The Role of Advanced Smart Sensors within Structural Health Monitoring: An Analysis of Case Studies from the United States

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Abstract

Urban settlements are under immense pressure to use the limited resources they have most effectively to manage advanced urbanisation. With the rising threat of potentially devastating natural disasters, such as earthquakes, city management is under enormous pressure to create urban development's which are robust, sustainable and adaptable to the consistently changing environment.

One such technology for future development is that of smart sensors. Smart sensors offer opportunities to deliver real-time, wireless, structural health monitoring (SHM) systems. Through the development of data management techniques, the information generated between the smart sensor networks can provide vital information for cities to monitor and control the structural integrity of urban infrastructure.

This research aimed to explore the role in which advanced smart sensor technologies play in monitoring structural health of critical infrastructure within the United States (U.S), with a focus within high-seismic areas, to aid in the understanding of the effectiveness of this emerging technology.

The methodology for this research called upon several approaches, including the review of smart sensor technologies based on a comprehensive qualitative case study analysis, together with literature review, and industry expert interviews. Case study reviews enabled the research to further elucidate the technical and practical implementation of SHM sensors within architectural technology to establish a vital role which smart sensors play within a practical SHM application.

The research concluded that there are a variety of commercially available sensor prototypes which could provide effective alternative solutions to traditional reactive visual inspections with real time, continuous structural monitoring. The integration of this technology within architecture holds the potential to transform relationships between building design and facilities management by extending the life of assets as well as improving the sustainability and resource challenges of cities.

The implementation of smart sensor technologies in urban architecture within high-seismic areas would ensure the right technology and communication systems are in place to warrant long-term planning and serviceability of structurally sound infrastructure. Nevertheless, the research recognised that realising the potential benefits will require further industry developments in innovative technologies and multi-disciplinary collaboration with regards to data collection and analysis. The research has identified an important line for research integrating architectural technology, smart technology, FM and data analytics. With this collaboration, continuous, real-time wireless SHM monitoring within high-seismic areas would ensure structural damage can be detected before reaching a critical state, producing robust and resilient architecture for extended lifecycle operation.

Keywords: Smart Sensors, Critical Review, Structural Health Monitoring, Internet of Things (IoT), Communication Technologies

1. Introduction

The potential exists in the world's cities for creating high quality and future proof infrastructure, dependent on urban development's being efficiently managed. Modern city infrastructure must be robust, resilient and adaptable to the consistently changing environment and omnipresent threats of catastrophic events presented by climate change. A total of 1808 earthquakes were recorded across the world in 2018 alone (USGS 2019) and with an estimated three-quarters of all deaths from earthquakes due to building collapse (Cross 2015), scientists warn a large increase in earthquakes in the coming years could cause tremendous tragedy. Figure 1 illustrates the rising occurrence of earthquakes over a magnitude of >3M in the United States of America (U.S); highlighting a significant increase of these natural disasters in previous years. Thus, it is critical that the right technology and skills are in place to ensure long-term planning for structurally sound and resilient urban infrastructure.

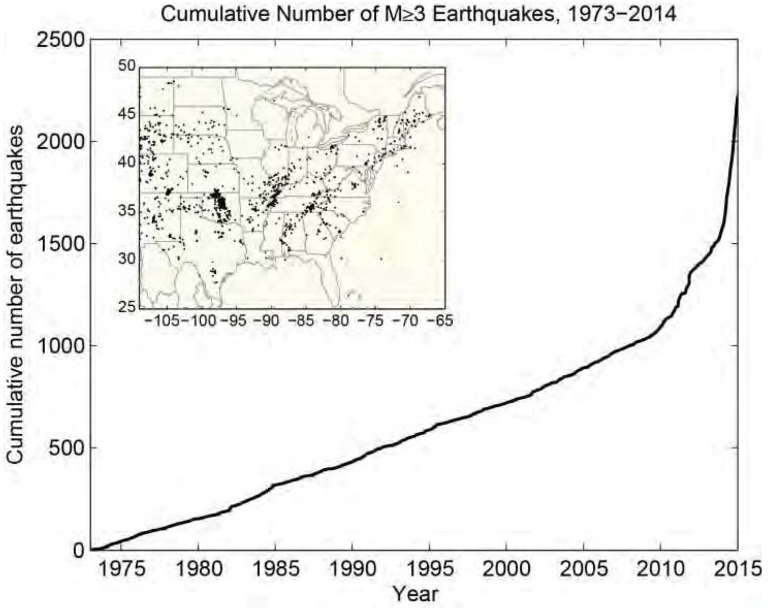

Figure 1: Cumulative number of earthquakes over magnitude of 3.0 in U.S (Jacobs 2015)

Additionally, with a rapid growth of urban populations it is predicated one out of every two now prefers to live within an urban environment, see figure 2 (Grover and Walia n.d), with an estimated 6 billion people living in urban areas by 2050 (Hancke, Silva and Hancke 2012). With this rapid pace of urbanisation, the necessity of high rise and multi-storey buildings has increased due to pressures to meet the needs of the growing urban population, producing some of the most dangerous constructions across the world. One precedent can be demonstrated in China, when in 2008 an earthquake destroyed over 7000 school buildings which were constructed under inadequate building regulations in order to complete the project as quickly as possible to meet the increasing urban migration within the country

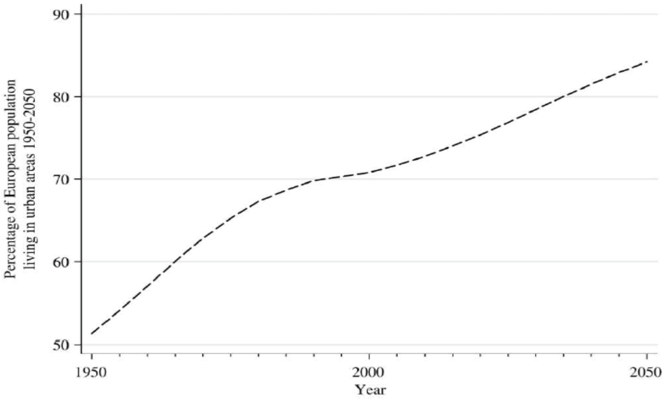

Figure 2: Rising populations in urban areas (Caraguli, Bo and Nijkamp 2011, fig 1, pp 65)

(Cross 2015). Thus, these poorly engineered structures resulted in major loss of life and resources.

This increasing migration puts a huge strain on the world's resources within urban areas, and with 3m sqf of office space currently under construction in downtown Los Angeles alone (Slowey 2019); it is vital to make cities greener and more sustainable. Buildings and cities can play a far more significant role in mitigating the use of resources than we might assume. To address these challenges, the vision for future urban developments is the design of 'Smart Cities'. Smart Cities use intelligent digital technology to promote performance as well as monitoring and controlling of its infrastructure to respond to global challenges (RICS 2017). One aspect within these cities would be the development of smart buildings. These would not only have the potential to drastically improve sustainability, but also to minimise the risk of structural deterioration within high-rise city buildings.

Smart sensing can be placed at the heart of smart buildings (Hancke et al 2013); with possible improvements enabled by sensing technologies being immense. Smart sensors have the potential to continuously monitor a structures technical condition through structural health monitoring (SHM) systems. SHM can fundamentally change the way critical urban infrastructure is maintained resulting in extension of lifecycle and more efficient use of resources (Klikowicz, Salamak and Poprawa 2016). Having the ability to monitor the integrity of structures in real-time can provide an awareness of possible structural damage, thus improving the safety of the public as well as improving reliability of the infrastructure during natural disasters such as earthquakes. It is hoped the result of this research will be valuable to the industry in providing a deeper understanding of the role and impact advanced smart sensors can have within the monitoring and reduction of deteriorating infrastructure in urban developments.

1.1 Aims and Objectives

The aim of this research was to develop an understanding of the role in which advanced smart sensor technologies play in providing structural health monitoring of high-rise buildings within high seismic areas. The key objectives were as follows:

- To develop an understanding of various advanced smart sensor technologies and their role in monitoring deteriorating infrastructure.
- To review current industry practical application of advanced sensor technology in improving structural integrity within urban infrastructure developments.
- To gain a deeper understanding of smart sensor data management and communication network operations.
- To outline constraints that might be faced within the practical application of advanced smart sensor technologies.

2. Material and Method

Within this study, three case studies were considered regarding various advanced smart sensor networks and applications within civil infrastructure in cities. Firstly, application of SHM sensors along the Alamosa Canyon Bridge were studied in order to evaluate the application of both wired and wireless accelerometer sensors. Further to this, a field validation test conducted on the Oakland Bay Bridge project within the U.S was considered. This established an in-depth level of knowledge regarding alternative smart sensor technology available. Finally, research was conducted on the application of advanced smart sensors within the high-rise Di Wang Tower. Analysis of this case study allowed for an efficient comparison between advanced smart sensor application in bridge structures and high-rise buildings.

The qualitative method within this research involved unstructured interviews with the aim of gaining a deeper understanding into the phenomenological approach to smart sensor technology to gain a deeper understanding of the practical application of advanced smart sensor technologies. In order to develop this strategy a range of professionals from a variety of industries were interviewed to critically discuss the themes which had been identified with regards to the previously analysed literature. These themes included: Sensor Parameters, Communication Networks, Data Management and Power Constraints. Industry experts included a business development manager for CENSIS, an industry-led innovation center for sensor and imaging technology; a senior computing lecturer with detailed knowledge within the IoT; a senior control room operator and a condition monitoring engineer within the oil and gas industry and lastly an experienced party wall surveyor with experience utilising smart sensors for vibration monitoring. Interviewees were asked a series of unstructured questions to allow open-ended comments, as illustrated in table 1 below.

Table 1: Unstructured Interview Question Guide

Number	*Question Guide*
1	What projects are you currently involved in which utilise smart sensor technologies?
2	What performance measurements were monitored? (eg. material strain, vibrations, traffic management, temperature?)
3	What type of sensors were used? (eg. accelerometers, piezoelectric, fibre optics?)
4	How were the sensors installed? (eg. Wired or wireless?)
5	Was specific training required to install the sensors?
6	How do the sensors communicate with each other? (eg. wifi, Bluetooth, open source?)
7	How do you secure and store the sensor data information? (eg. password protection? Cloud storage?)
8	Is there specialised training required to manage the data within a network management system?
9	Is there an alarm feature enabled for measured data reaching a certain threshold limit?
10	How are the sensors powered? (eg. Solar, Ethernet, battery?)
11	What were any constraints within the implementation of these sensors?

The results from the industry interviews, case study review and literature analysis established a vital role in which advanced smart sensor technology can play in SHM applications. A comparison of the full technical data of each sensor type analysed can be seen in table 2 below.

Table 2: Technical Data of Smart Sensor Technologies

	Crossbow CXL01LF1 MEMS Accelerometer	*Sensor Highway II F30a AcousticEmission (AE)*	*ADXL202 Acelerometer*
Parameter	2 axis acceleration and vibration sensor	Vibrations, cracks, fatigue	2 axis dynamic and static vibrations
Processing Platform	WiMMS	WiFi/Cellular	MICA Mote (Tiny OS)
Network (WPAN)	Proxim RangeLan2 (IEEE 802.11b)	WiFi (IEEE 802.11)	Linksys WAP11 (IEEE 802.1b)
Data Range	200kbps (137 – 304m)	Unavailable	11000kbps. (91 – 152m)
Installation	Retrofit	Retrofit Outdoors	Retrofit
Power Source	9V Battery	Phantom Power, Selectable 5V, 28V	3V to 5.25V Battery
Size	4’’ x 4’’ x 1.5’’	0.75’’x 0.85’’	0.4’’ x 0.4’’ x 0.2’’

2.1 Alamosa Canyon Bridge

The Alamosa Canyon Bridge was constructed in 1937 and is located in New Mexico (Farrar et al 2000) and demonstrates an excellent example in the utilisation of both wired and wireless sensor networks. Research conducted by Lynch et al (2003) measured ambient vibrations within the bridge which originated from continuous heavy traffic. To measure the dynamic response of the bridge to vibrations, two different accelerometers were installed upon the span's girder web: one wired and one wireless. The deployment of two different sensors types allowed information to be obtained for the comparison of tethered sensor technology to the more recent, less commercialised, wireless technology. In this field validation study, accelerometers were the primary sensor types implemented in order to measure the structural response of vibrations due to traffic loads.

The cable-based system employed was the Piezotronics PCB336C accelerometer. This sensor was chosen for the field validation test due to the high sensitivity and broad amplitude range it adopts. The installation of these sensors provided challenges in regard to the care and maintenance of the wires across the girders. Mounted adjacent to the cable based system was the Crossbow CXL01LF1 MEMS wireless accelerometers (Lynch et al 2003). Similar to the wired sensor system, the CXL01LF1 is a high sensitivity MEMS accelerometer with high-stability characteristics with a WiMMS processing platform and power supplied from 9V batteries.

To assess the effectiveness of both sensor networks deployed along the bridge, a sizable vibration test was conducted which employed an impact blow from a modal hammer as well as ambient vibration test produced by a large truck driving over the bridge.

2.2 San Francisco Oakland Bay Bridge

The San Francisco Oakland Bay Bridge (SFOBB) is one of the largest SHM research projects conducted by Mistras Group to date. When construction was completed in 1936, the bridge was named the longest spanning bridge in the world. Due to the location within such close proximity to two major fault lines within the U.S, the SFOBB was at risk of future catastrophic structural failures due to the seismic activity within the area, therefore providing an excellent test area for SHM applications.

Due to the busy traffic flow and limited maintenance access across the bridge, a system was required that could continuously monitor the structural integrity of the bridge, in real time, in order to prevent future collapse and structural deterioration over time. SHM through the use of smart sensor technology can represent an advantage over periodic visual inspections due to the improvements within public safety as well as real time monitoring; determining structural failures from miniscule cracks.

640 advanced smart acoustic emission (AE) sensors were deployed across 384 structural eye bars within the superstructure, mounted to the surface with a cyanoacrylate adhesive to provide an acoustic coupling between the sensor and the structure (Johnson et al 2012). AE techniques draw great attention to the analysis of fatigue and deformation within a material due to the immediate indication of materials under stress and damage. The role of advanced smart sensors presents the ability to detect significant cracks from initiation, with AE sensors detecting small bursts of energy emitted during crack initiation and growth. The sensors can be mounted within the structure in order to continually collect data within real time; ensuring any microscopic cracks in inaccessible areas are detected from as small as 0.1in.

2.3 Di Wang Tower

Within recent years there has been a clear necessity for an effective and economical method for managing the health of tall buildings throughout their lifespan as failure of such a structure would result in immediate fatal loss of life and economic loss. Even with the recent upsurge of attention for SHM systems, the use of wired sensor technologies has seldom been used for the SHM of tall buildings. Therefore, vibration measurements resulting from strong typhoon threats were carried out within the Di Wang Tower, by Ou et al (2005), using wireless smart sensors technologies.

The Di Wang Tower implemented an advanced smart sensor network which composed of various wireless sensor nodes, utilising ADXL202 accelerometers (Lynch and Loh 2006). The deployed wireless accelerometers are capable of measuring the dynamic response of the building to vibrations caused by environmental loads; this data is then transmitted to the base station. Utilisation of such state-of-the-art smart sensor accelerometer technology, applying the MICA Mote processing platform, provides the ability to measure the structural integrity of the Di Wang Tower in real-time, at low-cost and low power consumption.

3. Results

Vibration tests conducted within the Alamosa Canyon Bridge case study with the Crossbow CXL01LF1 MEMS accelerometer drew out several important results which demonstrate the benefits of wireless smart sensors for structural health monitoring. These include the minimal installation time of wireless sensor nodes to the structural steel girders by magnetic mounts over the cable-based technology; with the network being installed in approximately half the time (Lynch et al 2003). Furthermore, the Crossbow CXL01LF1 MEMS wireless accelerometer prototype was capable of collecting sensor data at almost exactly the same accuracy as that of the cable-based system. Demonstrating accurate data recording from wireless technologies.

Use of the Proxim RangeLan2 network transceiver within the Crossbow CXL01LF1 sensor allows for an energy efficient wireless sensor network while providing a large communication range up to 450 feet (137m) within heavy construction material. This communication data range would allow for significant distance between distributions of sensor nodes within a building, therefore reducing the quantity of sensors required, and subsequently sensor network costs.

However, the WiMMS processing platform installed within the Crossbow CXL01LF1 accelerometer delivers a limited size of memory capacity thus, reducing the amount of data that can be stored and transmitted from the sensor. If continuous earthquake tremors resulted in significant amounts of data, the opinion of the CXL01LF1 MEMS accelerometer would be that it is incapable of measuring continued vibration data. Concluding that the use of the WiMMS processing platform is unsuitable for the installation within high-rise structures.

The five Crossbow CXL01LF1 accelerometers mounted evenly across the Alamosa Canyon Bridge field test established limitations presented through the necessity of a 9V lithium battery pack to supply power for the sensor node. Due to the limited fifteen hours of continuous monitoring it delivers, the application of these sensors within inaccessible structural elements in a high-rise structure would make it difficult to charge or replace these batteries throughout the life-cycle of the building. Demonstrating that further research is required to advance this system.

Unattended and remote condition monitoring within the SFOBB project has established further smart sensor technologies which could provide unattended structural monitoring through the use of AE technology. The AE sensors demonstrated a resilient and robust installation system for harsh, outdoor environments and were installed using a cyanoacrylate adhesive which allowed for ease of installation. Another major advantage of employing this sensor technology is presented by the ability of the main board to perform data collection from the various AE nodes, which would allow for numerous sensors to be deployed across a high-rise building. These nodes have the capability to detect mechanical deformation within a structural component when a material undergoes stress, this stress then creates transient elastic waves. These waves are converted into electrical signals for full signal processing, crack location detection and alarm signalling; therefore, minimising the need for continuous visual inspections by creating an alarm monitoring and notification solution to SHM.

Nevertheless, AE sensors need to be tailored to fit independent structures due to the differentiating signals produced from a variety of materials, creating higher development costs for commercial application. However, the adoption of an alarm signal systems would ensure any measured vibrations or miniscule cracks which appeared within a material would be highlighted immediately, reducing resource costs to repair or maintain the structural element.

Results from the Di Wang Tower case study and the use of the ADXL202 accelerometer confirm that the sensor technology utilised within a high-rise building is similar to that of any structural infrastructure. It is a low cost, low power sensor in which both dynamic and static acceleration can be measured across 2 axes. The Linksys WAP11 wireless operating system provides an excellent prototype of a high-speed data range up to 11000kbps; one of the largest data transfer speeds established within this research, across a range of 300 - 500 feet (91m – 152m). Additionally, the MICA Mote processing platform employed is the most commercialised platform out of the smart sensors analysed within this research due to its open source wireless platform thus, higher data memory for continuous real-time monitoring.

4. Discussion

Detailed discussion on the findings collated within this research provide an understanding of the role in which advanced smart sensor technologies play in the monitoring of structural integrity of high-rise buildings within high seismic areas. There are copious amounts of research within academic literature which emphasise the importance of developing smart city initiatives in order to create sustainable future proof urban infrastructure. It can be expected that findings presented through a quantitative case study analysis will corroborate the opinion that smart wireless technology has the potential to play a vital role within the monitoring of structural integrity in high-seismic areas.

The Alamosa Canyon Bridge case study demonstrated the operative monitoring and processing capability of a wireless sensor in comparison to a wired system, with one of the main constraints of sensor implemented highlighted through interview analysis being that the associated costs of implementing wired SHM systems within high-rise buildings would be infeasible. Concluding that wireless sensor technology is a more feasible and adventitious option as demonstrated by the highly reliable and precise data they generate: at a drastically reduced cost.

One important objective to consider in the practical implementation of sensor technologies within high-rise buildings would be the quantity of sensor nodes required. Alamosa Canyon Bridge case study analysis demonstrated that the lack of traditional coaxial wires can allow the sensors to be positioned anywhere across a regular structural element. Providing an effectual understanding of various smart sensor technology communication networks.

Analysis of the SFOBB project outlined various practical constraints with implementation of smart AE sensors. Research illustrated that there are a limited number of AE sensor nodes which can be connected to a single main board interface. If this system was to be installed within a high-rise structure, there would be the requirement of various main board systems, demanding additional space for installation. Furthermore, the adoption of a cyanoacrylate adhesive eliminates any air between the substrate and the sensor, providing an effective coupling method. Yet if deployed outdoors, this coupling may become weathered, therefore fails to ensure an effective connection technique.

Review of the wireless sensor nodes deployed to enable continuous sensing, communication and damage detection within the Di Wang Tower established a deeper understanding of smart sensors for improved structural integrity monitoring. In the context of high-rise buildings, many structural responses to loading and strain will be regularly monitored in real-time within high seismic areas. The commercialised platform with 'off-the-shelf components' which was utilised would ensure the cost of the sensor nodes would be as low as possible. If 'off-the-shelf' parts are utilized, field deployment costs can be kept to a minimum and therefore have the potential to drastically reduce the main operational cost constraints.

One key objective to achieve in the development of the research aim is the comprehension of smart sensor data management techniques and communication network operations. With the significant increase of smart sensor technologies and devices connected to the IoT for big data analytics, management of sensor data is becoming an increasingly important consideration. Plageras et al (2017) state the IoT is the key for the control and the surveillance of 'Intelligent Buildings'. Technological advancements have allowed for advanced smart sensors to filter data which focus on high impact and vibration measurements, allowing for simpler interpretation of data and monitoring of asset health across a wireless network. The real time monitoring and data management achieved through automatic scheduled readings of sensor data can present a highly efficient strategy for data management techniques within a high-rise building to improve safety and reliability of infrastructure by detecting damage before it reached a critical state.

A significant finding discovered within this research was the benefits in which the implementation of an alarm signal system would provide within a high-rise SHM communication network. Information gathered from the smart AE sensors implemented on the SFOBB project demonstrated the effectiveness of an alarm signal in securing the asset health of structural elements if a threshold vibration limit was measured. Application of an alarm signal system would ensure evacuation procedures would transpire when a high level of vibration or structural damage was recorded within the high-rise structure, ensuring safe evacuation of occupants before a fatal collapse.

A key characteristic in the understanding of smart sensor data management would be to increase the perception of data and network security. A vital characteristic highlighted within industry research, in which interviewees further corroborated, was that security was an important aspect to consider. Suggesting that LoWPAN and ZigBee would be the most appropriate and secure communication networks while also allowing for further password protection if required. One interviewee discussed the advantages offered through cloud storage, concluding that for secure and reliable data management systems, verification procedures which allow only certain authorised devices to join the wireless network and storage systems would be highly manageable.

Communication network operations are critical to recognise in the development of smart sensor technologies for SHM within high-rise buildings. All three smart sensor technologies within the analysed case studies employed some spectrum of RF wireless technology, such as Bluetooth or ZigBee networks. Al-Sarawi et al (2017) states that two of the most commonly used wireless communication network systems are that of LoWPAN and ZigBee, implying that long range RF wireless communication technology is the most pertinent for advanced smart sensor applications in high-seismic areas.

The objective in outlining constraints in the practical application of advanced smart sensor technologies was achieved though analysis of the key connections recognised within field validation tests. This was the constraints of battery power and high installation costs. Kintner-Meyer (2005) state that in building automation applications, power consumption is of critical importance. Obtaining a single power source for embedded sensors that do not require batteries is still a major limitation to the application of advanced smart sensor technology.

Each case study anaslysed relied on some form of battery power for operation. Kintner-Meyer (2005) claim that for building maintenance, a smart sensor must have a minimum of three to five-year battery life in order to be efficient. Analysis of the case study research concluded that the battery power utilised within each project would fail to meet this standard. There are strategies in which power consumption can be reduced, for example lowering frequency ranges which are monitored as well as the regularity in which the sensor performs an assessment of structural integrity. This process may allow the battery life of the sensor to be extended, however it is still highly unlikely that batteries alone can provide power for the entire lifecycle of the building. Discussions from industry professionals further supported this outcome, with interviewees explaining the constraints presented with battery power alone for advanced smart sensors due to the requirement of continuous rotation of batteries or wired power sources.

One interviewee discussed the advantages in the implementation of a solar power aspect within smart sensors. Although a successful protype was produced, it can be argued that sunlight is not always available for application within inaccessible areas; concluding solar power would be infeasible within structural elements. Therefore, conclusions were drawn that battery power remains a vital constraint and an infeasible option for wireless sensors in the construction of high-rise buildings.

The implications of the evolution of smart sensor technology and intelligent buildings requires the practice of Architectural Technology to rethink their traditional involvement in building management. With the most significant transition within the industry due to buildings becoming data-rich environments from omnipresent sensors of activity. With this rise in IoT, big data analytics and cloud capabilities, no single organisation can harvest the full potential of a fully smart environment; therefore, the architecture profession would require innovative industry collaborations for efficient management systems, such as Siemens' partnership with Capgemini. Furthermore, with an ambiguous understanding of regulations and smart sensor protocols; the future intelligent building concept is in it's infancy.

The limited understanding of the role in which smart sensor technologies currently play within industry practice of SHM in high-rise buildings ensures the outcomes of this research are significant due to the increased awareness that cataclysmic events, such as earthquakes, pose a critical threat to the structural integrity of urban infrastructure in cities of the future. The comprehensive understanding gained within academic and professional industry research provided practical insight into both benefits and limitations across a variety of advanced smart sensors and their role in monitoring deteriorating infrastructure. The key constraints of costs and battery power are the main limitations in smart sensor technologies for SHM applications in high-rise buildings. The research recognised that although there may be significant initial upfront capital required for practical installation of wireless sensor technologies, the perceived benefits for lifecycle maintenance outweigh the cost restrictions. Utilisation of sensing technologies provide insight into a buildings response to vibrations, stresses and strains with real-time, continuous monitoring. This therefore improves operational efficiencies, extending the life of assets, reducing the risk of catastrophic failures as well as improving sustainability for Smart Cities of the future.

5. Conclusions

The vision of future urban developments is continuously evolving in order to efficiently manage the rapid increase in urbanisation expected within the coming years. Structural health monitoring is one of the most important components in the maintenance technology for civil infrastructures. With the additional rising occurrence of earthquake tremors threating the structural integrity of critical urban infrastructure within the U.S; innovative technological advancements may present the ability to ensure long-term planning for safe and reliable urban infrastructure. Reoccurring earthquakes with low magnitudes will still cause major structural damage over the life span of a high-rise building, and with an estimated three-quarters of all deaths in earthquakes due to building collapse (Cross 2015), regularly occurring earthquake tremors present an immense threat.

These pressures create an urgency for cities across the globe to find smarter approaches to solving issues regarding the safety of its critical urban developments. The analysis conducted of previous academic literature provided a comprehensive understanding of the characteristics of future smart city initiatives that aim to alleviate the threats that climate change and rapid urbanisation present. Academic literature states that education is one vital part of the future of Smart Cities along with the development of intelligent digital technology to promote performance within buildings; hence the ability to monitor and control critical infrastructure to respond to global challenges.

The role which advanced smart sensor SHM technologies play within high-seismic areas was established through both case study and industry research, developing the understanding that the goal of SHM is to improve safety and reliability of infrastructure by detecting damage before it reaches a critical state. Therefore, an awareness was obtained that a smart structure utilises sensing technologies to provide insight into its response to vibrations, stresses and strains with real-time, continuous monitoring. To ensure modern city infrastructure is robust, resilient and adaptable to the consistently changing environment, this research presents a variety of advanced smart sensor technologies which can offer an effective SHM system over the expected lifespan of infrastructure. This is made possible due to the physical and digital worlds converging; bringing greater efficiency and new opportunities.

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