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DIGITAL BUILDINGS: USING SENSORS TO MONITOR THE PERFORMANCE OF CONCRETE BUILDINGS DURING THE CHRISTCHURCH EARTHQUAKE REBUILD

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ABSTRACT:
Following the devastation of the Canterbury earthquake sequence a unique opportunity exists to rebuild and restructure the city of Christchurch, ensuring that its infrastructure is constructed better than before and is innovative. By installing an integrated grid of modern sensor technologies into concrete structures during the rebuild of the Christchurch CBD, the aim is to develop a network of self-monitored ‘digital buildings’. A diverse range of data will be recorded, potentially including parameters such as concrete stresses, strains, thermal deformations, acoustics and the monitoring of corrosion of reinforcement bars. This procedure will allow an on-going complete assessment of the structure’s performance and service life, both before and after seismic activity. The data generated from the embedded and surface mounted sensors will be analysed to allow an innovative and real-time health monitoring solution where structural integrity is continuously known. This indication of building performance will allow the structure to alert owners, engineers and asset managers of developing problems prior to failure thresholds being reached.

A range of potential sensor technologies for monitoring the performance of existing and newly constructed concrete buildings is discussed. A description of monitoring work conducted on existing buildings during the July 2013 Cook Strait earthquake sequence is included, along with details of current work that investigates the performance of sensing technologies for detecting crack formation in concrete specimens.

The potential market for managing the real-time health of installed infrastructure is huge. Civil structures all over the world require regular visual inspections in order to determine their structural integrity. The information recorded during the Christchurch rebuild will generate crucial data sets that will be beneficial in understanding the behaviour of concrete over the complete life cycle of the structure, from construction through to operation and building repairs until the time of failure.

Key-words: Structural health monitoring, SHM, smart building, sensor system, sensing system.

INTRODUCTION
Civil infrastructure is a central component necessary for a functional society, playing an important role in providing safety and security to the community. Buildings are one element of the built environment that are continually subjected to a combination of irregular dynamic and static forces, such as seismic and gravity loads respectively. These forces influence the building’s structural integrity, and therefore its overall performance and safety. Following the destructive Mw 6.3 Christchurch earthquake in New Zealand on 22 February 2011 [1], many buildings in the central business district experienced severe structural damage, resulting in 185 fatalities, with two reinforced concrete buildings suffering complete collapse, alone resulting in 135 deaths.

Currently there are no quick and reliable diagnostic tools available to determine the in-place integrity of infrastructure and no way to validate the assumed design parameters once construction is complete. Instead, the standard practice to determine the integrity of a structure involves inspections where
highly qualified personnel must visually inspect the building, which often results in a subjective and time consuming opinion. Structural damage frequently propagates from within the structure itself, meaning that indicators of loss of integrity may be hidden from the human eye and consequently go unseen.

Following the Canterbury and the recent M\textsubscript{L} 6.5 July 2013 Cook Strait [2] earthquake sequences in New Zealand, there is high demand from building owners and occupants to be able to quickly determine whether buildings are safe to work and live in. This challenge forms the motivation behind the presented research to provide and validate an effective solution to ensure that the Christchurch rebuild is designed with resilient and innovative technologies to position the city as safe, liveable and sustainable.

**STRUCTURAL HEALTH MONITORING**

With the majority of engineering problems, the first and fundamental step towards achieving a solution is gathering accurate and reliable data. There are three key approaches that can be used for assessing the seismic performance of civil infrastructure, which involve computer analyses, laboratory tests and natural laboratory tests [3]. In the context of earthquake engineering, the last approach involves assessing the performance of actual structures during actual ground motions. A rapidly emerging process for assessing the health of infrastructure in the built environment is through the adoption of structural health monitoring (SHM) techniques. SHM is currently an area of particular interest to engineers across the world as it has been found that the safest and most durable buildings are those that are well managed and SHM offers a viable solution for the future monitoring of buildings [4]. As new sensing technologies and data acquisition systems are being developed, SHM is rapidly gaining widespread acceptance worldwide.

During seismic activity, the response of an instrumented building is recorded and analysed, allowing fundamental data sets to be generated from field tests. The analysed data can be used to improve and verify structural building codes to enable engineers in the future to design superior buildings.

The applications for sensor technology are increasing rapidly. Sensors are currently being used for applications in industries such as medicine, telecommunication and automobile. Sensors are continually being developed with advanced capabilities, such as increased computer power with faster and more reliable data transmission. With the cost and size of sensors becoming cheaper and smaller at a fast rate, it has been forecasted that sensors in the near future will be installed in dense arrays to eventually monitor the entire built environment [5]. There is currently a gap between modern sensing technologies and their application and applicability in the field for monitoring the structural performance of buildings. Research and experimental validation tests are required to assess the limitations, challenges and performance of installing new sensor technologies to monitor certain aspects of concrete structures.

Most buildings need to be inspected at regular intervals during the operational life of the structure. To reduce the costs of instrumentation and monitoring, it is cost effective to install a monitoring system during the construction phase of the building to allow continuous monitoring over the complete lifespan of the asset. In the Christchurch rebuild, the majority of buildings in the central district are to be rebuilt, and therefore the main focus is on the development and validation of monitoring systems for installation into newly constructed concrete buildings.
The level of damage sustained within a structure can be detected with various degrees of sophistication, depending on the ability of the monitoring system to detect and predict damage. The four common levels that a SHM system can be classified as are: able to detect the presence of damage (level 1); detect probable location of damage (level 2); detect probable extent of damage (level 3); and predict the safety and remaining service life (level 4) [6].

There are two different levels of monitoring that can be performed on a structure, and these are categorised at the local and global level. Monitoring at the global level is associated with understanding the behavioural performance of the whole building, whereas monitoring at the local level is associated with the behaviour of an individual element inside a building, such as a concrete beam, and the performance of the materials that constitute that specific element. The two different levels of monitoring each have unique advantages, and in order to create a fully instrumented digital building, monitoring needs to be conducted at both the local and global levels.

The proposed research plans to utilise the Christchurch rebuild as a unique opportunity to restructure the inner heart of the city using innovative and emerging technologies, and it is hoped that the research presented in this paper will assist in transforming Christchurch into a resilient city where future generations can safely live and play.

CREATING A DIGITAL BUILDING
A digital building can be treated analogous to a living organism where a continuous flow of information about the condition and environment is monitored. In order for a building to be capable of recording and communicating useful information, the building needs to have a system equivalent to that of a human body. The building needs its own nervous system, brain and voice line to allow the building to be self-monitored and to alert the outside world of developing problems prior to catastrophic failure [7]. For example, the process of assessing the health of a sick person involves an examination and diagnosis with a registered doctor who in turn recommends a cure to the patient. The process of assessing the health of a digital building needs to have a similar process to that of the human, as is shown in Figure 1.

Digital buildings in the future will essentially have sensor technologies built within and throughout the concrete materials of the building. A combination of embedded and surface mounted sensors, including wireless, fibre optic and traditional wired sensors will be installed to generate a real-time collection of information. The monitoring system will measure a diverse range of parameters by utilising a number of advanced sensors and technologies. The sensors will focus primarily on

Figure 1 – The process for assessing the health of a human (top) and the health of a building [7].
recording structural characteristics, but will also be capable of monitoring comfort levels inside and around the building. Structural parameters will cover the spectrum between performance and surveillance of the structure, including concrete stresses, strains, cracks, accelerations, thermal deformations, acoustics and the monitoring of corrosion in reinforcing bars. Functional performance factors include air flow and quality, humidity, heating and lighting levels. Through the creation of smart analytics, the final goal is to create a durable sensor system that has the ability to alert building occupants and owners of developing problems in the structure, prior to failure thresholds being reached, thus creating a self-monitored ‘digital concrete building’.

EXPERIMENTAL INVESTIGATION OF EXISTING BUILDINGS
During the July 2013 Cook Strait earthquake sequence having an epicentral region located near Wellington, New Zealand, many buildings experienced a severe level of structural damage. The Cook Strait earthquakes presented a unique opportunity to install sensors into a number of existing buildings to understand the performance and limitations of these sensors for recording large amounts of data during aftershock excitations. The first main earthquake was a $M_L 5.7$ event on 19 July 2013, and a series of earthquakes of gradually increasing magnitude followed during the next couple of days, with the largest being an $M_L 6.5$ event occurring on 21 July 2013 [2]. The epicentres of the earthquakes were located approximately 50 km from Wellington, the capital city of New Zealand.

During the period from 24 July to 28 October 2013, seven structures in Wellington were instrumented with micro-electromechanical (MEMS) based tri-axial accelerometer sensors. Due to the limited preparation time and number of available sensors, the buildings that were instrumented were selected to cover a wide spectrum of different parameters, including different construction material types, soil foundation classes, and building size and shape. There were over 500 aftershocks with a magnitude of 3.0 or greater in the month following the first significant Cook Strait earthquake, which provided sufficient ground movement at the location of the instrumented buildings to excite the sensors and enable data on building performance to be recorded. Three of the seven buildings that were instrumented were built predominately from reinforced concrete materials, and details of the experimental investigation of the three buildings are presented.

Two of the instrumented buildings, the Old Public Trust building (Figure 2a) and the Saint Mary of the Angles church (Figure 3) are classified as historic concrete masonry structures with significant importance and heritage value. The third building, the Wellington Central Exchange is a more modern
concrete structure and consists of two buildings located adjacent to each other. The number of sensors installed into the Old Public Trust building, the Wellington Central Exchange buildings and the Saint Mary of the Angels church were 33, 16 and 6, respectively.

The observed damage to each of the three buildings varied. The Old Public Trust building had the most severe level of damage, with longitudinal cracks to the underside of the flooring system (Figure 2b), with the severity of damage increasing with storey height above ground. The Saint Mary of the Angels church and the Wellington Central Exchange building showed minimal visual indications of structural damage.

The data collected from tri-axial accelerometers that were installed throughout the three buildings was used to experimentally calculate the modal characteristics and assess the dynamic performance of the buildings. The first three modes of frequency and damping values for each of the three buildings were found, which were made available to assist engineers with inspections. It was found that the sensors were extremely sensitive to small excitations, and detected seismic events with PGA values of as low as 0.004 m/s².

An example of the results that were able to be generated from the sensors in the Old Public Trust building is presented. The Old Public Trust building was heavily instrumented at the top two floors where the cracks in the floor diaphragm were critical. The data collected from the sensors at these floors was analysed to successfully show that the accelerations that were measured near the middle of the floor diaphragm were greater than the accelerations at the ends. This finding revealed that the floor diaphragm responded in a twisting behaviour. Figure 4 shows the out-of-plane acceleration

![Image of the church](image)

Figure 3 – The Saint Mary of the Angels church that was instrumented during the Cook Strait aftershock sequence.

Figure 4 – Results generated from the sensors installed in the Old Public Trust building.
profile of the damaged floor diaphragm, with the bold lines overlaid to represent the observed longitudinal cracks. The results aligned with the damage patterns observed throughout the building and therefore it was concluded that the sensors were capable of providing data enabling the dynamic performance of existing buildings during aftershock excitations to be determined.

SENSOR TECHNOLOGIES FOR NEW CONCRETE BUILDINGS
In this section the implementation of sensors into newly constructed concrete buildings is discussed. As sensors continually become smaller, cheaper, and more accurate, the installation of dense grids of sensors throughout a structure using these emerging technologies is becoming increasingly feasible and economically viable.

When monitoring the performance of non-homogeneous materials, such as concrete, the sensing system needs to record data at small increments to allow for variations in the material properties including discontinuities and local defects. Embedded long-gauge sensors are capable of recording more accurate data as compared to short-gauge sensors in non-homogeneous materials [7]. Long gauge sensors measure average strain over a predefined length taking all crack formations into account, whereas short-gauge sensors measure strain over a smaller section. The measurements from short-gauge sensors can vary depending on their location relative to the position of crack formations. For example, in Figure 5 the two short-gauge sensors, \( g_{lb} \) and \( g_{rb} \) record strain measurements at locations next to each other, but the strain recorded in sensor \( g_{rb} \) is significantly greater due to the formation of the crack along the monitoring plane 2-2.

Numerous researchers have stated that the behaviour of crack propagations in concrete structures are of critical importance [8], as cracks can lead to sudden failure and have devastating consequences. After an earthquake, the presence of surface cracks on concrete elements in a building gives a visual indication of the level of damage sustained to that building. The magnitude, orientation and location of cracks act as an effective tool for estimating how buildings performed during an event and aid engineers during safety inspections to determine whether the building is safe to re-occupy. During the Canterbury earthquake sequence, many structures did not perform to their predicted behaviour and severe cracks were observed in many buildings within the city CBD.

There are a number of different sensing technologies currently available that are potentially suitable for monitoring the performance of concrete structures. A brief overview of the types of modern sensor technologies and their potential applicability for the SHM of concrete infrastructure is presented below, with particular emphasis given to crack detection. These sensor technologies include fibre optic sensors, wireless sensors, piezoelectric sensors and image filtering sensor techniques.

![Figure 3 - Comparison of short and long-gauge sensors installed in a concrete element [7].](image-url)
Fibre optic sensors were first installed into concrete structures in early 1988 and have many potential monitoring applications in the field of engineering [9]. Fibre Optic sensors can be used to sense at discrete locations or over the entire length of the installed fibre. The three main fibre optic sensing technologies can be classified as point sensors, long-gauge sensors and distributed sensors, and each type requires different techniques for collecting and analysing the data, as shown in Figure 6. Fibre optic sensors detect changes in the built environment through small alterations of the fibres’ refractive indices as light travels through. Fibre optic sensors are traditionally capable of measuring stresses, displacements and temperatures.

Discrete point sensors are used for detecting strains and temperatures across a small localised area of material and are ideally suited for monitoring homogeneous materials. Long-gauge sensors are better suited for monitoring strains and temperatures at a larger scale, and are suitable for heterogeneous materials such as concrete. For distributed fibre optic sensors, the fibre itself is the sensor and is sensitive at all points along the fibre length. Distributed sensors are good for monitoring the integrity of structures at the global level, especially long infrastructure such as pipelines. The key advantage with distributed sensors is that they effectively replace hundreds of individual point or long-gauge sensors. The two techniques used for monitoring distributed sensors are Raman and Brillouin scattering, as shown in Figure 6. Raman scattering is limited to detecting changes in temperatures, whereas Brillouin scattering is capable of measuring changes in both temperatures and strains [10]. The main disadvantage with using distributed fibre optic sensors for monitoring the performance of concrete is that the techniques and equipment needed is very advanced and requires specialist knowledge from an expert in the field.

Fibre optic sensors have the advantage of being small in size, require no electrical power, can withstand high temperatures and are immune to electromagnetic interferences. The disadvantages with fibre optic sensors include the high costs associated with the interrogation equipment and splicing between fibres.

Arrays of optical fibres have been embedded in concrete specimens to detect the presence and development of cracks within concrete, as shown in the image in Figure 6. Embedded fibres can contain displacement sensors at selected locations along the length of fibre to record data, as the transmission properties differ along the length of the fibre. Once a crack forms and widens, the fibres spanning the crack are subjected to concentrated strains which can result in fibre rupture as the crack width increases. It is recommended that embedded fibres are wrapped with plastic tubing for protection during concrete pouring but it has been shown that the protective coating decreases the

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**Figure 4** - The three types of fibre optic sensing technologies and the corresponding techniques that are commonly used (left) and an example of fibres embedded in a concrete beam (right).

<table>
<thead>
<tr>
<th>Fibre Optic Sensors</th>
<th>Point Sensors</th>
<th>Fabry-Perot Interferometers</th>
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<td></td>
<td>Long-gauge Sensors</td>
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<td>Distributed Sensors</td>
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**Table:** Summary of fibre optic sensing technologies and corresponding techniques.
sensitivity of the fibre for detecting cracks [11]. One main factor when choosing fibre optic sensors is the diameter of the fibre core, as large core sizes are more resistant to damage during concrete pouring but are less sensitive for detecting hairline cracks [11].

Fibre optic acoustic sensors have been proven to be useful for detecting structural damage in concrete structures, and can be multiplexed with fibre optic displacement sensors to enhance the efficiency of the monitoring system [12]. Acoustic based sensors measure emissions that are released in concrete as the level of stress increases. The emissions provide an indication of the location and severity of structural damage to the structure (level 2 damage detection, as discussed on page 3).

**Wireless Sensors**

The transfer of information via a wireless network can be traced back to invention of the radio around 1895 [13]. Initial interest in the development of wireless networks was mainly in response to eliminating the need of tethered wires, and therefore reducing the installation costs and increasing the potential for large arrays of sensors installed throughout a building. Lynch (2006) explains that wireless sensors are not standalone sensors, but can be an autonomous data acquisition platform that allows traditional sensors to be connected [14]. One of the main advantages of wireless sensor networks is the makeup of computational resources which offer great potential for individual wireless sensors to carry out on board data processing prior to communication with the central data repository unit.

Past literature has investigated the performance of embedded wireless sensors in concrete elements to monitor the initial curing phase and subsequent integrity and strength of the specimen during service life [15]. Testing has also been conducted to detect concrete surface cracks using conductive surface sensors and radio frequency identification technology (RFIT) [16]. The electrical resistance of conductive surface sensors increases as cracks form on the concrete surface, and by incorporating RFIT the signals can be wirelessly transmitted to a central hub for storage and analysis [16].

**Piezoelectric Smart Sensors**

Recent investigations for detecting cracks in concrete specimens include using piezoelectric patches, also referred to as ‘smart aggregates’, which are small cylindrical shaped sensors that can be embedded into concrete. Smart aggregates have been experimentally tested in reinforced concrete beams and columns, and the sensors showed good potential and capability for detecting passive defects, such as holes and inclusions, as well as actual crack formations [17-19].

**Image Filtering**

The use of image filtering techniques for detecting and monitoring surface cracks is currently an area that is attracting interest in the field of SHM due to rapid advancements in camera capabilities and automated detection algorithms. Image filtering techniques detect cracks in concrete through generic programming software and filters that enhance the presence and size of cracks based on the pixel differentials of the recorded 2D images [20, 21]. Advanced methods are being developed that include the measurement of crack widths by deriving the spatial changes in brightness patterns [22].

**INNOVATIVE CRACK DETECTION METHODOLOGY**

The aim of the methodology described in this section is to experimentally test a range of different sensing technologies to determine the performance and limitations of the sensors for detecting crack formations in concrete elements. The data collected from the experimental crack detection tests will
contribute towards the main goal of creating a digital building incorporating an innovative system for comprehensively validating the performance of concrete structures in the built environment.

The ability to monitor and measure crack formations in concrete specimens is of particular interest to engineers and building occupants. The data generated can be analysed to provide crucial indications regarding the integrity of the monitored element and also a global indication of the damage to the entire building. During inspections, cracks are typically observed only on the surface of concrete specimens, as inner cracks are often difficult to examine and measure. It is common for cracks to initiate at the interface where reinforcing steel and concrete bond together, and as the loading increases or creep occurs the inner cracks propagate to the outer surface where they become visible. Therefore, embedded sensors that are capable of monitoring internal cracks are of great importance.

**Experimental Test Description**

An experimental test for monitoring cracks in concrete specimens subjected to tensile and bending loads is currently in progress at the University of Auckland. The test aims to compare and validate the performance of currently available sensing technologies for detecting crack formations that occur on the surface and inside concrete specimen. The proposed level of detection system for monitoring surface cracks is aimed to detect the presence, location and size of cracks (level 3 detection, refer to page 3 for the damage detection levels), while the sensors used to monitor inner cracks is aimed to detect the presence and location (level 2).

**CONCLUSIONS**

Buildings that are well managed are the safest and most durable structures. The ability to measure flows of information throughout a building is fundamental to creating digital buildings of the future that utilise innovative and next-generation monitoring systems. SHM is currently an area of particular interest as it offers a potential solution for the future monitoring of buildings. With the cost, size and capability of sensors becoming cheaper, smaller and more advanced it is becoming increasingly feasible and economically viable to have sensors installed ubiquitously.

There is currently a gap between modern sensing technologies that are being developed and their application and applicability to monitor the structural performance of buildings. The ability to detect the presence of cracks in concrete structures has an important role in the damage assessment of buildings. Further research and experimental validation tests are required to assess the limitations and practicality of installing the latest sensor technologies to monitor the performance of concrete structures.

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