

# Structural Damage Detection and Health Monitoring

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Readers who have recently visited or purchased a newly built house may have started to notice the standard inclusion of “smart home” technologies. The smart system can automatically control environmental parameters, such as temperature or window shading, based on the ambient conditions or can be sent via verbal request to go on online shopping errand. Security systems linked to the smart system can alert residents of potential visitors based on the integrated motion detectors, and increasingly, who the visitor is, using advanced facial recognition software. Such smart home functionalities are the fruits harvested from decades of research in network technologies, artificial intelligence, embedded electronics, advanced sensors, among others. Numerous researchers around the globe have innovated and labored long hours to bring cutting edge ideas to life and finally to application. Thus, despite the highly complex mathematics and engineering that drives smart home systems, an increasingly large part of the population has started to take such innovations for granted. Even the lay person has a functional, albeit naive understanding of such systems and can seamlessly use them to improve their lives. However, the smart home is only one of many microcosms that comprise the larger realm of the so-called structural health monitoring (SHM) [1–3].

Zooming out to the big picture, one can see that society lives in and is supported by numerous, intersecting layers of large-scale infrastructure. We rely on the transportation infrastructure to go to work or get back home; we need the sewage system to keep our living places hygienic; we depend on the energy network to power our devices and appliances. The list can go on, and while we may not notice when everything works as intended, if any layer of infrastructure is suddenly made absent, society can come to a standstill. Thus, the health of infrastructure is paramount in the list of national priorities. This notion is paralleled by the National Academy of Engineers Grand Challenges for restoring urban infrastructure. For infrastructure, the main antagonists to good infrastructural health are corrosion [4,5], vibration and fatigue [6–8], aging [9], natural and man-made disasters [10,11], which work to either gradually or rapidly induce structural failure [12,13]. For years, we have relied on manual inspections to detect damage and determine whether remediation was necessary. This reliance on manual labor is time consuming and highly skill dependent. Damages deep within concrete structures may not be realized until it is too late [14,15]. The result is a pressing situation in which large swaths of structures across the nation are in desperate need of maintenance and improvements, as highlighted by the dismal infrastructural grade issued by the National Report Card in 2017. We have furthermore arrived at a point at which we need to consider the future where an increasing population will place even further loads onto the already strained infrastructure. Recognizing the implications of this impending crisis, researchers from all types of backgrounds are racing to innovate technologies that can revolutionize our current way of dealing with infrastructure that is each day accumulating damage that is not always visible even to the trained eye.

The range of research, partly captured in this issue, is stratified from foundational research into the behavior of structures to prototype systems that are soon ready for commercialization. Some examples of research directed towards better understanding of structural behavior in this special issue include the modeling of various structural responses to normal and disaster level loads. Researchers have worked on modeling the behavior of structural components such as columns and shear walls [16,17], as well as different types of transportation infrastructure such as roads, railways, tunnels, and bridges [18–22]. In areas prone to typhoons, researchers modeled the behavior of high-rises to strong winds [23,24]. On the smaller scale, the propagation of guided waves has been modeled to help predict corrosion [25]. In contrast to theory and modeling are experimentalists who take a more hands on approach and perform testing. Examples include the flexural testing of high-performance steel beams, steel bar corrosion [26], testing of bonding behavior in reinforced concrete [27], among others [28,29]. At a higher level, using the current understanding of system mechanical behaviors, investigators have developed methods to identify, extract features, and classify the health of different structures using minimal knowledge of system behavior [30–35]. Supporting such work are other researchers that specialize in the long-term monitoring of damage and help strategize everything from sensor placement to understanding what the key parameters that need to be monitored are. Examples include work on developing of positioning systems that determine the best locations to measure structural vibrations, monitoring of tunnel deformations using GPS systems, monitoring of pipes to blast forces, etc. [36–41]. A large number of investigators focus on damage detection [42–46], in which sensing technologies are used to characterize (e.g., location, size, depth, etc.) damage at a shorter time frame than typical monitoring techniques. Examples include the use of vibration and acoustic signals to detect water leaks [47], the use of infrared to detect damage in beams [48], utilizing acoustic emission to detect wearing in pin connections [49], and the training of deep learning neural networks to identify damage in composite pipelines [50], and much more [51].

An interesting subset of the research on SHM and damage detection is driven by the multi-functionalities of piezoelectric materials [52–54], such as PZT (Lead Zirconate Titanate), which has a strong piezoelectric effect and is often used to generate and detect stress waves for SHM [55–57]. PZT has high bandwidth [58,59] and is often used to fabricate acoustic emission sensors/probes [27,49]. As reported in this special issue, PZT transducers have demonstrated the potential for a staggering range of applications [25–27,35,42,49], including the development of smart transducers that have recently shown to be able to monitor the health of structural components and interfaces and detect debonding and delamination damages. A recent development has even demonstrated the ability to use piezoelectric transducers to communicate information across a structure [60], potentially also picking up on damage as the stress waves propagate across the structure. All the above research and development have the potential to work with each other to produce new technologies and understanding in ways that cannot be expected. Examples can be found in the most recent research in bolt looseness detection [61]. The bolt is among the most ubiquitous structural component found in almost all types of infrastructure [62,63]. The importance of the bolted connection is for instance supported by recent Bureau of Safety and Environmental Enforcement (BSEE) statements that warn how disastrous oil spills can result from neglecting to constantly inspect and monitor bolted connections in offshore equipment. Recent research has shown the innovative ways to use vision [62] and vibro-acoustic signals [63] to rapidly detect and even quantify bolt looseness. For example, by listening to the sounds generated by the light percussion of a bolt by a small impactor [64,65], a neural network, combined with complex signal processing algorithms, can tell the operator the preload of the bolt [66], and potentially what other bolts (e.g., if installed in a flange) need servicing. The percussion-based method shall have potential in damage detection of various civil structures, such as concrete filled steel tube structures and steep plate composite structures. Another emerging research in SHM is the use of robotic vehicles to perform inspection and damage detection in areas that are inaccessible or not easy to access to human [67,68].

Despite the seemingly grim situation of current infrastructural health, the volume of research activity aimed at structural health monitoring and damage detection is rapidly expanding and evolving. The innovation presented in this issue and in other literature should give the reader a sense of optimism for the future. Perhaps soon in our lifetimes, highly intelligent infrastructure, analogous to the increasingly commonplace “smart home”, can be something that can be taken for granted by the masses.

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