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Effective telematics application of wireless and fiber bragg grating sensors for structural health monitoring of tall buildings

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ABSTRACT

In recent years, there has been an increasing interest in the adoption of emerging sensing technologies for instrumentation within a variety of structural systems in civil and building engineering. Wireless and fiber bragg grating sensors are emerging as sensing paradigms that the structural engineering field has begun to consider as substitutes for traditional tethered monitoring systems. A benefit of each sensors structural monitoring systems is that they are inexpensive to install because extensive wiring is no longer required between sensors and the data acquisition system. Researchers has been discovering that wireless and fibber bragg grating sensors are an exciting technology that should not be viewed as simply a substitute for traditional tethered monitoring systems. Rather, these sensors can play greater roles in the processing of structural response data; this feature can be utilized to screen data for signs of structural damage. Also, sensors have limitations that require novel system architectures and modes of operation. This paper is intended to present a summary review of the collective experience the structural engineering community has gained from the use of wireless and fiber bragg grating sensors for monitoring structural performance and health of tall type buildings.

Keywords: wireless sensors, fiber brag grating sensors, structural health monitoring, tall building

1. Introduction

Throughout industrialized world buildings are constantly losing their original functions as passive containers and now tend to interact with the activities taking place outside and inside them. Buildings are now able to 'control' themselves, to program their own systems and to maintain their own consumption of materials and energy. This revolution is principally because of the impact of new electronic technologies and telecommunications. The changing work environment and the new requirements in terms of work economy, lighting, space, wiring, air conditioning and, in general, of the relationship between mankind and technology are no longer subjects discussed by specialists only.

Words like 'intelligent building', 'smart building', 'CIB (Computer Integrated Building)' and 'building management' have left the domain of engineering and architecture and have entered many aspects of our working and private lives. The new electronic technologies used in tall buildings make them comparable to a complex biological system consisting of closely integrated functions and organs.

The sensors provide real-time information about the status of the system and the environment and this information is then compared with the reference values. If the inner status of the system moves outside the set conditions, the decision algorithms activate the effectors which then carry out necessary corrective measures. Moreover, sensors are main technology for structural health monitoring in civil and building engineering. Structural health monitoring attracts increasing interests in civil and building engineering due to its potential ability to alert managing staff of a impending, dangerous state of a structure in advance. Additionally, structural health monitoring helps to estimate the extent of damage and to evaluate, afterward, the structure's remaining service life once a disaster occurred [1], [2]. To design structures that are safe for public usage, design methodologies and standardized building codes have been created. Unfortunately, structures are frequently subjected to harsh loading scenarios and heavy environmental conditions not anticipated during design that will result in long-term structural deterioration. For instance, recent seismic events, including the Chi-Chi (1999), Kobe (1995), Northridge (1994), and Loma Prieta (1989) earthquakes, reveal civil structure vulnerability to failure and damage during natural catastrophes. To design safer and more durable structures, the engineering community is aggressively pursuing novel sensing technologies and analytical methods that can be used to quickly identify the onset of structural damage in an instrumented structural system [3], [4]. Called structural health monitoring (SHM), this new paradigm offers an automated method for tracking the health of a structure by integrating damage detection algorithms with structural monitoring systems.

Structural monitoring systems are widely adopted to monitor the behavior of structures during forced vibration testing or natural excitation (e.g. winds, earthquakes, live loading). Structural monitoring systems can be found in a number of common structures including ships, aircrafts, and civil structures. For instance, some building design codes mandate that structures located in regions of high seismic activity have structural monitoring systems installed [5]. The monitoring system is primarily responsible for collecting the measurement output from sensors installed in the structure and storing the measurement data within a central data repository. To assure that measurement data are reliably collected, structural monitoring systems employ coaxial wires for communication between the repository and sensors. While coaxial wires provide an immensely reliable communication link, their installation in structures could be labor-intensive and expensive. For instance, structural monitoring systems installed in tall buildings have been reported in the literature to cost in excess of $5000 (USD) per sensing channel [6]. As structural monitoring systems expand in size (as defined by the total number of sensors), the cost of the monitoring system can rise rapidly than at a linear rate [7].

Global-based damage detection refers to numerical methods that consider the global vibration characteristics (e.g. natural frequencies, mode shapes) of a structure to identify a damage. Global-based damage detection was primarily proposed as a result of the availability of structural monitoring systems that could be installed in a structure to receive response time histories. Nevertheless, with tethered structural monitoring systems costly to install, the nodal densities of majority systems have been low (frequently, only 10–20 sensors are installed in a single structure). Such small numbers of sensors are badly scaled to the localized behavior of damage, frequently rendering global based damage detection hard to implement. Particularly for structures exposed to extensively varying operational and environmental loadings, such as civil structures (e.g. buildings, bridges, dams), damage detection using global vibration characteristics is even more challenging [8].

To address the limitations present sensing technologies place on both local- and global-based damage detecting methods, the research community is actively investigating new comprehensive technologies that can advance the current state-of-practice in structural monitoring and SHM. Thus this paper highlights representation of wireless and fiber bragg grating sensors as one of potential sensing technologies that can help advance the structural engineering field's ability to economically realize SHM.

2. Wireless sensors for structural health monitoring of tall buildings

Interest in wireless sensors was primarily motivated by their low-cost attributes. The eradication of extensive lengths of coaxial wires in a structure results in wireless systems having low installation costs. These low costs promise wireless monitoring systems defined by large nodal densities as compared to traditional tethered monitoring systems. With potentially hundreds of wireless sensors installed in a single structure, the wireless monitoring system is better equipped as well to screen for structural damage by monitoring the behavior of critical structural components, thereby implementing local-based damage detection.

Wireless sensors are not sensors per se, but rather are autonomous data acquisition nodes to which traditional structural sensors (e.g. linear voltage displacement transducers, strain gages, accelerometers, inclinometers etc.) can be attached. Wireless sensors are best viewed as a platform in which mobile computing and wireless communication elements congregate with the sensing transducer. Perhaps the largest attribute of the wireless sensor is its disposition of computational resources with the sensor. These kind of resources can be leveraged to allow the sensor to exucute its own data interrogation tasks. This capability is immensely attractive within the context of structural health monitoring (SHM). So while cost has been an early motivator for considering the installation of wireless sensors in structures, the fact that the wireless sensors are a new and modern sensing paradigm offering autonomous data processing is fueling recent excitement. In particular, wireless sensors proposed for SHM will be responsible for screening their own measurement data to identify the possible existence of damage. Yet, many data processing algorithms have been embedded in wireless sensors for autonomous execution.

2.2. Performance validation of wireless sensors

2.2.1. Field deployment in civil infrastructure systems

The deployment of wireless sensors and sensor networks in actual civil structures is perhaps the best approach to assessing the limitations and merits of this nascent technology. In particular, buildings provide complex environments in which wireless sensors can be thoroughly tested. The transition of wireless monitoring systems from the laboratory to the field has been demonstrated by a number of research studies and investigations. In all of these studies, the objective of the researchers has been to assess the performance of a variety of wireless sensor platforms for the adequate measurement of structural acceleration and strain responses. Common to most of the studies reported, the accuracy and sensitivity of the wireless monitoring systems are compared to that of traditional cable based monitoring systems which have been installed alongside their wireless counterparts.

Fig. 1. The Di Wang Tower, Guangdon, China [9]

Ou and his co-workers have described a series of field experiments using MICA Motes installed in a large building. The Di Wang Tower, located in Guangdong, China, has been selected for the installation of a wireless structural monitoring system comprised of eight MICA Motes. The Di Wang Tower, shown in Figure 1, is 79 stories tall and is constructed as a hybrid structural system using reinforced concrete and steel. Potentially susceptible to vibrations during typhoons, the building is instrumented to better perceive its wind response behavior. The wireless sensors, applying ADXL202 accelerometers, measure the acceleration of the Di Wang Tower's 69th floor. The sensors are configured to sample data at 100 Hz and to transmit their measurements to a centric data repository. Acceleration response data collected by the wireless monitoring system are almost identical to those recorded by a cable-based monitoring system [9].

To record the dynamic response of full-scale residential timber buildings, Arici and Mosalam (2003) have demonstrated their work using a dense wireless sensor network for monitoring. In general, 56 wireless Motes are installed upon the first floor of a three-story timber structure that is excited at its base by a shaking table applying real seismic ground motions. Analog Devices ADXL202 accelerometers coupled with each Mote are used to register the acceleration response of the structure. After the response is collected, the data are wirelessly connected to a centric data repository where system identification interrogation occurs. In parallel to the wireless monitoring system is a dense array of traditional piezoresistive accelerometers whose outputs are registered by a tethered data acquisition system. A comparison of the acceleration time-history records illustrate that the structural accelerations recorded by the Motes are comparable to those recorded by the conventional piezoresistive accelerometers. Although some Motes exhibit communication mistakes including loss of data, the test successfully highlighted the potential for the installation of dense arrays of wireless sensors for structural monitoring applications [10].

Similar to the study reported by Arici and Mosalam (2003), Glaser (2004) has described the installation of a wireless sensor network upon the full-scale wood-frame building. During the study, 25 Motes are installed upon the first floor whereas 33 Motes are mounted to a single glue laminated beam. The intention of this instrumentation strategy is to illustrate the capability of a dense wireless sensor network to monitor both local and global structural responses. A key finding reported by Glaser (2004) is the poor performance of the wireless communication channel when data are sampled at 100 Hz. Peer-to-peer channel failure is revealed to be highly dependent upon the interference encountered from radios, cell phones, TV cameras, and other electronics in the examining area. To account for lock-ups in the communication channel, the structural response data are alternately downloaded from each problematic Mote from a laptop base station placed in close proximity. After the data are collected from the wireless sensor network by the central data repository, various post-collection analyses are performed to successfully identify the presence of both local and global damage [11].

An essential advantage of wireless sensor networks over traditional cable-based monitoring systems is the collocation of computational power with the sensing transducer. In substance, this feature transforms the wireless monitoring system into a genuine SHM system where damage detection is completely automated. Currently, many engineering algorithms, including wavelet transforms, Fourier transforms, and system identification models, have been embedded. But, wireless sensor networks should be viewed as a decentralized architecture offering analogous processing of measurement data. Extensive research is needed to arrive at truly distributed data interrogation schemes designed explicitly for the decentralization and parallelism offered by wireless sensor networks.

As the field of sensor networks matures and wireless sensors, the technology must continuously be installed in real (actual) structures to completely validate performance in the complex field environment. In the future, researchers will attempt to install ever greater numbers of wireless sensors in actual (real) structures. Large-scale deployments, defined by greater nodal densities, will continue to illustrate the scalability of wireless sensor networks for SHM.

3. Application of fiber bragg grating sensors for SHM of a tall building under construction

Among all the sensors that can be used in structural health monitoring or smart structures in the future, fiber Bragg grating (FBG) sensors protrude as the most promising sensing element.

In comparison to traditional electricity based sensors, FBG sensors display many advantages including: 1) low energy loss and electromagnetic inference immunity, which is preferable in the applications of long-distance health monitoring; 2) multiplexing ability to allow for quasi-distributive monitoring of strains by one fiber; 3) great sensibility over a wide measurement range; 4) flexibility and slenderness such that added mass and stiffness to the host structure can be neglected [1, 12]. Moreover, FBG sensors exhibit tolerance to harsh construction conditions and excellent long-term performance [13].

The past decades have witnessed an intense research effort to embed FBG sensors that monitor many kind of structures, especially buildings and bridges [1, 14]. Nevertheless, tall buildings are not generally monitored, especially during its construction phase [15–17]. Current investigations highlight, a monitoring system consisting of FBG sensors was constructed to monitor: 1) temperature increase within concrete due to hydration process, 2) strain variation of the basic column on the underground floor because of the subsequent addition of upper 18 floors, and 3) relatival long-term displacement between two sinking foundation blocks. For these purposes, FBG strain sensors and temperature were bonded on the rebars of the column and the 1st floor beam before concrete pouring. The FBG sensors have operated unceasingly approximately for more than five months after installation. Concrete pouring process was accurately monitored in terms of hydration course. Strain variation in the basic column was registered when upper floors were sequentially built up together with the temperature records outside and inside concrete. Records of temperature were also applied for compensation of FBG wavelength variations during strain monitoring. Such strain monitoring data and onsite temperature could provide valuable information for future building construction.

3.1. FBG encapsulation techniques

Leng et al. in 2005 have suggested various designs of FBG sensor protection depending on the usage area. These include sensors for metallic surfaces, concrete structures and CFRP composites [18]. Designs include FBGs embedded inside steel tubes, Carbon Fiber Reinforced Plastic (CFRP) prepegs, steel rebars, etc. The packaged sensors have been assessed for optimum strain transfer between the test specimen and sensor by using non-linear finite element analysis. Concrete cylinders orchestrated with FBG sensors and electrical resistance strain gauges have been subjected to compressive loading and the results revealed from both type of sensors to be in proper agreement. Authors also claim that because of the greater resolution, FBG strain sensors would be able to rectify the initiation of failure of structures earlier than the strain gauges.

Dawood et al. have presented in detail a procedure to embed FBG sensors between the cross-ply laminate and foam core of Carbon Fiber Reinforced Plastic (GFRP) sandwich material using vacuum infusion technique [19]. The sandwich structure consisted of a single layer of polymer foam sandwiched between two layers of Carbon Fiber Reinforced Plastic (GFRP) skins. An array of six multiplexed FBG sensors was applied. The area of the gratings was remained uncoated to provide better mechanical coupling to the Carbon Fiber Reinforced Plastic (GFRP). The FBGs were to be included between the skin of the sandwich and the core. The optical fiber was then balanced and laid up along the center line of the foam core. The constituted sandwich specimen was then accommodated in a vacuum bag and resin/hardener mixture infused inside. The specimen was treated for 15 h at room temperature. This type of packaging is useful and applicable in sensing microscopic localized defects like debonding of the GFRP material. The FBG being completely embedded in the test specimen is able to detect the internal defects of the specimen at an early stage. Nevertheless, the embedding process is involved and requires a higher degree of precision and care. Repeatability and accuracy have been found to be satisfactory under dynamic and static loading conditions.

Lu and Xia have applied FBG sensors directly included into Carbon Fiber Reinforced Plastic (CFRP) sheets for real-time monitoring of reinforced concrete (RC) beams [20]. The authors assert that in this case there is no need of a adhesive layer or protective coating between the bare the FBG sheets and Carbon Fiber Reinforced Plastic (CFRP). Hereby, the measured strain from the FBG–CFRP composite ensures the active strain measured without incurring any dampening effect. This is a special advantage over other encapsulation technique. Reinforced Cement Concrete (RCC) beams instrumented with FBG-embedded Carbon Fiber Reinforced Plastic (CFRP) sheets were subjected to compressive load. A theoretical calculation of strain at distinguish loading conditions using the Young's Modulus and dimensional values of the RCC beams was proceeded. The measured values were in good convention with the theoretical strain values. Another immensely commonly used and simple packaging technique of FBGs for strain monitoring in concrete structures is to install the sensors in a steel rebar and then use the rebar at the site of measurement.

Chung and Kang [21] have applied such a technique where they have allocated a six-FBG multiplexed fiber in a groove cut in a steel rebar and used a rapid curing adhesive to integrate the fibre to the rebar. This FBG embedded rebar has been applied at the site of strain monitoring. However, before using this kind of packaging it is important to study the strain transfer characteristics of the adhesive and the rebar material for adequate strain measurement.

Two significant issues connected with the use of FBG sensors as health monitoring tool in civil and building structures are their greater fragility and cross-sensitivity to more than one measurand. Special a thermal encapsulated FBGs that take care of the strain temperature cross-sensitivity are available [22], [23] and [24]. Lo and Kuo have proposed a thermal packaging of FBGs using a metal coating that serves as thermal compensator [22]. An FBG 1 cm in length is written using a phase mask. It has a central wavelength of 1532.93 nm at 30°C. The fibre substrate is quartz and a copper coating of 5-μm thickness is deposited onto the substrate using electroless plating technique. Quartz having a much lower thermal expansion coefficient than copper, any rise in ambient temperature results in a greater expansion of the copper than that of the FBG. This compresses the FBG and creates a negative strain on it, in this way compensating for the temperature-induced wavelength shift of the FBG. This proposed technique of temperature compensation thus involves a simple bi-material that is feasible and reliable for mass production.

Moyo et al. have reported a packaged FBG that is appropriate for use in the harsh conditions of the construction industry and also takes care of the temperature compensation of the sensors [24]. The packaged sensor is dumb-bell shaped and consists of two FBGs placed closely. One FBG, sandwiched between two layers of carbon composite material, is epoxied on the dumb-bell surface and is prone to both temperature and strain changes. Another FBG, encased in a metal tube is prone only to temperature perturbations. Several tests were executed on these packaged FBG sensors and the data compared against conventional foil strain gauges. Tensile tests were reported on steel rebars and the sensor response was revealed to be linear and closely correlated to those of foil gauges. Static test on merely supported reinforced concrete beams instrumented with the sensors also showed approximately linear response, thus justifying installation procedures and the packaging of the sensors. Dynamic tests on the beam were carried out using an impulse hammer and the maximum strain recorded by the FBG and foil gauges were respectively 55 and 58 micro strain. The packaged sensor was also included inside a concrete cylinder, which was subjected to compressive load. Only the strain sensor has shown a high sensitivity whereas the temperature-monitoring sensor was nearly unaffected.

It may be noted that in most cases, the strain sensitivity of an encapsulated FBG is essentially different from that of the bare FBG. Hence calibration of the encapsulated FBG sensor must be performed before it is put into real-world application.

4. Conclusion

A significant advantage of wireless sensor networks over traditional cable-based monitoring systems is the disposition of computational power with the sensing transducer. In substance, this feature transforms the wireless monitoring system into a genuine SHM system where damage detection is completely automated. Currently, many engineering algorithms, including wavelet transforms, Fourier transforms, and system identification models, have been embedded. Though, wireless sensor networks should be considered as a decentralized architecture offering parallel processing of measurement data. Extensive research is needed to arrive at truly distributed data interrogation schemes designed explicitly for the parallelism and decentralization offered by wireless sensor networks.

As the field of wireless sensors and sensor networks matures, the technology must continuously be installed in real (actual) structures to completely validate performance in the complex field environment. In the future, researchers will attempt to install ever greater numbers of wireless sensors in actual (real) structures. Large-scale deployments, defined by greater nodal densities, will continue to present the scalability of wireless sensor networks for SHM. Nowadays, the majority of wireless systems have been left within a structure for the duration of testing. In the future, field tests will be elaborated to test wireless sensors in longer-term deployments. Tests like these could offer opportunities to improve duty cycle usage strategies, to assess system performance versus environmental factors, and to examine the long-term reliability of wireless sensors.

Consequently, Fiber Bragg grating sensors has also demonstrate a great potential as a structural health monitoring tool for civil structures to ensure structural integrity, durability, and reliability. The advantages of applying fiber optic sensors to a tall building include their immunity to electromagnetic interference and their multiplexing ability to transfer optical signals over a long distance.

Besides, a few remaining issues in the application of FBG sensors need to be addressed. In composites, where these sensors are to be embedded, wavelength shift compensation due to the temperature effect is still not possible without compromising the fibre's resolution. As well as, the multi axis measurement of strain in structures is still an active area of research [25]. Moreover, for all practical situations, due to their brittle nature, it is necessary to encapsulate the bare FBG sensors before mounting them on any structure. However, the adhesive layer and the protective layer absorb a part of the strain and the indication given by the FBG is not the true strain on the structure. Lau et al. have researched a theoretical modeling of the bonding characteristics at the interface of bare fibre and coating, adhesive and coating layer, adhesive layer and host material and validated the results using FEM tools [26]. The study concludes that for better strain transfer from the host material to the FBG sensors, a subtle layer of adhesive, a great modulus coating material and a sufficient embedding length of the sensor is necessary.

Thus, this article illustrated overview of potential application of the wireless and fiber bragg grating sensor for structural health monitoring in civil and building engineering. Additionally, after almost three decades of research in wireless and FBGs, technology for SHM using wireless and FBG sensors is on the verge of maturity. The main thrust of technology development at present should be focused on the various application areas of civil infrastructure monitoring using wireless and FBGs and the standardization of the procedure.

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