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An Improved Monitoring System via the Integration of Structural Health Monitoring and Earthquake Emergency Alert Technologies

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Abstract: As a result of the advantages it offers in construction management and maintenance, structural health monitoring for civil structures is becoming more popular in Europe and throughout the world. The main advantages of using such methods include cheaper inspections, more accurate research into the behavior of structures under dynamic loads, better seismic protection, and real-time or near-real-time observation of structural response and evolution of damage, which helps with post-earthquake scenario production and rescue efforts. As a result, Structural Monitoring Systems is a very multidisciplinary field, in which researchers from a wide variety of fields and institutions may work together to improve the effectiveness and reliability of these systems, the benefits of which are almost self-evident. Nowadays, developments in wireless sensor networks, techniques for determining modal properties, and damage detection systems are among the most urgent issues in the sector. Although modal identification and damage detection algorithms have improved, sensor technology has advanced at a faster rate.

Keywords: Structural Health Monitoring, seismic monitoring network, automated operational modal analysis

Introduction

Monitoring a structure's health and pinpointing where damage has occurred are becoming more crucial in the field of civil engineering. To determine whether damage has occurred, pinpoint its position, estimate its degree, and assess how it will affect the remaining life of a structure, structural health monitoring (SHM) employs in-situ, non-destructive sensing and analysis of structural features[1]. Although SHM is a relatively new paradigm in civil engineering, evaluating the condition of a building using tests and measurements has been standard practice for quite some time; as a result, evaluation and inspection standards have been available for quite some time (). SHM aims to achieve the same results as this method, but it makes use of cutting-edge sensing, instrumentation, communication, and modeling tools to do this[2].

The data collected by such systems could be put to good use in a variety of contexts, including the assessment of the structural integrity of a building, the assessment of earthquake damage, the determination of a building's remaining useful life, its repair and retrofitting, its management, and its rehabilitation[3]. According to, increased structural productivity is a direct outcome of less downtime and increased dependability, with monitoring data providing valuable insight into structural behavior for use in future design iterations[4]. To achieve these goals, a Structural Health Monitoring system should be built on a modular framework that allows for the integration of different kinds of sensors. In addition, developments in IT and communications guarantee data delivery even under extreme circumstances. In this work, we will examine and share some early findings from the deployment of an integrated SHM system encompassing several buildings throughout a large region[5]. Environmental and structural reaction to loads may be tracked with the use of a suite of sensors that make up a monitoring system.

The monitoring infrastructure typically relies on cable connections between distant sensors and a centralized data collecting system [6]. This is accomplished via the dissemination of information over the whole monitoring network. That's why it's requiring more work now to develop efficient algorithms for processing data, especially ones that account for this novel design[7]

Managing data and combining information from several sensors, each of which measures a unique physical characteristic, is another important job. Several methods have been developed for damage detection based on various mechanical and physical concepts[8]. There are, however, two broad categories into which they may be placed: The primary set of methods, dubbed "modal-based" algorithms, is concerned with monitoring the structural reaction before and after damage in relation to the mechanical features (natural frequencies, etc.) of the structure. The second method, on the other hand, relies on post-processing of measurement data (through ARMAV modeling, wavelet decomposition, etc.) to identify abnormalities. In both circumstances, current breakthroughs in information technology are being used to implement approaches that automate the detecting process[9]

The system relies heavily on discovering the structures' operational modal parameters in order to function. Modal identification has recently been automated by the use of certain methodologies that enable complete integration of modal identification into SHM systems[10].

Data reduction and transmission must also be handled reliably, especially in the aftermath of an earthquake when there is likely to be a decrease in communication capacity; wavelet-based techniques seem to be particularly promising in this area[11]. There have been several novel methods presented in this area recently. Recent and cutting-edge uses focus on the potential for communication between systems for detecting earthquakes in advance, monitoring their condition, and controlling their behavior[12]

Within this context, a monitoring system may be put to use in crisis management, traffic regulation, damage assessment, and the design of post-earthquake scenarios. As an example of emergency management in the aftermath of an earthquake, the usage of monitoring systems on subsurface pipeline networks may be cited. Damaged gas utilities, in fact, can generate secondary catastrophes and, as a result, substantial losses. Data indicating sudden shifts in gas pipeline pressure might trigger an immediate cutoff. Traffic may be managed in a similar fashion provided data on the condition of critical facilities is readily accessible[13]

Having information on which bridges are still functional may aid in the planning of a route to the disaster region for rescue workers and supplies. Performance degradation, weather, fatigue, overloading, natural calamities, and artificial acts like the bomb explosion, fire, etc.

all contribute to a steady decline in a civil structure's efficiency over the course of its lifetime. The many slabs, pillars, beams, roof, etc., that make up a structure. The strength of various parts varies. As expected, component strength decreases with increased frequency of use. Several losses occur as a result of the strength drop. A building has been damaged if it has undergone alterations that compromise its functionality. It is crucial to address the extent and location of the losses. As a building sustains more damage, its load-bearing capability decreases. Timely repair is crucial to prevent the structure from collapsing as a result of the damages[14].

Using a variety of methods, Structural Health Monitoring keeps tabs on where and if any damage has occurred in civil structures. Periodic checks may be made, or checks can be made in response to specific occurrences such as an earthquake, fire, etc. A rapid evaluation of the building's efficacy after severe occurrences is useful. The first step in SHM is a visual inspection of the structures, followed by the collection of damage-related data. The present status of the building's health may be assessed by statistical analysis of these readings. The operation of a SHM is shown in Figure 1.

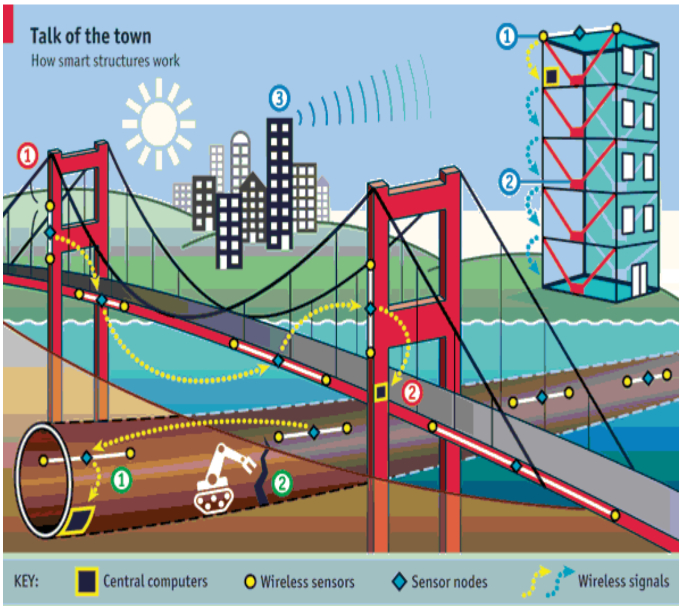

Figure 1.1 Structural Health Monitoring

With SHM, wireless sensor nodes are placed throughout the building at various predetermined intervals. In order to make judgments regarding the state of the building, the information collected by these sensor nodes is sent through wireless signals to a central computer, as indicated in Figure 1.

Literature Review

Terranna Haxton et.al (2021) Water quality can be monitored, problems may be confirmed, and the efficacy of emergency or remedial measures can be checked by using manual or grab sampling in drinking water systems. In this study, we investigate where regulatory sampling may best serve emergency response efforts. Manual sample sites were determined in order to optimize total nodal coverage of the system using an optimization formulation based on the literature. The results demonstrated the viability of sample sites in validating situations for which they were not originally conceived. Average performance was lowered by 3-4% when comparing emergency response optimization to regulatory situations, and by 7%-10% when applying regulatory optimization to choose sample sites for emergency response. To maintain geographical and water age variability with little performance influence, secondary limitations were included into the design. This study demonstrated the need of regulatory sampling sites for these networks during emergency situations.

Emily Zechman Berglund et.al.,(2020) Infrastructure issues caused by aging infrastructure and rising demands may be mitigated with the help of a variety of technologies made available via smart city projects. Yet, technological, financial, and societal restrictions and critiques prevent the full realization of the promise for infrastructure and urban development offered by smart cities models for infrastructure management. Sensors, crowdsourcing, citizen science, actuators, data transmission, the Internet of Things, big data analytics, data visualization, and the blockchain are just some of the smart technologies discussed here that may be used to infrastructure management. The purpose of this article is to examine the use of enabling technologies in smart infrastructure programs across a variety of civil engineering fields, such as transportation, water, air quality, energy infrastructure, solid waste management, construction engineering and management, structures, and geotechnical systems.

Haydee Blanco et.al 2019 The use of structural health monitoring (SHM) in older buildings is becoming more popular. In order to provide engineers with accurate data for management and decision making, this instrument monitors, validates, and reports on the state of the structure. The purpose of this essay is to show the monitoring systems created during the dismantling of the propping system from multiple brickwork domes of a modernist church. Arch and dome motions must be meticulously tracked, hence a technique for monitoring suitable loading operations was established.

Abdullahi M. Salman, et.al.,2018 One of the deadliest and most destructive natural catastrophes is flooding. Flooding affects millions of people every year and costs the global economy an estimated $50 billion. There has been a dramatic rise in the frequency of floods and the economic damages they cause over recent years. Population increase, intensifying urbanization, deteriorating infrastructure, and the potential effects of climate change all point to a continuation of this pattern in the years ahead. Researchers have made efforts in recent years to account for these aspects in flood risk models. Yet, many obstacles remain. This work attempts to analyze existing methods for estimating the possible effect of climate change, population expansion, expanding urbanization, and deteriorating infrastructure on flood risk in order to better understand where further study is needed in this area.

Motivation for SHM

The concept of "smart buildings" has brought more focus on SHM in recent years. These days, it takes more than just sand and bricks to construct a structure. Intelligent buildings combine physical structures with electronic systems. The lifespan of buildings may be extended via routine maintenance. It will also forestall the worst-case scenario. Bridges, railways, highways, etc., all contribute to a country's economy in different ways. If these systems go down, it might have a devastating impact on the economy and on people's lives. Damage detection at an early stage aids in preventing major issues. The structures whose useful lives are over must be maintained extensively. Figure 2 shows that in 2016 a 6.4 magnitude earthquake occurred. The earthquake triggered the full collapse of a 17-story skyscraper known as Golden Dragon, resulting in 59 fatalities. As seen in Figure 3, a building in Bangalore recently collapsed.

Figure 2 Weiguan Golden Dragon building collapse due toearthquake (2016)

Figure 3 Building collapse at Bangalore, India (2016)

Several buildings throughout the globe fall every year. The Federal Highway Administration (FHWA) reports that a number of bridges are unsafe due to structural flaws, and that some older bridges are also ineffective due to technological advancements. FHWA estimates that roughly 150,000 bridges fall under this category (USDOT, 2007). It would take roughly 57 years to repair or remove all such damaged bridges, according to a 2006 analysis by the Federal Highway Administration. From 2005 through 2024, yearly roadway and bridge maintenance costs are estimated to reach $78.1 billion (Holt & Hartmann 2008). The data on the broken bridges are shown in Table 1.

Table 1. Percentages of rural and urban bridge deficiencies, by number of bridges

		2002	2004
Rural Bridges	Structurally Deficient	15.1%	14.4%
	Functionally Obsolete	11.4%	11.0%
Urban Bridges	Structurally Deficient	9.2%	8.8%
	Functionally Obsolete	21.9%	21.6%
Total Bridges	Structurally Deficient	13.7%	13.1%
	Functionally Obsolete	13.8%	13.6%

An overview of the structure of a BHM system is shown in Figure 5. Many sensors are installed in buildings to keep tabs on their condition. One sensor node in a group acts as the cluster's CH. Sensing devices are used to monitor environmental conditions that might lead to cracking, such as temperature, corrosion, etc. A cover meter is a device used to measure the thickness of a concrete cover, among other parameters. Although the threshold based data are potentially interesting to users to make judgments regarding the health state of buildings, the measured values are conveyed to the CH when they meet the threshold limit. Increased monitoring frequency and data collection for a suitable period of time are implemented if threshold values are exceeded, allowing for reliable conclusions to be drawn regarding the state of the building. All of the sensors' readings are combined, and then sent to a central health monitoring facility for processing. Analysis outputs are presented graphically in the form of reports, forecasts, etc.

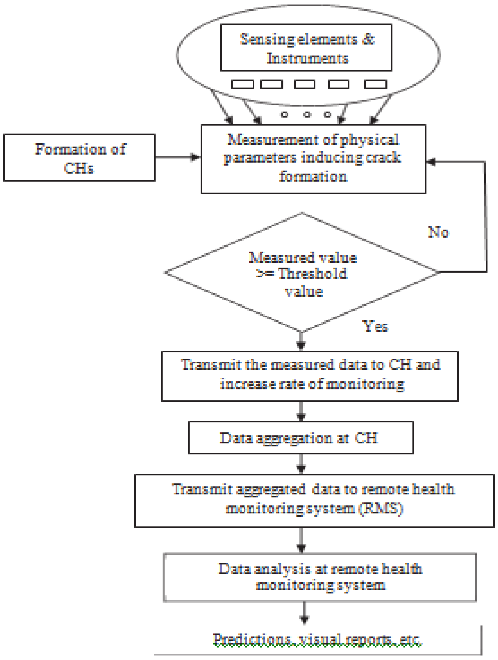

Figure 5. Building health monitoring system

Machine Learning Based Compressive StrengthPrediction of Cementations System

Examples of common supplementary cementitious materials (SCMs) include hydrated lime, calcium carbonate, fly ash, silica fume, and ground granulated blast furnace slag. Monitoring the physical and chemical reaction between these cements and water during hydration is crucial for their practical use. The mechanical characteristics of cement are strongly impacted by the hydration process, particularly at the very young age. Hence, it is crucial to have a method of real-time monitoring and prediction in order to understand the processes of hydration and the development of strength from a young age. In this study, we provide a PZT-based EMI method for predicting the compressive strength of different cementitious systems using machine learning. At the early age of hydration, FTIR, XRD, and SEM studies are used to evaluate the spectral characteristics, mineral components, and surface morphology of the cementitious systems. Compressive strength is measured in terms of comparable structural characteristics determined by the EPS arrangement. In addition, empirical relations were used to calibrate the comparable structural characteristics with age. This chapter describes the detailed experiments performed on several cementitious systems, and how the resulting EMI data was used to inform the subsequent machine learning models.

Experimental Program

With a 0.45 w/c ratio, the paste was prepared using three different cementitious systems: ordinary Portland cement (OPC; 95% clinker, 5% gypsum), fly ash-based cement (FA-based cement; 30% FA, 65% clinker, 5% gypsum), and limestone calcined clay-based cement (50:50 calcined clay and limestone, 2:1 ratio; 45% clinker, 5% gypsum). Table 1.2 displays the OPC and mineral admixture chemical characteristics. A metal mold measuring 70.1 mm on a side was used to cast all the samples. To capture EMI measurements and temperature fluctuations over time throughout the early-age hydration process, an EPS was inserted in the center of the specimen at the time of casting alongside a K-type temperature sensor. The EMI test was performed using a 30 kHz to 300 kHz scanning frequency and an E4980A LCR meter., as shown in Figure 6

Table 1.2: A comparison of chemical properties of OPC and mineral admixtures

Constituents (%)	**LC^2**	**Raw clay**	**Limestone**	**OPC**	**FA**
LOI	9.21	10.28	36.96	1.69	1.72
CaO	28.29	0.06	44.24	63	44
SiO_2	34.28	54.67	11.25	22	32
Al_2O_3	19.45	27.69	2.53	5	10
Fe_2O_3	3.43	4.93	1.55	3.299	6
MgO	1.38	0.13	1.96	2.12	2
SO_3	1.58	0.01	-	1.42	2.5
Na_2O	0.31	0.12	0.5	0.3	0.48
K_2O	0.27	0.25	0.28	0.71	0.4
TiO_2	1.63	1.68	-	0.46	-

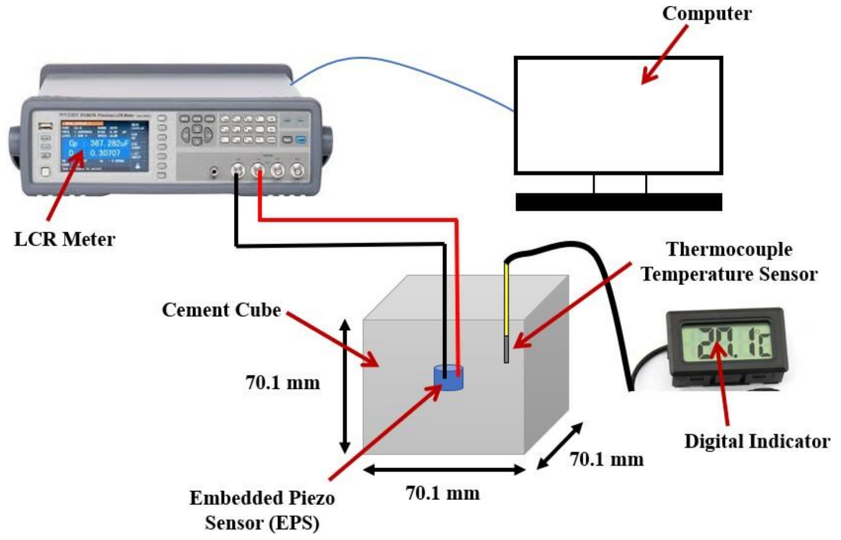

Figure 6: Experimental setup of the signature measurement

Analysis Based On Strength Development

Many cementitious systems' compressive strengths at several phases of strength development are shown by destructive analysis in Figure 7. The results show that the LC3 cementitious system generated higher early strength at 5 days and 7 days compared to the FA and OPC cementitious systems. These results were repeated in the published literature. In addition, the finer clay used in LC3 accounted for its superior early age strength development relative to FA. When tested for compressive strength up to 28 days, LC3 matched OPC, while the FA cementitious system lagged behind both. The FA cementitious system's slower pozzolanic reaction at younger ages meant it took longer to attain maximum strength, although constant strength improvements were noted up to 90 days...

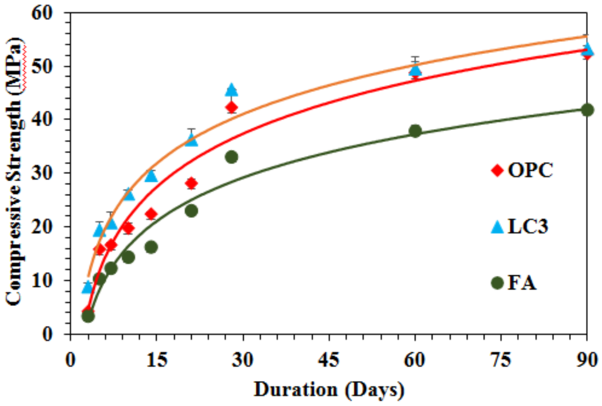

Figure 7: Destructive analysis result of compressive strength of different cementitiou systems during strength development

Conclusion

The capacity to track a structure's health throughout the course of its useful life in order to minimize maintenance and associated downtime is gaining prominence as a key component of asset management. Non-destructive evaluation methods like visual inspection have largely replaced destructive ones in the field of structural health assessment. Nevertheless, these methods often need extensive amounts of time spent sitting idle. As SHM may save money by cutting down on the need for human inspectors, it is gaining popularity (Achenbach, 2007). In recent years, there has been a rapid expansion of novel sensors, and MEMS and wireless sensing have become highly sought-after additions to SHM systems. Nonetheless, the adoption of optimized and autonomous SHM systems is slow. After a brief overview of a few representative instances from across the globe, this article dives into an analysis of a few key factors involved in deploying a comprehensive SHM system that encompasses several buildings spread over a large area. By combining a number of different sensors and pieces of hardware into a cohesive whole, a powerful Structural Health Monitoring system has been developed.

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