Real-time monitoring to investigate structural performance of hybrid precast concrete educational buildings

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The motivation and implementation of a real-time structural health monitoring (SHM) strategy to determine the structural performance of a number of educational buildings recently constructed in Ireland is discussed in this paper. In recent years, smart materials with embedded instrumentation has been installed in a number of buildings at the National University of Ireland Galway during the construction phase, which allows continuous monitoring of the behaviour of the structure.

Instrumentation installed on a number of projects, described in this paper, allow many important aspects of structures to be monitored during construction, as well as in the operational phase of the building such as temperature, concrete and reinforcement strain, deflection, and response to the environment.

Keywords: Structural health monitoring; hybrid precast concrete; vibrating wire gauges; real-time monitoring; structural performance; smart materials.

Introduction

Structural Health Monitoring (SHM) can be defined as 'the use of *insitu*, non-destructive sensing and analysis of structural characteristics, including the structural response, for purposes of estimating the severity of the damage and evaluating the consequences of the damage on the structure in terms of response, capacity, and service-life (Guan, Karbhari, & Sikorsky, 2006). SHM typically consists of continuous or periodic monitoring of a structure using sensors that are either embedded in it or attached to its exterior (Bisby & Briglio, 2004). Historically, monitoring of buildings was motivated by the need to understand their performance in extreme events, such as earthquakes and storms. However, in recent decades, SHM has emerged as an increasingly important tool in Civil Engineering to understand how structures behave during construction and operation. Although SHM is not a new concept, it is only relatively recently that Civil Engineers have adopted SHM for the design, construction and management of buildings which are not likely to be subject to extreme events. The trend towards increased service life and durability of structures means that monitoring systems which permit the condition of the structure to be measured and which detect the possible onset of damage and/or deterioration of the structure will become increasingly important. A SHM system, if correctly designed and implemented, can be used for assessment of current condition of the structure, residual life prediction and detection of deterioration of a structural component (Buenfeld, Davies, Karimi, & Gilbertson, 2008).

SHM Strategy

One of the key benefits of SHM is the improved understanding of insitu structural behaviour. This paper presents the SHM strategy which has been developed in National University of Ireland Galway (NUI Galway) in order to monitor the structural and environmental performance of a number of buildings and outlines some of the results from the strategy. Sensors installed during the construction phase of a number of projects allow real-time monitoring of the structure during the construction and operational phase. This paper describes some applications of the data from the insitu instrumentation for a number of educational buildings constructed in recent years.

Methodology

The general SHM methodology (Figure 1) which was implemented for the three projects described in this paper is as follows:

(1) Design and configuration of SHM system

The location, number and type of sensors which allow real-time monitoring of specific variables during the construction and operational phase of the buildings is the first step when implementing a SHM system. It is important for any SHM system that the sensors chosen are robust with respect to their environment to which they are exposed and the purpose and motivation for the SHM is clearly defined.

(2) Data communication

There were a variety of methods through which data can be managed after the sensors were installed. The frequency of measurement of data is determined by the variable being measured (temperature, strain etc.) and the intended use of the data. Typically, less frequent data acquisition can be specified after the construction phase is completed. A Campbell Scientific data acquisition system consisting of data loggers, multiplexers, Ethernet and Compact Flash Module that automatically collects data from the sensors was used in all projects. The datalogger can communicate over a local network or a dedicated internet connection via TCP/IP, transmitted wirelessly to the site office and/or data can also be downloaded manually to a laptop on site. After commissioning of the buildings, data is collected over a local network and saved to a dedicated server in NUI Galway. Wired sensors were predominantly used in these projects due to cost and time constraints. However, it is expected that wireless systems will replace wired monitoring systems in the future as the technology and robustness of wireless sensors improves.

(3) SHM maintenance

Regular maintenance of the SHM system is required to ensure that the data is recorded and reliable. All external sensors and wiring should be inspected periodically to check for damage or failure and replaced if necessary. Embedded sensors in general cannot be inspected and, thus, some redundancy is designed into the SHM system because of the relatively harsh environment when embedded in concrete and possible damage during the construction phase. A system is required to ensure that the data is reviewed regularly and any unexpected anomalies in the data are noted and investigated. Depending on the nature of the data and type of sensors, some processing of the raw data is required to filter the data to remove unwanted effects ('noise') that is not required for the purposes of SHM. Filtering of raw data makes the post-processing and interpretation phase of the process easier and more efficient. Examples of filtering data include modifying data for thermal effects or removing data where sensors have recorded data outside their allowable range. In addition to maintenance of the SHM system, it is also important to note events (concrete pours, removal of props, application of finishes/cladding etc.) that occur during the construction phase so that they can be related to the raw data during the post-processing phase.

(4) Data management

Adequate memory must be provided for storage of both the raw data and processed data. The SHM strategy for these projects was to monitor the long-term performance of the buildings and, therefore, the raw data is stored on a dedicated server with protected access. The location, type and reference for all sensors must be documented clearly to allow for future interpretation of the data. It is envisaged that the data will be stored for many years and will be available for students and professionals for teaching and research applications. A MySQL database is used to store long term data from sensors and the database is accessible remotely via web using a PHP application, or using MySQL Workbench.

(5) Post-processing

Arguably, the most important component of a SHM strategy is the post-processing of the raw data recorded from the sensors. The purpose of the post-processing is to convert the raw data into useful information about the behaviour of the structure when subject to various external effects (structural, environmental, thermal) during construction and the operational phase of the building. The ultimate goal of SHM is to provide reliable information on the behaviour of the structure which can be calibrated against numerical models and compared with predicted behaviour in codes of practice (e.g. Eurocodes).

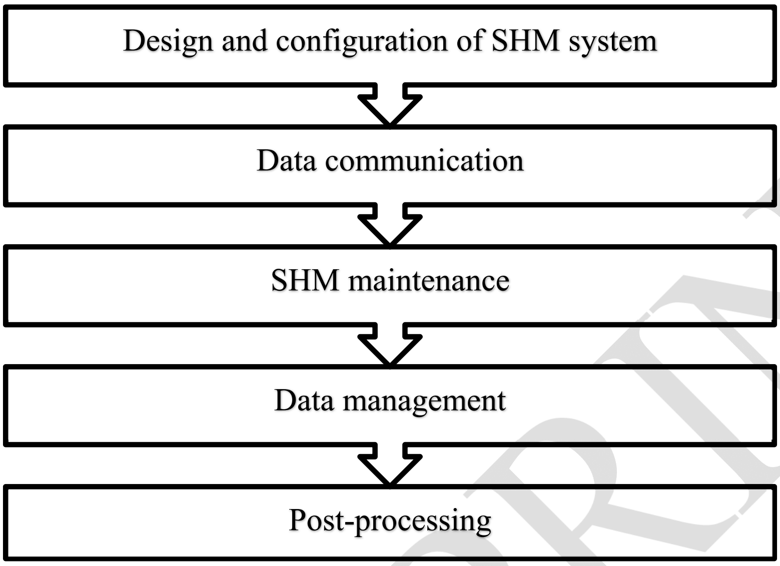

Figure 1. Visual schematic of the SHM methodology

Demonstrator buildings

Since 2010, sensors have been installed in three demonstrator buildings (i) the Engineering Building (EB), (ii) the Institute for Lifecourse and Society (ILAS) and (iii) the Human Biology Building (HBB) which are all located at the NUI Galway campus in Galway, Ireland. The three buildings are predominantly constructed using hybrid precast reinforced concrete components and insitu reinforced concrete.

In all buildings, sensors were installed in both precast concrete and insitu concrete elements which provide rich information about the actual building performance when subject to actual structural and environmental loads. Real-time monitoring offers potential benefits in relation to optimisation of structural components by understanding the actual behaviour of components in use and the possibility to develop and calibrate numerical models that predict structural performance. The information from the real-time monitoring also offers the opportunity to compare actual behaviour with predicted behaviour using structural codes, such as Eurocodes. The majority of the instrumentation is embedded within the structure so that long-term effects such as creep and shrinkage of concrete components can also be investigated.

Sensors

The SHM strategy implemented in NUI Galway used a number of sensors embedded in the structural components of the building to monitor and record the various parameters with respect to the structural end environmental performance. These sensors include (Figure 2):

- Vibrating Wire (VW) gauges (Gage Technique model TES/5.5/T) which are embedded in concrete and measure strain and temperature.
- Electrical resistance (ER) strain gauges (Tokyo Sokki Kenkyujo model FLA-6-11) bonded to steel reinforcement in concrete, which measure uniaxial strain.
- IP98 rated thermistor sensors (ATC Semitec model IP 68) which are capable of measuring concrete temperature.

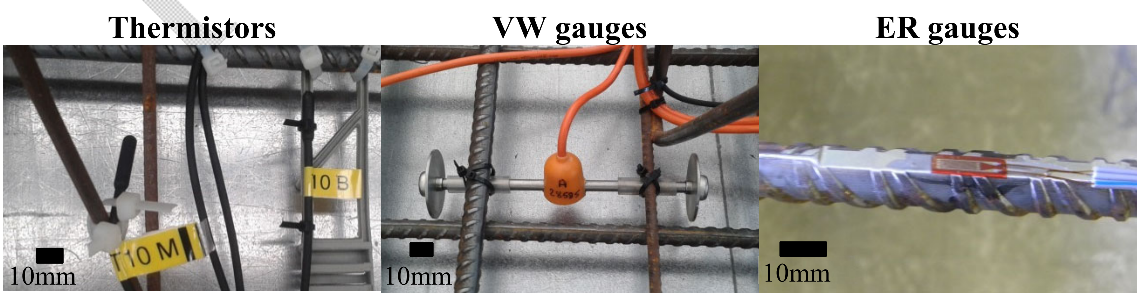

Figure 2. Sensors embedded in the buildings' structure

Weather data from the NUI Galway weather station (IRUSE, 2016) located on the main campus was recorded to provide accurate environmental data (air temperature, relative humidity, wind speed, solar radiation, etc.) for the concrete elements which are monitored using embedded sensors. This data is used to develop and calibrate numerical models predicting the behaviour of the concrete elements. The deformation of some concrete elements was recorded during the construction phase using digital surveying and digital image correlation. In addition, the embedded sensors are also used to investigate the environmental and energy performance of the buildings (Hajdukiewicz, Byrne, Keane, & Goggins, 2015).

Material Testing

To complement the data from the embedded sensors in the concrete, a comprehensive material testing programme was undertaken to measure the properties of the concrete (compressive strength, tensile strength, modulus of elasticity, etc.) in which the sensors are embedded. When predicting the behaviour of concrete elements, it is critical that the properties of the concrete are determined as its properties will change over time depending on loading and environment (Neville, 1995).

Engineering building

Overview of the building

The Engineering Building at NUI Galway integrates all engineering activities on campus and was open to the public in July 2011. It was the first building in which real-time monitoring using embedded sensors was utilised to investigate the performance of buildings at the NUI Galway campus. The 14,250m^2 building is the largest engineering school in Ireland and accommodates approximately 1100 students and 110 staff. In addition to its teaching and research functions, the building was designed such that it acts as a learning/teaching tool for undergraduate students through the use of the real-time data from the sensors installed throughout the building (‘living laboratory’)

(Goggins, Byrne, & Cannon, 2012). In the Engineering Building, three key concrete elements were instrumented during construction; a prestressed double tee beam, a prestressed transfer beam and a void form flat slab (VFFS). Further details of these elements and the SHM systems employed may be found in Goggins et al. (2012). However, the next section contains some details of the novel void-form flat slab (VFFS) system as an example of how the SHM system has been used within the engineering building.

Void form flat slab (VFFS)

This project utilised a void-form flat slab (VFFS) system for the majority of flooring in this building. This innovative form of flat slab system was implemented for the first time on a large scale project in Ireland in this building. The reinforced concrete slabs contain high-density polyethylene hollow void formers to replace concrete over the middle height of the slab, where the slab primarily experiences bending stresses with relatively low shear stresses (Figure 3). Those hollow void formers not only reduce the structural dead load of the slab (resulting in saving on the material cost and allowing larger slab spans), but also increase the thermal resistance of the slab.

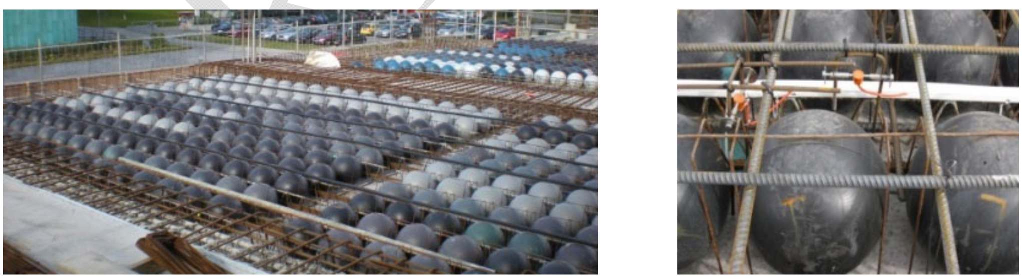

Figure 3. Cobiax VFFS system being installed in the EB (left) and with gauges installed (right)

One of the areas of investigation for the VFFS was the measured strain profile through the section of the concrete slab and comparison with the theoretical tensile strain capacities derived using codes of practice such as Eurocode 2 (CEN, 2004) and

American Concrete Institute (ACI, 1992). During the early phases of construction, there is potential for cracking to occur if the tensile strain capacity of the concrete is exceeded. Early-age cracking can lead to problems with respect to durability and loss of serviceability of the floor structure. Strain profiles in the floor structure were calculated and compared with the tensile strain capacities determined using European and American standards. It was found that the measured tensile strain exceeded the theoretical strain capacity at only one instrumented section and this occurred at a mid-span section. The strain profiles this location for the top, middle and bottom of the slab are shown in Figure 4 and compared with the relative tensile strain capacities outlined by the respective standards. Some discussions of the behaviour of the void form flat slab (VFFS) system with respect to strains and potential cracking is available in (Hajdukiewicz et al., 2015).

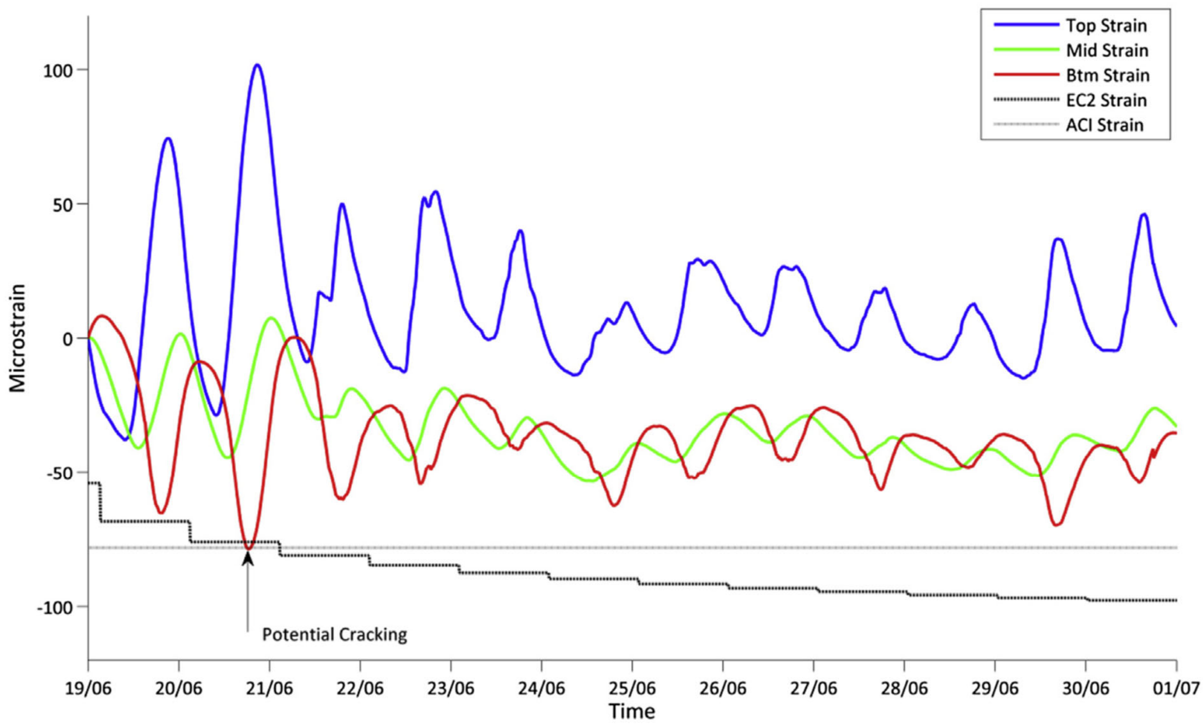

Figure 4. Strain profile at one of the instrumented sections in the Engineering Building (Hajdukiewicz et al., 2015)

Evaluating structural capacity

The application of insitu instrumentation and utilisation of the data was previously demonstrated for the EB in relation to assessing the structural capacity of the floor so that more efficient and economical design can be formulated, particularly for retrofitting and strengthening structures (Byrne & Goggins, 2013). The insitu data from the VFFS floor structure in the EB building was used to assess the load capacity of the floor for the purpose of assessing the possible increase of the flexural capacity of the floor using fibre reinforced polymers (FRP's) because of a change of use of the floor structure (increase in imposed load). One of the most critical parameters when calculating externally bonded FRP reinforcement for concrete structures is the existing strains on the soffit of the slab. Using the data from the embedded instrumentation, it was possible accurately determine the strains on the slab soffit.

The structural capacity of the slab was calculated using American Concrete Institute and FIB design guidelines (Bakis et al., 2002; FIB, 2001) and also by using substituting the calculated insitu soffit strains from the instrumented slab for their corresponding values in the aforementioned design guides. Design solutions were determined for the three most common types of externally bonded FRP materials (carbon, glass and aramid). It was found that the layout and shape of the external FRP reinforcement was quite similar for all design solutions, but that there was a significant reduction in the amount of FRP (i.e. number of layers etc.) when utilising the data from the insitu instrumentation. Insitu strains were almost 20% less than those calculated using the design guidelines. Overall, the ACI design procedure required the most externally bonded FRP reinforcement, followed by the FIB design procedure and the least amount of reinforcement was determined using the insitu data. Depending on the FRP material used and the design guideline, the comparative cost saving when using the instrumented data varied between 4% and 25%. Figure 5 illustrates the comparative unit cost for the three types of FRP when utilising the design guidelines and the insitu data.

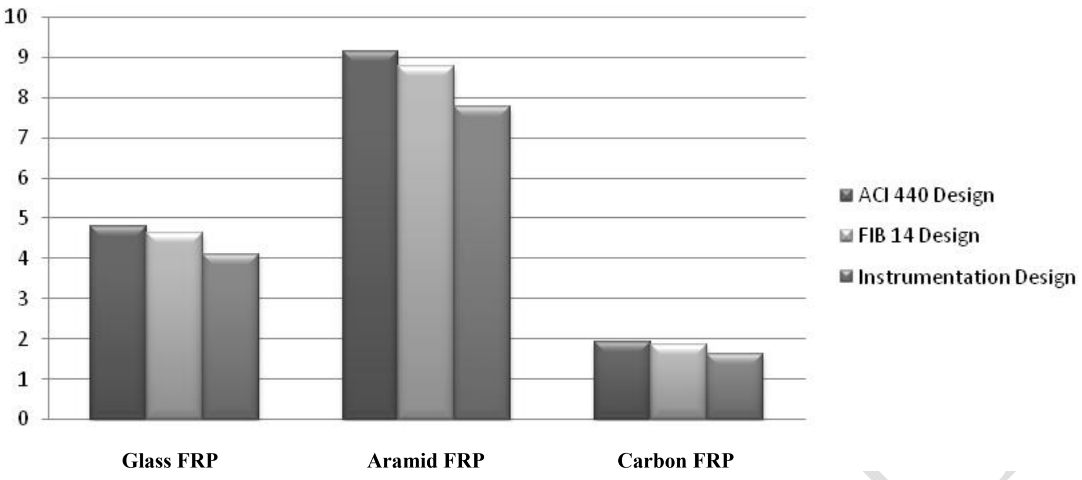

Figure 5. Graph showing comparative unit cost of materials for retrofitting of void form flat slab (Byrne & Goggins, 2013)

Institute for Lifecourse and Society building

Overview of the building

The Institute for Lifecourse and Society (ILAS) building in NUI Galway commenced construction in July 2013 and was completed by September 2014. The building occupies a gross floor area of approximately 3600 m^2 and has been built with two separate wings (two storeys high East wing and three storeys high West wing) designed around a large central atrium. The building accommodates mainly office spaces, seminar rooms and lecture theatres. The ILAS building is mainly built using precast concrete technology, including the building frame, lattice girder flooring, twinwall components and hollowcore slabs. In the ILAS building, sensors were installed in the hollowcore ground floor, hybrid concrete lattice girder floor (1st floor and roof) and the structural walls (internal and external). The primary focus of this research project was the heat transfer and storage characteristics of the precast building components (Goggins & Hajdukiewicz, 2014), although some vibrating-wire gauges were also embedded in the floor structure to monitor strains.

Hybrid concrete lattice girder floor

The 300 mm deep flat slab forming the first floor of the East wing of the ILAS building contains 59 VW gauges installed over 29 designated sections. The instrumented slab was an interior, two way spanning slab (of multiple spans) spanning 8.14 m in one direction and has two spans of 5.81 m and 4.21 m in the orthogonal direction (Goggins, Newell, King, & Hajdukiewicz, 2014). The floor plate used for the superstructure of the building is a hybrid precast and in-situ concrete flat slab system similar to that used on the EB, but without the hollow void formers.

The prediction of strains for concrete elements systems is extremely difficult to estimate accurately (Gilbert, 2001). The behaviour of a slab at service loads varies with time and depends on the extent of cracking, stiffness of the slab, creep, shrinkage and degree of restraint. The slab in the ILAS building is subject to strains from thermal, shrinkage, creep and flexural components. Because the data is recorded from the sensors after the building is operational, the long-term behaviour of the concrete elements can be analysed and compared with design guidelines. One of the difficulties of predicting long-term behaviour of concrete elements is that the properties of concrete change and evolve over time in response to environment and loading conditions.

The predicted strains in the first floor slab due to the various components determined using Eurocode 2 (CEN, 2004) are compared with the measured strains from the embedded VW gauges in Figure 6 for the twenty-six months (Oct 2013-Dec 2015 inclusive) after the floor was poured. The measured strains from the VW strain gauges are corrected for thermal effects so that only strain due to shrinkage, flexure and creep is determined from the gauge reading:

$$\mu\varepsilon_{load} = \mu\varepsilon_{actual} - \mu\varepsilon_{thermal} = \Delta\varepsilon + \Delta T.\alpha_{vw} - \Delta T.\alpha_c \tag{1}$$

where $\Delta\varepsilon$ is the change in measured strain; ΔT is the change in temperature; α_{vw} is the coefficient of thermal expansion of the VW gauge and α_c is the coefficient of thermal expansion of the concrete.

The dominant predicted strain component is shrinkage and this accounts for over 80% of the strain induced on the first floor slab. However, the predicted strain due to flexure and creep is likely to be underestimated as it is very difficult to determine the contribution due to imposed loading acting on the floor after the building is operational. When the ILAS building was completed, approximately 10 months after the first floor slab was poured, the predicted strain (in accordance with Eurocode 2) was 317 microstrains and the measured strain was 262 microstrains. The predicted strains are based on assumed relative humidity of the ambient environment and design values for the concrete properties.

The measured and predicted strain values compare reasonably well considering the relatively large coefficient of variation for both creep (20%) and drying shrinkage (30%) when using the approach of Eurocode 2 (CEN, 2004) for determining strains. The accuracy of predicted strains using Eurocode 2 with the measured strains in the concrete slab appears to improve over time and are less accurate at predicting the early-age strains in the slab during the construction phase. This may suggest the difficulty in modelling the actual slab conditions during construction in which the environment can change relatively quickly. One of the areas of investigation will be to review predictive models for long-term behaviour and their sensitivity to input parameters such as compressive strength, relative humidity and air temperature.

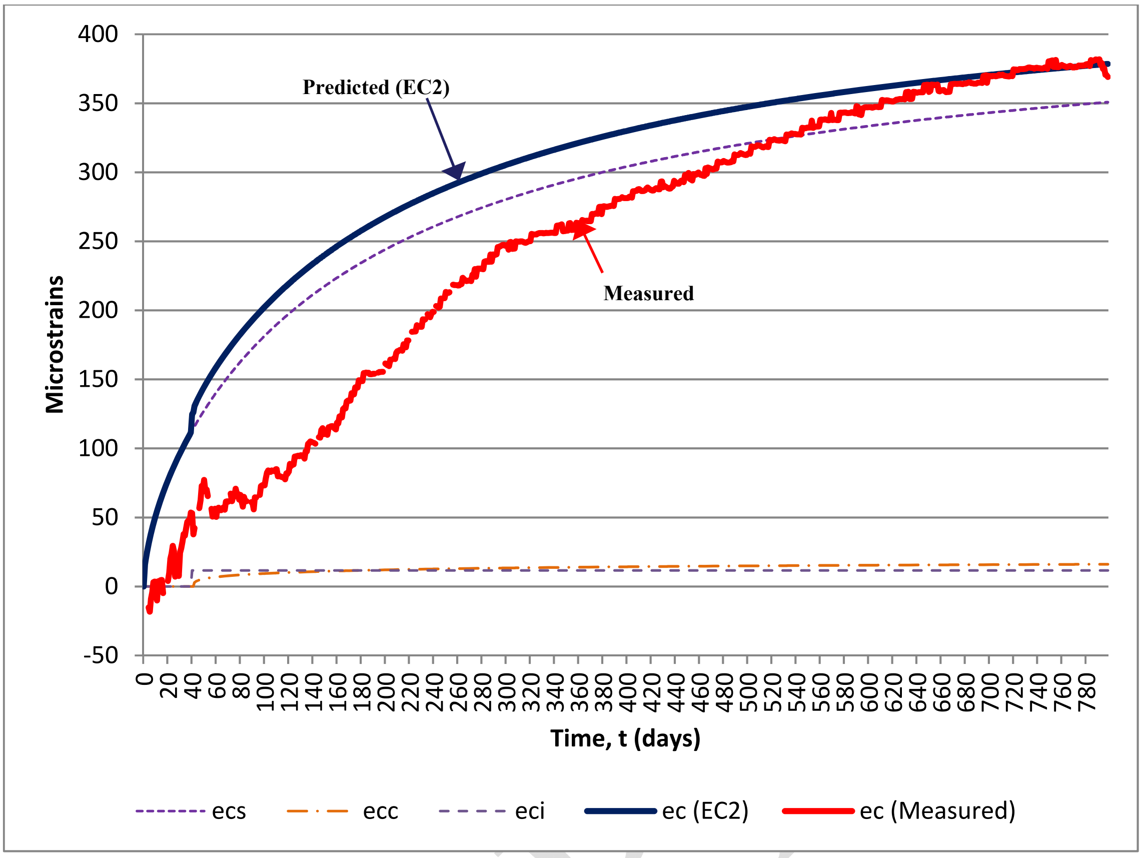

Figure 6. Comparison of predicted strain (EC2) and measured strain in ILAS building (ecs = shrinkage strain, ecc = creep strain, eci = flexural strain)

Of the three demonstrator buildings presented in this paper, the ILAS project was the least successful in relation to data acquisition from the embedded sensors. Due to time constraints during the construction phase of this project, there was limited time for installation of embedded sensors and a number of the sensors were damaged during the construction process. Lessons learnt from this project were taken forward to the next project in relation to protection of wiring and sensors during construction, particularly when insitu concrete is poured on site.

Human biology building

Overview of the building

The Human Biology building (HBB) is a four storey building over basement and roof level plant enclosure with a gross floor area of 8200m^2. This facility will encompass three schools; Anatomy, Physiology & Pharmacology and Therapeutics. The building will be a teaching and research facility with lecture theatres, laboratories, offices and meeting rooms. Construction commenced in January 2015 and the expected construction period is 19 months (July 2016). It is anticipated that the building will achieve an A rating under the Commercial Energy Rating marking scheme and a BREEAM Excellent rating.

The Human Biology building is primarily constructed using precast concrete elements, including the building frame, twinwall system, hybrid concrete lattice girder slabs and hollowcore slabs which were designed, manufactured and installed by Oran Pre-Cast Ltd. Embedded sensors were positioned in the two-way spanning second floor of the Human Biology building in two zones to monitor the strain and temperature in the concrete floor structure (hybrid concrete lattice girder flat slab) during the construction and operational phase of the building. The overall slab thickness in the second floor is 400mm and this consists of a 65mm thick precast lattice girder plank (Figure 7) and 335mm insitu concrete topping. The lattice girder truss that protrudes from the plank provides stiffness in the temporary state and increases composite action with the insitu structural concrete topping. The precast planks are temporarily propped until the structural concrete topping has reached the required compressive strength.

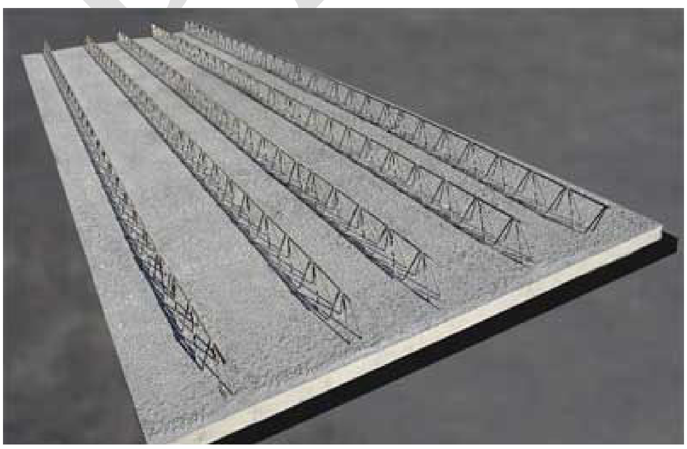

Figure 7. Precast Concrete Lattice Girder Plank(© Oran Pre-cast Ltd.)

The VW gauges were positioned along a number of orthogonal grids in the floor structure at over 30 designated locations so that two-way spanning behaviour of the floor structure could be monitored. At most locations, four VW gauges were positioned through the depth of the slab (1 in the precast plank and 3 in the insitu topping) so that the strain and temperature profiles through the slab could be measured (Figure 8).

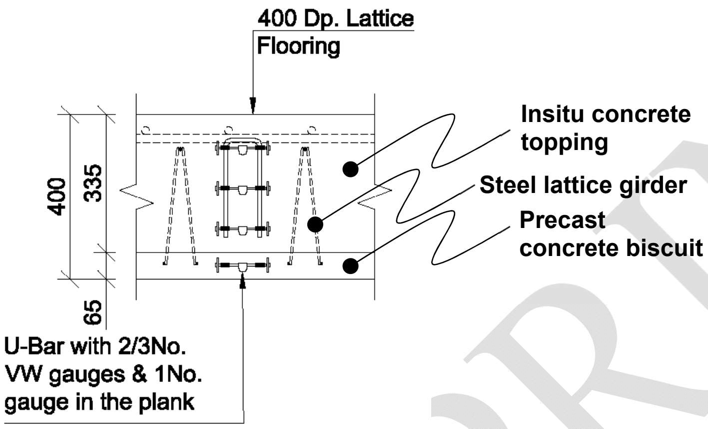

Figure 8. Typical section showing locations of vibrating wire gauge installed in the flat slab system.

The embedded sensors in the floor structure allows the actual strains in the slab to be measured during the construction phase, so that the impact of the temporary propping for supporting subsequent pours and their removal can be monitored and assessed. Deflections of the slab is also being monitored using a precise level and digital image correlation system, which will be compared to estimates from the strain measurements. Furthermore, the configuration of embedded sensors in the slab permits the behaviour of the slab to be analysed along a number of gridlines and compared with theoretical behaviour based on codes of practice such as Eurocode 2 (CEN, 2004). It is envisaged that this research project, in conjunction with laboratory testing of lattice girder precast planks, will be used to optimise this floor system with respect to design and construction. Some preliminary results from this project are discussed in following sections.

Early-age thermal effects

Nine VW gauges, which record strain and temperature, were embedded in one of the 65mm thick precast lattice girder planks prior to manufacture and data was recorded immediately after the plank was cast. Data was continuously recorded for this plank during curing, delivery and erection on site so that strain and temperature history of the precast plank could be analysed throughout the life cycle of the product from cradle to end of life. Figure 9 shows the temporal temperature in the precast concrete plank and ambient air temperature (dashed line) for the first week after its manufacture. Because the planks were cast during the summer, temperature curing was not used by the precast manufacturer in this case. In the first 24 hours after casting (25^{th} June 2015), the peak in the concrete temperature due to the heat of hydration is noted and contrasts with the falling ambient air temperature during the night. The peak in the concrete temperature occurs 10 hours after casting and the maximum difference between the air temperature and the concrete temperature is approximately 5.5°C. It is noted that the peak temperature is slightly less for the three gauges located close to the perimeter of the plank (less than 300mm from plank perimeter) as the plank cools more quickly along its external surfaces. However, because the concrete plank is relatively thin (65mm), after the first 24 hours the concrete temperature in the plank is relatively uniform for all nine VW gauges and correlates with the ambient air temperature.

This contrasts markedly with the concrete temperature in the insitu structural topping in which the heat of hydration is more significant because of the thickness of the concrete (335mm thick), as well as the insulating properties of the precast plank resulting in only one surface of the insitu concrete being exposed. The concrete temperature in the insitu topping at one location in which three VW gauges are embedded to measure strain and temperature through the concrete (top, middle and bottom) are shown in Figure 10. The temperature for the VW gauge in the precast plank at this location is also shown. For the first 7 days after pouring, the temperature in the concrete exceeds the ambient air temperature and it is only after 7 days that the heat generated from the hydration process has fully dissipated. The effect of the diurnal temperature changes are clearly visible in the measured temperature in the concrete floor. Similar to the precast plank, the peak in concrete temperature occurs 10 hours after casting and at this point, the maximum temperature differential between the air and concrete temperature is approximately 13°C. As expected, the peak temperature is recorded for the VW gauge in the middle of the insitu topping as the internal section of the slab will be slowest to cool down. The effect of the heat of hydration from the insitu topping on the concrete in the precast plank can be noted almost immediately after pouring and results in a peak increase in temperature of 9°C.

For ‘thick’ concrete sections (typically greater than 500mm), the temperature rise due to the heat of hydration can result in excessive thermal stresses and cracking generated by restraint to thermal movement. For the 335mm thick insitu topping in this project, the temperature differential through the slab is small (Figure 10) because of the relatively thin section which allows the concrete to cool comparatively uniformly as the heat is readily lost to the environment. The temperature differential recorded between the VW gauges in top, middle and bottom of the insitu topping did not exceed 3°C and the maximum differential occurred during the cooling phase.

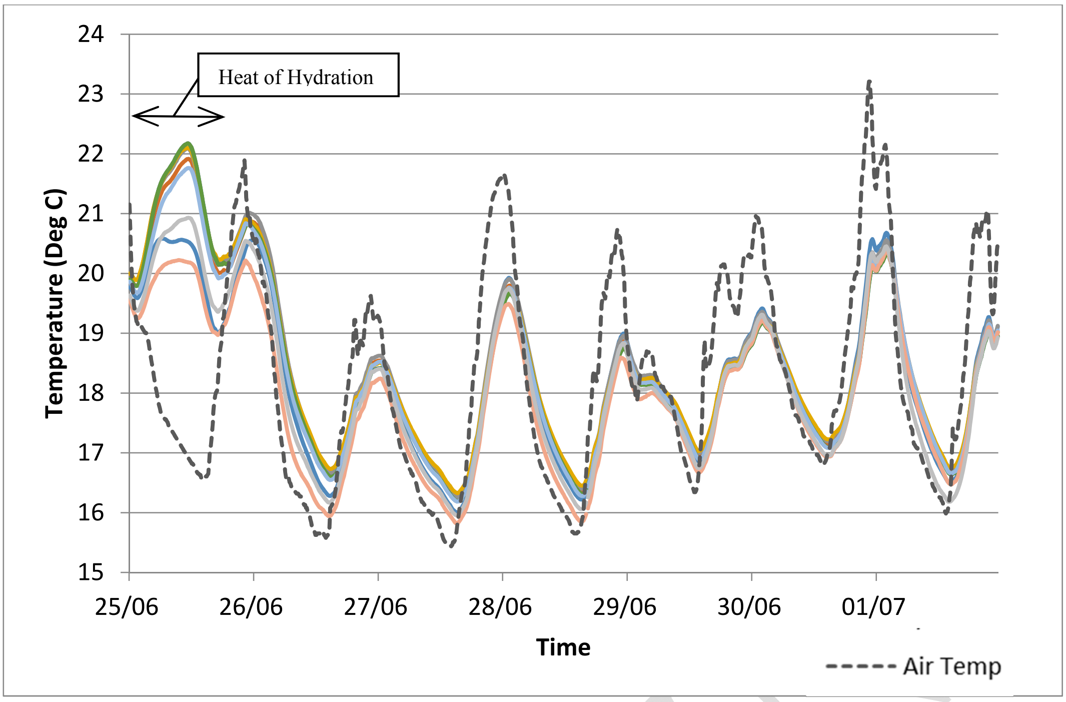

Figure 9. Concrete temperatures in the 65mm thick precast plank (7 days after manufacture)

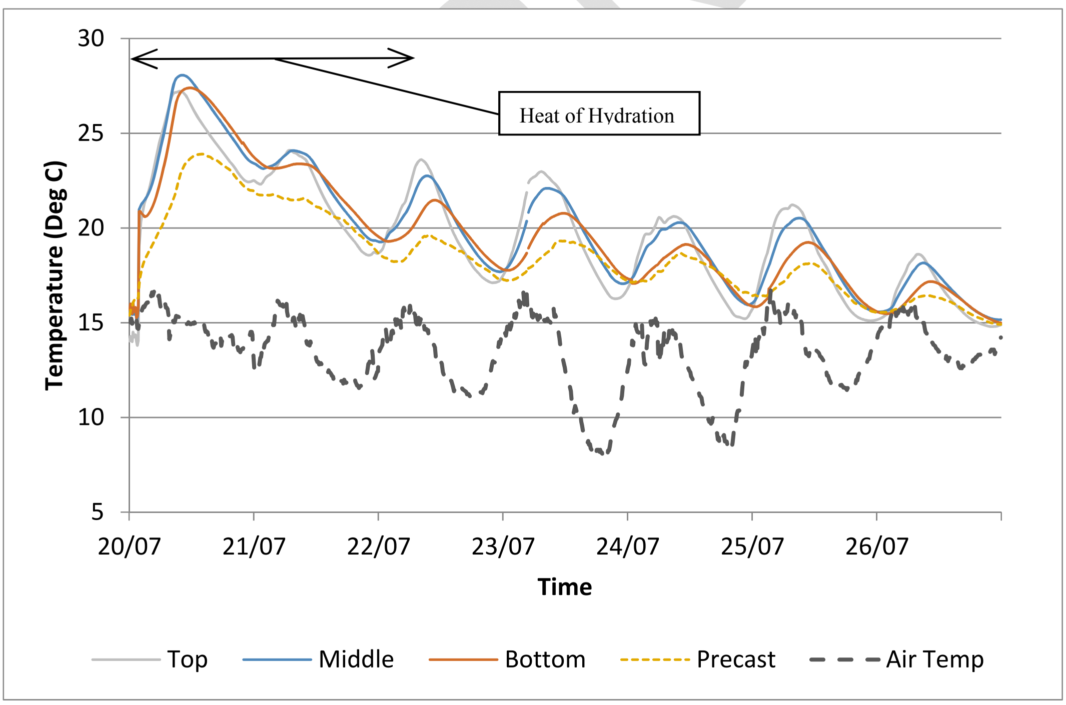

Figure 10. Concrete temperature in 335mm insitu structural topping (7 days after pour)

The increasing use of high-performance concrete with higher compressive strengths and lower permeability has seen an increased concern in relation to early age cracking which can affect durability and service life of concrete structures. In addition, discrepancies between performance of construction materials in the laboratory and their observed performance in the field has been reported (Gulis, Lai, & Tharambala, 1998). Because of this uncertainty, the design of concrete structures to ensure long-term in-service performance can be problematic. Therefore, the use of insitu instrumentation can be used to appraise material properties, construction procedures and design methods with respect to the actual behaviour of concrete structures.

Predicting the potential for early-age thermal cracking is very difficult at the design stage because of numerous factors which affect the behaviour of the concrete and the limited information on the concrete known at design stage. CIRIA Report C660 by Bamforth (2007) gives guidance on predicting the early–age thermal behaviour of concrete sections based on a comprehensive testing programme undertaken at University Dundee (Dhir, Paine, & Zheng, 2004). However, the report recommends thermal modelling for reliable predictions which takes account of the formwork and exposure conditions. Based on thermal modelling, it predicts that the maximum temperature differential in the insitu topping would be 13°C, but this figure is highly dependent on the thermal diffusivity of concrete, surface conditions and the environmental conditions (wind and solar gain).

As an upper bound, Fitzgibbon (1976) estimated that the peak temperature rise under adiabatic conditions is 12°C/100kg per cubic metre of concrete, regardless of the type of cement used. Therefore, assuming a 100% CEM I cement for the insitu topping, it could be expected that the peak temperature be as much 40°C (total cement content of insitu topping was 330kg/m^3). However, in this project 30% GGBS was used as a cement replacement in the concrete mix and this would help to reduce the heat of hydration generated during curing. The predicted peak temperature differential for the insitu topping using CIRIA Report C660 is approximately 19°C, but other factors which can affect the peak temperature are the variation between cements, placing temperature and actual thermal conductivity of the precast plank. The measured peak temperature of 13°C equates to a temperature rise of 4°C/100kg per cubic metre of concrete. In terms of minimising cracks, the general rule of thumb used by designers is to limit temperature differentials to 20°C, although this figure is dependent on the type of aggregate used in the concrete mix. It can be seen from the above figures that the CIRIA Report C660 provides upper bounds for the peak temperature and temperature differentials for a specific concrete pour.

The strain and temperature profile for three VW gauges through the depth of the insitu topping at one location is shown in Figure 11 for the first 7 days after pouring. After the dormant period of the hydration process, which lasted approximately 2 hours, there is a significant step change in tensile strain varying from 20με near the bottom of the insitu topping to 40 με at the top of the insitu topping due to the heating phase and the resulting expansive strains. Typically, the measured strains are greater for the gauges near the top of the insitu topping in comparison with the gauges near the bottom of the insitu topping which may be partially explained by the restraining effect of the precast plank. After the cooling phase of the heat of hydration is finished (approximately 2-3 days), thermal strains are significant and the concrete is subject to daily fluctuations in strains in response to the diurnal ambient air temperature. There are varying recommendations for the coefficient of thermal expansion of concrete (α_c) in the literature. Eurocode 2 (CEN, 2004) recommends a value of 10με/°C for normal weight concretes although values can typically vary from 8-13με/°C depending primarily on the type of aggregate used (Bamforth, Chisholm, Gibbs, & Harrison, 2008). The daily changes in strain due to thermal effects can be estimated by multiplying the coefficient of thermal expansion of concrete (α_c) and the measured temperature change in the concrete. It should be noted that whilst the floor structure is propped, the measured strain is a combination of thermal, shrinkage (autogenous and drying) and creep. The thermal strain component is the dominant strain and accounts for the majority of the measured strain in the early-age stages of the concrete floor. For this analysis, the coefficient of thermal expansion of concrete is taken as 10με/°C in accordance with Eurocode 2 and it is estimated that the magnitude of thermal strain exceeds the magnitude of total strain due other strain components (shrinkage and creep) for the first 7 days after the pour of the insitu topping.

The strain which occurs in structures during the early-age thermal effects are rarely measured but actual strain data is of great importance when trying to understand the early-age behaviour of concrete elements and the potential to optimise future design and construction procedures (Bamforth, 2007).

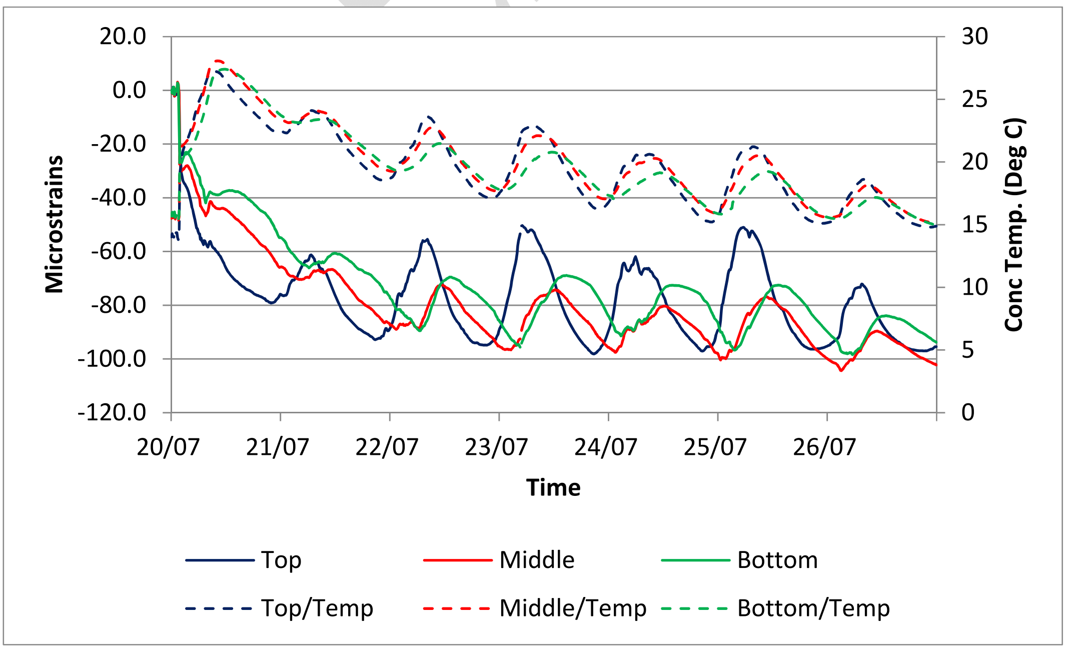

Figure 11. Strain and temperature profile in insitu topping (7 days)

Construction stage behaviour

During the construction phase, the precast planks are temporarily supported by props which are erected prior to installation of the planks. The precast planks acts as permanent formwork and contain the bottom reinforcement. As the concrete frame is constructed upwards, the floors constructed below the floor under construction must support the self-weight of the next floor. When the compressive strength of the insitu concrete had reached a specified strength, the supporting props were dropped and re-applied so that each floor was supporting its own self-weight. The embedded sensors in the slab at second floor allow the behaviour of the slab during the construction phase to be monitored and compared with analysis undertaken by the designers.

A linear elastic model finite element (FE) model was developed by the designers which models the precast floor as a 400mm thick slab with 65mm high and 130mm wide recess along all joints between precast planks. The material properties for the slab are assumed to be uniform and the same as the insitu section of the slab. During the construction stage, the measured changes in strain through the 400mm thick section can be analysed. The strain profile in the middle of the second floor slab when the second floor is poured (13th August 2015) and when the props are dropped (28th August) is shown in Figure 12. At this location, there are three VW gauges located in the insitu topping and one VW gauge in the precast plank. The measured strain profile suggests that the slab is still linear elastic and therefore can be considered 'uncracked'. As expected, the change in strain on the 28th August is a reversal of the change in strain on the 13th August as the second floor partially supports the self-weight of the third floor above and then the load is removed as the props are dropped to the third floor.

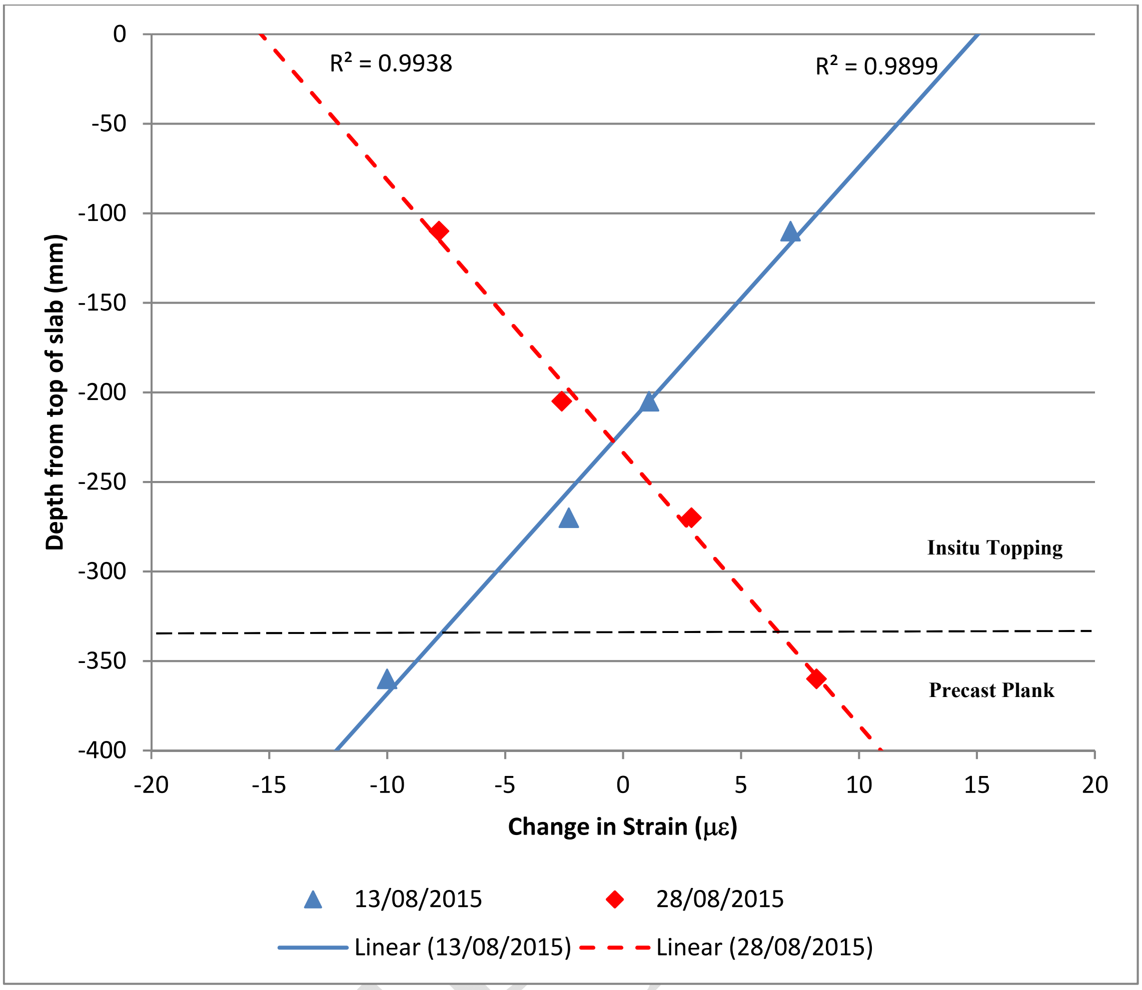

Figure 12. Strain profile through second floor

The measured changes in strain when the props to the second floor were dropped and when the props were removed can be summated and compared with the predicted behaviour when the slab supports its own self weight. The measured changes in strain along sections of the slab were converted to bending moments assuming the slab is uncracked and using the concrete properties derived from material testing conducted on the concrete used on site for the second floor. The predicted bending moment using the finite element model and the bending moment derived using the measured strain is shown in Figure 13 along a gridline (GL H) in second floor. The measured strains were converted to bending moment for the case of no creep and creep (creep coefficient determined in accordance with Eurocode 2). In both cases, it is observed that the embedded sensors measured restraint at the edge of the slab (GL 27) where a simple support was assumed in design. Because of the hogging moment at the edge of the slab, the measured sagging moment at midspan is less than the design moment from the FE analysis. This illustrates why many design codes require additional torsional reinforcement at the edge of slabs to resist bending which may occur in real structures but is not determined during analysis.

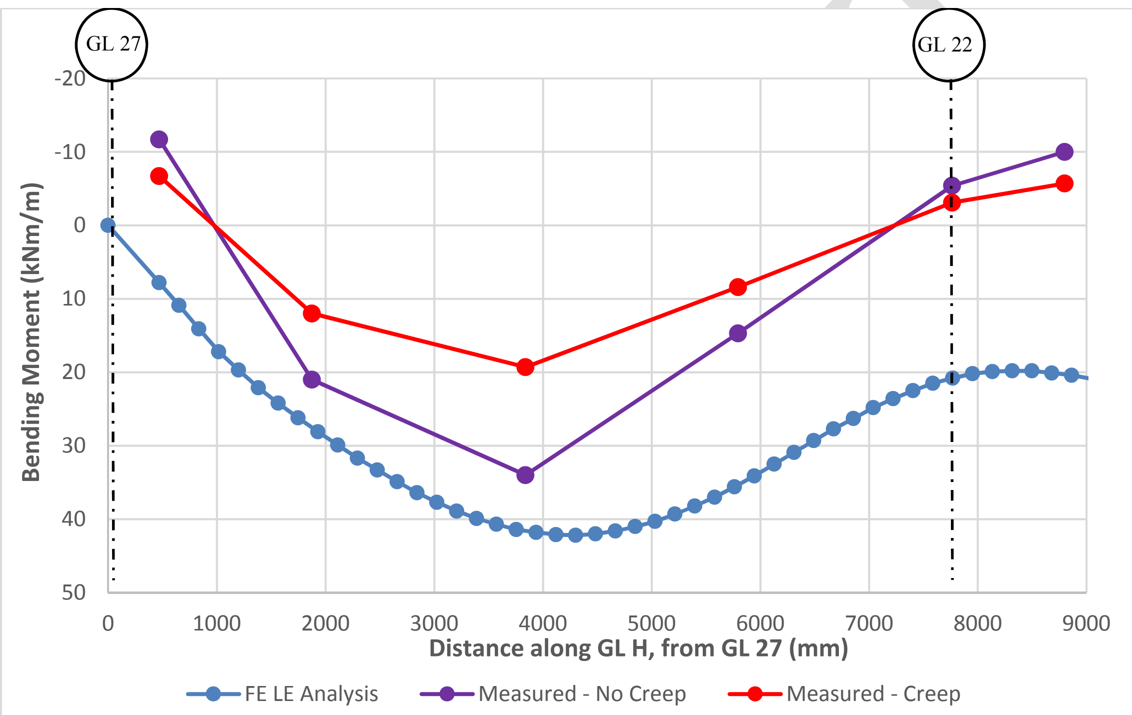

Figure 13. Bending moment in second floor along GL H

Conclusions

This paper presents the methodology and implementation of a real-time structural health monitoring strategy for a number of educational buildings at National University of Ireland Galway (NUI Galway). The sensors installed allow many important aspects of the performance of the buildings (structural, environmental and energy) to be monitored during the construction and operational phase of the building. In combination with the material testing, weather monitoring station and laboratory testing, this SHM strategy provides rich information about the buildings' performance. This real-time information is also available to students and researchers in NUI Galway to study and investigate environmental, energy and structural performance of the buildings.

Real-time monitoring offers potential benefits in relation to optimisation of structural components by understanding the actual behaviour of components in use and the possibility to develop and calibrate numerical models that predict structural performance. The information from the real-time monitoring also offers the opportunity to compare actual behaviour with predicted behaviour using codes of practice. The majority of the instrumentation is embedded within the structure so that long-term effects such as creep and shrinkage of concrete components can also be investigated.

With the rapid development in wireless and sensor technologies, the use of such technology to monitor the performance of structural elements will be an increasingly important tool for the design, construction and management of buildings in the future.

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References

ACI (1992). Prediction of creep, shrinkage and temperature effects in concrete structures, in ACI 209R-92, ed. Detroit, USA.

Bakis, C. E., Ganjehlou, A., Kachlakev, D. I., Schupack, M., Balaguru, P., Gee, D. J., . . . Gentry, T. R. (2002). Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. *Reported by ACI Committee, 440*(2002).

Bamforth, P. B. (2007) Early-age thermal crack control in concrete. CIRIA Report C660, London, UK.

Bamforth, P., Chisholm, D., Gibbs, J., & Harrison, T. (2008). Properties of concrete for use in Eurocode 2. *The Concrete Centre, UK*.

Bisby, L. A., & Briglio, M. (2004). ISIS Canada Educational Module No. 5: An Introduction to Structural Health Monitoring. *Prepared by ISIS Canada, 3*.

Buenfeld, N. R., Davies, R., Karimi, A., & Gilbertson, A. (2008). Intelligent monitoring of concrete structures: CIRIA Report C661, London, UK.

Byrne, D., & Goggins, J. (2013). *Evaluating the Structural Capacity of Concrete Elements through In Situ Instrumentation.* Key Engineering Materials, 569, 382-389. Trans Tech Publications.

CEN (2004). EN 1992-1-1, Eurocode 2: Design of concrete structures. General rules for buildings. ed. Brussels, Belgium.

Dhir, R., Paine, K., & Zheng, L. (2004). Design Data for Use where Low Heat Cements are Used. Concrete Technology Unit, Report No CTU2704, Dundee. DTI Research Contract No. 39/680, CC2257, University of Dundee, UK.

FIB (2001). Externally bonded FRP reinforcement for RC structures. *Bulletin, 14*, 165.

FitzGibbon, M. E. (1976). Large pours for reinforced concrete structures. Current Practice Sheet 2P/15/1, NO. 28. *Concrete, 10*(3).

Gilbert, R. (2001). Shrinkage, cracking and deflection-the serviceability of concrete structures. *Electronic Journal of Structural Engineering, 1*(1), 2-14.

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.

Goggins, J., & Hajdukiewicz, M. (2014). The influence of heat transfer and storage in structural precast building components on indoor environments. *Proceedings of*

Civil Engineering Research in Ireland (CERI 2014) Queens University Belfast, Northern Ireland.

Goggins, J., Newell, S., King, D., & Hajdukiewicz, M. (2014). Real-time monitoring of a hybrid precast and in situ concrete flat slab system. *Proceedings of Civil Engineering Research in Ireland (CERI 2014)* Queens University Belfast, Northern Ireland.

Guan, H., Karbhari, V. M., & Sikorsky, C. S. (2006). Web-Based Structural Health Monitoring of an FRP Composite Bridge. *Computer-Aided Civil and Infrastructure Engineering, 21*(1), 39-56.

Gulis, E., Lai, D., & Tharambala, B. (1998). Performance and Cost Effectiveness of Substructure Rehabilitation/Repair Strategies. *Draft Report*. Ministry of Transportation of Ontario, Downsview, Canada.

Hajdukiewicz, M., Byrne, D., Keane, M. M., & Goggins, J. (2015). Real-time monitoring framework to investigate the environmental and structural performance of buildings. *Building and Environment, 86*, 1-16.

IRUSE Weather (2016). Informatics research unit for sustainable engineering NUI Galway weather website. [Online] Available: http://weather.nuigalway.ie/.

Neville, A. M. (1995). *Properties of concrete*. 5th edn, Prentice Hall.