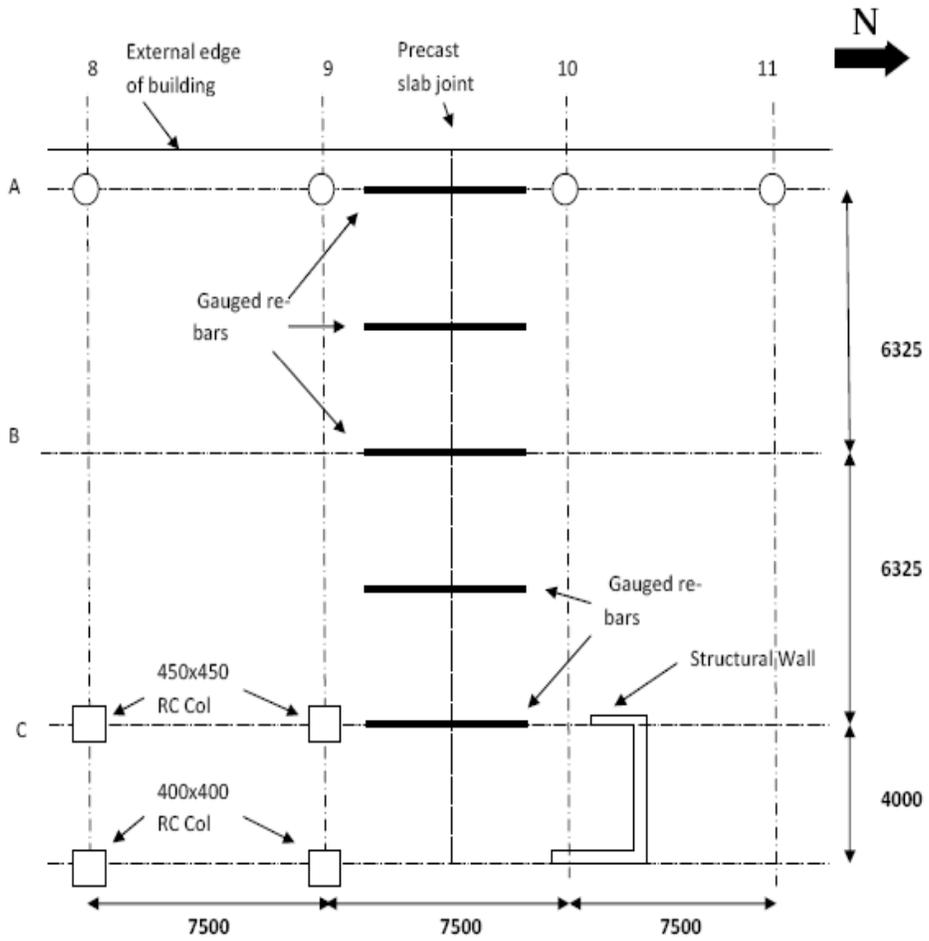
The NEB is the first building of its kind in Ireland to employ the void form flat slab system (VFFS). These are an innovative and novel form of flat slab system. They consist of spherical void-formers, positioned in the middle of the concrete cross section to reduce the overall self weight of the slab, but maintain full flexural strength allowing a two-way or bi-axial load transfer (Figure 6). Gauges were installed to monitor temperature and strain in the slab element primarily to explore shear transfer and two-way load action in this unique slab system. Observation of the system over time will allow the performance of the system to be quantified, including changes to the material properties of the structural slab system. Further areas for research include the effect of the passive ventilation system on slab temperature and linking this to the thermal properties of the slab and analysing the different aspects affecting the thermal mass of the concrete slab. Furthermore, it will be possible to analyse the development and dissipation of heat of hydration of cement and the effect ground granulated blastfurnace slag (GGBS) has on reducing this phenomenon.



**Figure 6:** *Void-formed flat slab with installed vibrating wire gauges.*

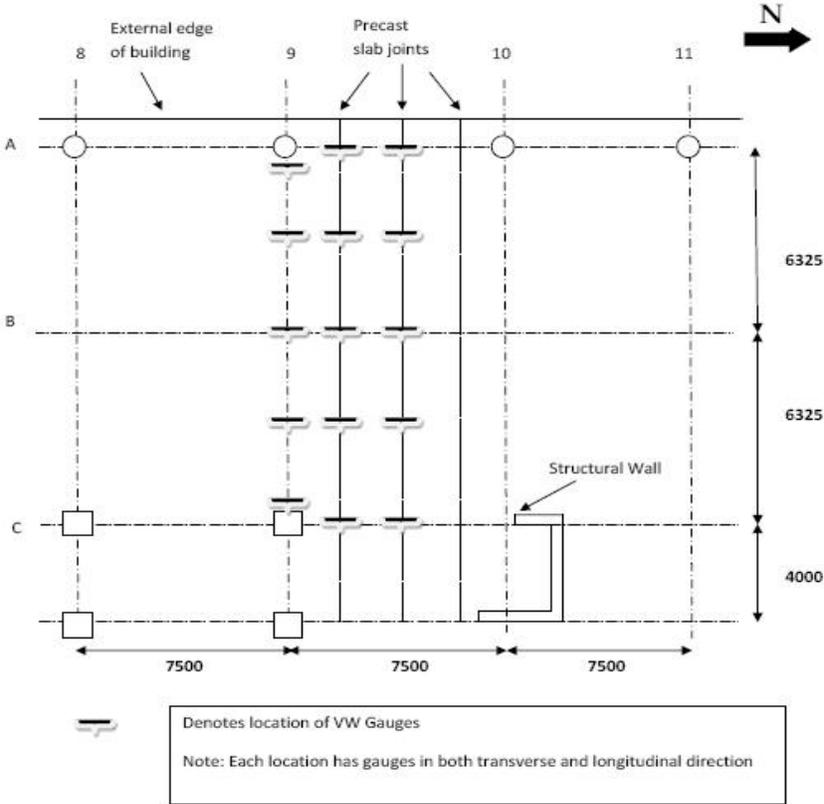
The area highlighted for instrumentation was a 7.5 x 12.65m bay located on the third floor of the building. Details of the instrumentation can be seen in Figures 6 and 7. The slab itself had an overall thickness of 450mm incorporating 315mm diameter void formers. The slab was constructed using two separate elements; the bottom 65mm of the slab comprising of a pre-cast concrete element and the top 385mm consisting of in-situ concrete. The precast panels were transported to site in separate panels, typically 12m in length and 2.4m in width. To ensure that two-way action is achieved between the different slab panels a series of reinforcement or ‘stitching’ bars were provided. These ‘stitching’ bars were centred on the joint between the pre-cast elements. The assumption is that these will provide sufficient bond between the slab panels to ensure transfer of load across the slab joints rendering the joints irrelevant to the completed structural performance.

Five specific locations across the slab bay were highlighted for instrumentation. Gauges were bonded to the reinforcement bars in adjacent panels of the pre-cast elements at the five designated locations in the slab bay. Each bar, 2.4m in length, was instrumented with four electrical resistance strain gauges (Figure 7). Bars within the pre-cast units consisted of H10’s (i.e. 10mm diameter bar, ribbed high yield steel). Electrical resistance gauges were also bonded to the reinforcement ‘stitching’ bars, which were placed over the joints between the pre-cast units. Each ‘stitching’ bar, 2.1m in length, was instrumented with six electrical resistance gauges along its length (see Figure 7). The ‘stitching’ bars were H16’s (i.e. 16mm diameter bar, ribbed high yield steel) spaced at 350mm centres and bundled in pairs. The gauges installed on the ‘stitching bars’ and those in the precast element were positioned so that they would be acting in the same vertical plane.



**Figure 7:** Plan view (top) showing location of instrumented reinforcement bars in void form flat slab bay and a North-South section view (bottom) showing layout of gauges at each section.

In addition to the electrical resistance gauges a number of vibrating wire strain gauges were placed in the in-situ slab both in the North-South and East-West directions at each of the five instrumented sections. Three vibrating wire gauges (positioned at the top, middle and bottom of the in-situ slab) were placed in the North-South direction to monitor strains in the same plane as the gauges installed on the reinforcement bars. Two vibrating wire gauges (positioned only at the top and bottom of the in-situ slab) were placed in the East-West direction to monitor the strains along the main axis of bending within the slab. The layout, including dimensions, of the vibrating wire gauges installed in the in-situ slab can be seen in Figure 8. To add to the five locations used for the electrical resistance gauges, vibrating wire gauges were installed at a further ten locations in the slab bay. Five were positioned along another joint in the pre-cast units and a further five positioned along the East-West column strip of the slab, as shown in Figure 8. In total, 100 electrical resistance gauges were installed on twenty reinforcement bars. Ten bars were installed in the bottom pre-cast elements and a further ten on the ‘stitching’ bars in the in-situ slab element. In addition, a total of 64 vibrating wire gauges were installed across the slab bay.



**Figure 8:** Plan view showing location of vibrating wire gauges in void form flat slab bay.

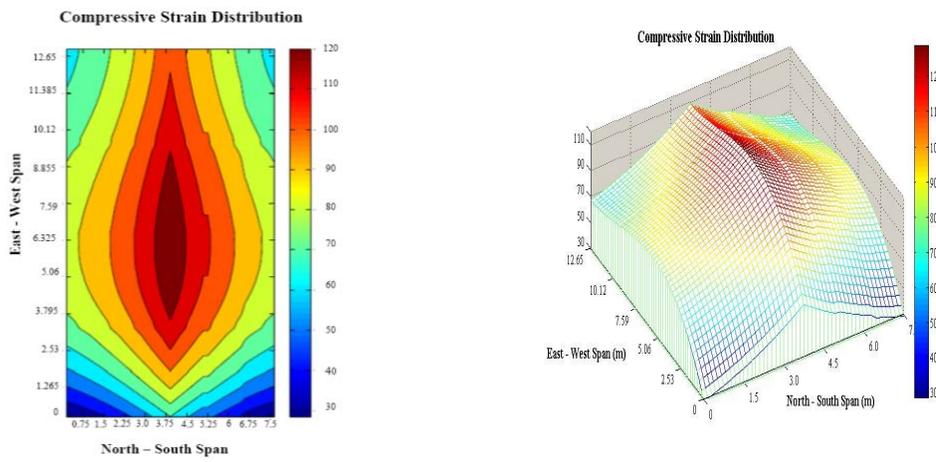
## Results of Instrumentation

The instrumentation installed in the NEB is generating real time data that both undergraduate and postgraduate students can access, providing real engineering problems for them to analyse. Results and data are continuously being interpreted with both temperature and strain effects being monitored within all of the instrumented elements. A detailed record of loading events (for example, depropping, placement and pouring of surrounding structural elements, installation of services and in-situ load tests) in the instrumented areas has been taken right from the initial construction of the building and it is possible to see the response of the structural elements to these events.

Results from the instrumentation of the structural steel truss clearly show the development of strain during load transfer. Strains in the region of  $800\mu\epsilon$  were recorded, which corresponds to an axial load of approximately 700kN. This corresponds to approximately 0.8 times the design calculations and loadings. Subsequent readings following load transfer show little change in the development of strain. This is in contrast to the concrete elements, where the phenomenon of creep and shrinkage mean the strain is continuously evolving, especially at this early stage of their design life. Results from the prestressed beams show significant development in compressive strain due to transfer of prestress. It has also been possible to follow the change in strain within the concrete elements following the changing of loading conditions.

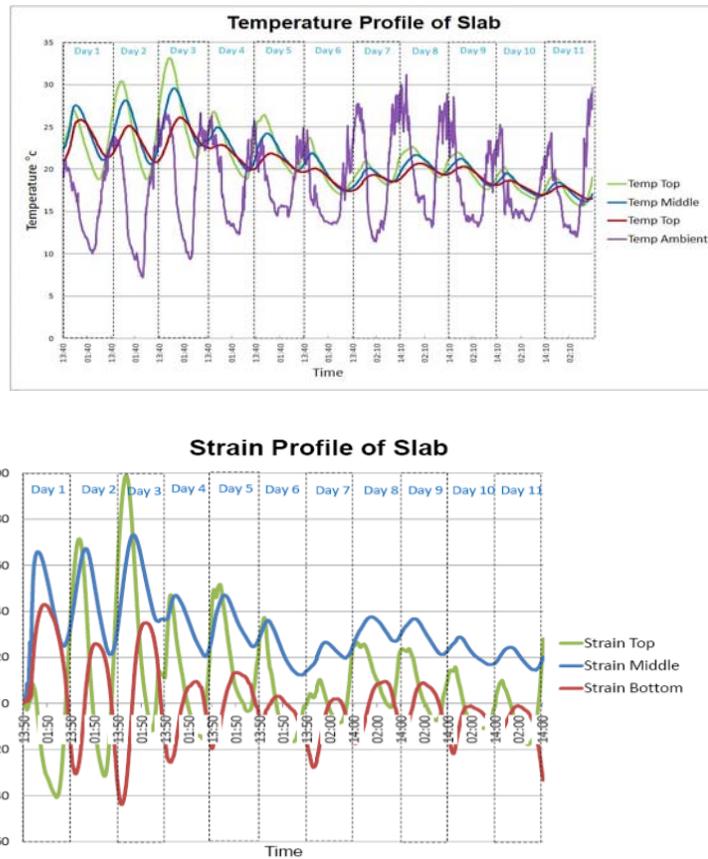
The layout of vibrating wire strain gauges at each instrumented section in the concrete elements have made it possible to establish the stress/strain profiles and, thus, the neutral axis of the concrete members for both the prestressed beams and VFFS. Comparison with design calculations allows a comparison between theory and practice. The location of the neutral axis is a critical element in the design of VFFS systems. The compression zone must not extend into the area containing the spherical void formers, as this may compromise the design. Quite often the sheer quantity of reinforcement ensures the neutral axis stays above the level of the void formers. However, in cases with excessive loads it is necessary to determine and verify the position of the neutral axis. Preliminary results from the NEB show that in some instances, particularly those at mid-span, the compression zone in the instrumented VFFS lie within the area of the void formers, but not at a level to cause concern. It is thought the provision of additional longitudinal steel reinforcement to aid in deflection requirements may be the reason for this incursion. The stress/strain profiles of the concrete elements can be established using the time dependent modulus of elasticity in accordance with BS EN 1992-1-1<sup>20</sup>. These profiles can then be used to illustrate how, for a concrete member in flexure, the strain profile acts on a pivot point located at the most compressed fibre. This

has been possible due to the detailed recording of loading events. It will also be possible to demonstrate to students the effect of limiting the depth of neutral axis to ensure that the concrete does not fail in compression, but that the tension steel yields before this occurs. Some of the visualisation tools to be used as teaching methods can be seen in Figure 9. They show the normal compressive strain experienced across the top of the VFFS unit at a given point in time. Measurements from the gauges, along with interpolation using an  $n^{\text{th}}$  degree parabola are used to plot the graphs.



**Figure 9:** Contour plot (left) and surface plot (right), some of the visualisation tools generated from the instrumentation of the VFFS, showing here the compressive strain distribution in the slab.

Figure 10 shows the temperature profile and corresponding strain profile at one of the locations in the VFFS. The time period coincides with the initial pouring of the concrete up to a period of eleven days after the event. It is clear to see the difference in the peak temperatures across the slab profile; higher temperatures are experienced in the top of the slab, as it is closer to the slab surface exposed to direct sunlight, while lower temperatures are present at the bottom of the slab. Furthermore, the effect of the heat of hydration are evident after the concrete was poured, as high temperatures are present within the slab over the first three days before the temperature recedes to a more consistent level. The daily fluctuation of strains within the slab due to the diurnal change in ambient temperature are also seen in Figure 10.



**Figure 10:** Temperature (top) and strain (bottom) profile of VFFS.

The temperature sensors within the vibrating wire gauges have also been used to establish the behaviour of the VFFS in relation to thermal mass. Thermal mass is based on the principle that heat will typically transfer between the concrete surface and the interior of the building at a rate that matches the daily heating and cooling cycle of a building. From the preliminary results it has been clear to see this diurnal temperature cycle within the concrete (see Figure 10). When analysing the temperature profile across the slab in relation to the ambient temperature there is a clear difference between peak and low temperatures. During the early phase of construction of the NEB when the slab was open to the elements there was a considerable fluctuation in ambient temperature between night and day. On average this ranged between 10 to 15°C. This diurnal variation in temperature was also evident within the concrete. The fluctuation was much less, however, with temperatures varying an average of 3°C in the top and middle of the slab and 4°C in the bottom of the slab. This small fluctuation, in comparison to the ambient temperature, is a clear reflection of the ability of the concrete slab to absorb and omit heat and its ability to regulate its own temperature. However, once the building was enclosed and weatherproof the diurnal ambient variation was only in the region of 5°C. As such the temperature of the concrete remained almost constant, varying no more than 1°C.

Another aspect which is clear from results is the temperature lag between peak ambient temperatures and those experienced within the concrete. Concrete's high specific heat capacity allows it to maximise the heat it stores, while its low thermal conductivity allows it to absorb and release heat over a longer period of time. This is what creates the lag effect. It was found that peak temperatures in the slab (top) occur typically five hours after peak ambient temperatures while temperatures within the middle of the concrete do not peak for a further hour and a half. There was similar correspondence with regard to low temperatures. It will be interesting to analyse the variation in temperature and thermal properties of the slab once the building is fully functioning and how temperature and thermal properties differ between the winter and summer months.

The fluctuation in temperature also leads to the creation of stresses and strains across the slab section. Results show that an downwards curling effect occurs at night as the top contracts relative to the bottom and in contrast a upward curling effect occurs during the day with the top expanding relative to the bottom. This was particularly evident during the early stages of construction when the slab was exposed to direct sunlight. This difference in temperature also leads to a differential shrinkage profile across the slab section and the combination of these two differential profiles can lead to the formation of significant stresses. Results show that the maximum tensile stresses experienced across the slab during the early phases of construction as a result of temperature and shrinkage differential profiles was in the region of 1.5 to 2.5 MPa. This is close to the theoretical tensile strength of the concrete slab, which was calculated in accordance with recommendations made in BS EN 1992-1-1<sup>20</sup>. It was found that, particularly during the initial few days of curing, the tensile strain capacity of the concrete was almost exceeded. These first few days are a critical time in the curing of concrete elements, as this is when the concrete may be most susceptible to plastic cracking. Further laboratory testing is needed to firmly establish the tensile strain capacity of the concrete mix. Although the tensile strain capacity may not have been reached, research has shown that if 50% of the tensile strength of concrete is exceeded microcracks begin to form and if this level increases to 70% the microcracks start to propagate<sup>21</sup>. This was the case in the NEB and it will be interesting to monitor the effect microcracking has on the long-term behaviour of the slab, particularly deflection.

## **Creating an Interactive Environment**

To harness the data from the instrumentation of the building a series of methods and procedures are being developed that will help create an interactive environment for the student. A 3D computational model of the building will be created, showing the overall building layout and location of the various sensors and gauges throughout the building. Students will be able to access real time data from the building by connecting into data ports located throughout the building. This will allow students to develop their data acquisition and analysis skills. Furthermore, it is envisaged to use the medium of the internet to develop and enhance the BMS within the structure. By integrating control networks and developing internet protocols users will be able to remotely access the BMS via the internet. This could facilitate the dissemination of data from sensors to a wider audience and not just for students and academic staff on campus.

There are also future plans for the creation of interactive structural laboratories for students. Some laboratory experiments require substantial equipment in both size and power. With the implementation of further load cells, gauges and sensors throughout the building it will be possible to develop various models to replicate experiments, which in normal lab conditions would be hard to achieve. One such example is a lightweight steel stairs (Fig. 11) within the building, which has been specifically designed by Arup to be susceptible to footfall-induced vibrations. It will act as a teaching tool, demonstrating the phenomenon of footfall vibrations to engineering students. The vibrations will be monitored through the use of accelerometers and the experiments validated through the use of relevant analytical and numerical models. The measured response of the accelerations obtained using accelerometers will then be made available for the students online. Another possibility for an interactive laboratory is through the instrumentation of the overhead crane in the structures laboratory. This will make it possible to demonstrate to students the theory and concept behind influence lines. The development of these virtual laboratories will also act to complement the evolution of local laboratory exercises. Through virtual laboratories the student will become more engaged; they will play an active role where they can actively manipulate a scenario and analyse the consequences. The final stage in creation of an interactive environment is through the creation of various teaching and learning tools. One such visualisation tool has already been created<sup>22</sup> and demonstrates the theory and design behind prestressed concrete. These tools will incorporate data obtained from instrumentation and will be similar in principle to other well known teaching tools (i.e. CALCrete and West Point Bridge Designer). These engineering education software tools will help bring to life engineering concepts that are quite often lost in a normal classroom.



**Figure 11:** *Lightweight steel stairs which will be used to illustrate the phenomenon of footfall induced vibrations.*

As well as the instrumentation of the building to monitor its performance, many elements of the building are also highly visible adding further to the learning environment for structural engineering students. A number of visual learning tools were identified for use within the building and a number of measures were taken to incorporate these during construction<sup>6</sup>. Reinforcement arrangements in a concrete slab, wall and foundation elements have been left exposed (see for example Figure 2). Instead of being encased within concrete the recesses will be covered by glass panels making reinforcement visible to the naked eye.

## **Concluding Remarks**

The objective of the project was to instrument several elements in the New Engineering Building at the National University of Ireland, Galway, so as to provide useful insight into the real time-varying behaviour of concrete and steel structures, for the benefit of undergraduate students and postgraduate researchers. It is considered that the proximity of the instrumented elements to lecturing spaces will confer a degree of immediacy on discussions of structural behaviour and energy performance, encouraging students to actively engage with the underlying engineering issues. Students will gain an excellent grounding in structural engineering through practical and theoretical teaching methods. The green building initiatives within the building will also help to make students more aware the impact their design will have in relation to sustainability. This is an area which is becoming more and more prevalent in today's industry, as we move towards a more holistic design approach.

Instrumentation of the structural members described above is now complete, and datasets are being continuously collected automatically on dataloggers. Various load tests have been carried out since their installation, and will be reported on later. Whilst analysis of results is at a preliminary stage, results to date display an encouraging level of consistency. Much interesting work remains to be done by way of analysis and ancillary testing before the potential benefits of this project are realised. However, the data generated from the embedded sensors has already led to a number of projects undertaken by final year undergraduate engineering students, allowing these students to achieve a deeper understanding of structural elements. Furthermore, the second author is also analysing shear transfer in void-formed flat slab systems, using insitu measurements from the embedded sensors in the new Engineering building. Many more undergraduate and postgraduate research projects, as well as smaller undergraduate projects embedded in various modules, will utilise data from the embedded sensors in the building's structure. Furthermore, video and photographic records of the process of construction, installation and testing will be of continuing benefit in the education of future engineers in the new Engineering building at NUI, Galway. The building represents a new approach to the teaching of engineering students; an approach which will be central to the continuous development of excellent engineering practice.

## **Acknowledgements**

This support of the New Engineering Building committee, the buildings office and members of the College of Engineering & Informatics (Energy Management Group and Building Structures Group) at NUI, Galway is gratefully acknowledged. Consultants ARUP and RMJM facilitated us at various stages. The success of a project of this nature is crucially dependent on the cooperation of people on site; in this respect we were most fortunate in relation to the main contractor, BAM Building, subcontractors Banagher Concrete and Oran Precast, and the resident engineer, who facilitated us throughout. The Civil Engineering technicians and postgraduate students at NUI, Galway played major parts in bringing this project to its present state. The second author is extremely grateful for the ongoing support of Arup Consulting Engineers and the Irish Research Council for Science, Engineering and Technology (IRCSET) through the Enterprise Partnership Scheme.

## **References**

- [1] Atman, C.J., Sheppard, S.D., Torns, J., Adams, R.S., Fleming, L.N., Lund, D: '*Enabling engineering student success; Final report for the advancement of engineering education*', Washington D.C., Morgan & Claypool Publishers, 2010.

- [2] Sheppard, S., Macatangay, K., Colby, A. & Sullivan, W.M.: *‘Educating engineers: designing for the future of the field’*, San Francisco, Jossey-Bass, 2009.
- [3] Jamieson, L.H. & Lohmann, J.R.: *‘Creating a culture for scholarly and systematic innovation in engineering education’*, Washington D.C., American Society for Engineering Education, 2009.
- [4] Royal Academy of Engineering: *‘Educating engineers for the 21<sup>st</sup> century’*, London, Royal Academy of Engineering, 2007.
- [5] ‘An engineer’s dream’ – NUI Galway opens €40m Engineering Building, *The Engineers Journal*, Vol. 65: Issue 4, July/August 2011, pp 219-24.
- [6] RMJM: *‘Teaching Tools’*, Project Report, 2008, RMJM Architects, Edinburgh.
- [7] Cannon, E. & Goggins, J.: *‘Teaching Tools – Instrumentation of New Engineering Building – Structural Engineering’*, Internal Report, College of Engineering and Informatics NUI Galway, 2009.
- [8] Tyler, R.G.: ‘Developments in the measurement of strain and stress in concrete bridge structures’. *T.R.R.L. Report LR189*, 1968
- [9] Tyler, R.G.: ‘Long term strains in the Medway Bridge’. *T.R.R.L. Report LR539*, 1973.
- [10] Mortlock, J. D.: The instrumentation of bridges for the measurement of temperature and movement. *T.R.R.L. Report LR641*, 1974
- [11] Barr, B., Waldron, P., Evans, H.R.: ‘Instrumentation of glued segmental box girder bridges’, *Proceedings IABSE Colloquium, Bergamo*, 1987, Monitoring of large structures and assessment of their safety.
- [12] O’Byrne, C.: ‘The monitoring of strain in a prestressed concrete bridge of box girder construction’. *MEngSc thesis*, NUI, Galway, 1988
- [13] Cannon, E., O’Byrne, C.: ‘In-situ instrumentation of concrete structures: a case study’. *Proceedings, Colloquium on Concrete Research in Ireland*, Queen’s University, Belfast, 2003.
- [14] Barr, P.J., Stanton, J.F., Eberhard, M.O.: ‘Effects of temperature variations on precast, prestressed concrete bridge girders’, *Journal of Bridge Engineering*, **10/2**, 2005.
- [15] Owens, A.: ‘In-situ stress determination used in structural assessment’, *Strain: An international journal for experimental mechanics*, **29**, 1993, p 115-124.
- [16] Scott, R.H., Gilbert, S.G., Moss, R.M.: ‘Load testing of floor slabs in a full-scale reinforced concrete building’, *Strain: An international journal for experimental mechanics*, **38**, 2002, p 47-54.

- [17] Scott, R.H., Gill, P.A.T.: ‘Developments in the measurement of reinforcement strain distributions in reinforced concrete members’, *Strain: An international journal for experimental mechanics*, **18**, 1982, p 61-63.
- [18] Moffat, K.R., Dowling, P.J.: ‘Shear lag in steel box girder bridges’. *The Structural Engineer*, Oct 1975 pp. 439-448 (+ discussion Aug 1976 pp. 285-298).
- [19] Cannon, E., Goggins, J: ‘The new engineering building at NUI, Galway as a teaching tool for structural engineering’, *BCRI Conference*, University College Cork, Ireland, 2-3 September 2010, p 609-17.
- [20] BS EN1992-1-1:2004, ‘Eurocode 2: Design of concrete structures – Part 1-1: General Rules for buildings’, CEN, 2004.
- [21] Federation Internationale du Beton: ‘*Structural concrete; Textbook on behaviour, design and performance, Volume 2*’, Switzerland, FIB, 1999.
- [22] Cannon, E., McDonagh, A, Burke, J: ‘Use of 3D modelling animation in the teaching of concrete structural design’, *BCRI Conference*, University College Cork, Ireland, 2-3 September 2010, p 83-92.