Creation of Smart Structures with the Aid of IoT

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***Abstract*—The key element needed for the creation of a smart structure is a robust network of sensors that measure parameters relevant to the behavior of the structure and its exposure conditions. Creation of smart structures is becoming feasible with the current developments in the Internet of Things (IoT) technology, sensors, wireless systems, internet, signal processing algorithms, and software technology. In the IoT technology, major components of the structure can interconnect among each other through real-time data sharing. The data is then processed using a smart control unit representing the brain of the structure that either send direct messages to the management office or order special actuators instrumented within the structure to take proactive measures to maintain the health and integrity of the structure. Structural health monitoring (SHM) is considered a form of smart application in structures allowing for early detection of structural deficiencies prior to local or catastrophic failures. This study provides a highlight for the use of IoT technology in smart structures through identifying various applications and key parameters of various infrastructure facilities.**

Keywords*—*Smart Structures, IoT, Sensors Network, Structural Health Monitoring.

I. Introduction

The cost of repair and rehabilitation of the infrastructure facilities due to deterioration and damage under aggressive events, such as earthquakes, tsunamis, hurricanes, blast, and collisions, are substantial. Therefore, it is becoming necessary to develop smart reliable sensors and materials with the ability to learn about their environment, minimize uncertainty, process information, and execute control actions in real time [1, 2]. The ambition in the near future is to have all essential infrastructure facilities smart, which will require significant investment in research and development to improve the current sensors and materials technologies. The benefits of such smart technologies will be priceless and can be visualized when estimating the cost of repair after a destructive event that can go up to billions of dollars. On the other hand, the expected savings in human lives exceeds all expectations. The current momentum in the applications of the IoT technology represents a major block toward smart cities including structures [3-5].

It is necessary that the essential infrastructure facilities (Fig. 1) continue performing most of their functional requirements during and after severe events. Depending on the expected loading conditions and environmental exposure, a smart structure must incorporate special features allowing for, 1) sensing the action, diagnosing the problem in real time, and taking control actions to avoid catastrophic failure, or ask for help through sending clear and simple messages about its pain. Smart sensors and materials are the required features that give the structures such smart functionalities. These systems must be appropriately selected according to the type of measurement to be performed, the required accuracy, and the operational environment. In addition, they must be installed at the critical locations in the structure so they can detect any change in the stresses, strains, durability problems, and possible occurrence of cracks that might lead to serious problems. Critical locations in a structure and its response to loading actions can be identified with the help of Finite Element Simulations [6, 7]. The essential urban infrastructure facilities include:

- Buildings: skyscrapers, hospitals, army buildings.
- Transportation: bridges, pavements, tunnels, airport runways, and ports.
- Lifeline: power plants, power cables, gas and water tanks.
- Ocean: offshore structures, seawalls, dams.

Infrastructure facilities may experience loading conditions and/or environmental exposures. The loading conditions can be sudden or extreme such as earthquake loading or acting continuously on the structure such as traffic fatigue loading. Environmental exposures can be salt-water exposure, thermal expansion and contractions, humidity, chemical attach, etc. These loading and environmental conditions are the reasons for various forms of problems (crack, damage, leaking, slip, delamination, stiffness loss, etc.) and catastrophic failures due to the induced vibrations, overstressing, deflections, settlement, corrosion, fatigue, fires and expulsions, scouring, etc.

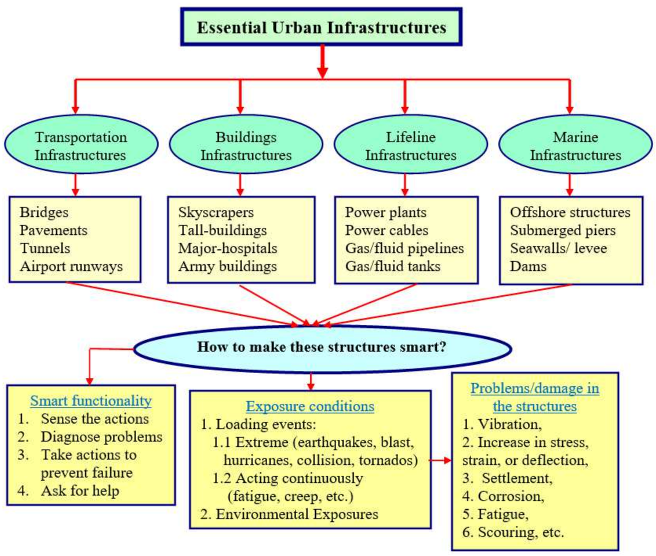

Fig. 1. Example Essential Infrastructure facilities

II. Main Features of Smart Structures

Smart structures are composed of materials that can determine their present state, decide what is the most desirable state, and carry out an appropriate response in a controlled manner. They are mainly made up of: (1) sensors, (2) actuators, and (3) smart control system.

A. Network of Sensors

The network of sensors is responsible for gathering information and describe the physical state of their environment. The information of the sensors are controlled and processed by intelligent control system. For example, sensors can check for the occurrence of undesirable vibrations or damage in continuous operations and send information to the control system either wireless or through compact wiring network. Typically they are either optical fibers or piezoelectric materials. Table 1 lists various sensors that can be used to monitor the condition of a bridge and its components.

TABLE I. SMART SENSORS FOR BRIDGES

Sensor Type		Advantage
Sensors for monitoring during construction	Concrete strength	Reduce construction time by allowing of early prestressing or removal of formwork.
	Strain sensors with high durability	Reliable information during the life of the structure.
	Displacements over water	Allow on line measurements with high precision of an important parameter.
	Durability parameters	Allow on line measurements instead of periodic tests.
Sensors for monitoring the structural behavior	Bearing sensors	Use of intelligent bearings as sensors of the global behavior of the bridge.
	Scour	Allow the implementation of active control in real structures,
	Absolute displacement measurement system	Assess bridge condition, design verification, and predict internal forces caused by settlement.
	Cable force measurement	Rapid and accurate (within 5%) force measuring device for maintenance of cables.
Sensors for monitoring the durability	Concrete degradation	Evaluate local stresses and pathologies (ex: alkali-silica reaction).
	Steel corrosion depth	Control reliability of steel structures due to corrosion.
	Fatigue sensors	Assess the fatigue by methods such as rain-flow counting procedures.

B. Actuators

Actuators represent the muscles in a smart structure. For example, in a smart structure, actuators can engage to prevent vibration or movement by applying controls after receiving information from the control system that builds up its decision based on the information received from the distributed sensors. Four types of actuators are commonly used in smart structures:

- Piezoelectric devices: respond to applied voltages by expanding and contracting. They are efficient for dampening vibrations and controlling stress in materials. Lead Zirconate Titanate (PZT) is widely used.
- Magnetostrictive materials: react to magnetic fields, and are also used to dampen vibrations. Terfenol-D (an alloy of Terbium, Iron and Dysprosium) is commonly used as this type of material.
- Magneto-Rheological (MR) fluids: a liquid that changes to a near solid when exposed to a magnetic force, then back to liquid once the magnetic force is removed. During an earthquake, MR fluid inside a damper will change from solid to liquid and back as vibrations activate a magnetic force inside the damper. Depending on the size of the structure, there could be an array of dampers. As the building begins to shake, the dampers would move back and forth to compensate for the vibration of the shock. When it's magnetized, the MR fluid increases the amount of force that the dampers can exert.
- Shape Memory Alloys (SMA): refers to the ability of certain alloys to undergo large strains, while recovering their initial configuration at the end of the deformation process spontaneously or by heating without any residual deformation. The particular properties of SMAs are strictly associated to a solid-solid phase transformation, which can be thermal, or stress induced. Currently, SMAs are mainly applied in medical sciences, electrical, aerospace and mechanical engineering and also can open new applications in civil engineering specifically in seismic protection of buildings.

C. Smart Control System

Handles the transfer of information in real-time computation and controls the actuator to perform the corrective action. The use of artificial neural networks [8] and structural health monitoring [9] are novel approaches for intelligence control of smart structures. Wiring is the typical way of connecting the sensors to the actuators and the controlling units. Minimizing the wiring from the system through the use of pure wireless systems reduces the possibility of wires damage and reduces the installation and maintenance costs. Remote monitoring and data acquisition systems (DAS) have given the opportunity for fast and massive data collection. The components of a typical wireless sensor are: sensor, solar panel, battery, transmitter, and receiver. The sensor feeds data to the transmitter, which utilizes wireless communications to send the data to a receiver located at the DAS. The transmitter requires a small amount of power, which can be supplied by a solar panel and battery. Wireless sensors are more sensitive and maintain the quality of the data better due to the elimination of long wiring runs.

III. PROBLEMS IDENTIFICATION IN STRUCTURES

Civil infrastructure facilities experience loading conditions that can be sudden or extreme such as earthquake loading, or acting continuously on the structure such as traffic fatigue loading. They are also exposed to environmental conditions such as salt-water exposure, thermal expansion and contractions, and chemical attach, etc. These loading and environmental conditions are the reasons for various forms of problems and catastrophic failures of the essential structures. The following items list the possible problems and exposures that may occur in structures due to various loading and environmental exposures:

A. Buildings:

- Vibration of buildings might cause local failures and possibly total collapse of the building if the natural frequency of the building is reached.
- Increase in the internal stresses, strains, and deflections to values greater than certain limits after which local or global failure occurs.
- Settlement in the footings/piles leads to increase in the applied moments and forces on the structural members, which might cause cracking in the walls and beams or total collapse if a major column failed.
- In general, environmental exposures have minor influence on buildings.

B. Bridges:

- Vibrations of the main cables in stay-cable/suspension bridges as well as vibrations of railways bridges might cause total collapse of the bridge if the natural frequency of the cable is reached.

- Corrosion of the steel and strand systems is a frequent problem that lead to total damage of the deck system.
- Traffic fatigue loading leads to rupture of the main steel or strand reinforcement of the reinforced concrete beams if exceeds certain range and number of cycles.
- Settlement in the footings/piles leads to increase in the applied moments and forces and consequent damage in the beams and slabs.

C. Lifeline Infrastructures:

- Possible fires and expulsions in the power plants may lead to local and global damages in the power plant members and facilities. The fires and explosions can occur as a result of human errors and machine machines misalignment as well as due to natural disasters such as earthquakes, severe tornadoes and thunderstorms.
- Leakage is the major problem in such type of structures. Leakage occurred as a result of sudden actions such as earthquake or due to creep or fatigue resulted from the sustained or repeated fluid/gas loading.

D. Marine Infrastructures:

- Scouring at a bridge pier in the river can be caused by general scour, contraction scour or local scour. Among them, local scour is the most critical and generally caused by the interference of the structures with river flow.
- Hitting of a major bridge pier by a large ship lead to global failure.

IV. EXAMPLES OF SMART ACTIONS

Use of smart damper systems to control the vibrations of the flexible structures, such as tall-buildings, long-bridges, railways, etc. In addition, smart damper systems can be used to produce internal resisting forces act when the critical strains, stresses, and deformations exceed certain limits due sudden actions such as earthquake or blast. Incorporating smart materials and sensors with capability of pre-warning of possible occurrence of local damage due to static or fatigue loadings as well as detecting its location if occurred. Local damage appears as crack, fatigue, slip, delamination, stiffness loss, effective force-resistance area loss, and so on. Strain is an alternative parameter, which can be used to describe deformation, study a crack opening and even detect the slip, and bonding. Pre-indication and warning from corrosion of the strands and main reinforcement through monitoring the chloride concentrations at the locations of the steel reinforcement and strand systems.

Self-deicing bridge decks can be done using smart concrete technology or by incorporating smart heating system inside deck concrete. Self-stressing can be done using SMA inside the concrete. On other hand the use of SMA inside the columns and beam-column joints of buildings will allow for the recovery of the original shape after severe action such as earthquake. Measuring and providing information wirelessly about the load-capacity of a concrete pile from both ends while driven into place can be achieved using a smart sensor system cast directly into wet concrete piles. Local scour monitoring can be done using fiber Bragg grating (FBG) sensors that can measure both the process of scouring and the variation of water level change. Real time monitoring and control of subsea pipelines and facilities can be done to develop a pipeline system that is auto adaptive to the environment so that real-time problem identification and corrective action can be implemented.

V. IMPLEMENTATION

After development of the smart sensors and materials as well as appropriate network algorithms to manage and filter the collected data, the effectiveness and reliability of the technology will be validated through small-scale prototypes [10] and through actual applications on selected essential infrastructures. For the field validation, major essential structures such as tall residential buildings and parking structures, suspension and truss bridges, offshore structures, and power plants can be selected. The structures can be instrumented with various types of sensors at the critical locations to monitor their structural performance and durability. The main parameters of interest in buildings will be the vibrations, displacements, strains, stresses, deterioration of concrete, and corrosion of the reinforcing steel bars and stand systems, especially in parking lot buildings. In bridges, the main parameters of interest will be vibrations, displacements, strains, stresses, deterioration of concrete, corrosion of steel and strand systems, and fatigue due to the various forms of loading and environmental exposures.

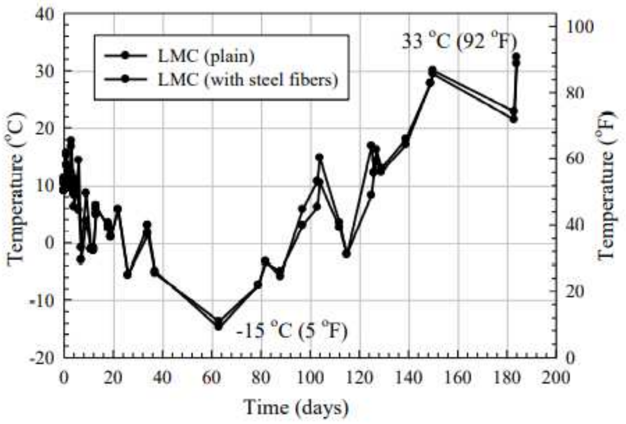

Fig. 2. Monitoring temperature variations inside the overlay

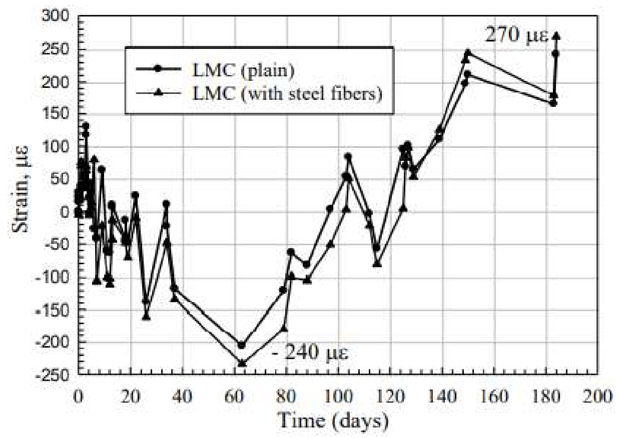

Fig. 3. Monitoring strain variations inside the overlay

In repair projects of damaged/deteriorated structural members such as pre-stressed girders with carbon fiber reinforced polymer (CFRP) composites, it is crucial to continuously monitor the bond between the CFRP composites and concrete to ensure full composite action. This can be done through a network of strain sensors that send real-time data to control unit that in turn analyze the data and communicate through internet with the management office in case a problem is detected. This technique is usually implemented in many projects throughout the world [9]. A solar power system is usually installed to provide continuous power for the monitoring system. Another application involves installing sensors inside a newly casted bridge deck concrete overlay for continuous monitoring of temperature and strain variations (Figs. 2 & 3), which allows for checking the occurrence of cracks or debonding.

Control of vibrations of pedestrian bridges having fundamental frequencies between 2 to 4 Hz.is an ideal example for the application of IoT technology for the creation of pedestrian bridges with the capability to sense, analyze, and take actions that counteract human-induced vibrations. Detailed structural-simulations are needed to capture the bridge response and identify critical locations under various potential load patterns. Such simulations are usually conducted with the aid of finite element analysis. Tuned mass dampers (TMD) are then designed with appropriate mass and stiffness to have a fundamental frequency matching the footbridge in order to optimize appropriate mass, stiffness and damping coefficient. Typical excitation control for a pedestrian bridge before and after installing TMD is shown in Fig. 4 [11]. The sensor-actuator unit architecture for such application can be sketched as shown in Fig. 5. It is imperative to note that this sensor-actuator system can be implemented for other structural applications and in early-warning systems as well [12, 13].

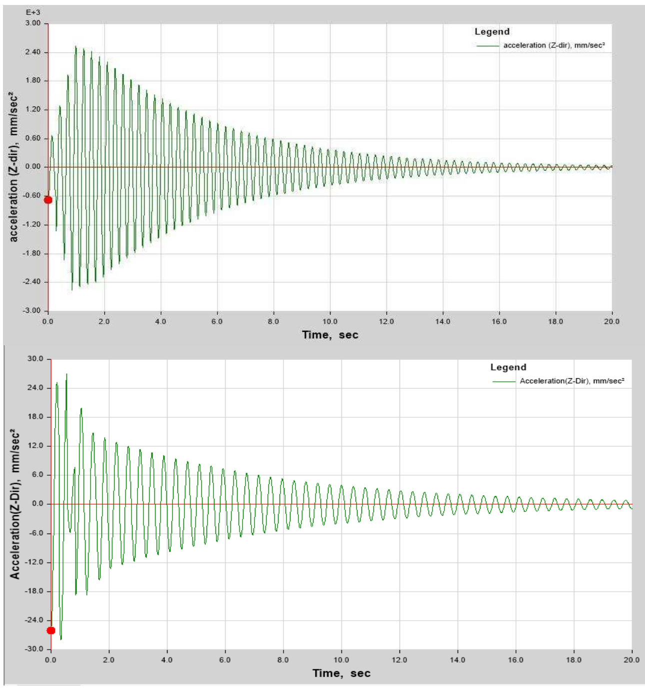

Fig. 4. Acceleration-time trace before (top) and after (bottom) TMD

VI. Conclusion

With the booming in the sensors technology, network, wireless, artificial intelligence, and IoT, the goal of smart structures is becoming feasible. This will lead to real-time monitoring and detection of problems that will prevent any catastrophic failure and will lead to substantial time and cost savings in terms of repair and management of infrastructure; in addition to the priceless savings in human lives. Unique collaboration between the structural, mechanical, electrical, and computer engineering expertise can make the desired goals very attainable.

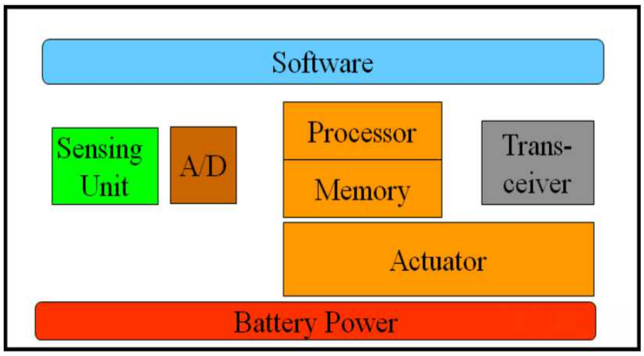

Fig. 5. Sensor-actuator unit architecture

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